Auckland
Regional Council
TE RAUHITANGA TAIAO

High Turbidity and the Restoration of Lake Wainamu

July 2005 Technical Publication 274

Auckland Regional Council
Technical Publication No. 274, July 2005
ISBN: 1-877353-94-9

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Auckland Regional Council

NIWA Client Report: HAM2005-074
July 2005

NIWA Project: ARC05231

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1 Executive Summary

Joint studies by NIWA, the ARC and the Lake Wainamu community have established that the high level of turbidity in Lake Wainamu is not caused by high phytoplankton levels and is unlikely to be produced by silt inputs from the inlet streams. The optical model developed for the lake indicated that its turbidity is caused mainly by suspended organic particles. The origin of these particles was not determined, but it appears likely that re-suspended silt from the lake bed is a major contributor.

Data on water quality (i.e., temperature, oxygen, turbidity, pH, conductivity) were collected from monthly monitoring and the use of 3 *in situ* datasondes recording at 20 minute intervals from September to December 2004. This high resolution, time-series data detected several lake-mixing events and indicated that silt from the lake bed is being periodically re-suspended in the water column, probably by wind-induced water movements. Analysis of meteorological data to link temperature reductions in the surface waters of the lake (indicative of water mixing) with wind direction and speed, is now required to confirm this.

Coverage of the lake bed in the littoral zone by algal mats and rooted macrophytes increased markedly in 2005 and can be expected to have consolidated sediments in shallow waters thereby reducing silt disturbance. This plant re-growth was accompanied by a marked reduction in suspended solids levels, a reduction in turbidity and an increase in water clarity. Secchi disc depth (providing a measure of water clarity) exceeded 2.5 m in 2005 and was well above the maximim value of 1.4 m recorded over the previous 9 years. It is close to the peak value of 2.3 m recorded in 1994 before the lake began to deteriorate, and is therefore now being restored.

The ‘trigger’ for the plant re-growth in the littoral zone is unknown. However, the removal of large numbers of exotic fish from the lake by the ARC’s netting programme may well have helped facilitate this. Such fish have been shown to reduce water clarity in other North Island lakes (Rowe et al. 2003), and their benthic feeding behaviour may well disturb the sediments thereby preventing plant seedlings from establishing and allowing more silt re-suspension by water movement.

A sudden increase in turbidity occurred in the lake on Sunday 31st October 2004 and was caused by the subsidence of a section of the sand-dune that fringes its north-western shoreline. This subsidence resulted in turbidity increasing from 10 to over 60 NTU and its effects lasted for two weeks in surface waters and over a month in bottom waters. Such events may be a natural consequence of dune encroachment into the lake, or they may be artificially induced. As a dune subsidence could potentially lead to macrophyte collapse, it will be important to determine whether such events are natural and whether prevention is feasible.

Water clarity in this lake is expected to continue to improve throughout 2005. However, its maintenance may depend on macrophyte coverage being sustained within the lake. The cause of the macrophyte collapse after 1995 is unknown and so it may re-occur. The options for macrophyte management therefore need to be determined in order to sustain the recovery of water clarity this lake.

2 Introduction

Analysis of water quality data collected between 1990 and 2000 for a range of Auckland lakes (Gibbs et al. 1999) indicated that water clarity declined in Lake Wainamu after November 1995. This decline in clarity (as measured by Secchi disc depth) was preceded by an increase in nitrate concentrations and turbidity in August 1995 but the causes of these changes are unknown. Macrophytes in Lake Wainamu were still growing to a depth of 5.5 m in April (autumn) 1995 (Champion 1995), and may have collapsed during the winter of 1995. This could account for the high nitrate and turbidity levels recorded in August 1995. However, the time frame for such events seems short. After 1996, the lake remained turbid (Secchi disc depth close to 1.0 m) and by 1999 the macrophytes were effectively absent.

The introduction of exotic fish (specifically koi carp) was raised as a potential cause of the decline in water clarity and macrophytes. However, a fish survey in 2002 (Rowe & Smith 2002) failed to find any evidence of koi carp in the lake. Other exotic fish species (perch and goldfish) were both present and abundant. A number of the goldfish were bright red and large (>200 mm long) and may have given rise to the earlier reports of koi carp being present. Neither perch nor goldfish were present in the lake in 1979 (Thompson 1979), so had been introduced since then. The fact that some goldfish were still bright red in 2002 and not the golden-brown colour associated with long-established feral populations indicated that the introduction of these fish may have been relatively recent and may have coincided with the introduction of the exotic macrophyte, *Egeria densa*, around 1991. Rowe & Smith (2002) indicated that these fish could well contribute to the current low water clarity of Lake Wainamu by disturbing lake sediments and helping to re-suspend silt, or by promoting phytoplankton growth through predation on zooplankton, or by a seasonally varying combination of both of these. However, there were insufficient data to determine the nature and causes of the high turbidity in the lake at this time.

In 2003, a small experiment was carried out in Lake Wainamu to examine the role of large fish such as perch and goldfish in silt resuspension and macrophyte regrowth (Rowe et al. 2003). Exclusion cages were placed over the lake bed in shallow (1.8 m max. depth) water in April 2003 and monitored over the next 3 months to determine whether the absence of fish would result in any changes in the surface of the lake bed. Over this period, algal mats appeared on the surface of the lake bed and formed small (5 – 10 cm diameter) patches both inside and outside the cages. These patches were larger and thicker inside the cages suggesting that fish disturbance of the lake bed could be occurring. The patches covered the silt and prevented its resuspension, however, once disturbed, the silt raised the turbidity of the water and settling experiments indicated that it would take at least seven days for the water to clear provided no further disturbance occured. Although the loss of macrophytes and subsequent disturbance of the lake bed by fish was a possible mechanism for the increase in turbidity in Lake Wainamu, a number of other mechanisms were also possible and could only be distinguished after characterisation of the suspended particles contributing to the high turbidity. In this respect, the high turbidity could be caused by one or more of; (a) inorganic clay particles introduced to the lake during flood flows in the inlet streams, (b) a high concentration of phytoplankton cells related to high nutrient levels, (c) a high level of organic particles (e.g., silt resuspended from the lake bed, iron flocs), or (d) a seasonally varying combination of several of these factors. A seasonally-based survey of water quality was therefore needed to characterise the constituents of the water contributing to its turbidity. Additional studies would subsequently be required to identify the provenance of these constituents and to throw some light on the mechanisms by which the high turbidity is maintained in the lake. Accordingly, a 2 year plan was developed, and the ARC contracted NIWA to carry out the first years work.

Specifically, NIWA undertook to:

- develop an 'optical model' of the lake in order to identify the main constituents of the water column contributing to low water transparency;
- help carry out monthly sampling of key variables (including phytoplankton and zooplankton) likely to affect turbidity and water transparency;
- use oxygen/temperature profiles and deploy data loggers at a range of depths (and locations) to determine the dynamics of lake stratification and water mixing;
- install exclusion cages to determine whether fish disturb the lake bed and hinder macrophyte re-growth; and
- analyse sediment cores to determine whether the existing plant seeds could re-establish the native macrophytes.

After this programme was developed and approved, funding became available for the ARC to successively reduce the density of exotic fish in Lake Wainamu by gill netting. Over the period April 2004-February 2005, a total of 2875 fish were removed from the lake including 2072 perch, 648 goldfish, 130 rudd, 14 tench, and 4 catfish. The netting was carried out over 3 occasions and reduced the relative abundance of perch, as measured by catch per unit effort (CPUE), from 7 fish net^{-1}night^{-1} to less than 2 fish net^{-1}night^{-1}.

Monitoring of the key variables affecting water clarity of the lake therefore assumed a second purpose, namely, to determine whether the reduction of these fish was associated with a change in water clarity and/or the variables that affect it. The data on fish removal will be reported separately, but by February 2005 the gill netting had reduced the relative abundance of perch in the lake by at least 70% (pers. comm G. Barnes). Rowe & Smith (2002) found that the fish fauna in Lake Wainamu was dominated by perch, goldfish and eels. The gill netting will have reduced the abundance of perch and goldfish in the lake (along with smaller numbers of rudd, tench and catfish present) but not the abundance of eels, gambusia or common bullies.

Because of the limited resources available for this investigation, some of the water sampling was carried out by the local community group. In addition, a proportion of the work related to identifying potential mechanisms that increase turbidity in the lake was funded by NIWA's Foundation for Research Science and Technology programme on lake ecosystems. As the ARC was unable to fund the second year of this investigation, this study has not been fully completed. This report therefore presents the interim results obtained to date and recommendations for the future based on this knowledge.

3 The optical model

3.1 Introduction

The aim of this model is to determine the dominant optically active components in the water. The main options are; CDOM (coloured dissolved organic material), phytoplankton, and non-phytoplankton suspended particles. Depending on which of these dominate, we can then begin to consider the best ways to address restoration of the lake.

Light attenuation is a product of scattering (b) and absorption (a) of light. Scattering in non-clear waters is overwhelmingly by particles and is the best correlate of Secchi disc clarity, whereas absorption is by the water itself, and by both dissolved coloured materials and particulate coloured materials. Absorption affects clarity, but will mainly affect colour in this case. Attenuation (K_d) is related to absorption and scattering in a complex way and is the observed rate of decline of irradiance with depth.

All three of these processes need to be measured to produce an optical model for the lake.

3.2 Methods

Scattering was assessed through both water clarity (Secchi disk) and turbidity measurements. Particulate concentrations were measured as total suspended solids and chlorophyll *a* (see section 4).

We measured spectral attenuation within the water column using the TRIOS submersible spectroradiometer. We also measured the beam attenuation coefficient using a beam transmissometer. This measures beam c (units m^{-1}), which approximates to scattering plus absorption (i.e., beam $c = b + c$). The scattering coefficient b (units m^{-1}) was estimated from the absorption coefficient a (units m^{-1}) subtracted from beam c.

The relative abundance of different types of particles were assessed from our estimates of particulate absorption. Gear failure and lack of availability limited these measurements to 2 months (December 2004 and February 2005).

We also measured the spectral absorption of filtered lake water, using a 0.2 μm filter and a 10 cm path length, to assess absorption by dissolved materials. We measured the absorption of particles on filters with and without bleaching by methanol. Bleaching removes plant pigments, and thus allows distinction between 'phytoplankton' particles and 'others'. For simplicity we used a correction factor of 2 for multiple scattering at all wavelengths.

3.3 Results

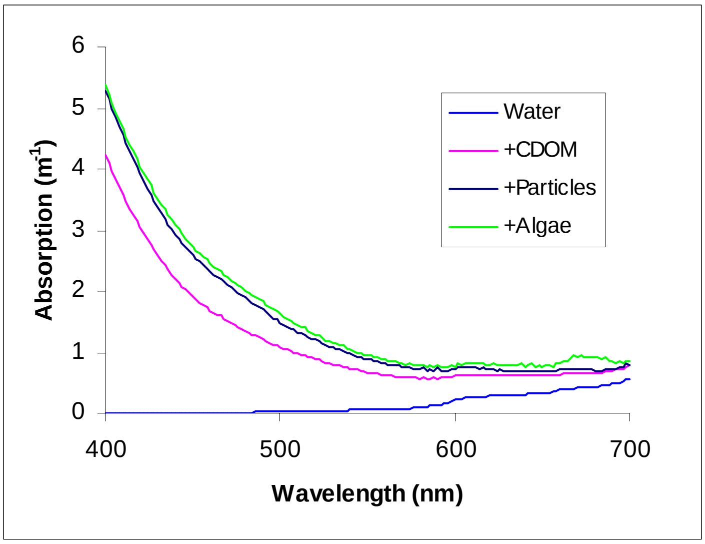
Figure 3.1 shows the deconvolution of the absorption coefficient in December 2004. It is apparent that, at this time, algal cells made very little contribution to absorption. The corollary of this is that little gain in water absorption can be obtained by reducing algal biomass.

There was a large contribution from CDOM to light absorption in this lake. CDOM is likely to be sourced from the bush catchment, from decomposition of the marginal vegetation (e.g., the floating sudd) and/or from decomposition of settled organic matter on the lake bed.

Particles with a similar absorption spectrum to CDOM also made a significant contribution. Together with CDOM, these coloured, non-algal particles contributed most of the absorption. The provenance of these coloured particles is one of the key issues for improving water clarity.

The orange-brown colour of the water is due to absorption of blue and green light within the water column. While Figure 3.1 contains no information on the nature of scattering particles, it suggests that the particles responsible for scattering will include a high proportion of non-algal material.

Figure 3.1:
Deconvoluted absorption coefficient from Lake Wainamu for December 2004. The plotted lines are cumulative, such that the lower line (blue) is for water, the next lowest line (red) includes absorption from water plus CDOM, the next line (black) includes absorption from water plus CDOM plus particles, and the last line (green) adds algae to the list.



The February 2005 data (Figure 3.2) confirm that the dominant components contributing to absorption tend to be CDOM, and non-algal particulates. At this relatively clear-water time, (Secchi depth was 1.95 m) algae played only a minor role in water column optics. Chlorophyll *a* concentrations measured in surface waters at this time were 3.4 mg m^{-3} with less occurring at 5 m (see section 4). Generally, we can expect an average absorption coefficient (*a*) of approximately 0.01 m^{-1}, for each mg m^{-3} of chlorophyll *a*; thus 10 mg m^{-3} of chlorophyll *a* would contribute an absorption of around 0.1 m^{-1}. The absorption due to pigments seen in the February data would correspond to a chlorophyll *a* concentration of approximately 7 mg m^{-3} . This is almost double that recorded in the lake at that time, nevertheless it still indicates that planktonic algae are not a major source of light absorption.

The absorption spectra of the non-algal particulates is similar to that of CDOM, and is typical of organic detritus (e.g., silt) and dissolved organic material bound to mineral particulates.

Figure 3.2:
The spectrally resolved, deconvoluted absorption coefficient for Lake Wainamu on 12 February 2005. (The blue line represents water only, the red line water plus CDOM, the black line water plus CDOM plus non-algal particles, and the green line the sum of all particles and chemicals).

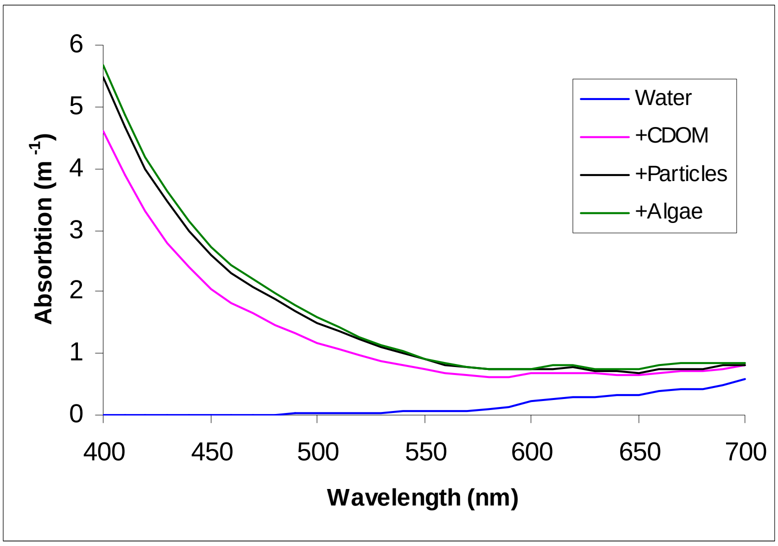


Figure 3.3 shows the absorption spectra for three of the components contributing to light absorption (i.e., CDOM, all particulates, and very small particulates) normalised to the maximum absorption of each. Small particulates represent material that passes through a GF/F filter (nominal pore size approx 1 μm), but not a 0.22 μm filter. Such materials are generally colloids, or very fine particulates. Particulate organic debris, or organic-coated mineral particles generally show a similar spectrum to CDOM, with absorption (*a*) increasing exponentially with decreasing wavelength, but at a slower rate of increase than CDOM. Our data are therefore consistent with the view that the

larger particulates are of this type. The very fine particulates fall between the CDOM and large particulates, but closer to the former.

Figure 3.3:

Absorption spectra for CDOM (lower, blue curve), particulates (upper, red curve), and small particulates (middle, green curve) in Lake Wainamu in February 2005. For comparison, the curves have been normalised to the highest absorption and plotted on a logarithmic Y-axis. The red curve is for particulates that pass through a GF/F filter, but are caught on a 0.22 µm membrane. (Text on the figures indicates best-fit exponential regressions between relative absorption and wavelength; the black lines are the regression lines).

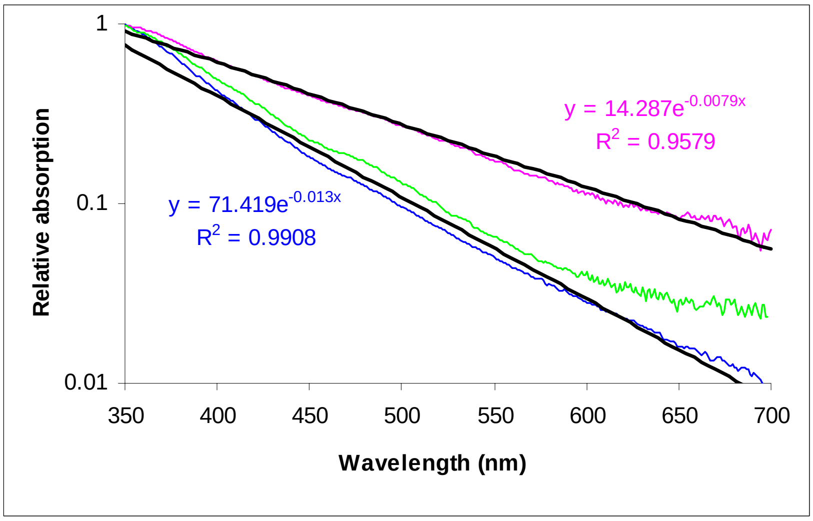
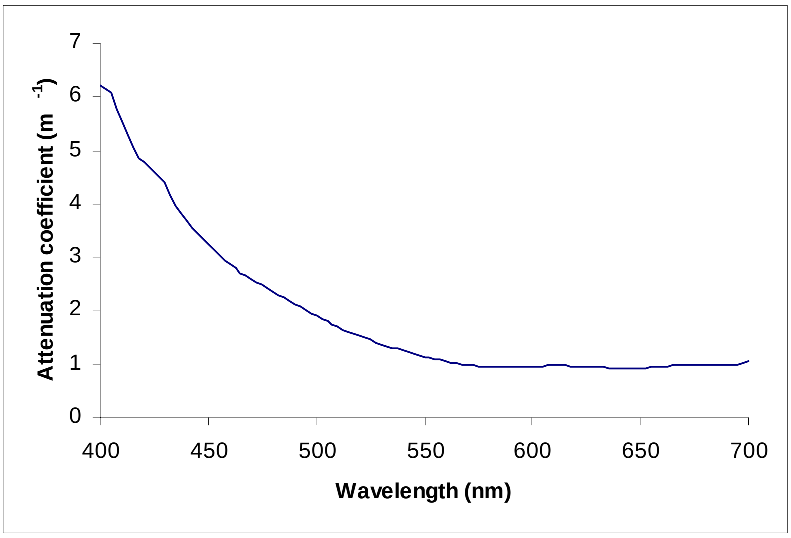


Figure 3.4:

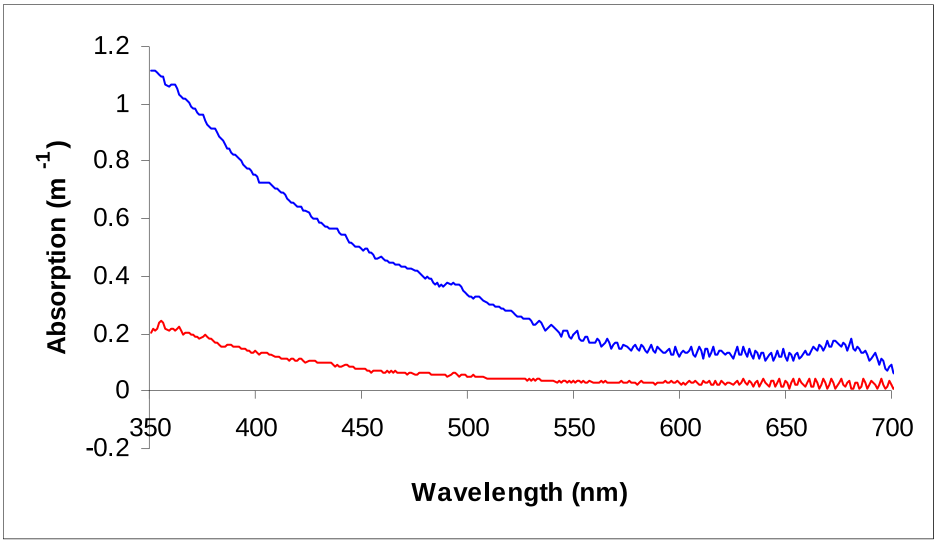
Spectrally resolved attenuation coefficient measured in the lake itself in February 2005.



The similarities in shape between the total absorption spectrum (Figure 3.2) and the attenuation spectrum (Figure 3.4) attest to the role absorption plays in determining the colour of the water. Average light attenuation over the photosynthetically active radiation (PAR) range was 1.01 m^{-1}. The measured downwelling light attenuation coefficient (K_d) for Lake Wainamu is, as expected, slightly higher than the absorption coefficient and thus, as also expected, shows the same dominant spectral shape when compared with deconvoluted spectra taken on the same day in February 2005 (i.e., Figure 3.4).

Overall, dissolved, very fine, and larger (non-algal) particulates are the major absorbers of light in Lake Wainamu. The possibility that the mineral component contains a large proportion of hydrated iron hydroxide/oxide was briefly tested by soaking a filter in 50% Nitric acid (to dissolve iron). This resulted in a small decrease in absorption (Figure 3.5), suggesting that the role of iron precipitates was minor at this time (i.e., February 2005). However, their role may have been greater in November 2004 (see sections 3.4 and 5.4).

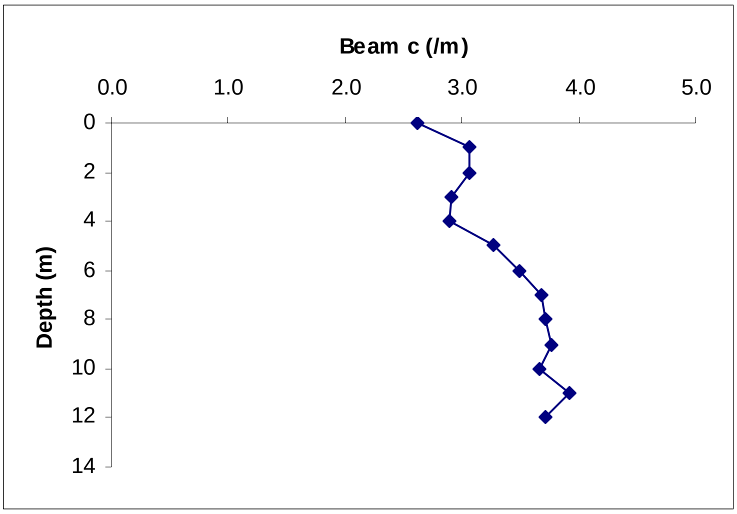
Figure 3.5:
Total particulate absorption in December 2004 at Lake Wainamu (upper blue line) and absorption due to acid-soluble materials (lower, red line).



To determine the total absorption at a given depth, we must weight the spectral absorption coefficient of a given variable by the irradiance spectrum at that depth. We can use the attenuation coefficient spectra obtained from the TRIOS spectroradiometer to do this. Using this correction, we can estimate that, at 2 m depth, total attenuation of 0.86 m^{-1} is made up as follows by water (0.23), CDOM (0.45), phytoplankton (0.04), and other particles (0.14).

In February 2005, beam *c* was approximately 3 m^{-1} in the upper part of the lake, increasing to nearly 4 m^{-1} deeper in the lake (Figure 3.6). For the depths where the absorption coefficient (*a*) was estimated from laboratory procedures, we can suggest that, since $c = a + b$, *b* (the scattering coefficient) approximates to 2.1 m^{-1}. Some degree of closure on this estimate of scattering can be obtained by comparison of beam attenuation with Secchi depth (1.95 m on the February sampling day). Examination of Figure 2.5 and associated text in Davies-Colley et al. (1993) shows that for a Secchi disk depth of 1.95 m and attenuation coefficient of 1 m^{-1} we could expect a beam attenuation coefficient of approximately 2.9. This is consistent with the estimates of beam c in the upper water column from transmission measurements with a beam transmissometer (Figure 3.6).

Figure 3.6:
Beam c (i.e., scattering + absorption) estimated from transmission measurements with a beam transmissometer in Lake Wainamu.



3.4 Discussion

Optical measurements have been made to construct a mathematical picture of what contributes to the absorption (*a*) and scattering (*b*) of light within Lake Wainamu. We are confident in these measurements because of the degree of internal consistency (closure). Good closures have been obtained, in that our estimates of *a* from laboratory measures are very similar to, but appropriately less than, the measured in-lake attenuation coefficient estimates, and the beam *c*, (i.e., *a*+*b*) estimates are consistent with measured Secchi disk depths. Estimates of *a* and *b* are also generally consistent with the measured chlorophyll *a* and turbidity. Finally, internal consistency is present in that our estimates of *a* and *b* agree with independent measures of K_d. There is a rough approximation of K_d as

$K_d = 1.17(a^2 + 0.174ab)^{1/2}$ (see Davies-Colley et al. 1993 for derivation and limitations).

This relationship predicts a K_d of 1.05 m^{-1} for Lake Wainamu on the February sampling occasion, and our measured average K_d for PAR was 1.01 m^{-1}. If the estimates of chlorophyll *a* concentration from phytoplankton *a* of ~5 mg m^{-3} are correct, the simple relationship

b = Chl$a$ x 0.09 (Vant and Davies-Colley, 1984)

suggests that, of the estimate of 2.1 m^{-1} for *b*, phytoplankton may contribute 0.45 m^{-1} or 21%. The majority is contributed by mainly organic, or organic-coated particles, and it is reducing these that may offer the best hope of increasing water clarity. The intense brown water colour, on the other hand, is mainly associated with dissolved organic matter, though particulate detrital material is also of importance. The low clarity in Lake Wainamu is not, at least on the occasions that we have sampled, been due to algal proliferation. Water quality *per se*, in terms of high algal growth potential, is not implicated as the major factor in the decline of the lake.

The nature and origin of the particulate organic matter could not be determined by this analysis and a number of sources are possible including wind-blown particles from the dunes, silt from the lake bed, iron flocs, fine suspended solids (e.g., clays) from the inlet streams, or a combination of these. Blooms of planktonic algae have been reported in the lake at times and these no doubt affect water appearance on these occasions and add to the turbidity produced by the organic particulates. Disturbance of silt on the lake bed by the introduced, bottom-feeding fish may also occur. Loss of macrophytes from around the edge may enhance re-suspension of silt by both wind and waves, as well as by fish. Iron precipitation (the lake is set in an iron-sand catchment) may be involved in mineral particle generation, but this seems to be a relatively small contribution at least in direct terms when the lake is well oxygenated. The lake is, however, polymictic and iron precipitation may be sporadically important when anoxic hypolimnetic water containing soluble reduced iron species is mixed to the surface and precipitates as insoluble oxidised iron (See section 5.4). Coating of these particles in organic material may disguise their origins from simple optical characterisation. The colloidal material indicated by the strong colour collected onto membrane filters may also contain ferric materials. Finally, the proliferation of the sudd vegetation around the margins of the lake may be an important source of colloidal and fine particulate organic matter.

4 Monthly water sampling

4.1 Introduction

Up until July 2004, water sampling in Lake Wainamu was carried out on a quarterly basis and samples were collected from the surface and at 5 m. This regime encompasses the major seasonal variations in key variables and any differences between 0 - 5 m, but quarterly sampling can miss critical periods in lakes such as the onset and break down of summer stratification, the true maxima and minima for certain variables, and in small lakes it may miss important changes related to local variations in climate or events. Similarly, sampling at the surface and at 5 m may miss important changes in deeper waters such as summer deoxygenation. Monthly sampling is required to provide a more detailed picture of temporal changes in key variables such as phytoplankton, nutrients, water transparency, and turbidity. Monthly sampling also provides an opportunity to obtain a better understanding of lake stratification and hence mixing processes from the changes in temperature and oxygen with depth. The sampling frequency in Lake Wainamu was therefore increased over 2004/2005 to a monthly interval. In addition water samples were collected from a greater range of depths to obtain a better picture of variation with depth.

The historic (back to 1993) seasonal data on water quality variables in Lake Wainamu provides a baseline against which the new data can be compared to determine any long-term changes in lake status. However, not all variables have a bearing on the issue of high turbidity in Lake Wainamu. Hence in this section we present the data for those variables that are related to the turbidity issue. The full dataset is archived by the ARC.

4.2 Methods

Each month the lake water was sampled by either the Auckland Regional Council (ARC), NIWA, or the local community group assisted by the ARC. Water samples were taken from the surface and from one or more of the deeper depths in the lake using a Van Dorn water sampler. Samples were also collected from the 2 main inlet streams. Water samples collected over 2004/2005 (up to April 2005) are listed in Table 4.1.

Subsamples of water were kept aside for later analysis of phytoplankton and zooplankton species composition by NIWA. Samples were preserved in lugols solution and 10% formalin respectively, and later examined microscopically. Species were identified and counts of cells (for phytoplankton) and individual animals (for zooplankton) were used to determine changes in species composition over time.

Analyses of the samples were carried out by WaterCare Services Ltd. in Auckland. Variables measured included chlorophyll *a*, conductivity, pH, suspended solids, and turbidity. Measures of plant nutrient levels included ammoniacal nitrogen, nitrate nitrogen, total Kjeldahl nitrogen, dissolved reactive phosphate (DRP), and total phosphorus. In addition to the water sampling, oxygen concentratrations and temperature levels throughout the water column were measured on each sampling date and the Secchi disc depth was recorded for the lake. The raw data provided by WaterCare Services Ltd. to the ARC were examined and corrected for spurious results and/or transcription errors. Data were plotted as time series to identify any major trends and correlation analysis was used to identify the main links between the variables affecting water clarity.

Table 4.1:

Location and timing of water sampling in Lake Wainamu.

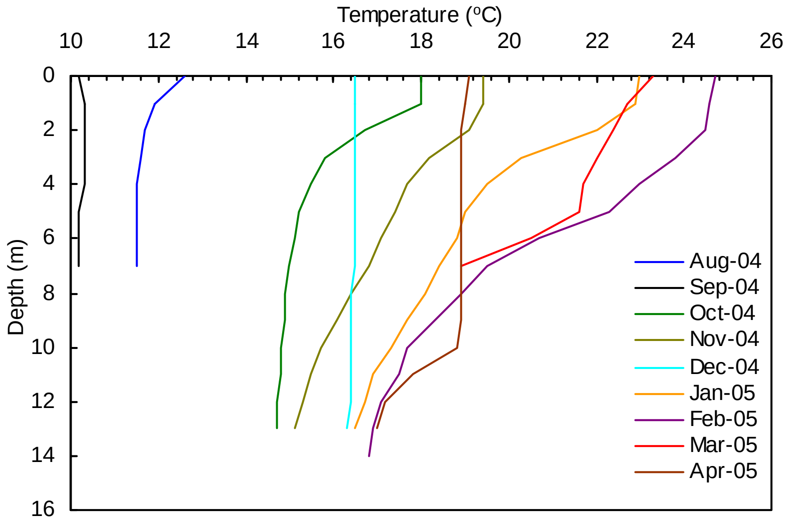
Month	Surface sample	Depths (m) of samples from the lake water column	Samples from inlet streams	
			Wainamu	Pudding
Aug 2004	Yes	5	Yes	Yes
Sep 2004	Yes	5	Yes	Yes
Oct 2004	Yes	1, 6, 9, 11	Yes	Yes
Nov 2004	Yes	5	Yes	Yes
Dec 2004	Yes	4, 8, 12 (plus tube sample)	No	Yes
Jan 2005	Yes	5	Yes	Yes
Feb 2005	No	4, 13.5	Yes	Yes
Mar 2005	No	2, 6	Yes	Yes
Apr 2005	Yes	3, 6, 9, 13	Yes	Yes
May 2005	Yes	8	Yes	Yes

4.3 Results

Water temperatures in Lake Wainamu ranged from a low of 10.1 ºC in bottom waters in September 2004 to a high of 24.7ºC in surface waters in February 2005 (Fig. 4.1). This range is typical of that reported for the past 15 years, except that 10.1ºC represents a record low for the lake. The previous lowest temperature was 11 ºC.

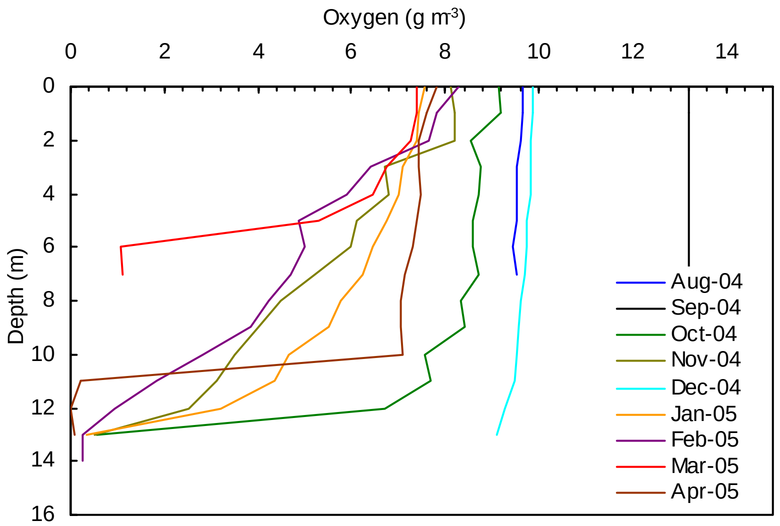
The lake was fully mixed in August and September. Lake warming started in October with thermal stratification developing at 2 m. Stratification intensified and the thermocline deepened as warming continued through spring. The lake was fully mixed again in December 2004, due to a prolonged period of rain, wind and cold weather. Stratification and lake warming resumed in January 2005 with the upper water column reaching maximum temperatures in February. At this time, surface water temperatures were close to 25 ºC whereas bottom water temperatures were some 8 ºC cooler at 17 ºC with the thermocline being a gentle gradient between 2 m and 12 m depth. Cooling occurred during March and the thermocline strengthened as it deepened with the warmer epilimnion extending down to 5 m. By April, temperatures in the epilimnion had dropped from 23 ºC to 19 ºC, and the thermocline had moved down to 10 m.

Figure 4.1:
Monthly temperature profiles in Lake Wainamu over 2004/2005.



Summer temperature stratification isolates surface from bottom waters in the lake and the lack of vertical mixing reduces the supply of oxygen to deeper waters allowing them to become oxygen depleted. This was evident in the oxygen profiles for Lake Wainamu during summer months (Fig. 4.2).

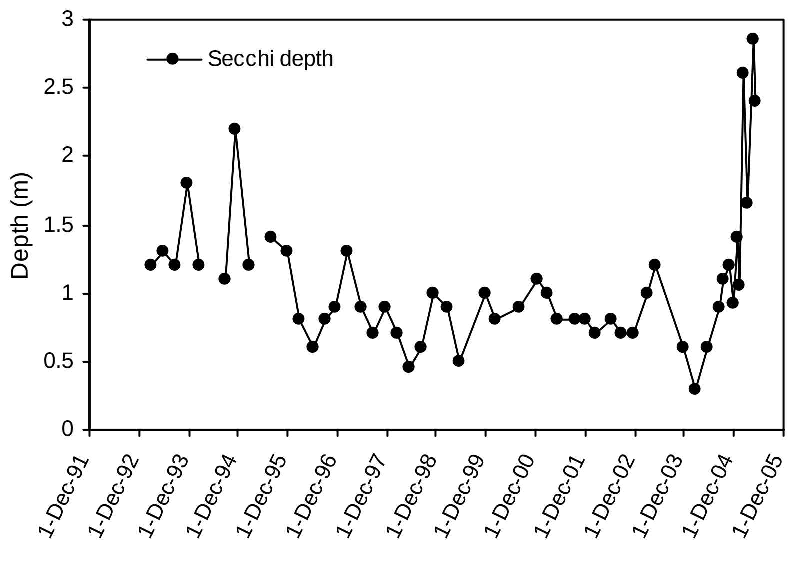
Figure 4.2:
Monthly oxygen profiles in Lake Wainamu over 2004/2005.



Oxygen concentrations were high when the lake was cold and fully mixed and declined markedly in bottom waters as stratification developed. Even in December, when the lake water was temporarily fully-mixed, a gradient in oxygen concentrations between surface and bottom waters was still present. When stratification was maximal (i.e., March 2005), oxygen concentrations fell from 7-8 g m^{-3} in surface waters (i.e., above 5 m deep) to less than 1 g m^{-3} at 6 m. At this time, the water below 6 m would have been close to anoxic and no fish or invertebrates would have been able to survive for long in this zone. Oxygen concentrations were restored down to 10 m by April, so the period of bottom water column anoxia for the majority of the lake was confined to about one month. In contrast the sediments of the lake were likely to have become anoxic as early as October 2004 and, except during the mixing event in December 2004, remained anoxic through to April 2005 and probably much later.

Changes in water clarity, as measured by Secchi disc depth, are shown in Fig 4.3. Historical data on all water quality variables monitored up to and including 1998 were previously reported by Gibbs et al. (1999). It is apparent that a major recovery in water clarity occurred in Lake Wainamu in January 2005, with Secchi disc values in excess of 2 m occurring for the first time since 1995 (i.e., 10 years ago).

Figure 4.3:
Secchi disc depths in Lake Wainamu (1992-2005).

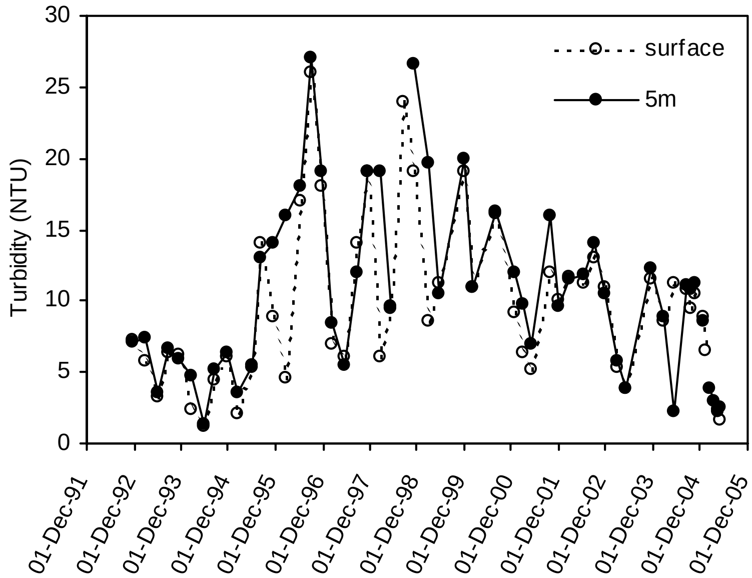


This recent change is also reflected in the monthly turbidity levels in the lake (Fig. 4.4). Turbidity levels increased abruptly in 1995 when peak levels rose to well over 10 NTU and remained over this level until January 2005. Since 1998, however, peak turbidity levels have tended to decline each year and they finally reached the pre-1995 levels in January 2005. Seasonal variation in turbidity levels is also apparent, within the limitation of the 3-monthly data resolution. Maxima tended to occur between August and November each year (i.e., late winter to spring months) with minima between

February and May (late summer to autumn months). In general, turbidity levels at the surface tracked those at 5 m, with the levels at 5 m tending to be slightly higher than those at the surface on most occasions. Peak levels occurred in 1996 and 1998 and have steadily declined since then.

Figure 4.4:

Turbidity levels recorded in Lake Wainamu (1992-2005).



Suspended solids concentrations also declined after 1998, however, this was more apparent in mid-water (5 m depth) than at the surface (Fig. 4.5). Suspended solids concentrations in other ARC lakes are generally greater in bottom waters than near the surface (Gibbs et al. 1999), but in Lake Wainamu showed little consistent pattern between depths until after 1998. Lowest levels occurred in 1999 and in 2004 and 2005. Highest levels (>8 g m^{-3}) ocurred in 1993, 1996, 1998, 1999, and 2000, but have not been recorded over the past 5 years.

The chlorophyll *a* concentrations in the lake are shown in Fig 4.6 at the surface and in mid-water, close to 5 m. Major increases (> 40 mg m^{-3}) in phytoplankton (i.e., chlorophyll *a* concentrations) occurred in surface waters of the lake in winter months (either May or June) in both 1996 and 1999, but such high levels have not been recorded since then. This may reflect the 3-monthly sampling regime which could miss short duration blooms between sampling visits, or the blooms may not have occurred. In 2005, chlorophyll *a* levels were generally very low (<5 mg m^{-3}). A small peak in surface chlorophyll *a* levels (13 mg m^{-3}) was recorded in August 2004 and corresponded with a bloom of the blue-green algae *Anabaena planktonica* (Table 4.2). This had a short duration, indicating that the quarterly monitoring programme has a high probability of missing peak biomass. Chlorophyll *a* levels rose again to >12 mg m^{-3}

on May 2005 suggesting that Lake Wainamu has a seasonal cycle with a winter maxima for phytoplankton production.

Figure 4.5:
Suspended solids concentrations in Lake Wainamu (1992-2005).

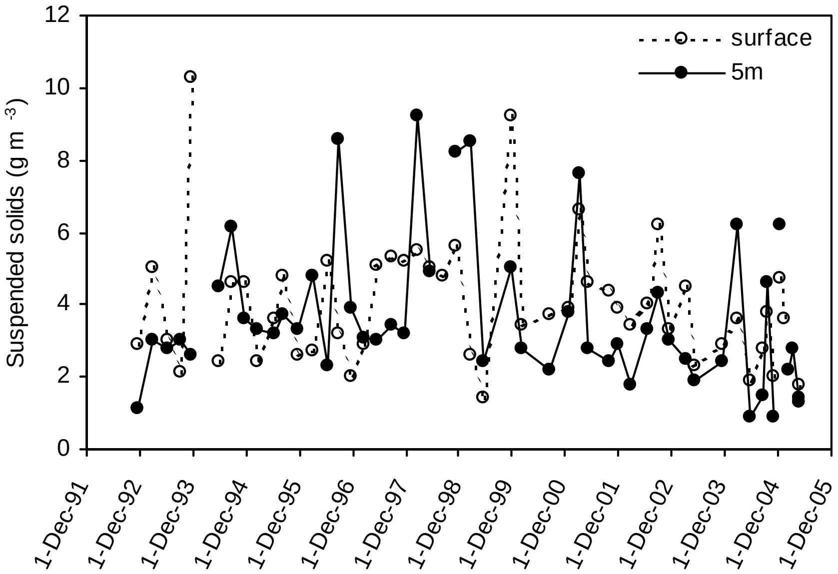


Figure 4.6:
Chlorophyll *a* concentrations in Lake Wainamu (1992-2005).

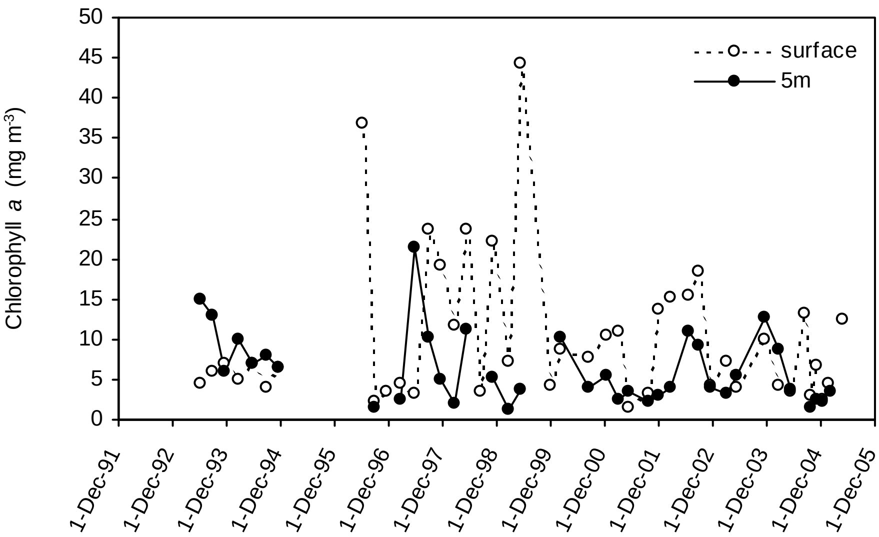


Table 4.2:

Phytoplankton species and % cell composition recorded in Lake Wainamu during 2004/2005 (blanks indicate where no cells for the species were found) .

Species	Proportion of total cells (%)						
	Aug-04	Sep-04	Oct-04	Nov-05	Dec-04	Feb-05	Mar-05
Blue greens (Cyanophyceae)							
Anabena planktonica	94.4	86.3	80.6	0.4	1.1	0.3	
Greens (Chlorophyceae)							
Scenedesmus sp.	0.1		0.8				
***Euglena acus* sp.**							
Ankistrodesmus / Monorahidium			2.7	2.6			
Elakotothrix gelatinosa			0.2				
Nephrocytium lunatum			0.4				
***Oocytsis* sp.**			2.0	3.1	0.2		
Quadrigula lacustrus			0.1				
Kirchneriella sp.				1.3		42.6	
Gloeocystis planctonica				2.9		11.4	
Planktosphaeria gelatinosa						4.6	80.5
Sphaerocystis schroeteri						4.6	
Diatoms (Bacillariophyceae)							
Asterionella formosa			1.9	6.6	79.6	13.7	
Aulacoseira granulata	2.0	0.1				1.1	1.4
Aulacoseira granulata var. angustissima	1.1	13.5	1.4		6.3		
Aulacoseria sp.							
Fragilaria crotonensis	0.8				2.0		
Melosira varians	0.7				2.4		
Desmids (Mesotaeniaceae, Desmidiaceae)							
Closterium acutum			0.5				
Closterium acutum var. variable				1.8	0.1		2.8
Closterium sp.							
Mougeotia sp.	0.1						
Staurastrum sp.						0.6	
Staurastrum tangaroaii				0.5			
Staurastrum pingue				0.5			
Staurodesmus unicorns var. gracilis							1.0
Chrysophtya (Chrysophyceae)							
Ceratium hirundinella				0.3			
***Cryptomonas* sp.**			0.5				
Dinobryon sp.				62.9	5.3	12.0	3.7
Euglenophyta							
Haematococcus sp.						1.1	
Trachelomonas sp.						3.7	1.0
Dylakosoma pelophilum							5.4
Dinoflagellates (Dinophyceae)							
Ceratium hirundinella	0.2		0.1				
Mallomonas akrokomos			6.2				
Dylakosoma pelophilum				6.3	0.3		
Peridinium sp						0.6	3.4
Flagellates/Unicells < 5µm	0.4		2.5	10.8	2.8	3.7	0.9
TOTAL CELLS	**119292**	**71214**	**666**	**1876**	**8323**	**350**	**1668**

Table 4.3:

Zooplankton species composition in Lake Wainamu during 2004/ 2005.

Species	Species composition (%)					
	AUG	SEP	OCT	NOV	DEC	MAR
Copepoda						
Misc. Nauplii	33.9	45.6	19.4	19.7	21.7	0.0
cf. *Mesocyclops leuckarti*	20.6	13.3	0.0	2.9	1.4	29.1
Calamoecia lucasi	34.0	28.4	6.5	23.5	10.1	43.3
Cladocera						
Bosmina meridionalis	0.8	4.7	35.5	1.4	2.9	12.5
Daphnia carinata	10.7	5.9	6.5	7.2	1.4	4.1
Rotifera						
Polyarthra spp.	0.0	0.0	9.7	21.2	0.0	0.0
Asplanchna spp.	0.0	2.1	22.6	3.4	1.4	0.0
Synchaeta spp.	0.0	0.0	0.0	1.0	0.0	0.0
Trichocerca spp.	0.0	0.0	0.0	19.7	58.0	0.0

4.4 Discussion

The temporal changes in water clarity in Lake Wainamu appear to be related to changes in chlorophyll *a* concentrations, turbidity levels and suspended solids concentrations. In particular, the increase in water clarity in 2005 was associated with a marked reduction in turbidity and suspended solids.

Low suspended solids also ocurred in both surface and bottom waters in 1999 but water clarity was low at this time. This is probably because chlorophyll *a* levels were high and so replaced suspended solids as the main contributor to turbidity and low water clarity.

Correlation analysis of time series data for suspended solids, turbdity and Secchi disc depth are closely related over the entire period (1995-2005) and not just in 2005 (Table 4.4).

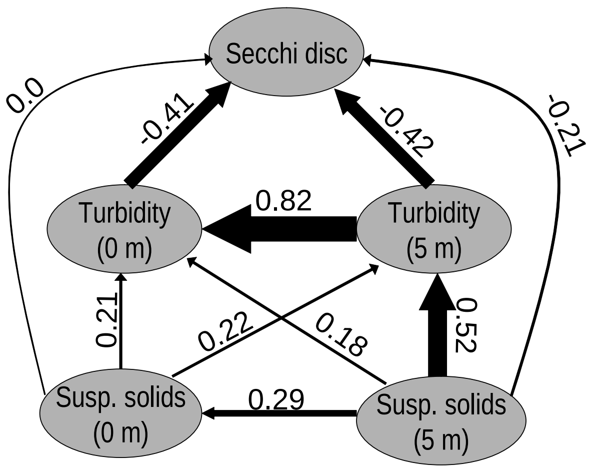
Table 4.4:

Correlation matrix for water quality variables measured seasonally in Lake Wainamu between 1993 and 2005 (correlations greater than 0.3 are significant at $P < 0.05$, the strongest correlations are shaded).

	Chlorophyll *a* at 0 m	Chlorophyll *a* at 5 m	Suspended solids at 0 m	Suspended solids at 5 m	Turbidity at 0 m	Turbidity at 5 m	Secchi depth
Chlorophyll *a* at 0 m	1.00						
Chlorophyll *a* at 5 m	0.24	1.00					
Suspended solids at 0 m	-0.02	0.05	1.00				
Suspended solids at 5 m	-0.11	-0.20	0.29	1.00			
Turbidity at 0 m	0.08	-0.24	0.21	0.18	1.00		
Turbidity at 5 m	0.11	-0.32	0.22	0.52	0.82	1.00	
Secchi depth	-0.22	-0.10	0.00	-0.21	-0.41	-0.42	1.00

In particular, the strength and direction of the correlations suggests possible causal pathways (Fig. 4.7). For example, Secchi disc depth was more closely related to turbidity than to all other variables. It was also inversely related to turbidity. In turn, turbidity at 5 m depth was most closely correlated with the turbidity at 0 m and was strongly related to suspended solids at a depth of 5 m.

Figure 4.7:
Correlations between key variables influencing water clarity in Lake Wainamu. The thickness of the black arrows indicates the relative strength of the relationship between two variables. The direction of the arrows indicates the likely direction of influence.



These relationships suggest that suspended solids concentrations at 5 m influence turbidity at 5 m which then affects turbidity at 0 m. Turbidity at both 0 and 5 m then reduced water clarity (Secchi disc depth). Neither the suspended solids concentrations at 0 m nor chlorophyll *a* concentrations at both 0 and 5 m were strongly related to secchi disc depth or turbidity. These relationships therefore suggest a mechanism in which suspended solids in bottom waters are driving the changes in turbidity levels in the water column and hence affecting the water clarity of the lake at the surface.

The monthly monitoring data indicate that the low water clarity and associated high turbidity in Lake Wainamu are not consistently related to high levels of planktonic algae as occurs in nutrient enriched lakes. In this lake, the turbidity is more a function of suspended solids. This finding concurs with the results of the optical model which also indicated a major role for suspended solids compared with planktonic algae.

5 Datasonde information

5.1 Introduction

Datasondes combine electronic data logging at high sampling frequency (mintues to hours) with a range of probes for measuring environmental variables and provide fine-scale, semi-continuous information on changes in environmental variables. Such changes often occur too quickly to be determined by monthly or quarterly sampling but analysis of changes over periods of minutes to hours can provide useful insights into the relationships among variables and hence on the causes of the changes. Datasondes are therefore a more useful tool than thermisters which record fine-scale changes in temperature only. However, datasondes are costly and produce large quantities of information, which then requires large amounts of time to process.

Datasondes are uniquely suited to the problems facing Lake Wainamu where short-term changes in turbidity need to be identified and followed throughout the lake to identify both their origin, spread, and duration. Such information does not replace longer term (e.g., monthly) sampling, but provides a very useful complement to it. Three datasondes were installed in Lake Wainamu to cover both bottom and surface waters as well as both ends of the lake.

5.2 Methods

The three sondes were each fitted with turbidity, temperature, oxygen, conductivity and pH probes and these were all calibrated in the NIWA laboratory before the sondes were deployed in the lake. The sondes internal clocks were set and synchronised and the sondes were programmed to record at 20 minute intervals from a fixed start time. Two sondes were placed near the middle of the lake close to its north-western end. They were fixed to a buoyed shotline with one sonde at 2.0 m below the water surface and the other sonde at 10 m. The lake bottom at this station was at 13 m. The third sonde was positioned at a depth of 2.5 m in 3.5 m of water in the shallower, south eastern end of the lake adjacent to the main inlet tributary. The sondes were all deployed in mid September 2004 and downloaded at monthly intervals when their batteries were replaced. The sondes were all retrieved in late December 2004.

The data were downloaded into Excel spreadsheets and checked and edited to remove spurious data. The sonde data were checked against the monthly water quality measurements (see section 4) and corrected to account for any machine induced biases, changes in calibration, and/or drift in values (e.g., from fouling of probes). Instrument differences in conductivity and turbidity from the monthly WaterCare Services Ltd. results were normalised to the WaterCare data although the units of $\mu S\ cm^{-1}$ have been retained in place of $mS\ m^{-1}$ for conductivity.

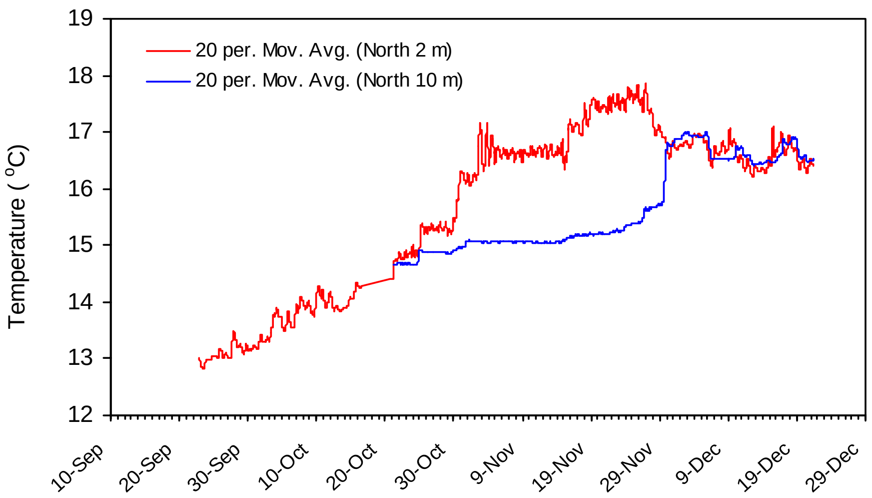
Large scale temporal changes in each variable, especially turbidity levels, were then examined and inter-relationships between the variables at various time scales determined by time series and correlation analysis.

5.3 Results

Changes in water temperature between surface (2 m) and bottom (10 m) waters over the mid-September to mid-December 2004 period are shown in Fig 5.1. Temperatures were much the same throughout the lake on the 22nd October, but diverged from then until 30th November when a major mixing event associated with strong winds resulted in complete mixing of the lake water and a similar temperature throughout the water column. A number of smaller mixing events occurred between 22nd October and 30th November and are indicated primarily by an abrupt increase in bottom water temperatures and a decline in surface water temperatures (more clearly shown in Fig. 5.2). December was characterised by a series of mixing events such that the lake remained fully mixed over this month. These data show that summer temperature stratification and water mixing in this lake are controlled as much by meteorological events (e.g., low fronts bringing wind and rain) as by an increase in solar radiation and hence air temperature. Complementary analysis of meteorological data would indicate the extent and duration of changes in wind and rainfall needed to result in full mixing (e.g., as occurred on 30th November, but not on 15th November).

Figure 5.1:

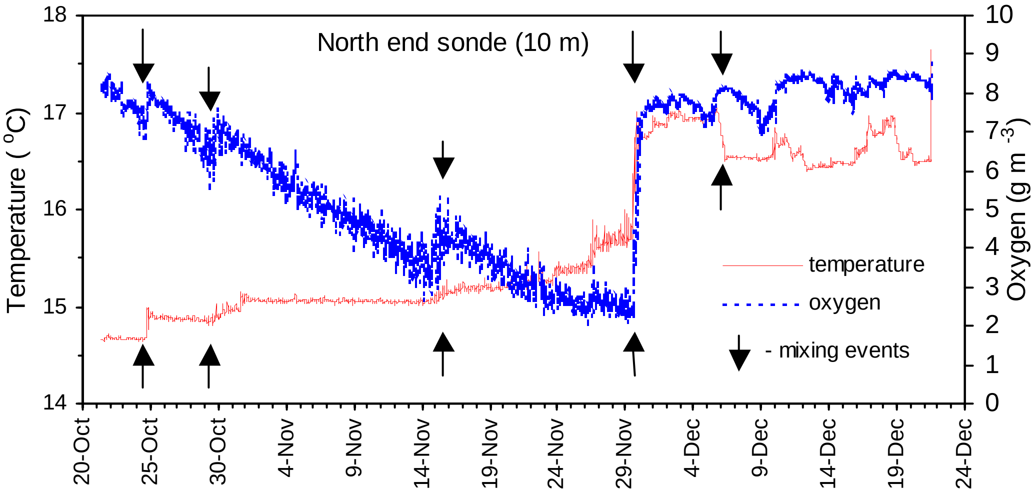
Differences in water temperature between the epilimnion or surface waters (i.e., at 2 m, red line) and the hypolimnion or bottom waters (i.e., at 10 m, blue line) in Lake Wainamu from September to December 2004 (lines are 20 point moving averages). Wide separation between the red and blue lines indicates a period of thermal stratification whereas close together, the lines indicate that the water column is completely mixed to at least 10 m.



The effects of lake mixing on oxygen concentrations in the hypolimnion are shown in Fig. 5.2. In general, oxygen concentrations at 10 m declined from 20th October to 29th November, with this decline being temporarily reversed on 24th October, 29th October and 15th November, when brief mixing events occurred. Full mixing on the 30th November resulted in oxygen concentrations being restored to the concentrations present before 20th October.

Figure 5.2:

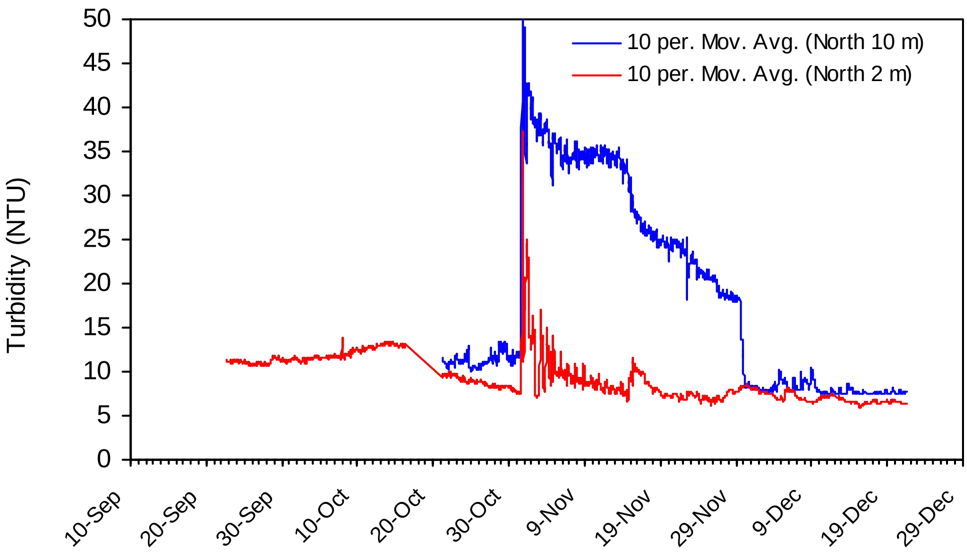
Changes in oxygen concentration in the hypolimnion (10 m) relative to temperature in Lake Wainamu between October and December 2005.



Turbidity levels near the lake surface and close to the bottom are shown for the period mid-September to mid-December in the north western end of the lake in Fig 5.3. Turbidity levels recorded near the surface (2 m) were already relatively high (11 NTU) by 22nd September. The level recorded from the water sample taken at this time was 10.8 NTU indicating close agreement between the sonde turbidometer and the measured values at 2m. Turbidity at 2 m and 10 m coincide on 30th November as the lake became fully mixed. Strong south-westerly winds occurred in the Auckland region at this time (Mangere Airport climate station) and so were probably responsible.

Figure 5.3:

Changes in turbidity levels at 10 m and 2 m in the north western end of Lake Wainamu between September and December 2004.



Turbidity levels in surface waters (2m) increased gradually in the north western end of the lake until mid-October after which a slow decline occurred. An abrupt increase in turbidity to a maximum value of 63 NTU occurred in surface waters at 3:50 pm on Sunday 31st October, 90 minutes after an even larger increase had occurred in bottom waters (10 m). This peak in turbidity levels in surface waters was followed by a steady decline over the next 14 days (compared with 29 days for turbidity in bottom waters) and it was characterised by large oscillations. The sharp decrease in turbidity at 10 m and the corresponding increase at 2 m on 15th November was related to a mixing event that occurred at that time (see Figs. 5.1, 5.2). This lowered the surface water temperatures while slightly raising both bottom water temperatures and oxygen levels. The large decrease in turbidity at 10 m to surface NTU levels on 30th November was associated with full mixing of the lake water (Fig. 5.1) and this event ended the 29 days of high turbidity in bottom waters. After this, turbidity levels at 10 m were similar to or greater than those in surface waters until the end of December.

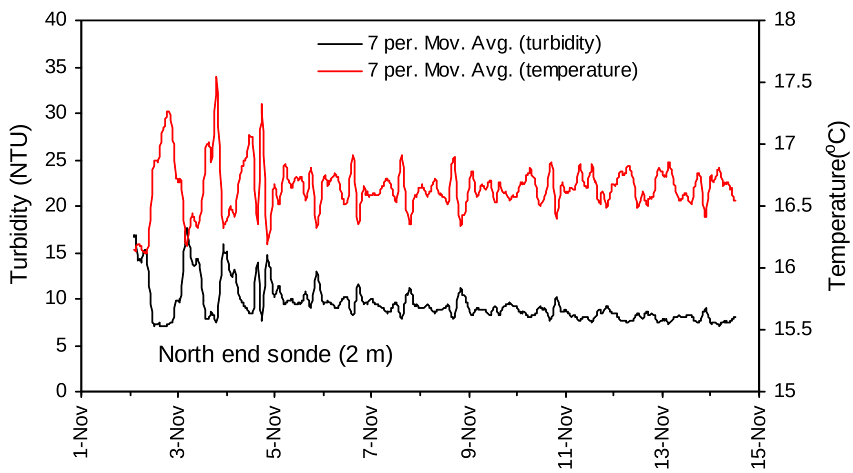
The sudden increase in turbidity on 31st October is believed to have been caused by a major subsidence of the sand-dune on the north western edge of the lake. Local residents have observed such subsidences on previous occasions and indicated that they are induced by children throwing water onto the steep slope of the dune (S. Wheeler, pers comm.). However, such subsidences may also occur naturally as an inevitable process of dune formation and movement inland. The timing of increased turbidity levels in surface and bottom waters indicates that this subsidence initially increased the turbidity of bottom waters and that this turbidity subsequently spread to surface waters.

The oscillations of turbidity in the surface waters of Lake Wainamu following the sand-dune subsidence were closely mirrored by changes in water temperature (Fig. 5.4), with the main peaks and troughs exhibiting a near diurnal periodicity. While such a periodicty is normally associated with seiches, these are unlikely in such a small lake. Furthermore, the periodicity is not a smooth oscillation as would be expected from a seiche, but a near diurnal 'pulse' with warming occurring in phase with exposure of the lake to afternoon sun. These oscillations probably indicate daily expansion and contraction of the eplimnion as the bottom of the epilimnion was close to 2 m where the datasonde was positioned, and water below that depth had a very high turbidity (Fig. 5.3) associated with the sand-dune subsidence.

This subdaily periodicity and the inverse relationship between temperature and turbidity indicates the existence of periodic movements of water masses (with different temperatures and turbidity levels) around the fixed datasonde, and therefore reflects a more complex sub-surface pattern of water movement in the lake than might be expected from the size and shape of the lake.

Figure 5.4:

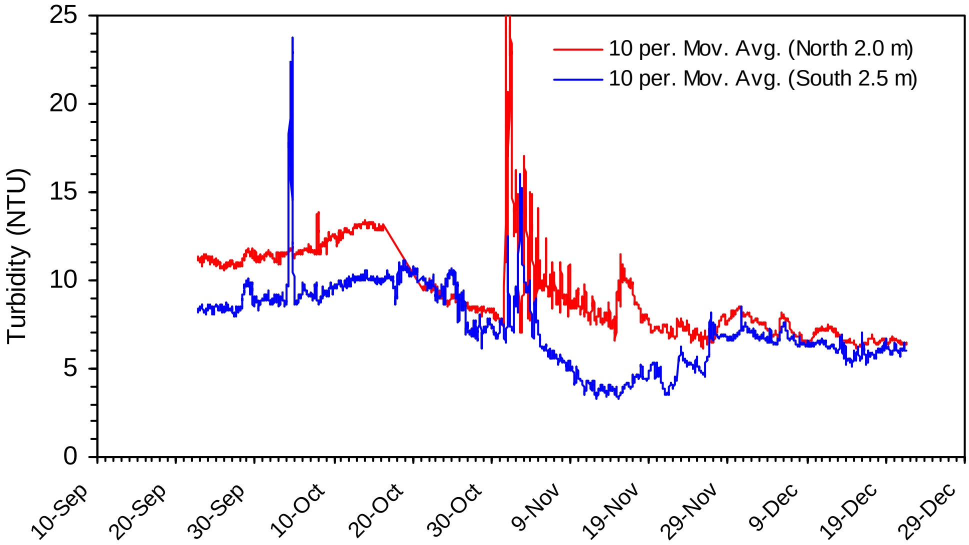
Periodic oscillations in turbidity and inverse correlations with temperature in the surface waters (2 m) at the north western end of Lake Wainamu following the sand-dune slump and ensuing increase in turbidity on 31st October 2004.



In general, the sonde data show that turbidiyy was always higher in the deeper, near-bottom waters of the lake than in the surface waters (Fig. 5.3). This is consistent with sedimentation of particles out of the surface waters and the re-suspension of sediment from the lake bed into the surface waters during strong wind events. The data from all 3 sondes show similar turbidity levels during the strong, wind-induced mixing event on 30th November 2004 (Figs. 5.3 & 5.5) indicating that, not only did the lake mix vertically, it also mixed laterally along its length.

Figure 5.5:

Changes in turbidity in the surface waters of Lake Wainamu between September and December 2004. Turbidity levels at 2.5 m in the south eastern end of the lake are contrasted with those at 2 m the north western end.



Turbidity levels in the south eastern end of the lake were generally much lower than those in the north western end of the lake (Fig. 5.5). Exceptions occurred during late October (including immediately after the sand-dune subsidence) and over December. In general, the changes in turbidity in surface waters of the south eastern end of the lake mirrored those in the north western end. A gradual increase occurred until mid-October and was then followed by a gradual decline until the marked peak following the sand-dune subsidence. Turbidity levels increased in the south eastern end of the lake some 8-10 hours after the subsidence increased turbidity in the north western end of the lake giving an indication of the travel time of the shock wave circulation flow through the lake.

The largest increase in turbidity in the south eastern end of the lake occurred on Monday 4th October, when the lake was thermally stratified. This increase was not recorded at the north western end of the lake and occurred mainly during daylight hours over a 12 hour period. It was accompanied by a drop in water temperature (Fig. 5.6) but no change in pH, oxygen concentration, or conductivity. Wind records from Mangere (Fig. 5.7) show that this turbidity event coincided with a change in wind direction from the prevailing south-west to the north-east and then back again. This sequence of wind shifts has been known to cause seiching in large lakes (e.g., Lake Taupo) but in Lake Wainamu, a small elongated lake, the effect is more likely to result in a tilting of the thermocline allowing up-welling of bottom water at the south-eastern end of the lake until the wind changed the following day. As bottom currents can be extremely high (>1 m s^{-1}) in lakes, and Lake Wainamu is relatively shallow at the south

eastern end, upwelling could have re-suspended sediment present in the deeper regions of the lake into the surface waters at the point of upwelling. Localised sediment re-suspension by strong wave action and associated currents in this shallow region of the lake are also likely to have contributed to this increase in turbidity. Lateral dispersion may not have been sufficient to transport the particles to the north western end of the lake before they sedimented out of the surface waters again.

Figure 5.6:

Association between temperature decline and turbidity increase in the south eastern end of Lake Wainamu over the period 6 pm 2 October to 6 am on 5 October 2004.

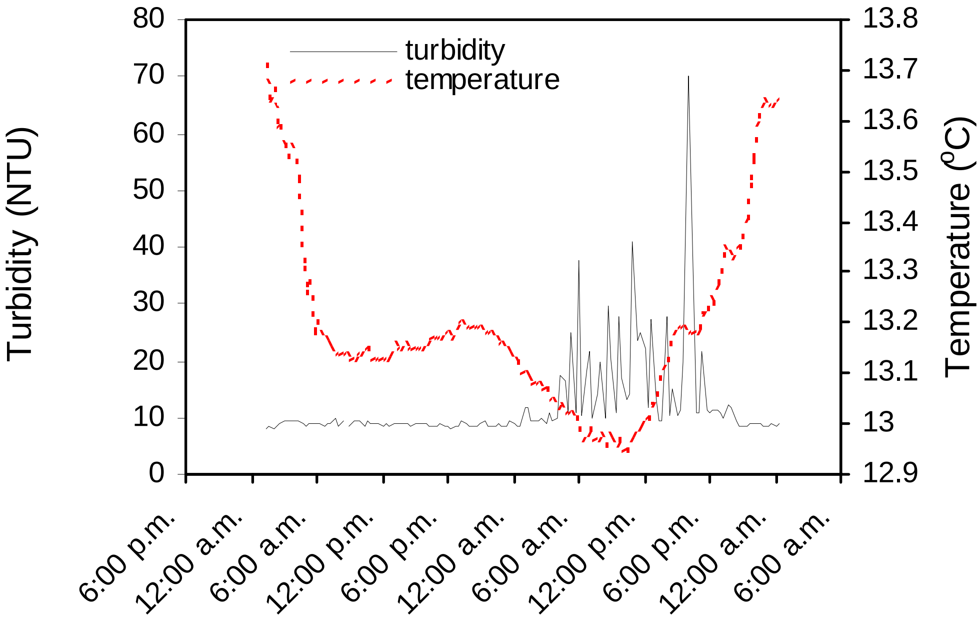
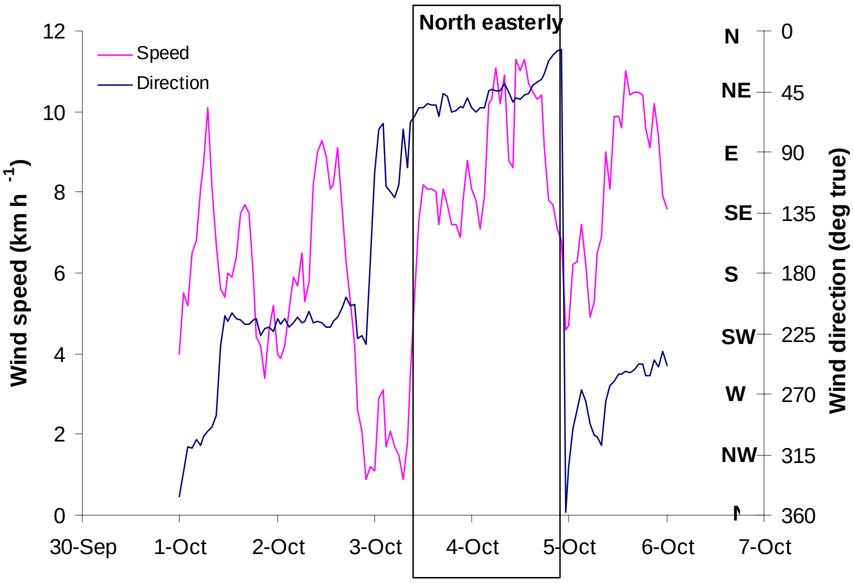


Figure 5.7:

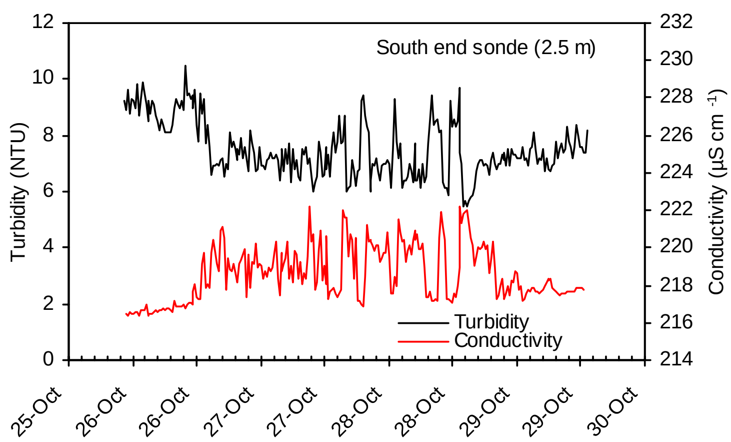
Wind speed and direction records from Mangere around the time of the 4 October event. Although Mangere met station is exposed to the west, it may not accurately represent conditions at Lake Wainamu because of the hills around the lake and its location 40 km away.



Changes in conductivity occurred at the south end of the lake between 25th October and 29th October 2004, and there was a strong inverse relationship between conductivity and turbidity over this period (Fig 5.8).

Figure 5.8:

Inverse relationship between turbidity and conductivity at 2.5 m in the south eastern end of Lake Wainamu between 25 October and 30 October 2005.

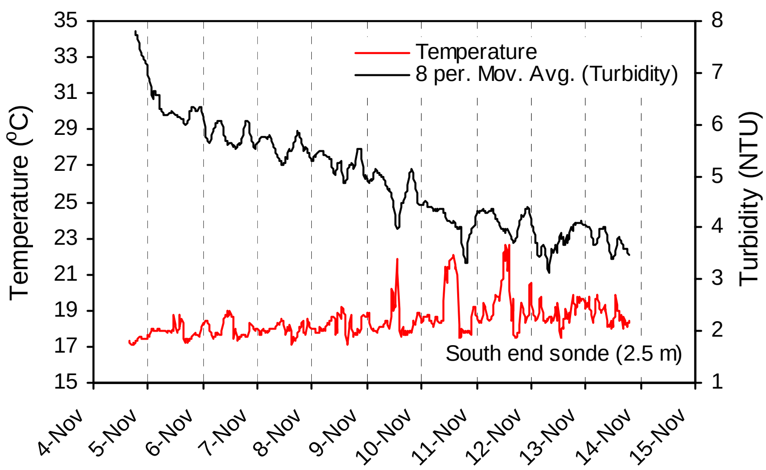


The increase in conductivity and decline in temperature may reflect the effects of increased stream flows at this site following a localised, but heavy rainfall event in the catchment. In general, higher conductivity water was associated with a reduction in turbidity, a decline in water temperature and a decrease in pH. In other words, an increase in rainfall, which is slightly acidic, is likely to have increased stream flow and in turn this will have resulted in a dilution of lake water in the south eastern end of the lake (i.e., around the stream inlet). This would acount for the reduction in pH and temperature in the vicinity of the stream mouth while turbidity was reduced. No such changes in conductivity were expected or recorded in the north western end of the lake. Analysis of meteorological data is required to reveal whether any major rainfall events (resulting in localised flood flows) occurred during this period or not and hence can provide tangible evidence to support this explanation. Although moderate rainfall events over the relatively pristine, bush-clad catchment of Lake Wainamu can be expected to increase the flow of relatively clear water from the Wainamu Stream into the lake, and thereby reduce turbidity levels near the stream mouth, flood flows may well increase turbidity.

The inverse relationship between turbidity and conductivity between 18th October and 30th October, suggests that a number of rainfall events could have reduced turbidity levels in the south east end of the lake over this period. However, such factors were not responsible for the steady decline in turbidity that occurred between 5th to 13th November 2004 (Fig. 5.9). This period was characterised by strong diurnal fluctuations in temperature as well as by a steady overall increase in temperature. This pattern of temperature change would be expected during fine, calm weather and such conditions would allow suspended solids to settle, resulting in a slow but steady decrease in turbidity. The corollary of such a relationship is that unsettled weather with strong wind (and possibly rain) would be expected to both reduce water temperatures while increasing turbidity.

Figure 5.9:

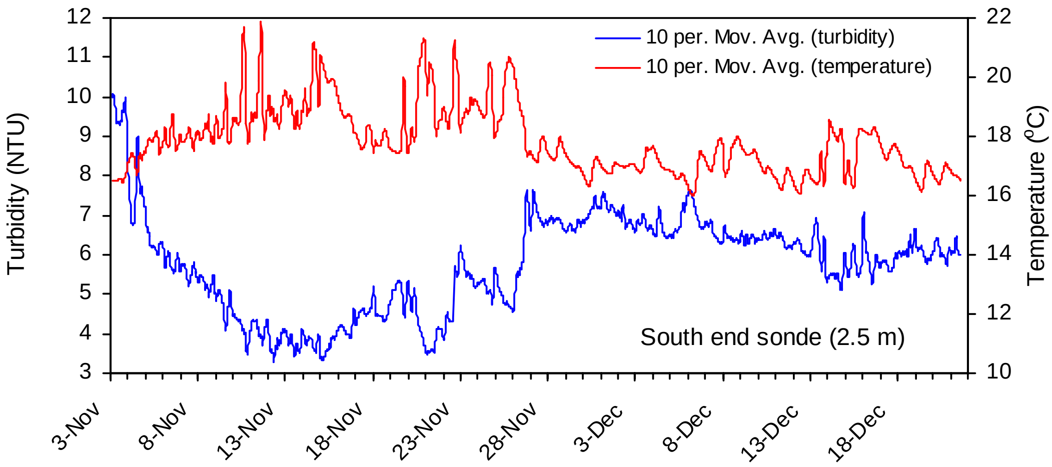
Diurnal periodicity in water temperature (especially on 10-12th Nov) are indicative of relatively calm conditions in the south eastern end of Lake Wainamu between 4-15 November 2004. Turbidity steadily declined throughout this period.



This weather pattern occurred during the period 3rd November to 22nd December 2004 in the south end of the lake. During this period, there was a strong inverse relationship between water temperature and turbidity with turbidity increasing in response to a decrease in temperature (Fig. 5.10).

Figure 5.10:

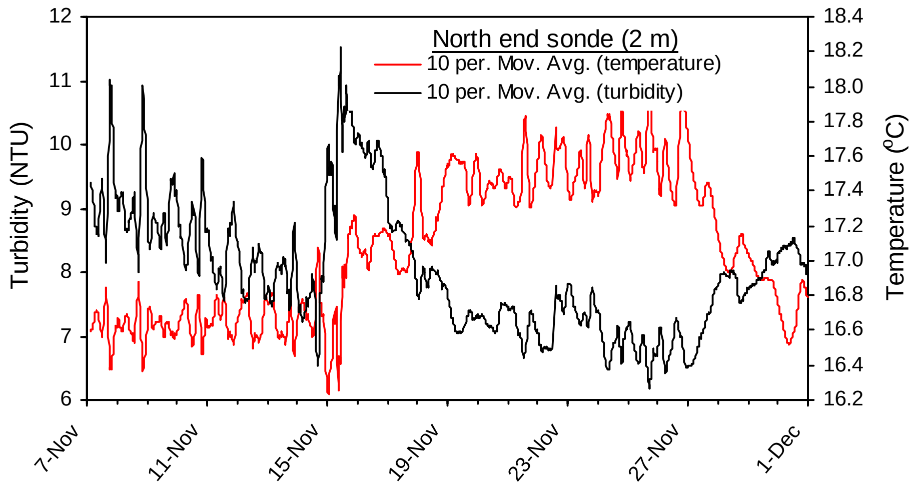
Inverse relationship between water temperature and turbidity in the south eastern end of Lake Wainamu between 3rd November and the end of December.



The strong inverse correlation between temperature and turbidity (r=-0.71) in the south eastern end of the lake indicated that there was little or no time lag between a decrease in temperature and an increase in turbidity. The temperature and oxygen data indicated that most of December 2004 was characterised by high wind (and possibly rain) which prevented thermal stratification and kept the lake mixed (Figs. 5.1, 5.2). The changes in temperature in the lake are therefore expected to reflect the effect of meteorological conditions (especially wind) on surface mixing of lake waters and hence on the maintenance of high levels of turbidity in the south eastern end of the lake.

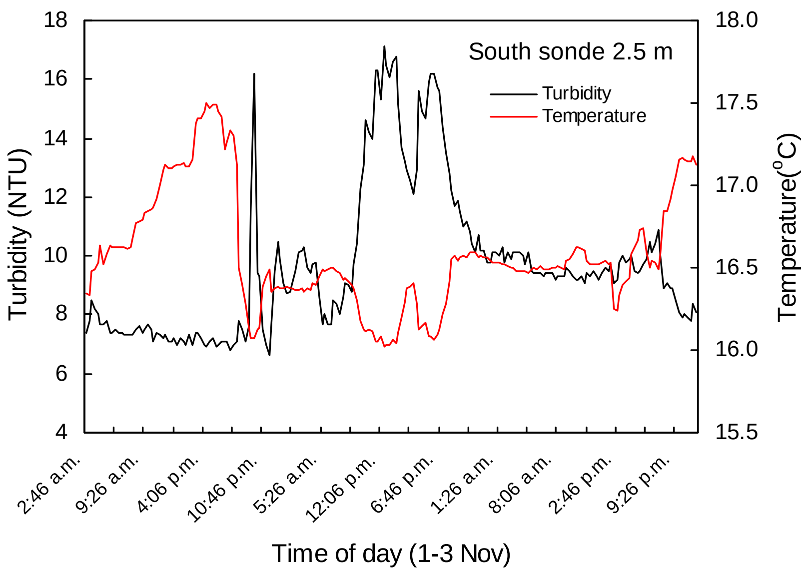
A similar inverse relationship (r = -0.69) between temperature and turbidity occurred in shallow waters in the north end of the lake (Fig. 5.11) between 7 - 30 November indicating the widespread importance of wind induced water mixing on the maintenance of turbidity in this lake.

Figure 5.11:
Inverse relationship between water temperature and turbidity in the north western end of Lake Wainamu between 7-30 November 2004.



There was also evidence for the fine-scale effect of temperature on turbidity in Lake Wainamu. Between 1-3rd November 2004, sub-daily increases in turbidity in the south eastern end of the lake were mostly associated with sudden decreases in temperature as shown in Figure 5.12.

Figure 5.12:
Large, sub-daily increases in turbidity (> 4 units of NTU) in the south eastern end of Lake Wainamu all followed sudden decreases in water temperature.



5.4 Discussion

The datasonde results indicated that the high turbidity in Lake Wainamu is likely to originate mainly from the re-suspension of organic particles within the lake. Phytoplankton has been discounted as a major source of turbidity (sections 3 and 4), and the optical model indicated that suspended organic particles (or organic coated particles) were mainly responsible. The main inlet stream is unlikely to be a significant source of suspended particles (e.g., clay), except perhaps during extreme floods. Although the sand-dune subsidence on 31st October may well have introduced some organic particulates into the lake, this will also have created an underwater shock wave and disturbed large amounts of silt on the lake bed.

The mechanism for the increase in turbidity associated with the dune subsidence is likely to have been controlled by in-lake chemistry and the conditions in the lake that existed before the subsidence. Monthly monitoring data for 2004 show that the water near the bottom of the lake was anoxic by November 2004 (Fig. 4.2). As Lake Wainamu was created by the advance of an iron-rich sand-dune across a valley, the sediments of the lake are likely to release soluble ferrous iron at dissolved oxygen concentrations below 3 g m^{-3}. Under the calm conditions that existed in October and November, the ferrous iron would form a ferrous oxi-hydroxide jelly-like layer on the lake bed which would further enhance the dissolution of iron from the sediment.

The slump of the sand-dune occurred when the lake was strongly stratified with substantial oxygen depletion in the bottom water column. The shock-wave associated with that slump would suspend the ferrous oxi-hydroxide from the lake bed and disperse it throughout the bottom water layer causing high turbidity. Seiche action associated with the shock-wave would also mix some of the bottom water into the surface waters causing a sudden increase in turbidity in the surface waters (Fig. 5.3). However, because ferrous oxi-hydroxide can only exist at low or zero oxygen levels, in the well oxygenated surface waters it would be rapidly oxidised to insoluble ferric hydroxide which, being heavy, would rapidly sediment out of the surface waters. In contrast, the low oxygen concentrations in the bottom waters would maintain the ferrous oxi-hydroxide which, being a light flocculent material, would sediment slowly, thus maintaining a high but slowly decreasing turbidity level in the bottom waters.

When the lake mixing event occurred on 30th November 2004, the whole water column would have become fully oxygenated and all the ferrous oxi-hydroxide would be oxidised to ferric hydroxide which would rapidly sediment out of the water column. Subsequent wind mixing would stir up some of the ferric hydroxide and this can be seen as increases in bottom water turbidity during December 2004 (Fig. 5.3). The high particulate iron content of the lower water column was observed as staining of hand-lines and the plankton net during the monthly sampling on 24 December 2004 (M. Gibbs, pers comm.).

Although the dune subsidence increased turbidity levels for 2 weeks in surface waters (and longer in bottom waters), it was not responsible for the generally high turbidity levels occurring before and after this event. The datasonde information on turbidity levels and water mixing showed that wind is likely to play a major role in maintaining the high levels of turbidity in this lake. Although a likely mechanism is thought to be wave-induced re-suspension of the small organic particulates (i.e., silt) that settle on the lake bed in shallow waters, up-welling of bottom water may also have occurred and increased turbidity in surface waters. Wind may also blow some particulates into the lake from the sand-dune, however, the closer relationship between turbidity and suspended solids at 5 m than at 0 m suggests a bottom-up origin and indicates that silt from the lake bottom is the most likely source of the high suspended solids and turbidity.

Sediment disturbance by wave action is not expected to re-suspend the silt present on the lake bottom (i.e., in the deeper regions of the lake). Here, the relatively still waters will result in rapid sedimentation of particles, as occurred immediately after the major mixing event in early December 2004. However, sustained wind and wave action may result in the development of sub-surface lateral currents and up-welling in the deeper regions of the lake which could then transport turbid water from the deeper regions into the shallows. Such lateral water movement would have accounted for the rapid dispersion of silt from the northern to the southern end of the lake in Octeber following the dune subsidence. Installation of current meters, in conjunction with datasonde probes, would be required to identify such water movements. This, and further co-analysis of meteorological data in conjunction with datasonde measurements is clearly needed to help clarify the role of wind (and rain) in the maintenance of the high suspended solids and turbidity levels in this lake.

6 Macrophytes

6.1 Introduction

Macrophyte cover is a key factor suppressing the re-suspension of silt in shallow (e.g., < 5 m deep) wind-exposed lakes. However, its role in the relatively narrow, steep-sided and deeper (13 m max. depth) Lake Wainamu was unknown. Once macrophyte cover disappears, as occurred in Lake Wainamu after 1995, plants can re-grow provided sufficient light can penetrate to the lake bottom. Re-growth has occurred in other lakes following macrophyte collapse. For example, Lake Omapere in Northland has undergone several cycles of macrophyte growth and collapse over the past decade (Champion and Burns 2001). But re-growth will not usually occur in lakes that have become nutrient enriched and eutrophic, and where annual algal blooms and high densities of algal cells in surface waters result in a large reduction in light penetration. Nor does re-growth occur in lakes where constant disturbance of the sediments (e.g., either by exotic fish or constant wave action) occurs. Re-growth of macrophytes may also be prevented in lakes where the exotic macrophytes are completely eliminated and where the seed banks for native species are no longer viable. Such factors could all play a role in the failure of macrophytes to re-establish in a lake and so dampen the re-suspension of silt.

Lack of macrophyte re-growth appears to have occured in Lake Wainamu as the macrophytes were gone by 1999 (and probably earlier), and have failed to re-establish since then. Remnants of *Egeria densa* the main exotic species in the lake in 1995 were still present in 2003, but were restricted to very shallow waters around the lake edge and consisted of isolated stalks growing close to the rush beds (Rowe et al. 2003). Failure of these plants to re-establish around the lake's margins since 1999 will have been related primarily to the reduction in light penetration, but disturbance of the lake bed by fish browsing may also have contributed both directly (by uprooting small plant shoots) and indirectly (by increasing turbidity from silt and reducing light penetration). The optical model (section 2) indicated that the major cause of the reduced light penetration in this lake is probably the presence of CDOM (coloured dissolved organic matter). Non-algal particulates, which are the main source of low water clarity (and high turbidity) also reduce light penetration, but have a much smaller effect than CDOM. The CDOM is likely to originate from the catchment vegetation and/or the emergent vegetation and will therefore be a natural characteristic of this lake. It is possible, therefore, that macrophytes in Lake Wainamu are more sensitive to an increase in turbidity than in other lakes, because light penetration is already reduced by the high levels of CDOM. However, this assumes that plant re-generation is not limited by lack of seed stock, by fish disturbance of sediments, or by constant re-suspension of silt by wind and wave action.

To determine whether plant re-growth in Lake Wainamu was limited by seeds and/or by fish browsing, two investigations were undertaken. The first addressed the issue of seed distribution, type and viability in the lake sediment (i.e., whether macrophyte re-generation from seeds would occur if light levels were increased). The second used exclusion cages to determine whether fish browsing could be disturbing lake sediments and therefore restricting plant re-growth while contributing to silt re-suspension by water movement. The results of these investigations are reported below.

6.2 Methods

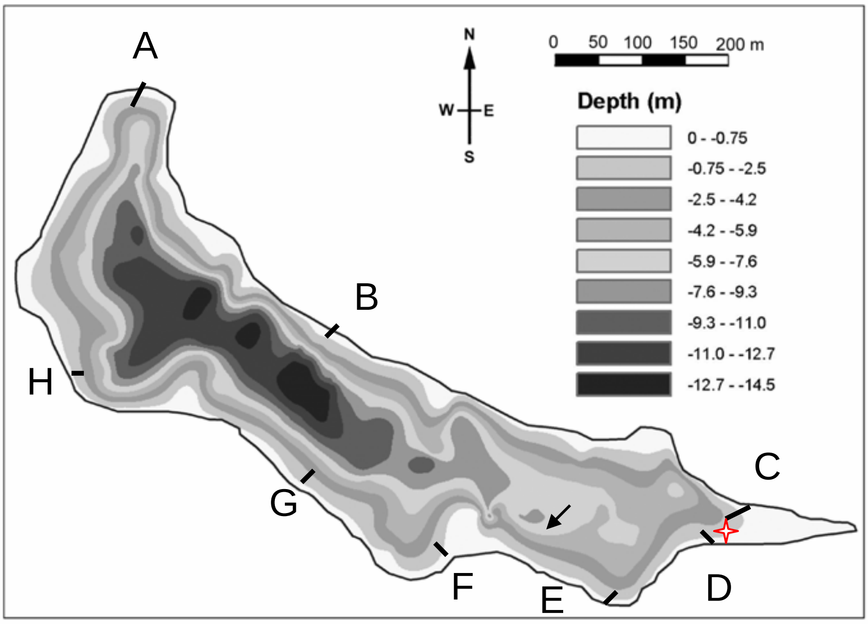
The collection of seed bank cores was made in late November. Intact cores of sediment with resident seed banks were taken by SCUBA divers (Fig. 6.1) across the depth range at eight widely separated sites (Fig. 6.2, Appendix 1). The depths selected depended on the depth of the dense reeds and rushes that excluded sampling in many shallow areas, as well as the constraints on sampling caused by the low visibility/light conditions in deeper water.

Four intact cores (100 mm deep, 85 mm diameter) were collected from each depth, and capped top and bottom. Cores were transported in water-filled chilly bins to outdoor culture tanks at Ruakura, Hamilton. They were then un-capped at the top and placed in 0.8 m depth of water under c. 8% ambient light – a level found previously to be favourable for seed germination but which minimised interference by algal growth. After three and six months, the cores were examined for the presence of seedlings as detected by direct observation.

Figure 6.1:
Diver retrieving intact cores (see at left) in Lake Wainamu.

To look for remnant seed banks within the sediment substrata, three deep cores (300 mm deep, 85 mm diameter) were collected from 7.0-7.4 m depth near to site E (Fig. 6.2). Cores were transported to the lab as above and sectioned at 50 mm intervals. Sections were sieved through a series of 800 µm, 500 µm and 250 µm mesh, and seed was identified and enumerated using an 'apparent' viability method (de Winton and Clayton 1996).

Figure 6.2:
Map of Lake Wainamu showing the sites where intact seed bank cores were obtained from and a site (arrowed) where deep cores were collected. The red star indicates where the shallow (1.5 m) and deep (2.2 m) exclusion cages were located.



Exclusion cages provide a way of preventing access by large fish to the lake bottom and therefore of seeing whether their benthic browsing habits are having an effect on the stability of sediments on the lake bed. Two steel-framed cages (800 x 800 x 600 cm high) covered with 20 mm plastic mesh on all sides except the bottom were placed in relatively shallow (1.5 m deep) and deep (2.2 m) water on bare areas of the lake bed in the south eastern end of the lake in November 2004 (Fig. 6.2). Photographs were taken of the lake bed inside and outside the cages. The cages were inspected again in April 2005 and further photographs were taken to determine any changes within the cages and any differences between the inside and outside of the cages.

6.3 Results

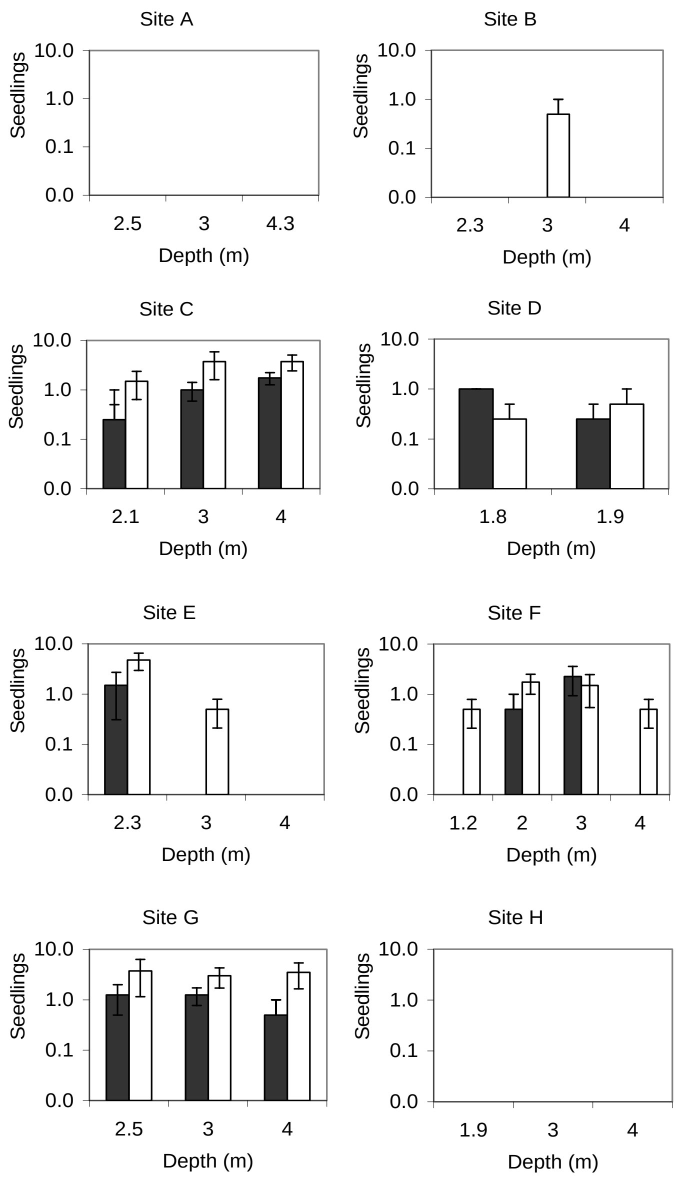
6.3.1 Seed distribution and viability

Almost all the seedlings that germinated from the intact cores were *Chara australis*, a native charophyte. It was suspected that several unidentified sporelings included *Nitella* species, but these did not attain a size where they could be identified. Six unidentified dicotyledons were recorded but never progressed past the two-leaf stage and were considered to be of terrestrial origin and not aquatic plants. Also recorded during the three month assessment were seedlings of the reed, *Eleocharis*. However, these did not survive to the second assessment. Further results are limited to the charophyte response only.

Measured seedling response was similar at both assessments, with generally small increases in seedlings noted at six months relative to three months (Fig. 6.3). Almost all of the seedling response (Fig. 6.3) was from cores collected along the south-eastern to eastern sites (Sites C, D, E, F, G, in Fig. 6.2). There were variable patterns of seedling response across water depths. Few, if any, seedlings developed from cores taken in the north-western end of the lake (Sites A, B, H in Fig. 6.2).

Figure 6.3:

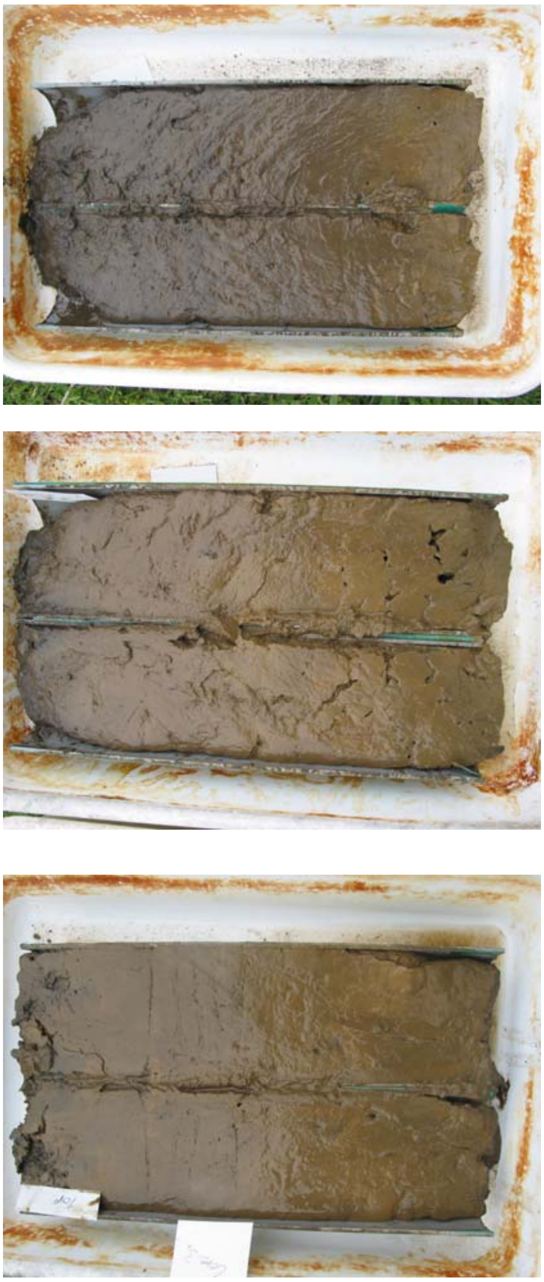
Average seedling response from intact cores (n = 4) collected from Sites A- H, Lake Wainamu after culture for three months (black columns) and six months (white columns). Error bars are ±1 SE of the mean. NB. Note log scale.



Forty-one percent of the cores collected showed a seedling response. The average overall seedling response from all cores after six months was 1.3 seedlings per core or 229 plants per m^2. No seedlings responded from cores taken at Sites A or H, while the highest response of 11.0 seedlings per core or 1939 per m^2 was recorded from a core collected from 2.5 m at Site G.

The deep cores comprised a silty substrate that became more dense and lighter in colour with depth, with distinct strata observable (Fig. 6.4).

Figure 6.4:
Three deep cores collected from c. 7 m, Lake Wainamu, split in half with top at left.

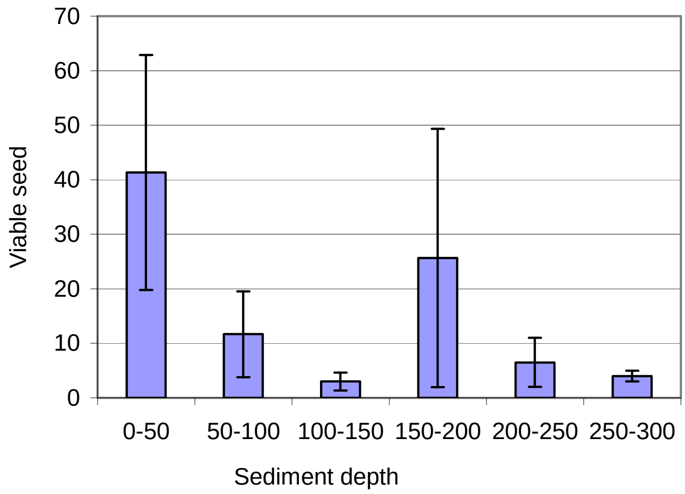


Viable seed recovered from the sectioned cores comprised oospores of *C. australis* (73%), *Nitella leonhardii* (15%), *Chara fibrosa* (6%), *Nitella pseudoflabellata* (5%) and small numbers of *Chara globularis* and *Nitella hyalina*. Inviable seed of *Potamogeton cheesemanii* and *Potamogeton ochreatus* was also detected, predominantly in the top 50 mm strata.

Overall, the average number of viable seed in the deep cores tended to decline with depth (Fig. 6.5). However, it was noted that seed number and distribution was quite variable in the depth sub-strata of the cores and that a large number of viable seed were detected at 150-200 mm in one core.

Figure 6.5:

Average viable seed numbers in 50 mm sections of substrata (n = 3). Error bars are ±1 SE of the mean.



Observations of submerged plant presence and abundance were made at core collection sites (Appendix 1). At Sites A and B (Fig 6.2), dense beds of reeds *(Eleocharis acuta, Typha orientalis*, *Baumea articulata*) and sprawling marginal plants (*Ludwigia* sp.) extended out to c. 2 m and a very thin fringe of *E. densa* was present on the outer edge of the reeds. No submerged plants were detected at Site C, where a thick band of *E. acuta* extended to c. 2 m depth. Site D was within a shallow region up a narrow arm of open water (Fig 6.2). Here, sparse *E. densa* was observed under overhanging bush right at the edge of the bank, whereas away from the bank at the core collection depths of 1.8 –1.9 m depth divers observed several small plants of *N.* aff. *cristata*. At Site E no submerged plants were seen and dense reeds again extended to c. 2 m depth. At Site F, the reeds were less dense and there was a high coverage of the lake bed by charophytes (>95% cover) growing amongst the reeds between 1.2 and 2 m depth. *N. pseudoflabellata*, *N.* aff. *cristata* and *C. australis* were present in this shallower region, with *C. australis* predominating and occurring down to a maximum depth of 3 m. Divers perceptions were that water clarity at Site F was better than elsewhere in the lake. Site G had low plant coverage of the lake bed (c. 1-

5%) of charophytes at 2.5 m, with no plants seen at 3 m depth or more. At Site H (Fig 6.2), *E. densa* extended from 1.9 m, covering 6-25% of the lake bed, to 3 m depth where coverage was 5% and plants were up to 2.5 m tall. Numerous live freshwater mussels (*Hyridella menziesi*) were also noted at 3 m.

6.3.2 Exclusion cages

In November 2004, the bed of the lake in the vicinity of the exclusion cages consisted of fine silt overlain with organic debris. It showed no sign of macrophyte growth or algal mats (Fig. 6.6). Thus, the algal mats apparent at this site in May 2003 (Rowe et al. 2003) had disappeared. The lake bed also showed little sign of disturbance (e.g., by fish) at this time. Feeding by fish species such as perch and goldfish is likely to be low during winter months and disturbance was expected mainly during summer and not winter months.

Figure 6.6:
Composition of the lake bed; (A) inside the cage in November 2004 and (B) close-up.

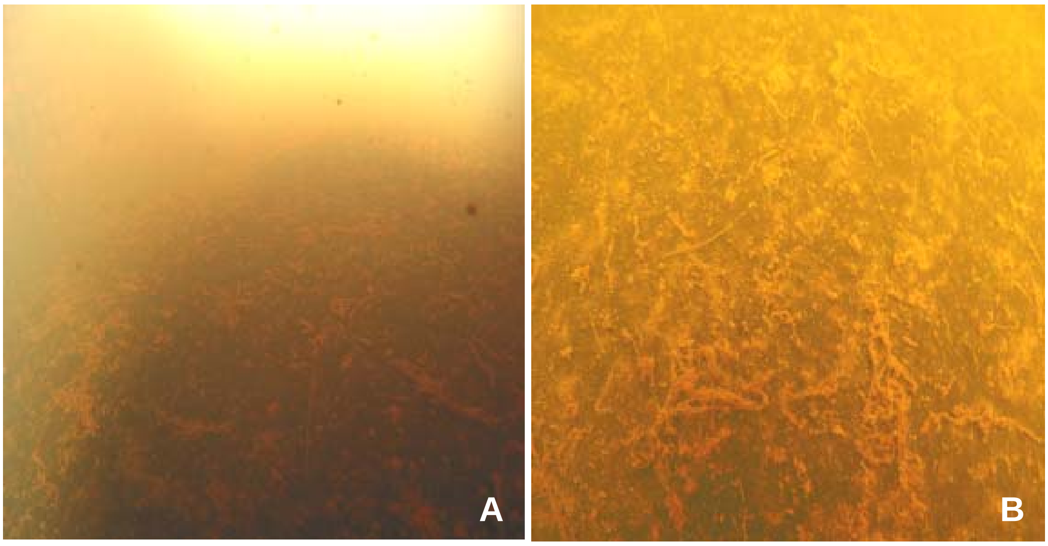
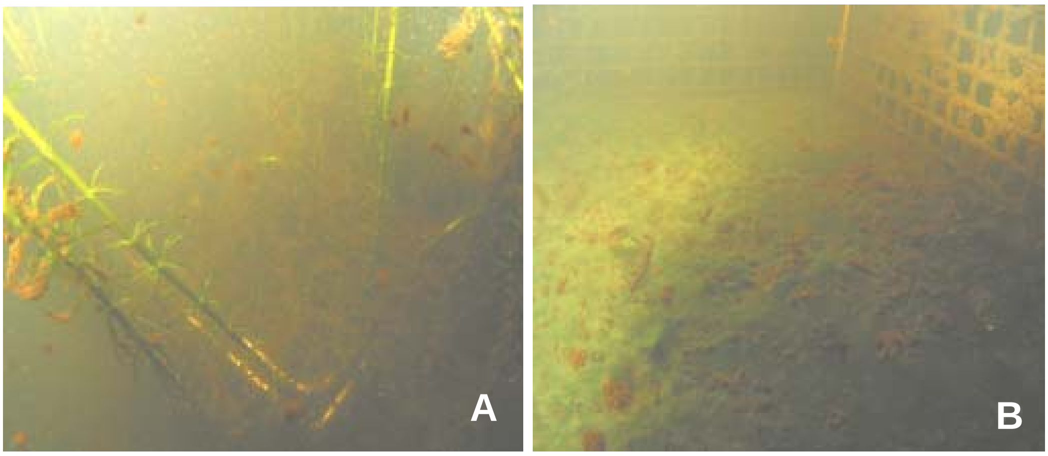
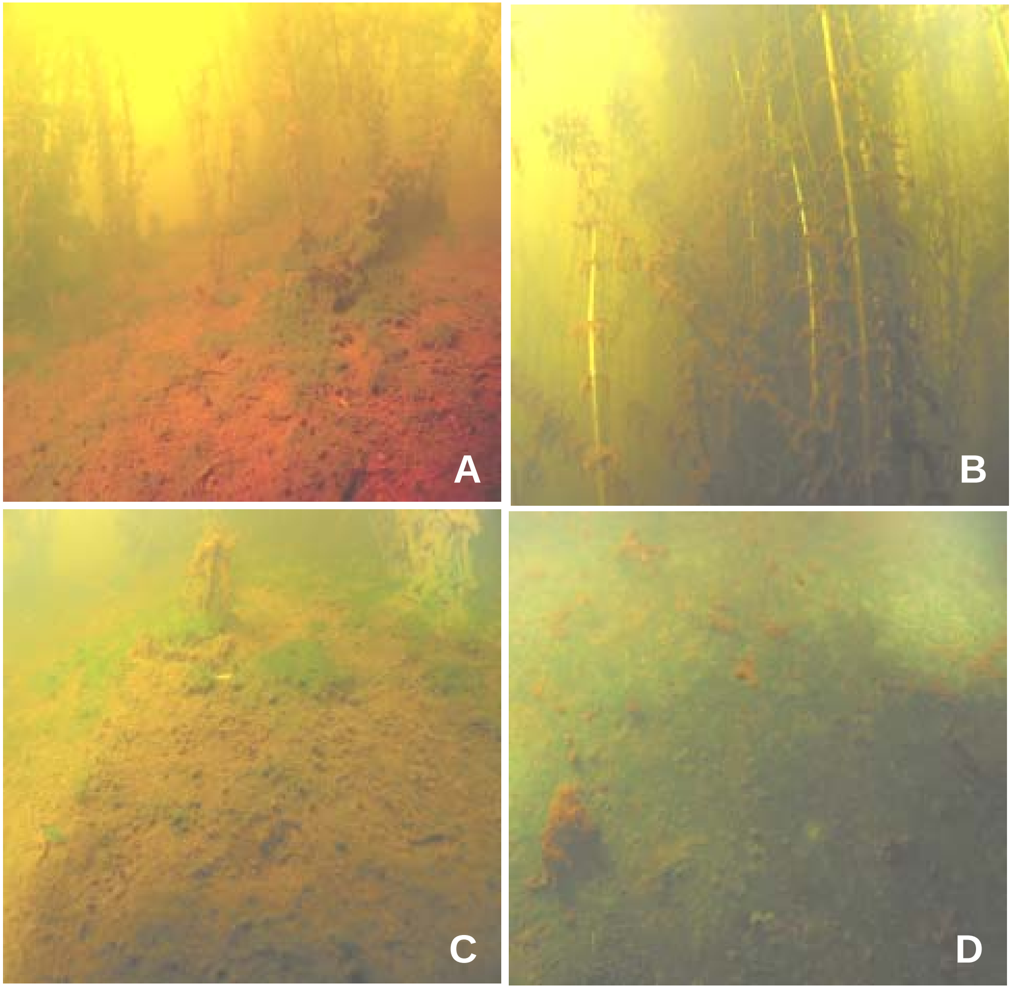


Figure 6.7:
Changes in the lake bed inside the cages by April 2005; (A) macrophytes growing through the roof of the shallow cage in 2005 and (B) the algal mat covering the entire bottom of the deep cage.



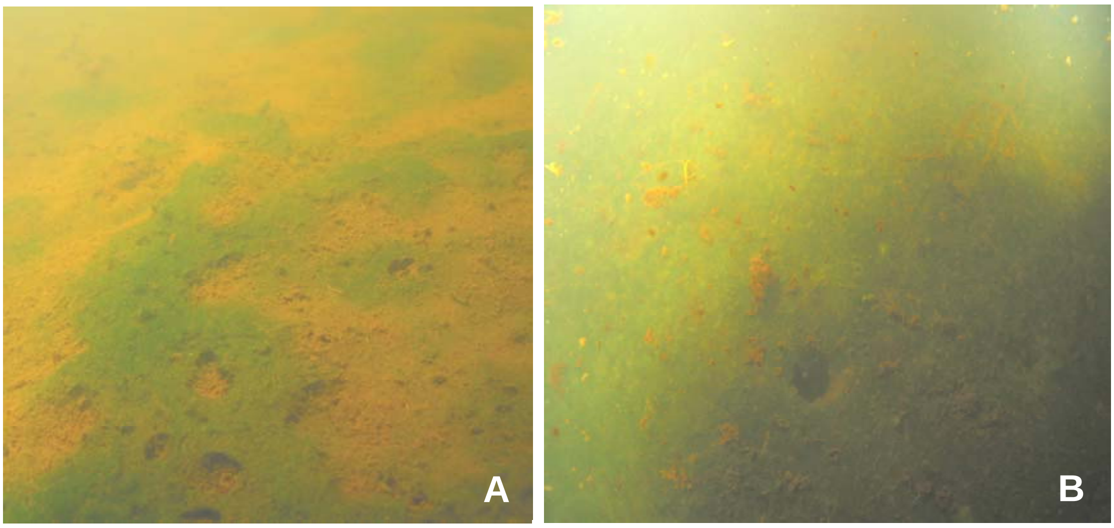
By April 2005, the cage in shallow water was completely overgrown with the macrophyte *Egeria densa*. Long (1.2-1.3 m) stalks were growing through the roof of this cage (Fig 6.7). In the deep cage, a mat of algae completely covered the lake bed (Fig. 6.7). Small amounts of silt spotted this mat but were likely to be a consequence of disturbance of the cage rather than a natural occurence. Similar changes in the lake bed also occurred outside the cages (Fig. 6.8). Macrophyte re-growth was evident in shallow waters, whereas patches of algal mat occurred on the lake bed in deeper waters.

Figure 6.8:
Lake bed outside cages in April 2005; (A,& B) macrophyte growth in shallow (<2 m) waters outside the cages, (C & D) surficial algal mats in deeper waters (> 2m).



There was some evidence that fish disturbance of the sediment was occurring, albeit at a minor level in April 2005. The algal mats in shallow water showed several holes with abrupt edges likely to have been caused by fish feeding. Furthermore, deeper holes through the algal mat were observed in some places and are consistent with eel habitats and behaviour (Fig. 6.9). The abundance of perch and goldfish in the lake had been reduced by gill netting by this time. The relative abundance of perch (the dominant fish species in the lake) had been reduced by more than 70%, and an unknown proportion of the rarer species (goldfish, tench, catfish and rudd) were also removed. As a consequence, little disturbance by fish was expected.

Figure 6.9:
Signs of dish disturbance to the algal mats covering the sediment; (A) holes in the mats in shallow water and (B) a deep hole through the mat in deeper water.



6.4 Discussion

Results from the intact sediment cores suggest that an establishment response is possible from seed banks in Lake Wainamu under favourable conditions of light and with minimal disturbance operating. For example, we can compare these results with the results of a similar exercise carried out in Lake Rotoroa (de Winton et al.1999, 2000). This de-vegetated lake subsequently became re-colonised by charophytes. The proportion of 41% of cores and average of 1.3 seedlings per core for Lake Wainamu compares favourably with values of 42% of cores and average of 1.7 seedlings per core that was obtained for Lake Rotoroa.

Both the presence of vegetatively-reproducing weed (e.g., *E. densa*) and de-vegetation events have been found to impact upon the density and diversity of seed reserves in lakes (de Winton & Clayton 1996). In this respect, the relatively large response from seed banks in Lake Wainamu could reflect the short length of time that *E. densa* supplanted native vegetation prior to the decline in water clarity (c. 14 years together). Charophyte oospores can persist for lengths of time in the order of decades, however, the absence of viable seed for higher plants (e.g., *Potamogeton* spp.) is in keeping with their suspected shorter seed life-spans.

The greater seed bank response from cores taken from the eastern and south-eastern regions of the lake may be related to persistent charophyte vegetation that was noted at some sites (e.g., Sites D, F and G, Appendix 1), or alternatively that seed bank presence had already enabled some recovery in these areas. Nevertheless, the presence of *E. densa* at most sampling sites means that this weed is likely to dominate in the long term.

The deep cores were sampled from a sedimentary environment (c. 7 m depth) which was beyond the historic extent of vegetation (c. 5 m). Seed numbers were therefore expected to be low, but the distribution of seed within the depth strata was thought likely to reflect seed production in the lake in general. The seed composition tallied with that of the intact cores, with *C. australis* being the most abundant in both. The presence of charophyte oospores to at least 300 mm sediment depth also suggests a long history of submerged vegetation in this lake. Although there was a tendency for surficial sediment (0-50 mm) to have amongst the highest density of seeds recorded per core; the patterns of seed distribution and density within the substrata were highly variable.

The changes in the shallow lake bed between November 2004 and April 2005 were marked and indicated that a widespread re-growth of the exotic macrophyte *Egeria densa* was occuring in shallow waters, with a corresponding growth of algal mats, particularly in deeper water. Both processes will tend to seal and consolidate sediments such that resuspension of silt by wave action, subsurface water currents, or by fish disturbance will be suppressed.

The occurrence of algal mats at the exclusion cage site in May 2003 (Rowe et al. 2003) but not in November 2004 (this study), indicates that they may vary seasonally and disappear over winter months. Their greater prevalence and coverage of the lake bed at the exclusion cage site in April 2005 indicates that some change in the lake had occurred. This may be an increase in light penetration associated with the gradual long term decline in suspended solids concentrations (see section 4). It may also be related to the removal of large numbers of the perch that had been observed feeding on invertebrates on the lake bed and/or of goldfish which feed on organic detritus.

7 Summary

In general, the high turbidity levels in Lake Wainamu are not a consequence of high phytoplankton densities. Peak chlorophyll *a* levels (>25 mg m^{-3}) have only been recorded twice in Lake Wainamu, once in the winter of 1996 and once in winter 1999. In 1999, the low water clarity in Lake Wainamu was caused mainly by planktonic algae because suspended solids concentrations were low at this time. Apart from this one instance, there has been a poor relationship between chlorophyll *a* levels, turbidity and Secchi disc depth over the past decade. The current high turbidity and low water clarity in this lake are therefore not related to high phytoplankton densities.

The optical model indicated that in 2005 phytoplankton could only account for about 21% of the light absorption in this lake. Even though a bloom of the blue-green alga *Anabaena planktonica* occurred during late-winter to early-spring in 2004, and would have increased chlorophyll *a* levels at this time, the measured chlorophyll *a* concentration of 23 mg m^{-3} was no larger than in previous years and well below the peak levels of 1996 and 1999.

The optical model indicated that suspended organic particles are the most likely cause of high turbidity in this lake. This result was re-inforced by the historical analysis of suspended solids, turbidity and Secchi disc data obtained by monthly water sampling. The results indicated strong links between suspended solids near the lake bed and turbidity in the surface waters of the lake.

Analysis of short-term, location-specific changes in key water quality variables in the lake in 2004 also revealed a strong link between increases in turbidity and decreases in water temperature. This relationship is thought to indicate an effect of wind (and hence water mixing) on the lake, however, meteorological data are required to confirm this. Although the lake stratifies during summer months, it is relatively easily mixed, as occurred in December 2004. Both partial and complete mixing events were associated with reduced water temperatures and changes in turbidity, supporting the likelihood of wind-induced water currents and wave action disturbing silt and increasing turbidity. Such events were only recorded once water temperatures exceed 15 °C and after the lake had started to stratify. The datasondes also revealed links between low water temperatures and raised turbidity in surface waters during summer months when water temperatures were high and could be cooled by rain and/or cold winds. However, such effects would not be recorded during winter when the temperature of the lake is uniformly cold throughout. At this time, wind induced water movements leading to increased turbidity would be more common, but are unlikely to be linked to low water temperatures.

There was no evidence that the turbidity in the lake was increased by rainfall events leading to increased flow in the main inlet stream. This assumes that high rainfall events producing flood flows did occur during the monitoring period (i.e., 22nd September-22nd December 2004) and require confirmation from meteorological data. The issue of flood flows aside, an increase in conductivity in the south eastern end of the lake, indicating increased stream flow from high rainfall was associated with a reduction in turbidity. This is thought to be a consequence of dilution of the lake water around the south eastern datasonde with less turbid stream water. Moderate rainfall events and increased stream flow are therefore expected to reduce turbidity in the shallow south eastern end of the lake. There was no corresponding effect in the north western end of the lake.

A large increase in turbidity was recorded on 31st October 2004 and subsequently affected the entire lake for up to 15 days in surface waters and 29 days in bottom waters. This increase in turbidity was thought to be caused by a large portion of the sand-dune in the north western end of the lake subsiding into the lake. The subsequent spread of this "slug" of turbidity within the lake indicated that there are complex subsurface currents that spread turbidity generated in one end of the lake to the other. Mixing events, such as destratification, sub-surface currents, upwellings and wave action on the lake edge will also spread the turbidity laterally as well as vertically from bottom to surface waters. Such mixing events are thought to be related primarily to changes in wind strength and direction. Current meters and a climate station would be required to measure and confirm this.

Diver observations and underwater remote video monitoring in 2002 and 2003 both indicated that the bottom sediments of Lake Wainamu were not sandy or rocky but composed mainly of fine, easily suspended silt. Macrophytes which normally grow around lake edges and suppress the effects of wind and wave action on silt disturbance were not present in shallow waters in 2002 or 2003, except in close association with the fringing rush beds, where isolated stalks occurred.

Exclosure cages designed to stop fish disturbance of the lake bed were placed on the bottom in shallow waters from spring 2004 until autumn 2005. Previous monitoring in autumn 2004 had established that algal mats were beginning to form on the lake bed, and were more dense inside the exclosures than outside them, where fish browsing could disturb the lake sediments. Monitoring in autumn 2005 indicated that, despite some disturbance by fish, the algal mats had continued to proliferate throughout the lake and that following consolidation of the lake bed, macrophyte re-generation was widespread. Dense growths of macrophytes (to a height of at least 1.2 m) were present both in the exclosures as well as outside them.

Culture of sediments to determine the distribution, species and viability of plant seeds indicated the potential for native vegetation to re-establish within the eastern and south-eastern littoral areas of the lake. Seed bank response was dominated by the native charophyte, *Chara australis*, with viable seed of up to five other charophyte species also present. An association between the presence of charophyte vegetation at the sampled sites and seed bank response was noted and seed banks may have been a factor in the development or maintainance of the vegetation, or alternately, seed banks may have been supplemented by the plants. However, the widespread presence of *E. densa* means that native vegetation is likely to ultimately be replaced by this competitive exotic weed.

This rapid regeneration and spread of the exotic macrophytes (*Egeria densa*) in Lake Wainamu followed an intensive programme of fish harvesting by the ARC designed to reduce the perch and goldfish populations in the lake, but not the other common species (e.g., eels). Catches of both perch and goldfish declined significantly over 2004 indicating an overall effect of netting on fish densities (pers. comm. G. Barnes). Whether this reduction in exotic fish has reduced sediment disturbance and subsequently allowed regeneration of the macrophytes or not is not known for sure. It could be coincidental, but this seems unlikely, especially given the strong negative relationship between water clarity in small North Island lakes and the occurrence of exotic fish, including perch and goldfish (Rowe et al. 2003).

It is unlikely that exotic fish such as perch and goldfish could, on their own, be directly responsible for the decline of the macrophytes as large populations of these fish occur in other lakes with no observable change in macrophyte beds over long periods of time. However, the recovery of macrophyte beds in lakes after they have declined could well be inhibited by exotic fish disturbance of the lake bed. Such disturbance occurs through the feeding activities of fish, and although benthic species such as goldfish, catfish and tench can be expected to be major culprits, even perch, which are known as a mid-water fish in European waters, were observed feeding on the lake bed and disturbing the sediment surface. This could inhibit the formation of algal mats and the regeneration of macrophytes from seed, and would allow wind/wave action to maintain high levels of suspended silt in the lake, so reducing light penetration, and further inhibiting macrophyte recovery.

Macrophyte re-growth is now being accompanied by a large reduction in both turbidity levels and suspended solids concentrations in the lake and by a marked increase in water clarity to levels not seen for over over 10 years. The lake therefore appears to be recovering quickly. Although an increase in macrophyte coverage is likely to be important for the maintenance (and further improvement) of clear water in this lake, the initial cause of the macrophyte decline after 1995 is unknown and the cycle of macrophyte decline and increased turbidity could therefore occur again. Such cycles appear to be a feature of some exotic plant species, particularly *Egeria densa*, but not the native plants. At present, a number of hypotheses for the boom-bust cycles of *Egeria* in New Zealand lakes have been proposed (de Winton & Champion 1993). Major risk factors for Lake Wainamu include; (a) a stressful light environment for submerged plant growth due to naturally high levels of CDOM, or possible increase in turbidity from sand dune subsidence, and the occupation of shallow zones by the fringing suds (floating rush beds), (b) the dependance by *Egeria* on maintaining a dense photosynthetic canopy at the water surface to sustain oxygen demands of the weedbed, and the vulnerability of this canopy to disturbance by grazing, (c) the lake's orientation, which means that it is vulnerable to strong southerly or northerly winds that may disturb *Egeria* beds, and (d) the presence of herbivorus rudd, which have the potential to build up a large population that may then become uncoupled from macrophyte biomass as the latter declines.

8 Recommendations

1. Identify and confirm the role(s) of wind in water movements and hence in the production of high turbidity levels in Lake Wainamu.

   This information will indicate the relationships between wind and lake mixing events including sub-surface currents in the lake and will help identify what practical measures can be used to reduce wind-driven water movements. It requires extraction and analysis of time-series data on wind and rainfall at the lake for the period when the datasondes were installed. If such data are not available, then installation of current meters and datasondes in the lake together with an accompanying anenometer and rainfall gauge would be required for at least several months over spring/summer when the lake is stratifying.

2. Dune height, slope and position relative to the lake edge need to be monitored periodically to indicate whether dune encroachment into the lake is a gradual process, or whether it occurs through sudden subsidence and, if so, whether such events can be prevented.

   Dune subsidence can have a major effect on turbidity levels in this lake and the resultant reduction of light in this already 'light sensitive' lake may subsequently help flip the lake from a clear-water macrophyte dominated state to a turbid one (NB. light levels are already low in this lake because of its high concentration of coloured dissolved organic matter, or CDOM).

3. Promote research on exotic fish to identify and confirm their role in disturbing bottom sediments of ARC lakes and thereby in preventing macrophyte recovery and/or fostering increased silt re-suspension.

   The precise role of exotic fish in contributing to the increased turbidity of Lake Wainamu is unknown. The macrophyte recovery could have been coincidental and related to a change in annual weather patterns as much as to the reduction in exotic fish. Research is clearly needed to identify the role of exotic fish in macrophyte suppression and hence to justify their continued control.

4. Fish removal should continue until it can be established that the exotic fish are not a threat to the lake's water clarity (see 3 above). However, once macrophyte recovery is completed (e.g., 100% coverage of exposed lake bed less than 2.5 m deep), the level of effort spent on fish removal could be scaled back (i.e., to once a year, in early spring, to reduce the spawning population before the spawning season begins).

   If water clarity, turbidity or macrophyte cover do start to decline again, and the role of exotic fish is not known, then the rate of fish removal would need to be increased again.

5.	A feasability study is recommended to identify and evaluate the future options for exotic plant and fish management in this lake.

Macrophyte re-growth needs to be encouraged in Lake Wainamu and the aquatic plant beds then managed to continue their key role in consolidating the sediments and inhibiting re-suspension of silt by water movements. There are three options for macrophyte management in this lake. Do nothing. This would allow the *Egeria* to spread and grow naturally in the lake. This is a no-cost option but the risk is that *Egeria* may collapse again at some time in the future (see section 7) resulting in a turbid lake once again. The second option would involve limited management of *Egeria* (e.g., periodic harvesting or spraying with herbicide) to prevent its over-growth and to minimise the risk of its collapse. This would involve a small but on-going cost. While minimising the risk of macrophyte collapse, it would not eliminate it. The third option would involve complete eradication of *Egeria* using a biological control agent (i.e., grass carp), then reduction of the grass carp to allow re-growth of the native plant species. This option would be more costly in the short term but may be cheaper in the long term. Once grass carp are removed, the native macrophyte species would then recolonise the lake and provide long-term stability for its water clarity. The *Egeria* eradication option would allow subsequent eradication of the exotic fish and hence restoration of the lake's full native biodiversity, but this could take from 5-10 years to effect, depending on funding. The lake would be turbid over this period and there is always the risk that both exotic plant and fish species will be deliberately re-introduced. Because of the range in management options possible, together with their varying costs, time frames, and environmental cost-benefits, a fuller analysis of options than can be provided by this 'partial' study is warranted and it should incorporate community concerns and wishes (see 6 below).

6.	The local community group needs to be consulted to inform them about the outcomes of this investigation and to determine their thoughts and preferences for the lake's future management by the ARC.

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10 Acknowledgements

This study was initiated by the efforts of the Lake Wainamu Community Group who subsequently played a vital role in assisting with water sampling. We thank Rebecca Ball and Natalie Wilkinson for their roles in coordinating volunteers and providing liaison. We also thank the Wheeler and Bethell families for their support and access to the lake. We acknowledge the funding provided by the Foundation for Research Science and Technology which complemented that provided by the ARC and helped underpin much of the methods development and analysis involved in this lake restoration project.

Appendix 1. List of sites, GPS positions and descriptions.

Site	Site description	GPS	Vegetation description
A	North-western end adjacent to entry point	E2641098 N6478647	Reeds to c. 2 m, very thin fringe of *E. densa* next to reeds.
B	1/3 along eastern shore	E2641244 N6478403	Occasional *E. densa* plants on outer edge of reeds at c. 2m.
C	At sharp end of lake, north western shore	E2641764 N6478225	No submerged plants sighted, reeds to 3 m.
D	Fish cage site up small stream area	E2641887 N6478137	Shallow site. Some *N.* aff. *cristata* at very low cover and *E. densa* at the bank side.
E	South-eastern end of lake	E2641659 N6478069	Reeds extended to c. 2 m.
F	2/3rd way down lake, southern shore	E2641473 N6478143	>95% cover of *N.* aff. *cristata* and *C. australis* at 1.2 to 2 m depth, plants parted to take cores. Core at 3 m on the cut-off of *C. australis*. Pock-marks in sediment at 4 m.
G	Half way along southern shore .	E2641297 N6478189	1% cover of charophytes at 2.5 m.
H	First bay around from sand dune	E2641012 N6478342	*E. densa* at 25-50% cover from 1.9 to 3 m depth. Live and dead mussels *E. densa* at 3 m depth, 2.5 m tall, 5% cover or less.