Management of the University of Waikato campus lakes:

Final report

CBER Contract Report Number 23

Prepared for the Site Committee of

The University of Waikato

by

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Management of the University of Waikato campus lakes:
Final report

EXECUTIVE SUMMARY

There are three small, shallow lakes on the University of Waikato campus, and all have high nutrient loadings, creating ideal conditions for plant and algal growth. These lakes were created by excavation during construction of the university for the purposes of stormwater detention. Water quality in the lakes has been a matter of concern to the University of Waikato Site Committee for a number of years, and the concern intensified in late 2000 with the commissioning of the WEL Energy Academy of Performing Arts, which was built with a view over Knighton Lake.

Knighton and Oranga lakes are very shallow (maximum depth about 0.65 m), and are usually very turbid. Periodically during spring and summer surface blooms of planktonic algae cause brightly coloured surface scums in these lakes. Proliferation of the introduced curly leaved pondweed (*Potamogeton crispus*) also occurs in spring and summer, and during flowering this plant protrudes above the water surface, trapping litter and duck feathers. Emergent plants also spoil the play of light and reflections on the water surface.

Chapel Lake is the deepest of the three, with a maximum depth of about 1.8 m. The water in Chapel Lake is generally clearer than in Knighton and Oranga lakes, algal growth is less, and pondweed does not occur in this lake. Chapel Lake represents the desired state for all the campus lakes.

The principal differences between Chapel Lake and the two shallower lakes (Knighton and Oranga) is that Chapel Lake has clearer water, fewer fish and ducks, and much less mixing than the shallow lakes. The likely cause of the low fish numbers in Chapel Lake is the stratification that periodically lowers dissolved oxygen in the bottom waters to almost zero. These conditions would restrict fish to the shallow edges where dissolved oxygen concentrations were sufficient.

Thus the main problem with Knighton and Oranga lakes appears to be that they were not excavated to a sufficient depth (about 2 m) when they were formed. Of all the possible solutions, deepening the lakes is the longest lasting and after it was done would have the fewest environmental risks. Some smells, fish deaths, and disruption in the vicinity of the lakes would be expected during the dewatering and excavation period.

COST ANALYSIS

We analysed the costs of treatments that could be used to alleviate the water quality problems apparent in Knighton and Oranga lakes, and estimated the time that the treatment would last and its risks. We assumed that Chapel Lake represents the best water quality possible in the context of the main purpose of the lakes as stormwater detention ponds. However, the water level recedes in summer in Chapel Lake, so addition of clean water would be useful to maintain water level. The rate required to equal evaporative losses of 3 mm day^{-1} is about 13 m^3 day^{-1}.

We considered several alternatives for algal control. While flocculant dosing might work for a short time, the temperature-induce mixing might resuspend the flocculated material. Ultrasound is an unknown technology in New Zealand, and may fail to control the target algal species. Booming to remove surface algae is time consuming, and only works with a favourable wind. This method cannot be relied on to remove algae when needed. Filtration is expensive and also has a high risk of failure. Resuspension rates might be too high to for this method to be effective. Also, wind can push surface algae away from the intakes for the filtration system. Operations and maintenance costs for filtration would also be considerable. Flushing was the option suggested by the original DSIR consultancy report. Our analysis suggests that water sufficient for effective flushing is not available.

For macrophyte control, manual removal of curly leaved pondweed has proved very effective and relatively cheap ($3,000 to 6,000 per year). However, it would be desirable not to have to do this. Weed matting appears not to be an option because of the high rates of gas production from the sediments. Grass carp would be an option, but though they relatively cheap to lease, the environmental assessment and potential antagonism from some sectors of the public probably mean that this is not a realistic option. Permission from the Department of Conservation is required for grass carp release, and the outlet screens would need to be improved and maintained to prevent escape of the carp.

Removal of ducks and fish is one option to reduce an external nutrients input and internal nutrient resuspension. Ducks can add significant amounts of nutrients to lakes, but total removal is probably not acceptable to the public or the local fish and game managers. Catfish removal is an option, though the use of poisons would require a consent from Environment Waikato. Netting in 1998 suggests that this method can remove a reasonable proportion of the catfish, but only with a considerable effort. The catfish biomass in Oranga Lake was greater than the accepted threshold 150 kg ha^{-1}, suggesting that fish removal might improve water clarity. However, there was no obvious improvement in water clarity following fish removal in 1998, probably because the shallowness and strong thermally induced mixing reduced the effectiveness of the fish removal.

CONCLUSIONS

The principal differences between Chapel Lake and the two shallower lakes (Knighton and Oranga) are that Chapel Lake has clearer water, fewer fish and ducks, and much less deep mixing than the shallow lakes. The likely cause of the lower fish numbers in Chapel Lake is the stratification that periodically lowers dissolved oxygen in the bottom waters to almost zero. These conditions would restrict fish to the shallow edges where dissolved oxygen concentrations were sufficient. The lower catfish abundance in Chapel Lake than in Knighton and Oranga lakes is consistent with fishing in 1996.

Thus most of the problems associated with Knighton and Oranga lakes appear to be caused by their insufficient depth. Of all the solutions considered, deepening the lakes would last the longest, and after completion would have the fewest environmental risks. One reservation is that Chapel Lake is also the smallest, most sheltered, and most shaded of the three campus lakes, and some of its differences could be attributed partly to these factors. If Knighton and Oranga lakes were deepened, some smells, fish deaths, and disruption in the vicinity of the lakes would be expected during the dewatering and excavation period.

Deepening Knighton and Oranga lakes is likely to make them react in similar fashion to Chapel Lake, with a similar mixing regime, light extinction coefficient, fish and plankton assemblages. This would reduce the fish populations and growth of curly leafed pond weed, and improve water clarity to the standard of Chapel Lake.

We conclude:

1. That the addition of bore water to Oranga Lake is having no adverse consequences for the water quality of either Oranga or Knighton Lake, and we recommend its continuation to maintain water levels during times of low rainfall. Adding water to Chapel Lake would maintain its level during dry summers.

2. That deepening Knighton and Oranga Lakes would reduce internal nutrient cycling and consequently reduce the nutrients available to support algal growth. These mechanisms of nutrient reduction are:

- Removal of the soft-nutrient-rich sediment that has accumulated in the approximately 30 years since the original lake excavation;
- Reduction of the frequency and duration of thermally induced penetrative convection that distributes nutrient-rich pore water from the sediment into the water column;
- Putting the lake bed out of reach of dabbling ducks, thereby preventing this potential source of nutrient cycling;
- Reduction of potential bioturbation of bottom sediments by fish, and nutrients from fish excretion. This would occur because lowered concentrations of dissolved oxygen in the bottom waters would reduce fish abundance.

3. That deepening the lakes would also reduce the amount of light penetrating to the lake beds. Light levels below the compensation point for the growth of the troublesome curly leaved pondweed would virtually eliminate the need for other control measures for pondweed.

4. That without the pondweed, and with the lake bed out of their reach, the habitat would be less suitable for ducks. A reduction in duck numbers would mean less nitrogen and phosphorus input from duck faeces, and less nutrient resuspension by duck dabbling.

Thus we recommend excavation of 1.3 m of the beds of both Knighton and Oranga lakes. The resultant basins would be about 2 m deep. Despite high cost of excavation, this solution has the most chance of success, would fix most of the problems that currently occur, and would be the longest lasting solution.

Finally, as an interim measure, the removal of catfish could be continued. Fish removal was effective in improving water clarity in some Dutch lakes (Meijer et al. 1999), and it is probable that too few fish were removed from Knighton Lake to improve water clarity. Before a commitment is made to the expensive option of deepening the lakes, another attempt could be made to assess the present fish population, and then to remove catfish if the biomass is > 150 kg ha^{-1}. Oranga Lake had an estimated catfish biomass of 200 kg ha^{-1} in 1998, but recent catch rates indicate that abundance might be less than 25% of that estimate. A more soundly based estimate of fish abundance would be very useful for understanding the management options. The Centre for Biodiversity and Ecology Research has a new fish capture tool in the form an electrofishing boat, and this could be highly effective at fish capture and removal.

INTRODUCTION

The campus lakes

There are three small, shallow lakes on the University of Waikato campus, and all have high nutrient loadings (Willis 1996), creating ideal conditions for plant and algal growth. These lakes were created by excavation for the purposes of stormwater detention during construction of the university. Water quality in the lakes has been a matter of concern to the University of Waikato Site Committee for a number of years, and the concern intensified in late 2000 with the commissioning of the WEL Energy Trust Academy of Performing Arts, which was built with a view over Knighton Lake.

Knighton and Oranga lakes are very shallow (maximum depth about 0.65 m), and are usually very turbid. Periodically during spring and summer surface blooms of planktonic algae cause brightly coloured surface scums in these lakes. Proliferation of the introduced curly leaved pondweed (*Potamogeton crispus*) also occurs in spring and summer, and during flowering this plant protrudes above the water surface, trapping litter and duck feathers. Emergent plants also interfere with reflections on the water surface (Table 1).

Chapel Lake is the deepest of the three, with a maximum depth of about 1.8 m. The water in Chapel Lake is generally clearer than in Knighton and Oranga lakes, algal biomass is lower, and pondweed does not occur in this lake.

Table 1. Area and depth of the University of Waikato campus lakes.

Lake	Area (ha)	Maximum depth (m)
Chapel	0.44	1.8
Knighton	1.01	0.6
Oranga	0.69	0.6

Two separate problems were obvious from a brief site inspection in November 2000. In spring 2000 extensive beds of the curly leaved pondweed had expanded in Oranga and Knighton Lakes, breaking their otherwise mirror-like reflective surfaces. As the weather warmed into summer, floating red and green scums of algae were apparent on the lee shore, depending on the wind, ambient temperature, and time of day. The university Site Committee considered the problems serious enough to warrant immediate attention, and in response the Centre for Biodiversity and Ecology Research (CBER) put forward a plan to resolve the short-term and long-term problems. CBER suggested using the following approach:

1. Investigate emergency remedies for algal scums;
2. Establish a long-term monitoring programme to assess water quality and the biological and physical response to alum dosing;
3. Assess the effect of bore water addition;
4. Prepare cost analysis for management options lasting 5-10 years or longer.

A study proposal based on these four objectives was accepted after meetings with the Vice-Chancellor on 5 March 2001 and by the Site Committee on 12 April 2001. To fulfil our obligations under the contract for these investigations, a series of reports were produced (Hicks 2001, Hicks et al. 2001, Hicks et al. 2002, Hicks and Bryant 2002). This report consolidates and supersedes the previous reports, and will consider the water quality and management options for all three lakes. Chapel Lake arguably represents an acceptable water quality state for the lakes on campus, and thus serves as a reference condition. We investigated methods of direct control of algae and macrophytes, methods of controlling internal nutrient cycling, and methods of controlling external nutrient inputs. These form three separate sections within the following report.

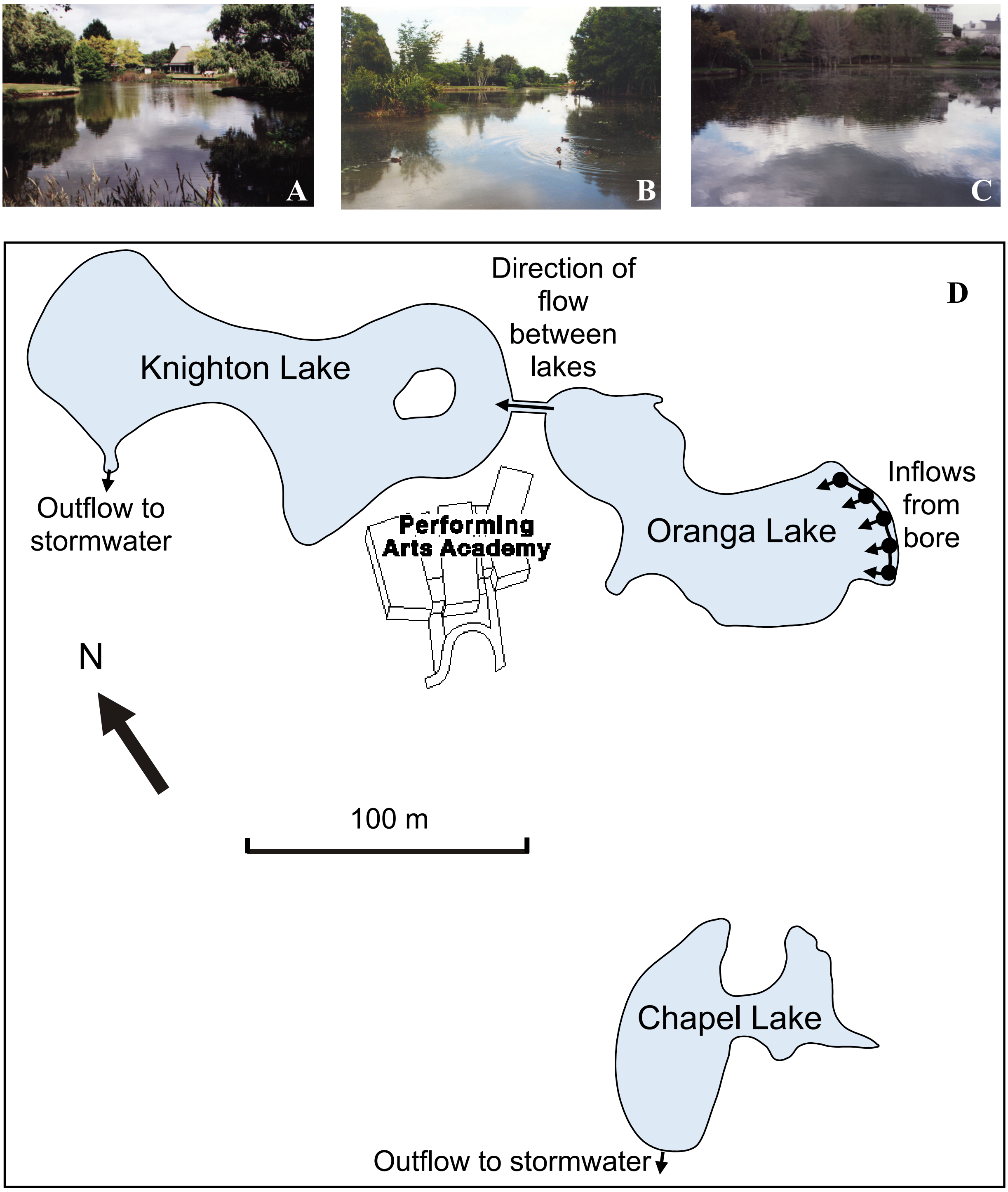


Figure 1. The campus lakes of the University of Waikato, showing A. Chapel Lake, B. Knighton Lake, C. Oranga Lake, and D. the location of the lakes and the WEL Energy Trust Academy for the Performing Arts.

Alternatives for management of water quality

A variety of alternatives have been used for control of water quality. The results have ranged from effective, long-lasting control of water quality to no effect.

Biomanipulation

In a review of 18 case histories in The Netherlands, Meijer et al. (1999) found that reduction of fish biomass could cause improvements in water clarity. However, the results were not always long lasting, and the mechanisms frequently remained unknown. Increases in macrophyte coverage and increases in the number of grazing zooplankton were the most usual causes of improved clarity. Reductions in fish biomass must be >75% for effective improvements, and the original fish biomass should be high (>150 kg ha^{-1}).

Dredging

Sediment removal has been used in several successful applications overseas (Cooke et al. 1993; chapter 17). Lake Trummen in Sweden is a particularly good example, where increasing the mean depth of the lake from 1.1 m to 1.75 m decreased total phosphorus in the surface waters by 90% and total nitrogen by 80% (Cooke et al. 1993; p504).

PART 1 - DIRECT CONTROL OF ALGAE AND MACROPHYTES

PLANKTONIC ALGAE

Seventeen algal taxa were identified by Dr U. V. Cassie-Cooper in a surface water sample from Knighton Lake collected on 16 February 2001. These samples were collected from the surface scums that had accumulated at the leeward (eastern) shore of Knighton Lake (Figure 2). The principal species among the taxa was the cyanobacterium *Microcystis aeruginosa*, which appeared as a pale-green surface scum 2-5 mm thick on the lee shore. On top of this pale-green scum were bands of a brick-red layer. This was most likely *Euglena sanguinea*, which can appear either as green spindle-shaped cells, or as floating, spherical, thick-walled dark red cells that seem to be hydrophobic. Also very common was the euglenoid *Trachelomonas volvocina*.

In the summer of 2001-2002 the rust-red *Euglena sanguinea* continued to form a thin scum on the water surface in both Knighton and Oranga lakes. The scum occurred from mid morning to mid afternoon on warm days. The pale green scums of *Microcystis aeruginosa* did not cause noticeable problems in the summer of 2000-2001, but Knighton and Oranga lakes have continued to be a muddy green colour that was probably caused by a mixture of phytoplankton and organic material resuspended from the lake bed by the strong mixing that occurred on most nights (Hicks et al. 2002).

On 3 July 2001, three methods were used to sample the phytoplankton and zooplankton:

1. 1-litre sample from 10 cm below the water surface;
2. 250-ml sample of the sediment-water interface, sampled by gently suction created by opening the bottle within 5 mm of the sediment surface;
3. 8-m tow of a 45 μm mesh plankton net thrown from the bank.

All three lakes were sampled between 1539 h and 1602 h. The lakes were sampled in the order Chapel, Oranga, Knighton at the sites as shown below. One sample of each type was taken from each lake (Figure 3). In addition, filamentous green algae were sampled from small wooden piles submerged in Knighton Lake.

Zooplankton were particularly abundant in Knighton Lake on 3 July 2001, and were dominated by *Bosmina longirostris*, which is hydrophobic when at the water surface. Also abundant were chydorids (*Chydorus* or *Pseudochydorus*), large *Asplanchna*-like rotifers, a *Keratella* sp. with a central spine, and a *Keratella* sp. with a lateral spine.

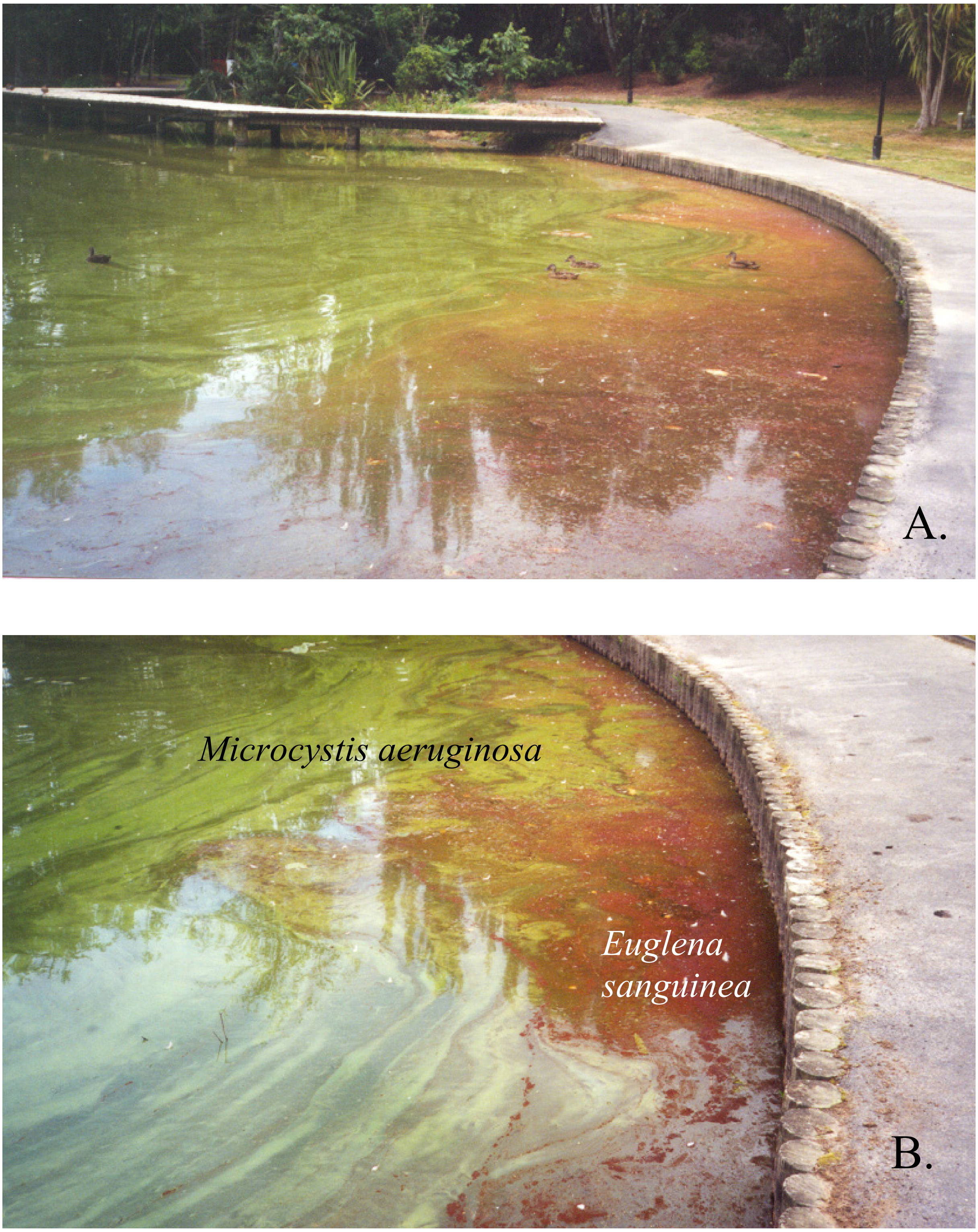


Figure 2. Algal scum at the leeward shore of Knighton Lake on 7 Feb 2001. A) the extent of the scum; B) close-up of the scums showing the predominant algal composition.

Photos: B. J. Hicks.

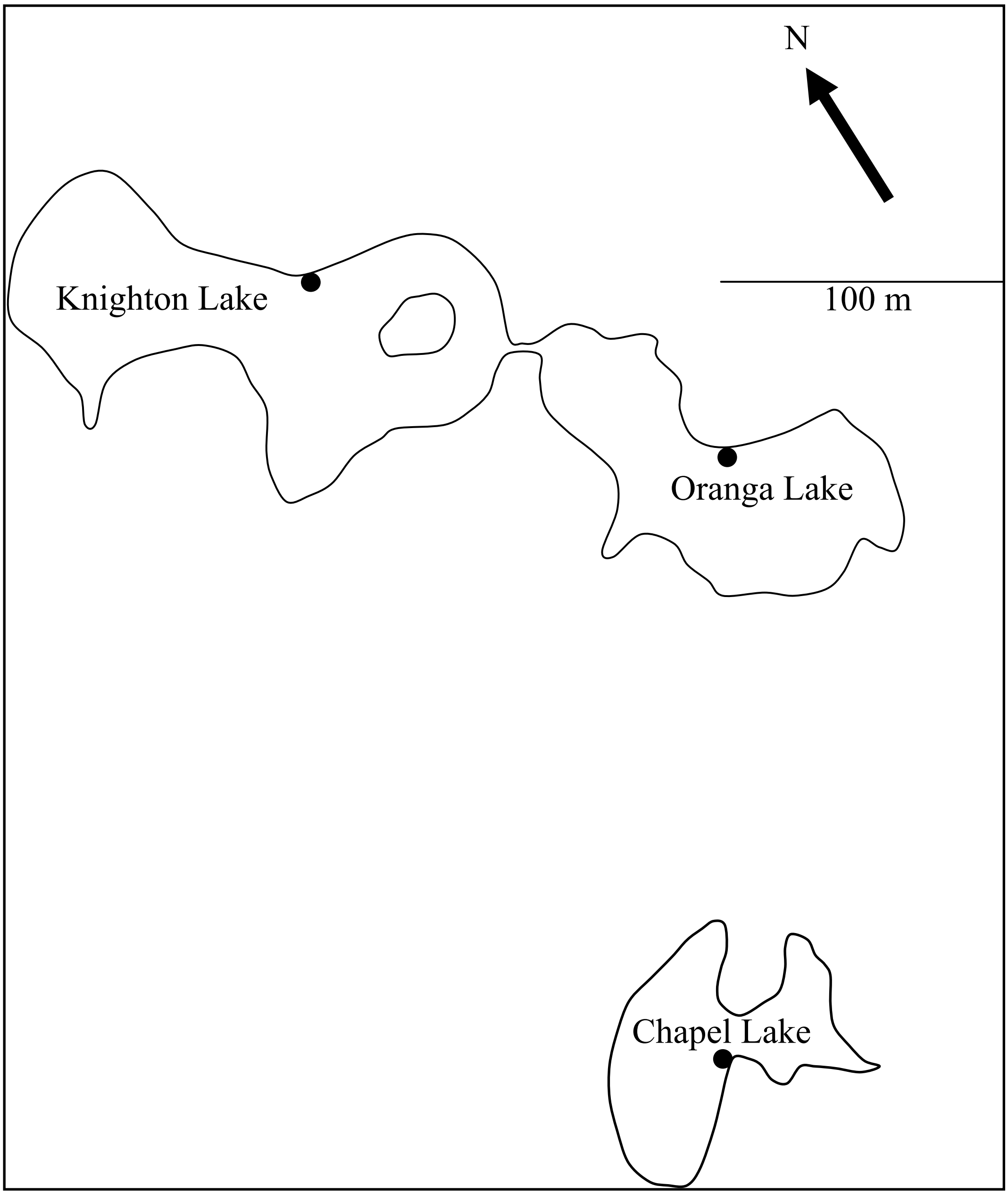


Figure 3. Phytoplankton, zooplankton, and algal sampling sites (denoted by ●) in the campus lakes on 3 July 2001.

Algal control

Resource consents

In treatment of water supplies, swimming pools, and ponds in golf courses, a variety of algaecides has been used to precipitate algae or to control algal growth. Discharge of any material into waterways normally requires a resource consent, and Environment Waikato advised in January 2001 that this would be the case for extensive use of flocculants. However, provided that the use in the campus lakes was on a trial basis for a restricted period only, and that we had the permission of the landowner (Tainui), then they would consider a "*de* *minimus*" approach, which would not require consent. We took this approach, and sought permission from Tainui.

Permission from the landowner
In mid-February 2001 we met with representatives of Tainui, and subsequently received approval from Waikato Raupatu Lands Trust to conduct a limited field trial within an area that allowed for best containment and least impact on the environment. In the event, this field trial was not conducted, and Tainui were advised accordingly.

Flocculation

One remedy for suspended organic or inorganic material, such as fine sediment or phytoplankton, is to use chemical flocculants to remove the suspended material from the water column. This is the approach taken in water treatment plants where clear water is required for drinking. The Hamilton City Water Treatment Plant (HCWTP) draws in water from the Waikato River upstream of Hamilton City, and uses a combination of liquid alum (aluminium sulphate) and Magnafloc® LT22S as a flocculation aid to bind particles to form a stable sludge (Geoff Goodrick, Operations Manager, pers. comm.). A final dose rate of 21-27 ppm alum is achieved. Because the flocculation process acidifies the water, lime is used to return the water to pH 7.5-8 before it enters the city's drinking water supply. At any one time the HCWTP has 20,000 litres of liquid alum on site.

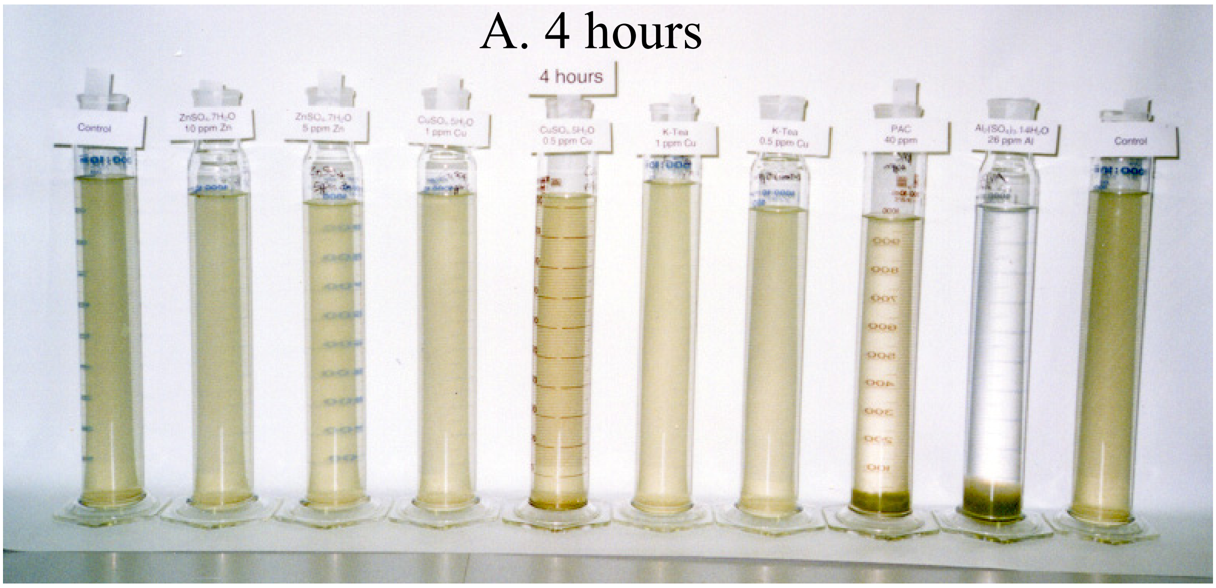
Fernz Chemicals in Morrinsville supply alum as a liquid with 61% $Al_2(SO_4)_3$ w/v at pH 2 in 1000 litre containers. The cost is \$300 per 1000 litre container, with a \$100 charge for filling and lease of the container, and a \$50 delivery charge.

Laboratory trials

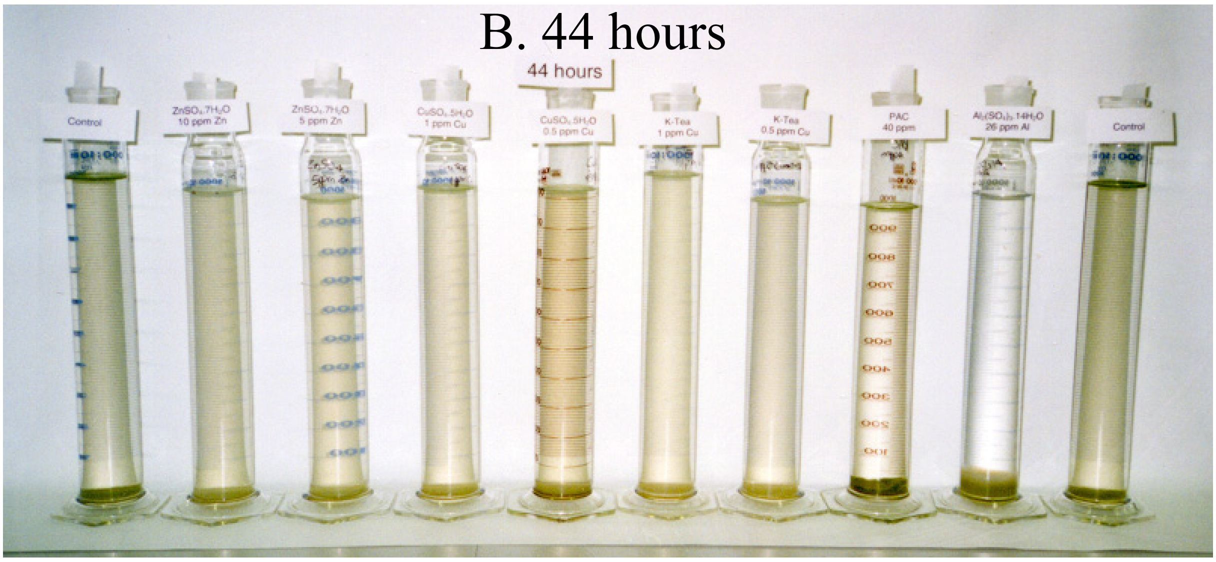
Algaecides and flocculants have potential for use in control of algae in the campus lakes, but probably only as an emergency measure. In the laboratory we investigated the effect on the algae of copper sulphate, zinc sulphate, and chelated copper, alum, poly aluminium chloride, and Magnafloc at various dilutions between 8 February and 1 March 2001. All worked in killing or flocculating the algae in the Knighton Lake samples. Griffin Corporation Australia Pty Ltd supplies the chelated copper compound K-Tea (Figure 4).

Further trials with alum at different concentrations showed that the most effective dose rate was 26 ppm Al, which had begun to work after 15 minutes, and had caused almost complete clearance of the water column within 3 hours of application (Figure 5). Alum at this concentration had the effect of reducing the pH from 8.0 before dosing to pH 4.3 at 80 h after dosing. The control with no added alum had declined from pH 8.0 to pH 6.7-7.0 over the same period.

Where aluminium accumulation is a concern, an iron salt (polyferric sulphate or PFS) can be used. Works Filter Systems in Hamilton supplies commercial quantities of a stock solution of PFS with 12.2% ferric iron. PFS worked moderately well as a flocculant at a 360 ppm dilution of the stock solution, with most flocculation occurring within the first 15 minutes (Figure 6). However, PFS stained the water to a deep yellow-brown colour, and at 360 ppm reduced the pH quite dramatically, from pH 9.1 before dosing to 2.9 about 20 hours after dosing. Lesser dilutions reduced the pH less, but resulted in a light flocc with poor settling ability.



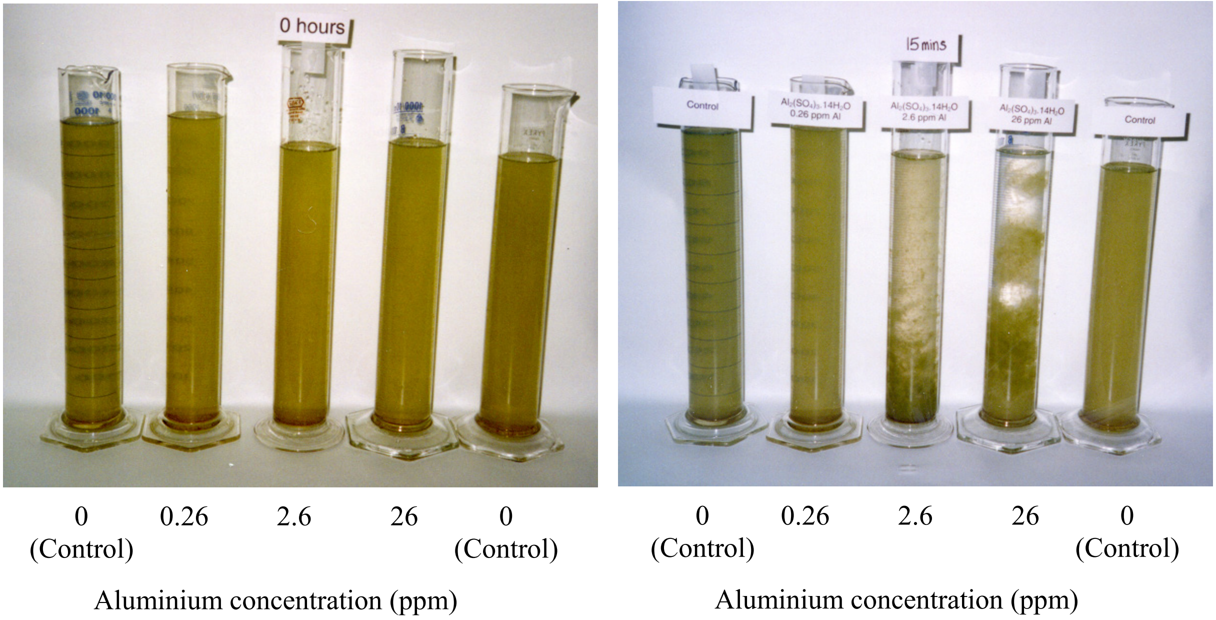
Control	10 ppm $ZnSO_4$	5 ppm $ZnSO_4$	1 ppm $CuSO_4$	0.5 ppm $CuSO_4$	K-Tea 1 ppm Cu	K-Tea 0.5 ppm Cu	PAC 40 ppm	Alum 26 ppm Al	Control



Control	10 ppm $ZnSO_4$	5 ppm $ZnSO_4$	1 ppm $CuSO_4$	0.5 ppm $CuSO_4$	K-Tea 1 ppm Cu	K-Tea 0.5 ppm Cu	PAC 40 ppm	Alum 26 ppm Al	Control

Figure 4. Flocculation and algaecide trials conducted on 8 Feb 2001 showing the action of copper and zinc-based toxicants, pool flocc (PAC - poly aluminium chloride) and alum (aluminium sulphate [$Al_2(SO_4)_3$]) on planktonic algae in water from Knighton Lake on the University of Waikato campus. Water clarity A) 4 hours and B) 80 h after dosing

A. 0 hours (nothing added) B. 15 mins



C. 3 hours D. 20 hours

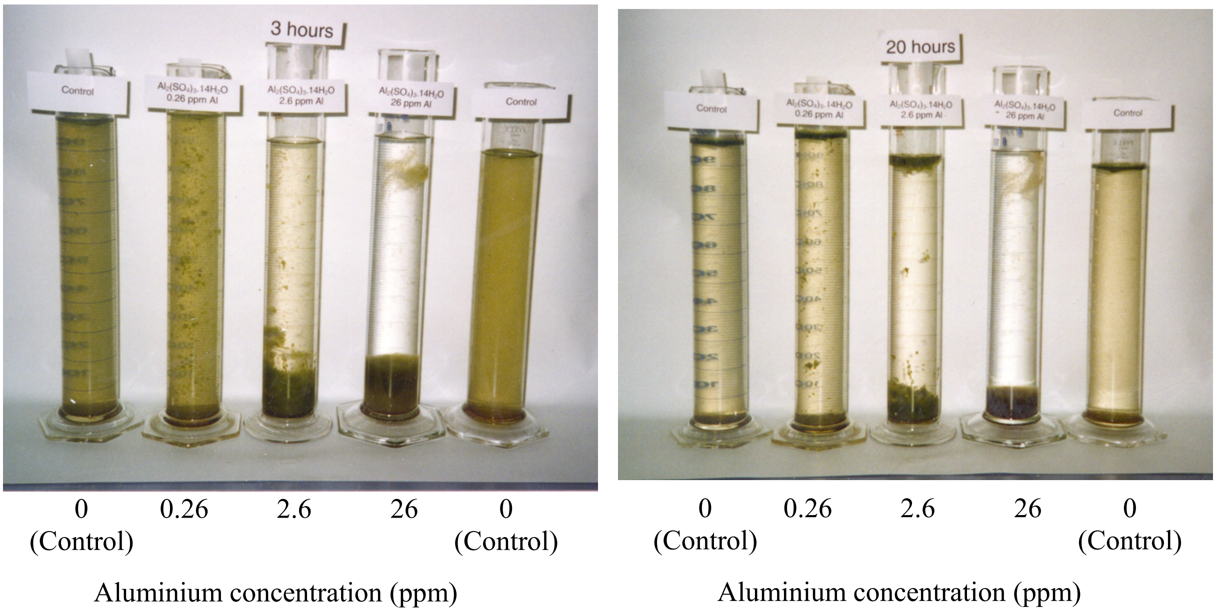


Figure 5. Flocculation test conducted over 20 h on 9 Feb 2001 showing the action of alum (aluminium sulphate [$Al_2(SO_4)_3$]) on planktonic algae in water from Knighton Lake on the University of Waikato campus.

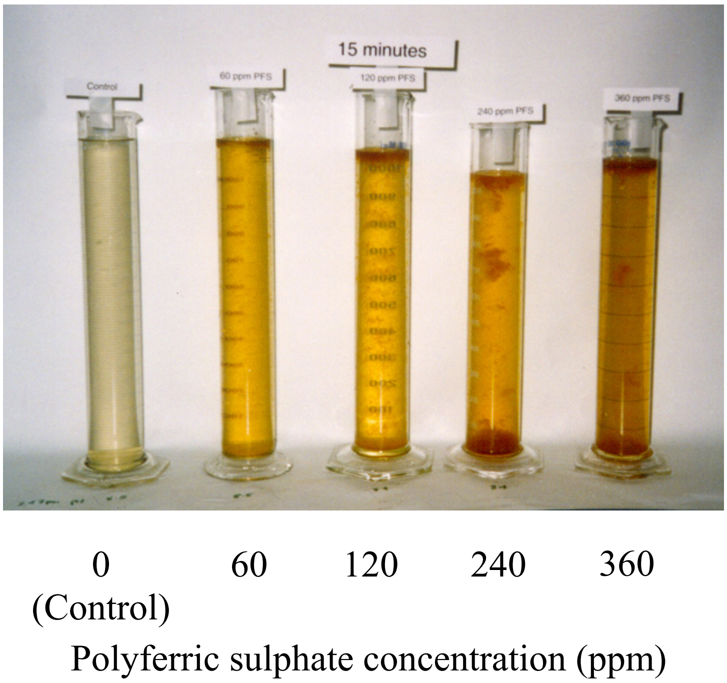


Figure 6. Flocculation test conducted on 1 Mar 2001 showing the action of polyferric sulphate (PFS) on planktonic algae in water from Knighton Lake on the University of Waikato campus 15 minutes after the addition PFS.

Polyelectrolyte flocculants, based on acrylamides, have been used in quarry operations to reduce sediment discharge. Magnafloc® 386, a cationic acrylamide copolymer available from Chemiplas NZ Ltd, is a primary coagulant. Magnafloc® 368, a polyarcylamide gel, applied directly to the water surface as dry beads (as recommended by the supplier) was difficult to dissolve, and not particularly effective as a flocculant.

From the tests done so far on chemical control of planktonic algae, flocculant dosing seems appropriate as an emergency measure. The sudden pH drop would cause fish deaths. Also, wind-drift of algae means that dosing is probably an all-or-nothing option, as treating small areas is not likely to result in effective prevention of scum formation. Alum seems to be the most effective flocculant for the scum-forming algae in the campus lakes.

Booming

When a gentle breeze has concentrated the algae on the leeward shore, the floating surface scum can be moved around by booming. In a novel approach, the grounds staff under the direction of Mark Thompson made up a 30-m floating boom of 10-cm diameter Novaflo piping with the ends sealed. Much of the surface scum was skimmed towards and out of the lake outlet at the western end of Knighton Lake by booming once or sometimes twice a day. The booming operation required two people.

Filtration, surface skimming, and nutrient stripping

We investigated use of a submersible pump and a coarse oat-straw filter system attached to a surface-skimming system. This was partly successful, but the surface skimming ability was limited somewhat by the low pump rate, and the pump size was limited by the available supply of electricity. There are several alternative suppliers of pumps and filter systems locally, and the feasibility of surface skimming, filtration, and nutrient stripping will be investigated.

Tom Holmes of Facilities Management Division arranged quotes from Amiad New Zealand Ltd, Barry and Sullivan Electrical, and Waikato Pump Services for a filtration system The cost of a sand filtration system was $52,885 (excl GST) for the installation of a 10 litre s^{-1} flow rate system. Graeme Cooper of Environment Waikato (EW) was been approached for their view on the requirement for a consent for the discharge of the back-washing water from the filter. EW did not at the time have a unified view on whether or not a consent would be required.

Flushing
The bore water additions were made to Oranga Lake at the suggestion of a previous consultancy report (Pridmore and Burns 1986), commencing in 1999. The objective was to provide flushing water to move suspended material out of the lakes via the outlets. The current flow rate has been determined by Earl Bardsley to be 17.5 m^3 h^{-1} over a 10-hour period, which runs from 10pm to 8am, 7 days a week, during the summer months. The bore pump is turned off during rainy periods. The current pumping regime yields a total addition to the lakes from the bore of 175 m^3 day^{-1}. The combined areas of Oranga and Knighton Lakes is 1.7 ha (17,000 m^2), so assuming an average depth of 0.5 m, the volume of the lakes is about 8,500 m^3, which means that with bore water additions alone, the detention time for the lakes is about 48 days. Given that evaporation also removes water (see below), the detention time could be as long as 68 days. As the net doubling time of algae in this productive system is in the order of a few days, clearly this rate of water addition is ineffective in flushing algae out of the system faster than it can reproduce.

The original consultants' report (Pridmore and Burns 1986) recommended a bore water flow rate of 8 litres s^{-1} (691 m^3 day^{-1}) between mid-October and mid-April to prevent algal blooms. This implies a detention time of about 25 days for water in Knighton and Oranga Lakes combined. At a flow rate of 5 litres s^{-1} (432 m^3 day^{-1}), the consultants considered that occasional algal blooms might develop. The current flow rate of 175 m^3 day^{-1} is inadequate to prevent algal blooms by flushing alone, both from Pridmore and Burns' theoretical approach, and from the evidence of current bloom formation.

The surface water level of Oranga Lake can be adjusted about 10 cm by the use of boards at the western outlet to Knighton Lake (Figure 1). Otherwise the level is controlled by inflows and evaporation. Given that one positive outcome of the bore water additions is maintenance of water levels during periods of low rainfall, investigation of alternative water inputs seems obvious. If one assumes that peak evaporation rates are 3 mm day^{-1} in the Waikato (Warwick Silvester pers. comm.), then the evaporation from the combined areas of Oranga and Knighton Lakes is 17,000 m^2 x 0.003 m = 51 m^3 day^{-1}, ignoring losses to groundwater. Purchase of this amount of treated water from Hamilton City Council (HCC), at 51 cents per kilolitre (= m^3), would be $26 per day. This assumes that HCC would sell this much water to the university during periods of high demand. Alternatively, diversion of the cooling water from the liquid nitrogen unit after it has flowed through the fernery is an option to be investigated. This discharge of drinking-quality water currently flows to waste through the stormwater system.

It appears that no water source is available at the moment to reduce algal scum formation by flushing alone, but the addition of water is useful in maintaining water levels through summer, which prevent unsightly beaches from developing at the shallow shores. The higher the water quality of this top-up water, the more it will improve the water quality of Oranga Lake.

Control of algae with ultrasound

An unusual solution to the problem of phytoplankton was suggested by Aburn Industries Ltd (15 Saddleton Road, Waiua Pa, RD 4, Pukekohe). This company markets a battery powered device that emits pulses of ultrasonic sound through the water. They claim that the device can cause a 75% reduction in nuisance bloom species such as *Ceratium*, an 80% reduction in *Trachelomonas*, and a 100% reduction in *Anabaena*. The mechanism of cell death is claimed to be disruption of the cell vacuole. A 45-W unit has a range of 150 m and costs $7,000. The spectrum of the wave output of the ultrasound is tuned to the cell sizes of the target algal species. Aburn Industries offered a 1-month trial free of charge that we did not take up. While *Trachelomonas* does occur in the campus lakes, *Ceratium* and *Anabaena* are not particularly troublesome. The international agents have the web site www.consultimex.com.

FILAMENTOUS ALGAE

As the water temperatures increase in spring, growth of filamentous algae and curly leaved pondweed in the campus lakes begins. By 28 August 2001 mats of the filamentous green alga *Spirogyra* started rising to the surface. These were removed by grounds staff from a boat. In December 2001 mats of *Spirogyra* occasionally floated to the surface of Knighton and Oranga lakes, and growth of this alga was still occurring in February 2002, though no mats were seen. As *Spirogyra* normally grows attached to a substrate, the algal mats probably begin growing attached to the lake bed, and then float to the surface as a result of buoyant trapped gas.

Mechanical removal of the mats of filamentous algae is a time-consuming job that would be unnecessary if there was insufficient light at the lake bed to support algal growth.

AQUATIC MACROPHYTES

Physical removal

Curly leaved pondweed normally appears first in Oranga Lake, followed approximately 1 month later by its appearance in Knighton Lake. At its greatest extent it can fill almost the entire volume of both Knighton and Oranga lakes, though usually a littoral fringe 1-2 m wide close to the shoreline remains free of pondweed (Figure 7). The pondweed was physically removed in December 2000 within a period of several weeks by a team of four people using mesh-covered forks and a small punt. This was quite successful, and involved 4 contract workers for 8 hours per day for 7 days, costing a total of $2,240 at $10 per hour. Pondweed has never been seen in Chapel Lake.

Figure 7. Oranga Lake in December 2000 showing extensive development of beds of curly leaved pondweed (*Potamogeton crispus*).

In 2001, an early, warm spring caused especially prolific growth of pondweed. By 29 August the first fragments of pondweed were seen floating on the surface of Oranga Lake, though rooted plants were not apparent because of the turbidity. By 27 September the pondweed covered about 50% of the surface area of the lake, and many plants had flower heads breaking the water surface. In Knighton Lake at the same time, isolated pondweed plants were apparent below the water surface, but few plants broke the water surface. A crew of 4 workers removed the curly leafed pondweed from Oranga and Knighton lakes between 12 November and 22 December 2001. During these 5 weeks the crew also weeded the lake bank edges, which accounted for 3 days. The weed removal was very thorough and prevented obvious weed regrowth for the rest of the summer. The cost of this work was $6,600.

In 2002, the cool spring delayed the growth of pondweed by about a month compared to 2001. In September 2002 some curly leaved pondweed was apparent in Oranga Lake. By 1 November 2002 the curly leaved pondweed had reached the surface and had begun to flower; about 60% of the surface of Oranga Lake with flowering pondweed. A few small patches of pondweed were seen below the water surface in Knighton Lake at this time (Mark Thompson pers. comm.). The weed was removed from Oranga Lake between 11 and 15 November 2002. The operation took 3 people 80 h at a cost of $12 per h, plus labour from university staff for 10 h at $15 per h. The work was carried out from 11 Nov to 22 Nov, and cost a total of $3,030. Because of the cool spring, weed removal from of Knighton Lake was unnecessary at this time.

Biomass and nutrient content

On 11 November 2002 the biomass of curly leaved pondweed was estimated by removing and weighing the weed from within five 1-m^2 quadrants with densest-looking weed beds in Oranga Lake. The mean wet weight was 5.55 kg m^2, and the mean dry weight was 0.440 kg m^2 (Table 2). At the time of sampling, the water depth had been lowered by 0.20 m to facilitate pondweed removal.

Table 2. Mean biomass of curly leaved pondweed (*Potamogeton crispus*) in five 1-m^2 quadrants in Oranga Lake on 11 November 2002. * Water at the time of sampling plus 0.20 m.

Quadrat	Water depth (m)	Corrected water depth* (m)	Wet weight (kg m^{-2})	Dry weight (kg m^{-2})	Wet weight of subsample (g)	Dry weight of subsample (g)	Dry weight/ wet weight
1	0.62	0.85	7.40	0.587	50.03	4.49	0.0898
2	0.51	0.74	6.05	0.480	40.61	3.35	0.0824
3	0.55	0.78	5.10	0.405	30.49	2.24	0.0734
4	0.53	0.76	6.05	0.480	54.44	3.95	0.0726
5	0.52	0.75	3.15	0.250	40.40	3.17	0.0786
Mean	0.55	0.78	5.55	0.440	43.19	3.44	0.0794
SD	0.04	0.04	1.41	0.112	8.36	0.76	0.0063
CV	0.07	0.05	0.25	0.253	0.19	0.22	0.0797
95% CI	0.03	0.03	1.23	0.098	7.32	0.67	0.0055

Assuming the mean biomass (Table 2) is representative of the Knighton and Oranga lake at maximum development of the pondweed, there could be 33 tonnes wet weight of pond weed in Oranga Lake (3.0 tonnes dry weight), and 56 tonnes wet weight of pond weed in Knighton Lake (4.4 tonnes dry weight).

Removal of the pondweed also removes nitrogen (N) and phosphorus (P) from the lakes. To estimate the amount of N and P removed with the pondweed we measured the N and P content of five samples of dry pondweed (Table 3). Assuming that these concentrations are representative of the weed in the entire lake, weed removal could remove up to 120 kg of N per year from Knighton Lake, and 82 kg from Oranga. It would also remove 30 kg and 21 kg of P per year from Knighton and Oranga lakes respectively.

Table 3. Nitrogen and phosphorus content of curly leaved pond weed, *Potamogeton crispus*, in Oranga Lake on 11 November 2002.

Sample	% N	$\delta^{15}N$	% P
1	2.46	1.39	0.692
2	2.58	1.58	0.705
3	2.81	1.77	0.726
4	2.84	1.94	0.785
5	2.76	1.33	0.492
Mean	2.69	1.60	0.680

Weed matting

Another way to suppress pondweed growth is to cover the lake bed with weed matting. Weed matting has been used successfully around boat ramps in Lake Rotorua to prevent the establishment of rooted aquatic weeds. Mark Thompson organised quotes for weed matting from R. J. Reid (NZ) Ltd, who quoted \$2,504 excl. GST to supply a 100 m^2 square of weed matting with chain to weight the edges. Much of this expense is for construction, as the matting itself is relatively inexpensive. Pegging with steel rods might be a cheaper way to fix the matting to the lake bed. The cost of 3.85-m wide matting is \$5.75 per m (excl. GST). Thus it would cost about \$30,000 excl. GST to cover the beds of both Oranga and Knighton lakes (17,000 m^2 area) for the matting alone. To this estimate would be added the costs of installation and fixing materials.

An experimental trial of weed matting was attempted on 14-15 February 2002. Two 10 m by 10 m squares of weed matting were positioned over the lake bed in both Knighton and Oranga lakes and weighted down with paving blocks. The cost of both mats was \$1,200. The mats did not sink immediately because they trapped gas. The mats were removed 3 days later because they had still failed to sink. Although they are supposed to allow water and gas through, the rate of gas evolution from the lake bed was faster than the diffusion of gas through the mat, and the gas that collected under the mats made them too buoyant to sink. This gas was probably a mixture of methane and carbon dioxide, with a small amount of hydrogen sulphide.

A series of small cuts were made in the matting to allow the gas to escape, and the mats were reinstalled in September 2002. Though the mats remained submerged in places they floated above the lake bed. Matting that was sufficiently porous to allow the gas to escape would also probably allow pondweed to grow through it.

Grass carp

Grass carp (*Ctenopharyngodon idella*) are large, herbivorous fish that have been successfully used in New Zealand to control and even eradicate aquatic macrophytes (Rowe and Champion 1994; Bannon 2001; Wells et al. 2003). These fish are supplied on a lease basis by New Zealand Water Management. Advice from the supplier is that the Knighton and Oranga lakes would need 30 fish per vegetated hectare, or 50 fish in total. The lease would cost \$1250 + GST, and the transport would cost \$350 + GST, to give a total cost of \$1600 + GST. The university would need permission from the Department of Conservation to release carp into the lakes, and to make the outlet secure so that no escape for the fish was possible. The university would probably also need to undertake an environmental impact assessment as stocking of grass carp is still controversial.

The cost of obtaining consents from EW and DOC, and installation of fish barriers to prevent escape, are likely to far outweigh the costs of the grass carp lease.

Light attenuation

The attenuation of light penetration with increasing water depth is one important control of the growth of plants in lakes. Light penetration was measured in all three lakes on an overcast day, and was rapidly attenuated (Table 4). The log-transformed data were fairly linear (Figure 8), and the slopes of the lines fitted by least-squares regression were used as the attenuation coefficients. The coefficients were 2.96 for Chapel Lake, 7.18 for Knighton Lake, and 6.99 for Oranga Lake.

Relative light attenuation can also be used to predict the depth below which plants and algae cannot grow because of insufficient light. One percent of surface light is a generally accepted light level at which photosynthetic organisms have their compensation point (i.e., Z_{eu}, where respiration equals photosynthesis), and below this depth plant growth is not possible. On 11 February 2002 this depth was about 1.4 m, 0.60 m, and 0.45 m for Chapel, Oranga, and Knighton lakes respectively (Figure 9). This suggests that at the deepest point Chapel Lake curly leaved pondweed is unable to grow at the lake bed. If Knighton and Oranga lakes were deepened to the depth of Oranga Lake, the growth of curly leaved pondweed is likely to be suppressed by low light levels at the lake bed.

Table 4. Profiles of downwelling and upwelling photosynthetically active radiation (PAR) the University of Waikato campus lakes on 11 February 2002.

Depth (m)	Downwelling PAR (µmol m^{-2} s^{-1})	Upwelling PAR (µmol m^{-2} s^{-1})	Percent of surface	Comment
Chapel Lake (1335 to 1348 h)				
0.00	523.10		100	Above surface
0.05	410.00	9.900	78	
0.25	158.00	4.270	30	
0.50	63.90	2.440	12	
0.75	33.30	1.270	6	
1.00	16.55	0.608	3	
1.25	11.50	0.000	2	Bottom
Oranga Lake (1402 to 1406 h)				
0.00	710.00		100	Above surface
0.10	247.00	5.320	35	
0.20	131.00	1.340	18	
0.30	66.46	0.231	9	
0.40	30.10	0.000	4	Bottom
Knighton Lake (1430 to 1435 h)				
0.00	164.50		100	Above surface
0.05	64.80	2.103	39	
0.10	36.55	1.246	22	
0.20	19.25	0.039	12	
0.30	10.13	0.000	6	Bottom

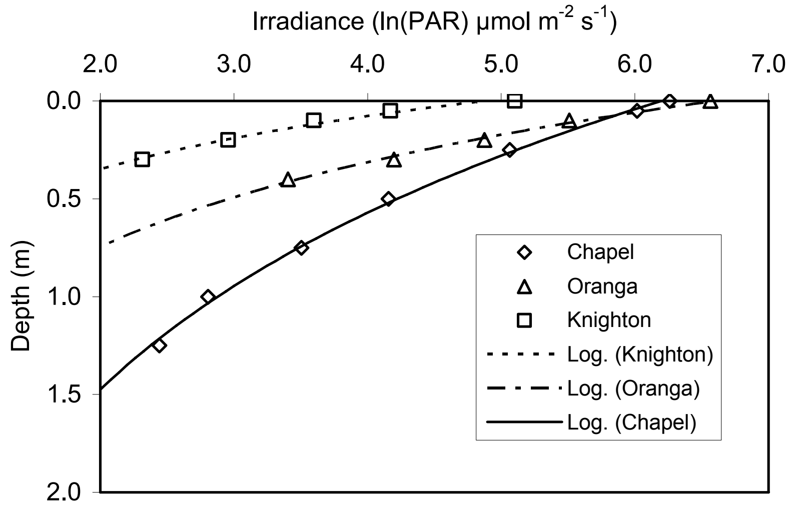


Figure 8. Attenuation of irradiance (downwelling light) with depth in the University of Waikato campus lakes on 11 February 2002. Ln(PAR) = natural log of photosynthetically active radiation.

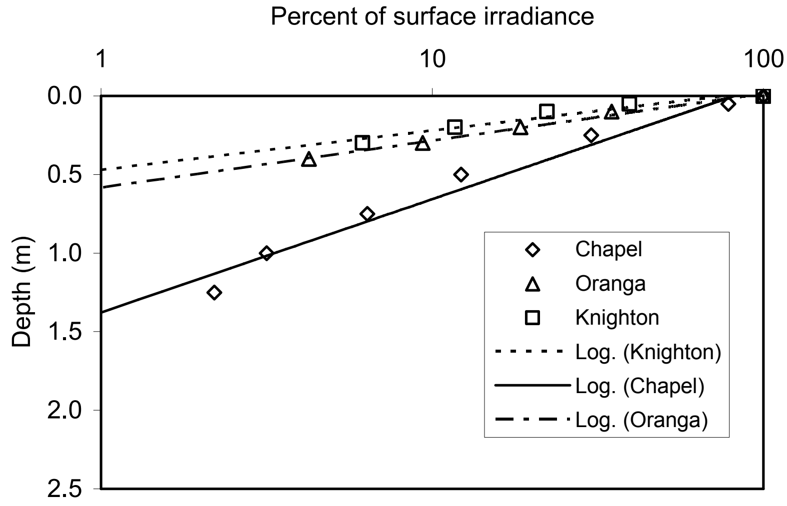


Figure 9. Relative attenuation of surface irradiance (downwelling light) with depth in the University of Waikato campus lakes on 11 February 2002 expressed as available light as a percentage of surface light.

PART 2 - CONTROL OF INTERNAL NUTRIENT CYCLING

Water quality and bore water additions

Water quality was monitored between July 2001 and November 2002 by measurements of electrical conductivity, Secchi depth, nutrient concentrations, and chlorophyll *a* concentrations. Nutrient concentrations were determined by the University of Waikato with a Lachat FIA autoanalyser. During most of this period bore water was added to Oranga Lake at a rate of 175 m^3 day^{-1}. The bore water additions were made over 10 h during the hours of darkness when the price of electricity was cheapest. To test the effect of the bore water addition on water quality, the bore water additions were ceased on 3 April 2002 and resumed on 4 June 2002. During the summer of 2001/2002 the water levels of Knighton and Oranga lakes remained stable and high because of the bore water pumping, whereas the water level in Chapel Lake decreased by 30-40 cm because of the lack of rainfall in February 2002.

Conductivity

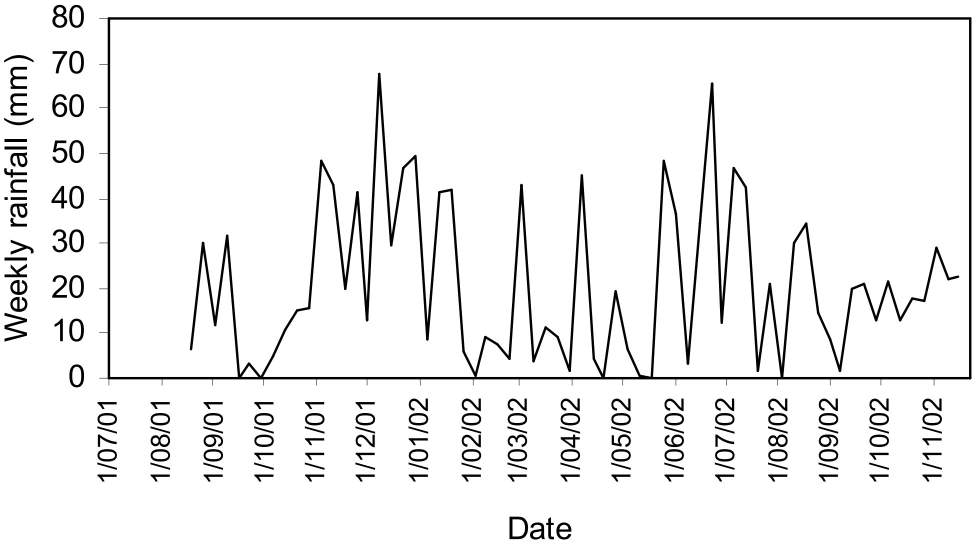
Electrical conductivity of water can reflect nutrient availability, with high conductance indicating the presence of more nutrients than at low conductance. Conductivities between July 2001 and September 2002 were greater than in 1996, and were usually much greater in Knighton and Oranga lakes (100-250 µS cm^{-1}) than in Chapel Lake (32-81 µS cm^{-1}; Figure 10B). Chapel Lake always had the lowest specific conductivity. Mean conductivities measured in 1996 were 62, 107, and 131 µS cm^{-1} in Chapel, Oranga, and Knighton lakes respectively (Willis 1996). Between July 2001 and September 2002 mean conductivities were similar in Chapel Lake, but greater in Oranga and Knighton lakes than in 1996 (Table 5).

Table 5. Mean conductivity in the campus lakes of the University of Waikato between July 2001 and September 2002. Data from 1996 from Willis (1996).

Lake	Specific conductivity (µS cm^{-1})			
	1996	2001 to 2002		
	Mean	Mean	95% CI	N
Chapel	62	54	5.4	26
Oranga	107	158	10.2	26
Knighton	131	163	15.8	26

The addition of bore water appears to reduce conductivity. During the period with no bore water additions there was a trend of increasing conductivity in Knighton and Oranga lakes (Figure 10B). Since water flows from Oranga Lake to Knighton Lake there is a hydraulic connection between the lakes. However, rainfall from 25 May to early July caused a rapid drop in conductivity in both lakes between 22 and 31 May 2002, just before the resumption of bore water additions on 3 April 2002. Thus although the bore water additions appear to reduce conductivity in Oranga and Knighton lakes, rainfall also influenced conductivity, with lower conductivities following rain.

A. Total weekly rainfall



B. Specific conductivity

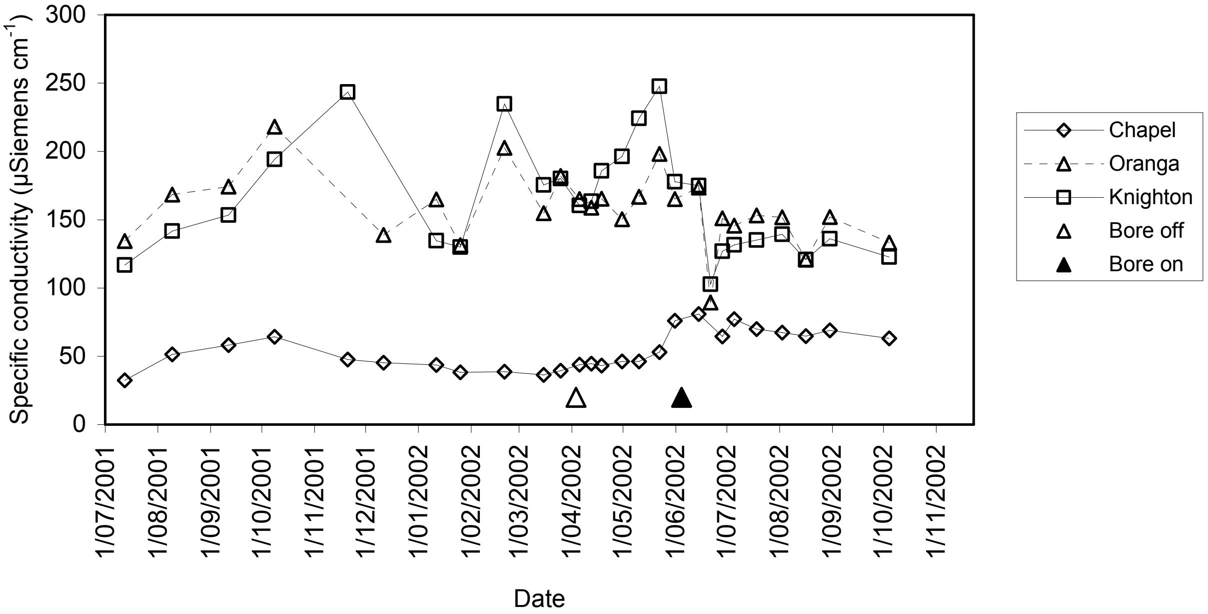


Figure 10. Seasonal variation in A. total weekly rainfall at Ruakura and B. conductivity of the campus lakes of the University of Waikato.

Plant nutrients

Nitrogen and phosphorus are important plant nutrients that determine the capacity of water to sustain plant life. The ratio of nitrogen to phosphorus (N:P) can be important in determining whether green algae or nitrogen-fixing cyanobacteria will prevail. Oranga and Knighton lakes had high concentrations of organic nitrogen and phosphorus, but low concentrations of nitrate-nitrogen and nitrite-nitrogen, and moderate levels of filterable reactive phosphorus.

Phosphorus concentrations were similar in all lakes, but the lower N:P ratios in Oranga and Knighton lakes suggests that nitrogen-fixing cyanobacteria are more likely to occur in these lakes than in Chapel Lake (Table 6).

Table 6. Concentrations of nitrogen and phosphorus in the campus lakes of the University of Waikato on 12 July 2001 determined by R. J. Hill Laboratories.

Nutrient form	Concentration ($g\ m^{-3}$)					
	Chapel		Oranga		Knighton	
	Sample 1	Sample 2	Sample 1	Sample 2	Sample 1	Sample 2
Total ammoniacal-N	< 0.01	0.04	0.02	0.01	0.07	0.05
Total Kjeldahl nitrogen	0.60	0.70	0.40	0.40	0.40	0.40
Total organic nitrogen	0.60	0.66	0.38	0.39	0.33	0.35
Nitrate-N + nitrite-N	< 0.002	0.002	< 0.002	< 0.002	0.045	0.017
Nitrate-N	< 0.002	< 0.002	< 0.002	< 0.002	0.041	0.013
Nitrite-N	< 0.002	< 0.002	< 0.002	< 0.002	0.003	0.003
Dissolved inorganic nitrogen	< 0.01	0.042	0.02	0.01	0.115	0.067
Total nitrogen	0.60	0.66	0.38	0.39	0.38	0.37
Dissolved reactive phosphorus	0.006	0.011	0.022	0.021	0.019	0.014
Total phosphorus	0.056	0.066	0.074	0.066	0.058	0.054
Total N:total P mass ratio	10.7	10.0	5.1	5.9	6.5	6.8

We did not identify the cause of nutrient fluctuations in the campus lakes, but they appear to be unrelated to rainfall and the addition of bore water. Ion concentrations, especially phosphate, showed fluctuations during the sampling period (Figure 11). The period with no bore water additions had depressed phosphate concentrations, and elevated ammonium concentrations. Following the peak in ammonia were peaks in NO_x (principally NO_3), presumably associated with nitrification of ammonium. However, as the same patterns were observed in Chapel Lake as in Knighton and Oranga lakes, the bore water additions seem not to be responsible. Nitrite ions (NO_2) were always at relatively low concentrations.

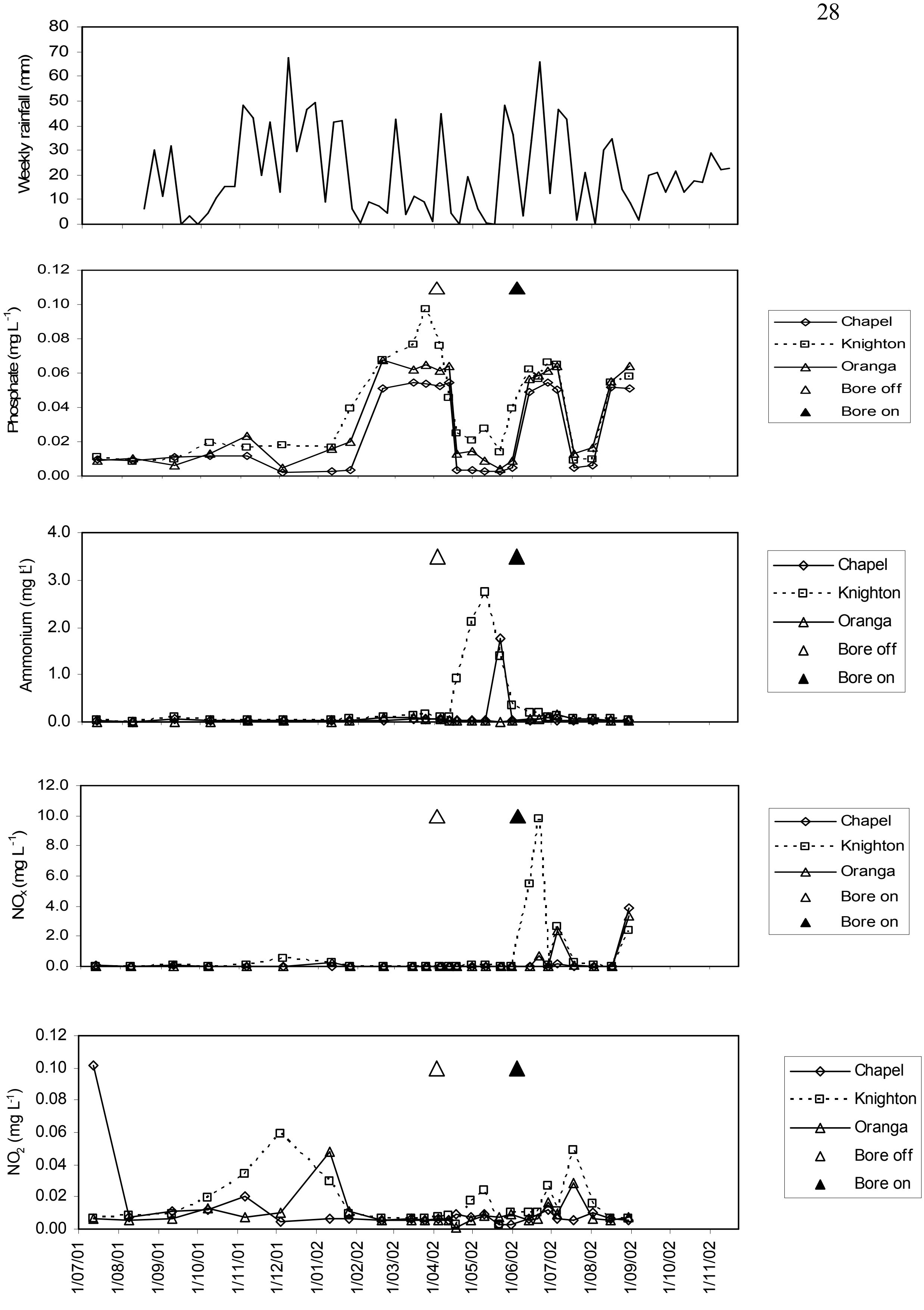


Figure 11. Seasonal changes in ion concentrations in the University of Waikato campus lakes.

Secchi depth

Water clarity can be measured by the depth at which a 20-cm diameter black and white disc (or Secchi disc) disappears when viewed from the water surface. This depth is known as the Secchi depth. The Secchi depth was usually deeper in Chapel Lake than in Oranga and Knighton lakes (Figure 12). Though all these Secchi depths reflect poor water clarity, Oranga and Knighton lakes have measurably lower clarity than Chapel Lake.

Likewise, Secchi depth in Oranga and Knighton Lakes also showed no response to the bore water additions (Figure 12). Chapel Lake normally had the clearest water (i.e., greatest Secchi depth), which approached 1 m in July 2002. The water was generally slightly clearer in Oranga than in Knighton Lake. No changes appeared to be associated with the bore water additions.

Dissolved oxygen

During the day in summer 2002, the bottom waters of Chapel Lake showed depleted concentrations of dissolved oxygen. While concentrations near the surface were ≥100% dissolved oxygen, the bottom water (about 1.6 m deep) had 1.2 mg L^{-1}, or just 10% of the oxygen predicted by the temperature at 22.4°C (Figure 13). Oxygen depletion to this extent will prevent fish occupying the area of depletion. The reduced dissolved oxygen concentration occurred when the lake was stratified, as the temperature profile shows a marked temperature drop within the top 0.5 m of the lake (Figure 13).

Chorophyll a *and suspended material*

The chlorophyll *a* concentrations, which are a measure of the concentration of algae in the water, fell in Knighton and Oranga lakes when the bore water pumping was turned off (Figure 14). Chlorophyll *a* concentrations increased slightly in Oranga Lake during the period with no bore water additions, and declined when water additions resumed. However, as the changes in the unmanipulated Chapel Lake showed a similar response over the same period the changes in Oranga and Knighton lakes were probably not a response to the bore water. Knighton and Oranga lakes had greater proportions of inorganic suspended material in the water column than Chapel Lake (Table 7).

Table 7. Mean percentage of organic and inorganic suspended sediment in the water column of the campus lakes of the University of Waikato in October 2002.

Lake	Site	Suspended sediment (%)	
		Organic	Inorganic
Chapel	1	56	44
Chapel	2	57	43
Knighton	1	33	67
Knighton	2	33	67
Oranga	1	33	67
Oranga	2	32	68

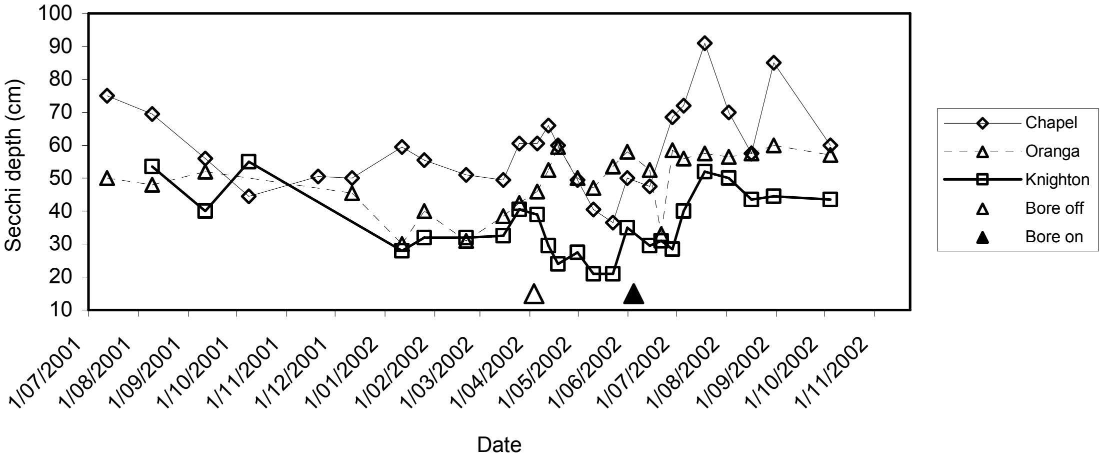


Figure 12. Seasonal variation in Secchi depth in the campus lakes of the University of Waikato. Greater Secchi depth indicates clearer water.

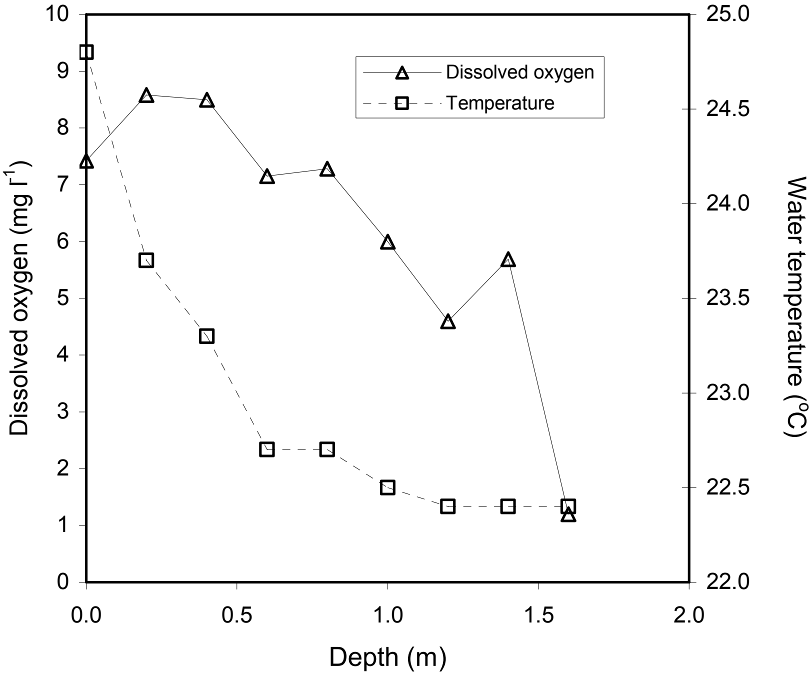


Figure 13. Dissolved oxygen profile in Chapel Lake at 1400 h on 25 January 2002. Water temperature ranged between 22.4 (bottom) and 24.8°C (surface).

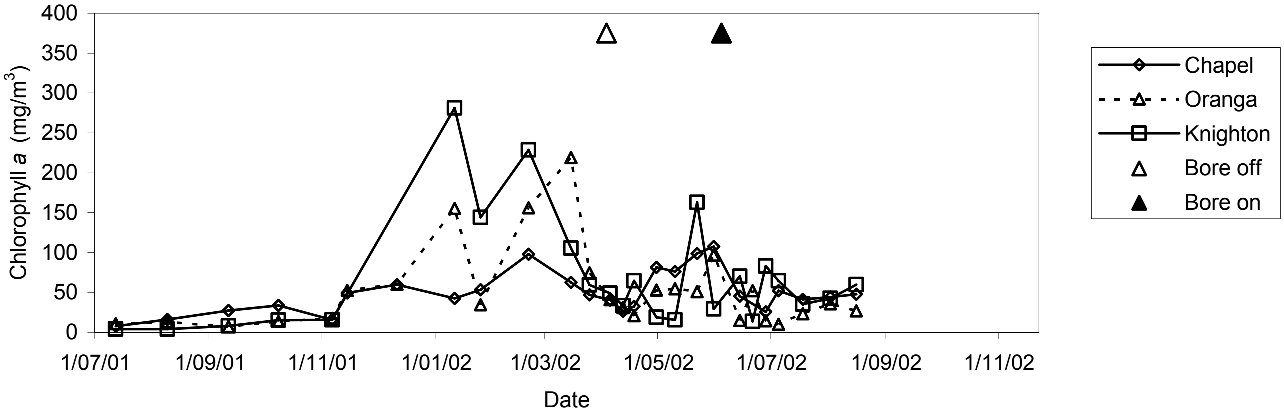


Figure 14. Chlorophyll *a* concentrations in the campus lakes of the University of Waikato.

Mixing processes

Surface and bottom water temperatures

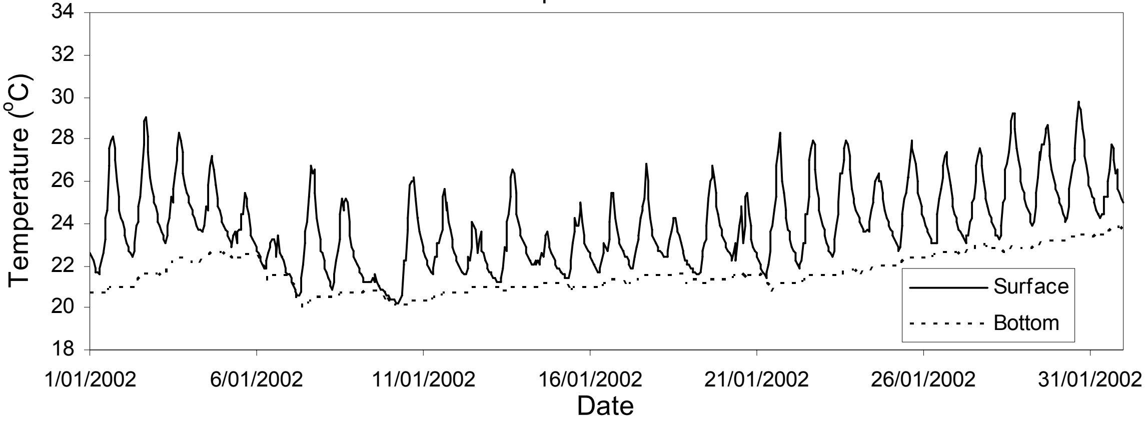
The soft, nutrient-rich sediments on the beds of the campus lakes are easily suspended by wind mixing and thermally induced water movement. We set out to evaluate the thermally induced mixing by logging water temperatures in the surface and bottom waters in all three lakes.

Stowaway Tidbit temperature loggers (Onset Corporation) were suspended at two sites in each lakes 10 cm below the water surface and 20 cm above the lake bed between July 2001 and November 2002. A typical period of record (January 2002) shows that Chapel Lake was usually stratified, whereas Knighton and Oranga lakes mixed strongly for about 8 h each night (Figure 15). Though surface waters of all three lakes undergo a diel cycle of warming and cooling, frequently of 6-8^{o}C, the extent of mixing induced by these temperature changes is profoundly different in Chapel Lake compared to Knighton and Oranga lakes.

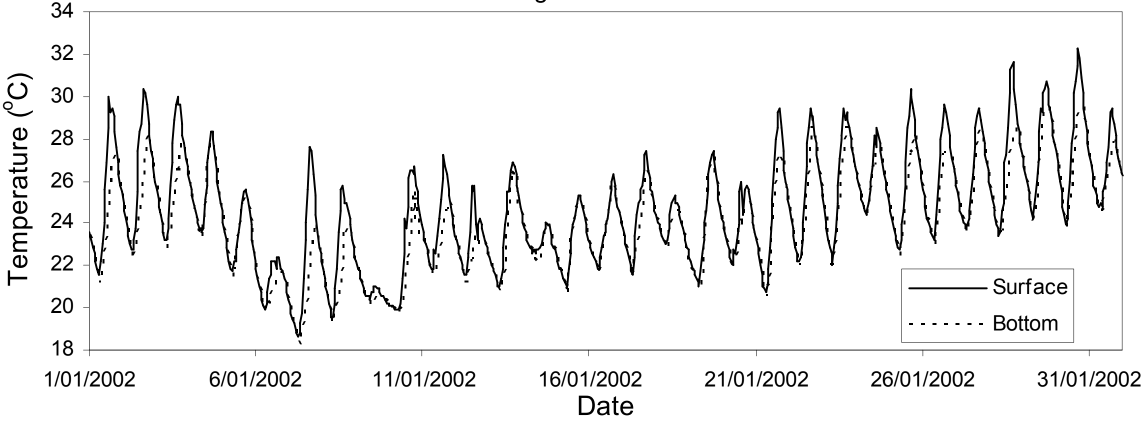
The surface water in Knighton and Oranga lakes cool faster than the bottom waters, with the result that at some point in the night the surface water is cooler than the bottom water. This is unstable, because cool water is denser than warmer water, and the cool, surface water therefore sinks, eroding the thermocline by penetrative convection. While the same cooling takes place in Chapel Lake, its greater depth prevents the mixing from reaching the bottom. The prolonged absence of mixing in the bottom waters allows the oxygen depletion observed in Figure 13 to occur. In contrast, thermally induced mixing in the very shallow Knighton and Oranga lakes disrupts the water column to the lake beds.

Throughout 2001 and the summer of 2002 Chapel Lake was mostly stratified, with only brief periods of complete mixing. Conversely, Knighton and Oranga lakes mixed every night. However, in the windy, cool period from April to August 2002, mixing occurred in Chapel Lake too (Figure 16). Knighton and Oranga lakes were strongly mixed during some part of most days for the period of record (Figures 17 and 18).

A. Chapel Lake



B. Knighton Lake



C. Oranga Lake

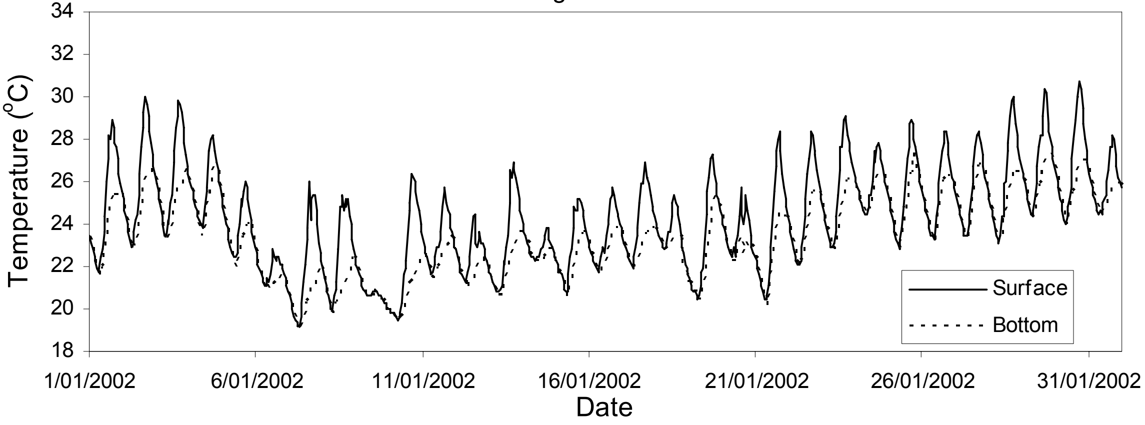


Figure 15. The temperatures of the surface and the bottom waters in A. Chapel Lake, B. Knighton Lake, and C. Oranga Lake in January 2002.

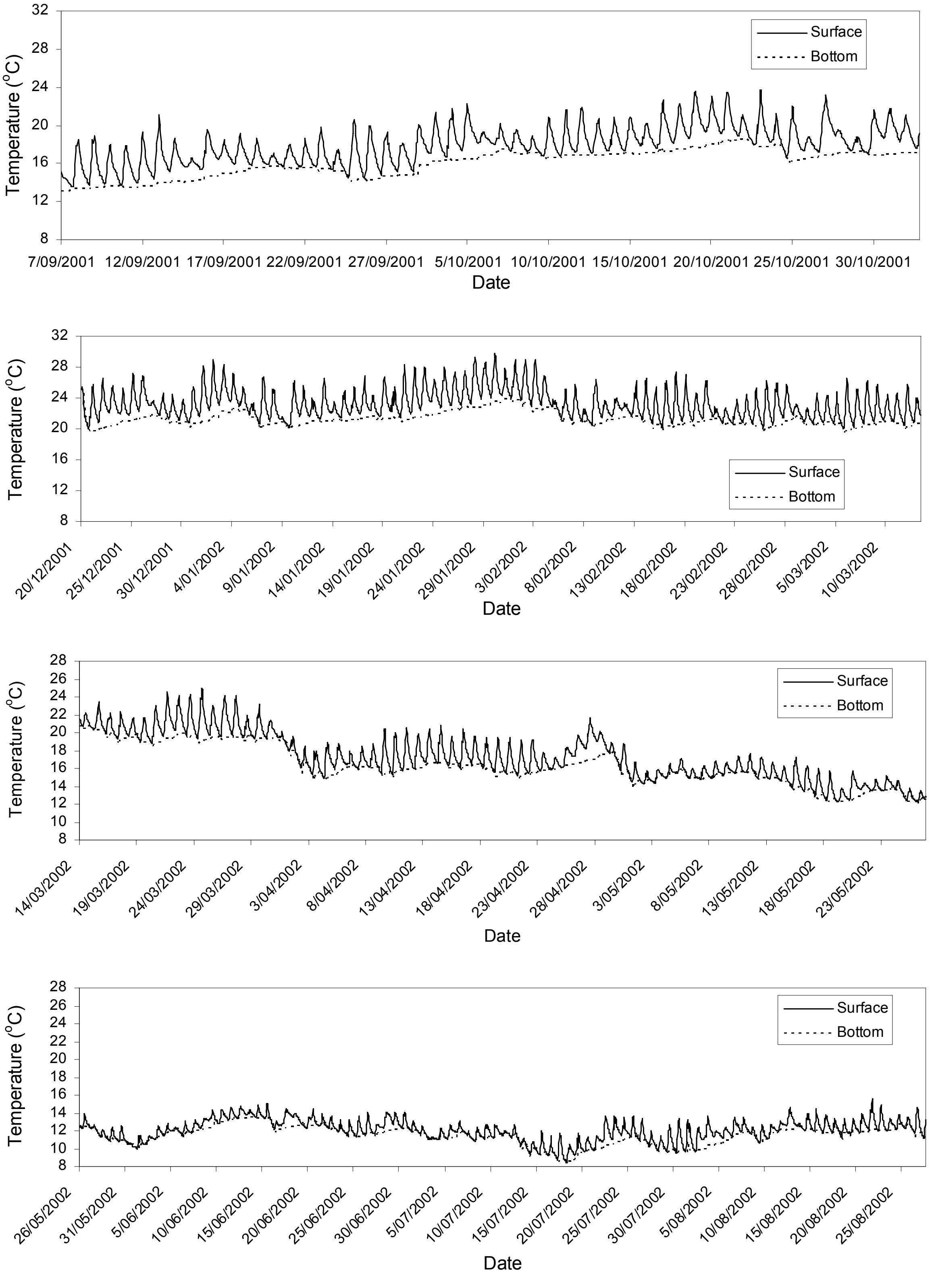


Figure 16. The temperatures of the surface and bottom waters of Chapel Lake from September 2001 to August 2002.

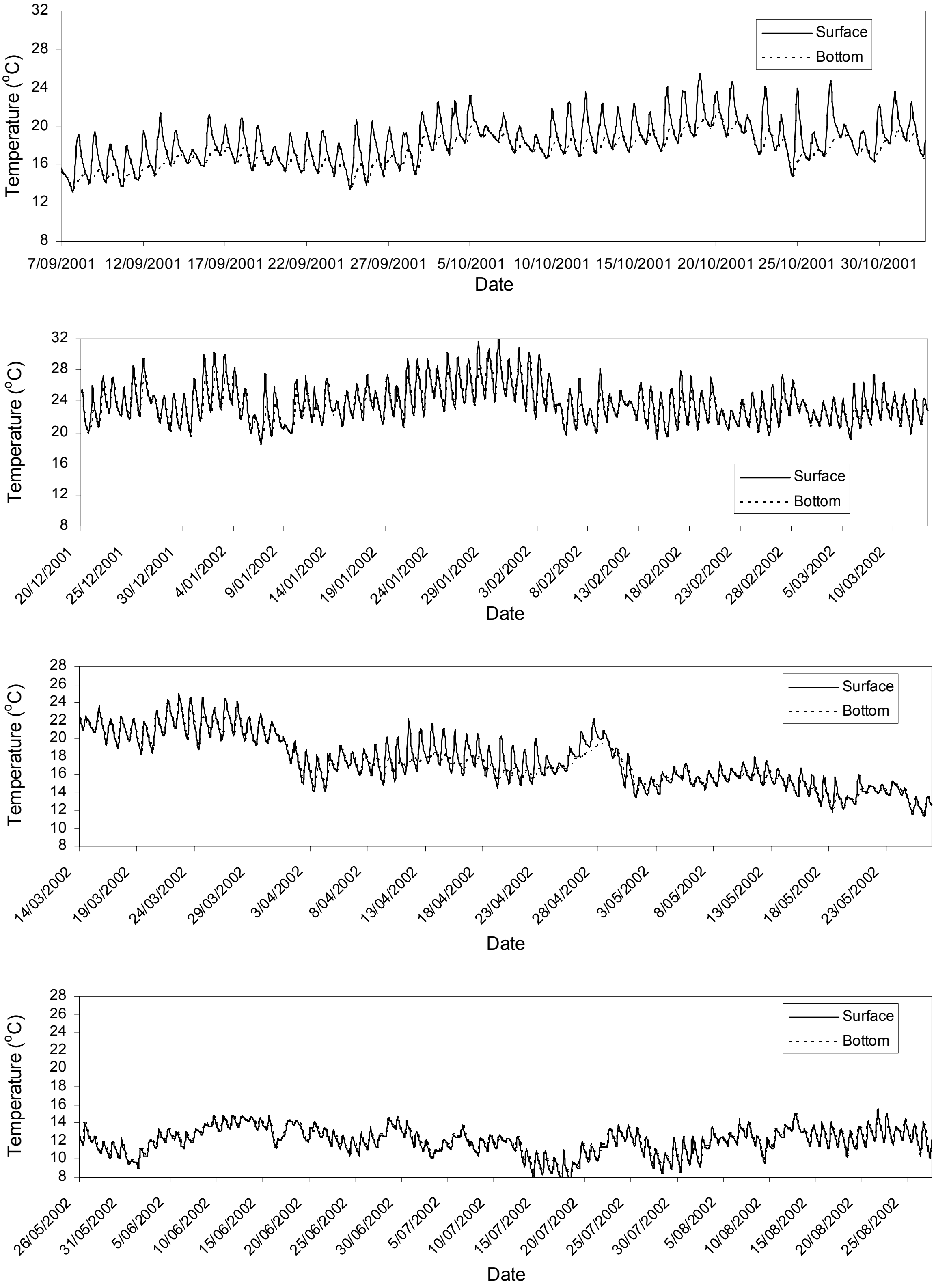


Figure 17. The temperatures of the surface and bottom waters of Knighton Lake from September 2001 to August 2002.

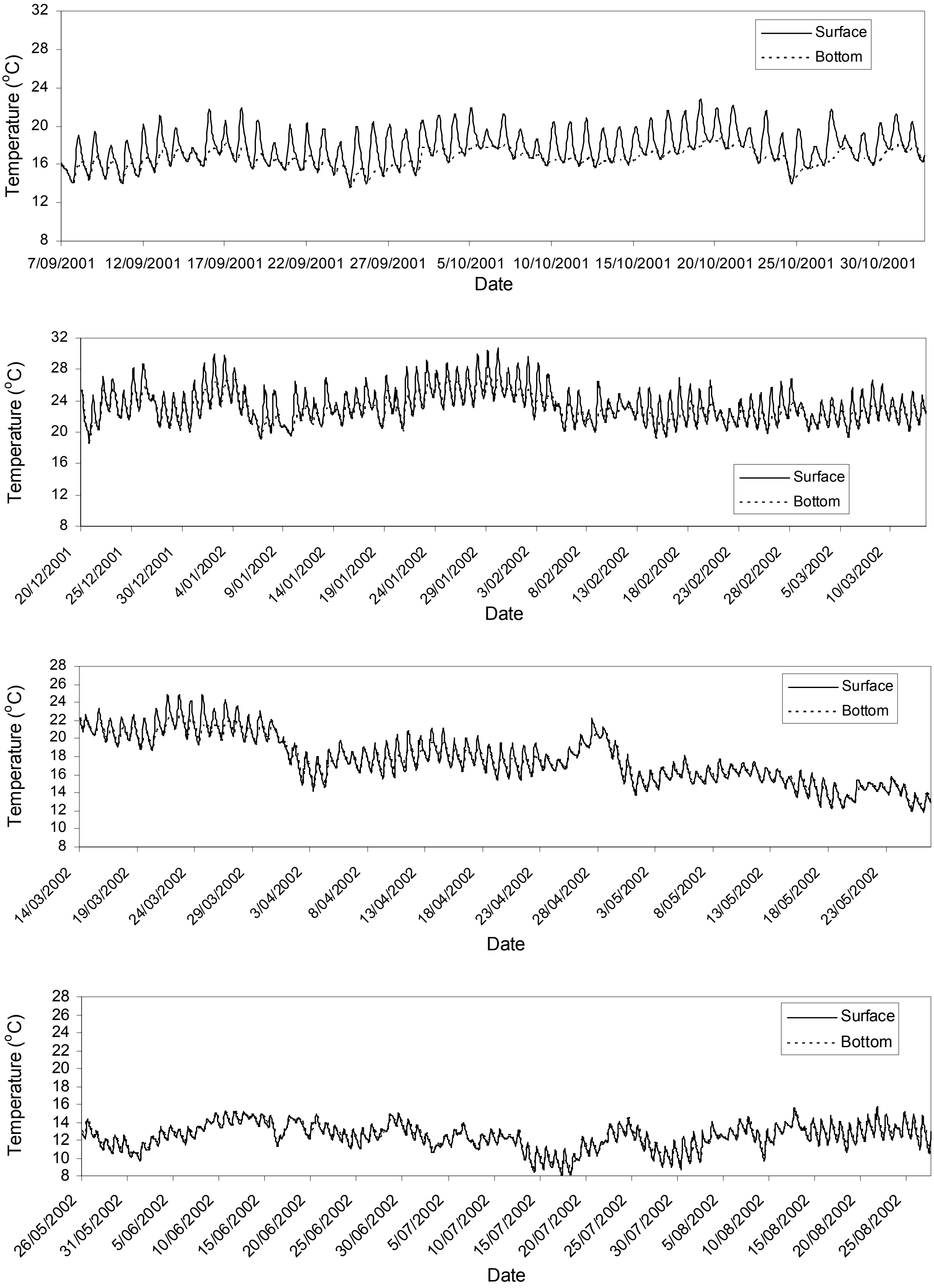


Figure 18. The temperatures of the surface and bottom waters of Oranga Lake from September 2001 to August 2002.

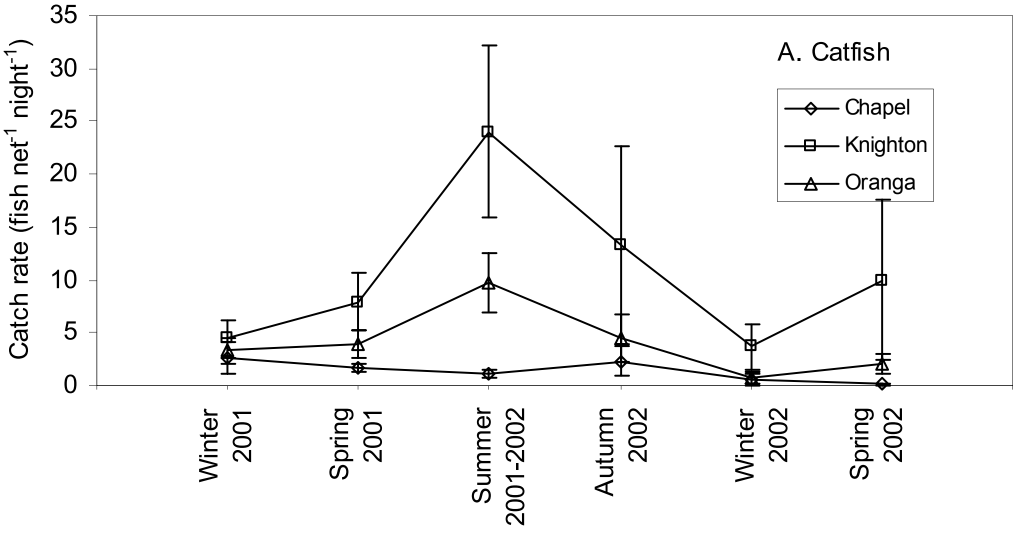
The difference between the surface and bottom water temperatures determines the extent of stratification, and by implication, the occurrence of mixing. When the surface temperature minus the bottom temperature was ≤ 0.1°C, we assumed that full mixing had occurred. Between September 2001 and August 2002, Chapel Lake spent just 15% of the time fully mixed, whereas Knighton and Oranga lakes were mixed for 47-52% of the time (Table 8).

Table 8. Duration of complete mixing of the campus lakes as determined by occurrence of times with surface minus bottom water temperatures ≤ 0.1°C between September 2001 and August 2002.

Lake	Number of hours		Proportion of time (%)	
	≤ 0.1°C	> 0.1°C	≤ 0.1°C	> 0.1°C
Chapel	1088	6182	15	85
Knighton	3805	3465	52	48
Oranga	3443	3827	47	53

Fish abundance

Ten fyke nets were set overnight on five occasions between winter 2001 and spring 2002, except for summer when 20 nets were set over two nights. The nets were baited with about 10 g each of trout pellets, and fish were sampled with replacement. Catch rates varied seasonally, with the greatest catches of catfish and eels in summer (Figure 19). Catches of catfish were greater than eels in Knighton and Oranga lakes, but similar numbers of catfish and eels were caught in Chapel Lake. Catch rates of both and catfish were generally greater in Knighton and Oranga lakes than in Chapel Lake, and these differences are assumed to reflect actual fish abundance. In an effort to estimate absolute fish density, several hundred fish were tagged during the course of the netting, but too few were recovered to make reliable population estimates.



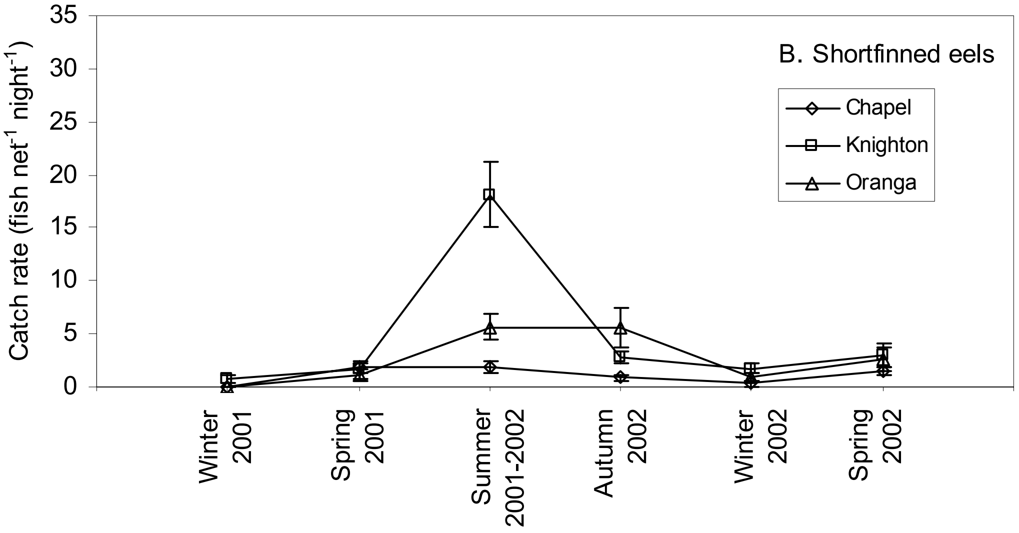


Figure 19. Mean catch rates of brown bullhead catfish and shortfinned eels in the campus lakes of the University of Waikato from winter 2001 to spring 2002. Error bars represent 1 standard error.

The mean catch rates for catfish in December 2001 were considerably lower than in February 1996, though the catch rates for Chapel Lake were always less than Knighton of Oranga lakes (Table 9). Catch rates eels, however, were similar between the two sampling periods. One explanation for the reduction in catfish catch rates between 1996 and 2001 is the removal of 1,329 catfish in 1998 (Table 10). Though fish were not measured, the netters observed that fish in the second catch, particularly in Oranga Lake, were all very small. This suggests that effective depletion occurred, and total number of catfish estimated by the removal method (Armour et al. 1983) was 792 ± 16 (population estimate ± 95% confidence interval). The weight-length regression for the catfish was

$$\text{weight (g)} = 9.32 \times 10^{-6} \text{ length (mm)}^{3.045}$$

The mean weight of 754 catfish from all lakes was 174 g. This suggests that the biomass of the total estimated population of catfish in Oranga Lake in 1998 (792 fish) was 138 kg, or 200 kg ha^{-1} based on the lake's area (0.69 ha). There was no obvious improvement in water clarity following fish removal in 1998

Table 9. Mean catch rates in February 1996 (N nets = 4) and December 2001 (N nets = 20) in the campus lakes of the University of Waikato. Number of nets = 4 in 1996, and 20 in 2002. SE standard error. Data for 1996 are from Willis (1996), with corrections based on total numbers caught.

Lake	Catch rate (fish net^{-1} $night^{-1}$)							
	Catfish				Shortfinned eels			
	1996		2001		1996		2001	
	Mean	SE	Mean	SE	Mean	SE	Mean	SE
Chapel	16.8	11.3	1.2	0.4	1.3	1.3	1.9	0.5
Knighton	98.3	44.7	24.0	8.2	18.8	7.0	18.2	3.1
Oranga	87.3	38.4	9.7	2.8	18.0	12.9	5.7	1.1

Table 10. The numbers of catfish removed from the University of Waikato campus lakes during successive captures by fyke net in 1998.

Month	Date	Number of fish
Chapel		
February	26	149
April	24	242
Total		391
Knighton		
February	25	99
April	23	78
Total		177
Oranga		
February	24	543
February	27	137
April	22	81
Total		761
Grand total		1329

Electrofishing in the margins

On 21 June 2001 we electroshocked 30 m of the Knighton Lake edge in a strip about 2 m wide on the south-western shore with a 240-V generator-powered electroshocker. The catch was 15 shortfinned eels (0.25 fish m^{-2}), 9 catfish (0.15 fish m^{-2}), and 4 goldfish (0.07 fish m^{-2}). All fish >100 mm long were marked with opaque white anchor tags and released back into the lake. Nothing was caught further than about 0.5 m from the margin. The water temperature was 9.0°C at 0920 h, which is near the lower limit for effective electroshocking. We also tried two beach seine hauls to the margin, which caught 30-40 mosquitofish and several bullies, but no catfish, goldfish, or eels.

SEDIMENT REMOVAL

Sediment removal is one method of reducing nutrient availability in the water column. Sediment removal is a regular practice at La Trobe University in Australia, where dredging is used to manage water quality in the shallow campus ponds. The Hamilton Zoo has also used sediment removal to improve water quality. About 12 years ago the ponds were dewatered, and the sludge was removed to a depression on zoo land. It took over a year to dewater sufficiently to bear a person's weight (Betty Collins, pers. comm.). Two ponds 0.6-1.0 m deep are part of a water recirculation system in the zoo. The water is passed through a 100 m^3 gravel filter. A third pond on zoo land, which contains the Waikato wetlands exhibit, is deeper still (up to 2 m deep), and is not part of the filtration and circulation system.

Deepening and sediment removal

Several methods to remove the accumulated soft sediments are possible, including removal by back-hoe, drag line, and suction dredging. In addition to the three quotes received so far for removal of about 30 cm of the soft surface sediment from Knighton and Oranga lakes ($46,000 to $267,000 excluding GST), Mark Thompson arranged for a further quote for excavation of the lakes. Kaipara Ltd, civil engineers of Beachlands, Auckland, visited the lakes on 27 Sept and will prepare quotes for removal of the top 30 cm of soft sediments, and for deepening by removal of 1.3 m of material.

Sediment removal has been used in several successful applications overseas (Cooke et al. 1993; chapter 17). Lake Trummen in Sweden is a particularly good example, where increasing the mean depth of the lake from 1.1 m to 1.75 m decreased total phosphorus in the surface waters by 90% and total nitrogen by 80% (Cooke et al. 1993; p504). The surface sediment was analysed for contaminant metals. This was necessary so that options for disposal could be established, because landfills refuse to accept high levels of some toxic metals (Hamilton City Council Works and Services).

Sediment analyses

In order to analyse concentrations of heavy metals in the lake sediments, six sediment samples were collected from each of the campus lakes in November 2001 (Figure 20). These were analysed by the Department of Chemistry, University of Waikato, for arsenic, barium, cadmium, chromium, copper, iron, mercury, manganese, nickel, phosphorus, lead, selenium, tin, and zinc. The average water content was 67% by weight. Samples of primarily organic sludge contained more water (70-80%) than samples with clay and sands, which had 30-45% water (Table 1).

Mercury, selenium, and tin were below the detection limits (DL) in every sample. The DL for mercury, selenium, and tin were 5, 7, and 10 mg kg^{-1} dry weight, or ppm dry weight, respectively. Some other contaminants occurred at quite high concentrations. Of the three lakes, Oranga is particularly contaminated in arsenic and zinc, with one sample exceeding the landfill limits for lead (O4; Table 12). Iron, barium, manganese, and phosphorus are also high, but are not listed as problematic for landfill. The origin of the arsenic and lead is not clear, but one possibility is spray drift of lead arsenate from the time when orchards were nearby. Lead arsenate was a widely used herbicide (Chris Hendy, pers. comm.).

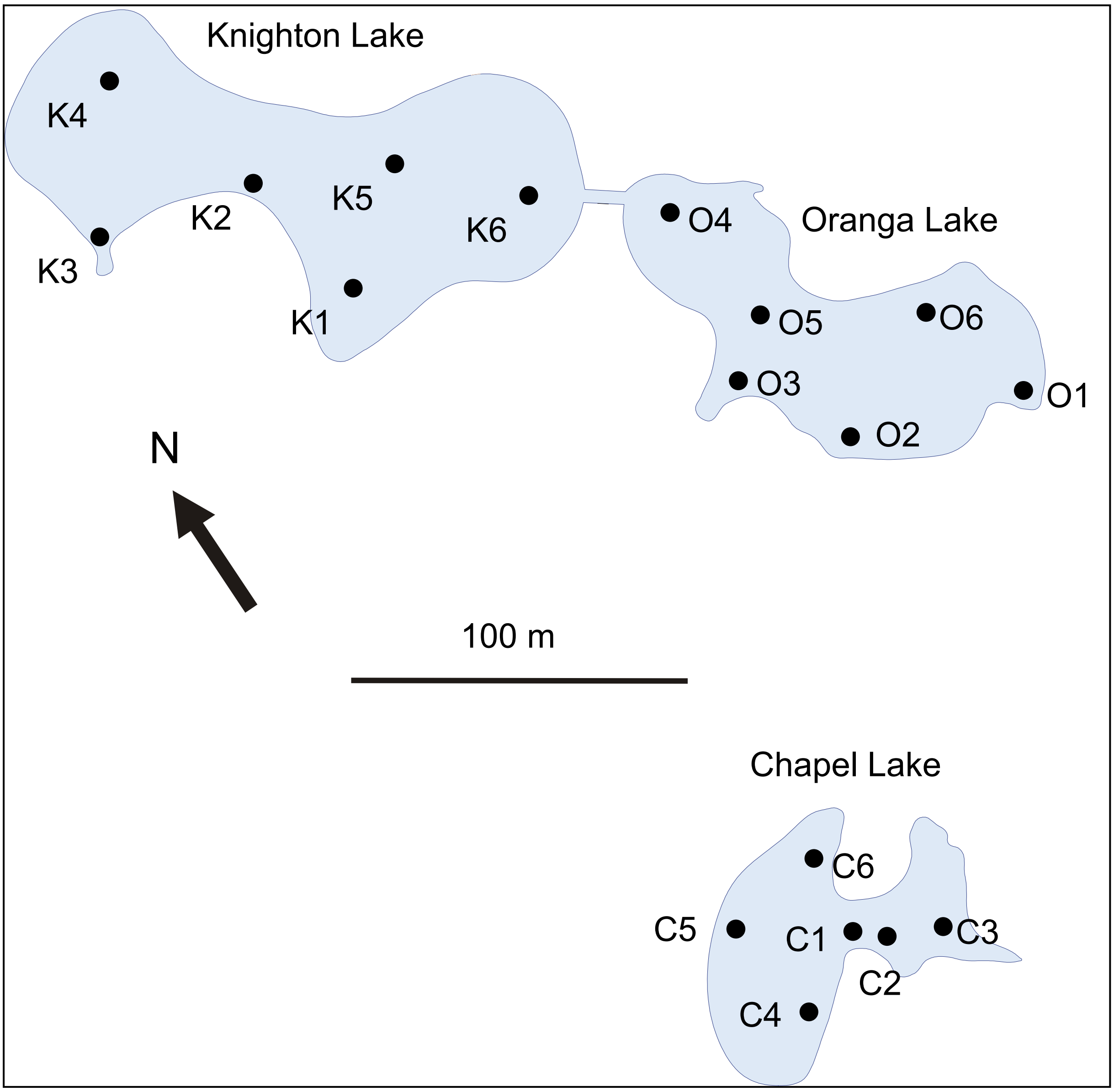


Figure 20. The location of surface sediment samples taken from the campus lakes of the University of Waikato in November 2001.

The concentrations of many of the elements in the sediments were strongly correlated with phosphorus or iron (Table 13). One explanation for this is that the algal growth bioconcentrated the contaminants, and then dropped out of the water column to form much of the surface sediment.

Disposal of the organic sediments, particularly those from Oranga Lake, would not be possible in a council landfill because of the arsenic. However, if the organic sediment was mixed with another 1 m of excavated soil, which would presumably be uncontaminated, the concentration of the arsenic in the final mixture of excavation spoil would be only about 25% of the values in Table 12.

Simon Male of Kaipara Engineering relayed the opinion of Sinclair Knight that the sediment appears to be acceptable for disposal on site, but a Land Use Consent will be required from the Waikato District Council. The type of consent depends on volume; below 2,500 m^3 per annum is a permitted use; up to 5,000 m^3 is a discretionary use, and over 5,000 m^3 is no longer a small cleanfill but is still reasonably straightforward to obtain a consent. We also require a discharge consent from Environment Waikato. As any excavation would be at a minimum 1.7 ha times 1 m (17,000 m^2 times 1 m = 17,000 m^3), and we would probably attempt to excavate in one summer, the excavation would exceed the limits of a small cleanfill. Kaipara Engineering could obtain the consents for the University at a cost. We will determine this cost.

Table 11. Sample weights of surface sediments taken from the campus lakes of the University of Waikato in November 2001. The sample locations are shown in Figure 20.

Sample number	**Visual description**	**Site description**		**Sample weight (g)**				**Water content**	
			Tray	**Wet**	**Net Wet**	**Dry**	**Net Dry**	**(g)**	**(%)**
Knighton Lake									
K1	Organic sludge	by pipe, in weed	1.715	26.429	24.714	11.724	10.010	14.704	59.5
K2	Clay	close to bank	1.771	54.146	52.376	30.674	28.903	23.472	44.8
K3	Organic sludge	by outflow, under bridge	1.745	65.280	63.535	13.510	11.765	51.770	81.5
K4	Organic sludge	middle of lake, in weed	1.730	55.285	53.554	12.377	10.647	42.908	80.1
K5	Organic sludge	middle of lake, in weed	1.735	60.151	58.416	17.806	16.071	42.346	72.5
K6	Plants	by inflow, in weed	1.712	52.410	50.698	12.173	10.461	40.237	79.4
Oranga Lake									
O1	Sand and plants	by bore inlet pipe	1.743	45.417	43.673	24.116	22.372	21.301	48.8
O2	Organic sludge	by McD's, in weed	1.757	60.069	58.313	11.241	9.484	48.828	83.7
O3	Organic sludge	in short arm, in weed	1.752	64.013	62.261	17.666	15.914	46.348	74.4
O4	Organic sludge	by outflow	1.764	49.572	47.808	14.799	13.035	34.773	72.7
O5	Organic sludge	middle of lake, in weed	1.738	47.054	45.315	8.903	7.165	38.151	84.2
O6	Organic sludge	by field drain, in weed	1.752	48.819	47.066	16.011	14.259	32.808	69.7
Chapel Lake									
C1	Organic sludge	off point	1.694	49.738	48.044	31.013	29.319	18.725	39.0
C2	Organic sludge	middle of lake	1.749	57.528	55.779	14.843	13.094	42.685	76.5
C3	Organic sludge	in short arm	1.788	47.080	45.293	12.485	10.698	34.595	76.4
C4	Organic sludge	under willows	1.814	60.587	58.773	9.614	7.800	50.973	86.7
C5	Sand and plants	off boardwalk	1.743	55.961	54.218	40.070	38.327	15.891	29.3
C6	Clay and sand	by road inlet	1.753	67.022	65.269	44.456	42.704	22.566	34.6
Mean									66.7

Table 12. Concentrations of potential contaminants in the surface sediment samples from the campus lakes in November 2001 expressed per kg of dry sediment weight. ND = not detectable. Elemental abbreviations with landfill limits in mg kg^{-1} (ppm): As, arsenic (1); Ba, barium; Cd, cadmium (10); Cr, chromium (100); Cu, copper (100); Fe, iron; Mn, manganese; Ni, nickel (100); P, phosphorus; Pb, lead (100); Zn, zinc (100). The location of sampling sites is shown in Figure 20.

	Concentration (mg kg^{-1} dry weight)										
Sample	As	Ba	Cd	Cr	Cu	Fe	Mn	Ni	P	Pb	Zn
Oranga											
O1	ND	52.7	0.7	12.5	13.3	7022	54	4.0	210	19.5	258
O2	16.0	311.9	4.6	79.0	95.9	48737	500	7.2	1187	98.5	854
O3	52.0	266.8	2.0	32.1	62.2	17509	206	9.0	740	163.8	1146
O4	60.1	228.6	2.3	46.0	92.4	20400	286	13.4	801	395.4	1958
O5	26.6	263.8	3.5	60.7	107.2	37496	572	8.2	978	141.1	1218
O6	41.9	195.1	1.8	29.7	57.6	16875	185	7.1	509	108.0	798
Chapel											
C1	14.6	81.6	0.1	6.2	5.2	2358	31	4.6	60	6.6	34
C2	21.8	117.4	0.7	14.0	36.9	4362	64	6.6	344	79.8	422
C3	29.1	132.7	1.5	26.6	53.3	7647	89	9.5	371	138.5	557
C4	16.3	180.1	1.2	23.0	50.5	6773	104	10.0	595	138.9	616
C5	ND	35.8	0.1	4.1	4.1	1657	15	3.0	57	6.4	31
C6	ND	142.1	1.1	19.2	4.1	12083	88	4.4	60	8.3	18
Knighton											
K1	44.5	131.8	1.0	18.6	14.8	10189	201	5.4	364	147.2	373
K2	ND	146.0	0.6	12.3	2.7	7096	15	4.4	40	10.9	15
K3	ND	149.9	1.1	18.7	30.3	10185	270	6.7	539	46.2	506
K4	ND	10.8	0.4	4.9	0.4	2137	92	5.6	17	0.3	242
K5	ND	240.5	1.2	18.9	24.4	9840	161	7.0	413	58.7	400
K6	ND	173.5	1.7	28.1	44.1	16020	265	7.5	627	81.0	1173

Table 13. Matrix of Pearson correlations between concentrations of elements in the sediment of the campus lakes taken in November 2001. Significant correlations (Bonferroni-adjusted $P < 0.05$) are shown in bold; the concentrations are given in Table 12.

	Arsenic	Barium	Cadmium	Chromium	Copper	Iron	Manganese	Nickel	Phosphorus	Lead	Zinc
Arsenic	1										
Barium	0.23	1									
Cadmium	0.023	**0.912**	1								
Chromium	0.026	**0.898**	**0.995**	1							
Copper	0.183	0.872	**0.891**	**0.899**	1						
Iron	-0.012	**0.884**	**0.982**	**0.977**	0.826	1					
Manganese	0.064	0.829	**0.926**	**0.925**	0.827	**0.953**	1				
Nickel	0.485	0.415	0.286	0.327	0.612	0.143	0.172	1			
Phosphorus	0.121	**0.967**	**0.954**	**0.953**	**0.915**	**0.920**	**0.885**	0.441	1		
Lead	0.753	0.368	0.255	0.305	0.507	0.167	0.251	0.866	0.395	1	
Zinc	0.652	0.704	0.577	0.606	0.81	0.509	0.561	0.821	0.693	0.871	1

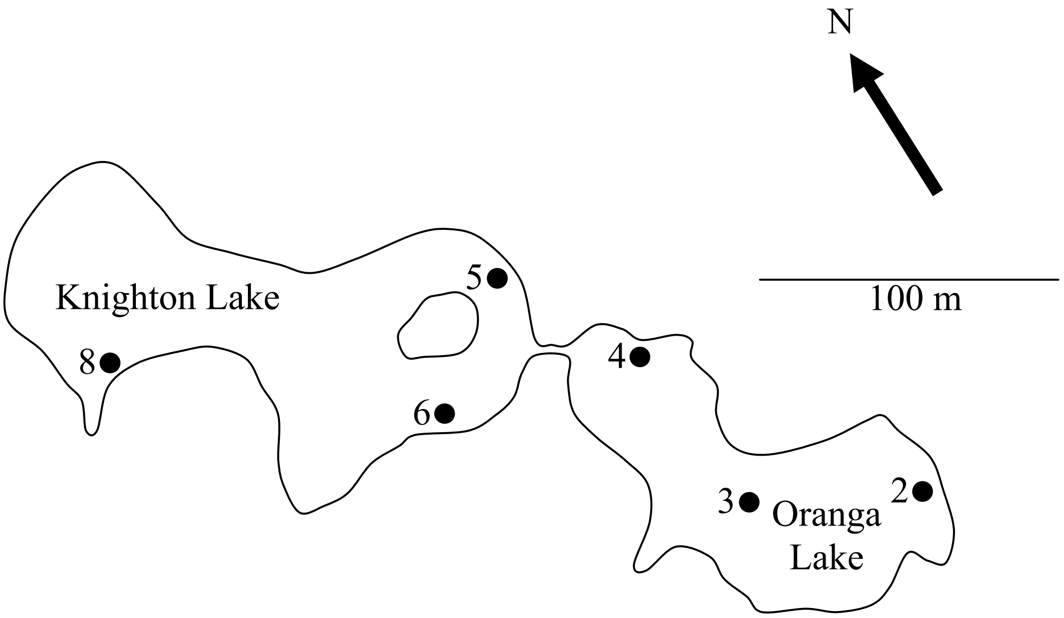


Figure 21. Location of sediment samples taken from 200-300 mm below the solid lake base in October 2002.

Further analyses of the deeper sediments of Knighton and Oranga lakes were carried out in November 2002 (Figure 21). There was no detectable nitrogen in the sediment. One sample from Oranga Lake, however, had high levels of phosphorus, lead, and zinc (Table 14).

Table 14. Contaminant concentrations in sediment samples from 200-300 mm below the solid lake base in the campus lakes of the University of Waikato determined by ICP-OES in November 2002. The location of sampling sites is shown in Figure 22.

			Concentration (mg/kg)							
Lake	Sample	Dry weight (g)	As	Cd	Cr	Cu	Ni	P	Pb	Zn
Oranga	2	2.4658	3.06	0.21	5.5	7.1	6.95	34.7	4.7	42.4
Oranga	3	2.1842	4.99	0.24	19.3	6.8	7.99	32.4	5.1	71.0
Oranga	4	2.1508	8.95	0.37	40.8	34.2	8.72	235.2	68.8	234.5
Knighton	5	2.1026	4.70	0.12	48.4	20.9	9.22	156.3	6.0	59.0
Knighton	6	2.3231	2.52	0.09	39.3	17.2	8.86	92.5	4.2	46.4
Knighton	8	2.5346	1.86	0.06	53.6	17.7	8.23	52.5	6.2	49.8

Time to fill the excavated lakes

We calculated the time that dewatered, excavated lakes would take to fill. Assuming

1. No losses to ground water;
2. Evaporative losses are maximal (6 mm day^{-1});
3. Bore water is the only source of water;
4. The bore water pumping rate is 17.5 m^{3} h^{-1} for 10 h day^{-1};
5. There are no losses to ground water.

The estimates suggest that it would take 15 weeks to fill Oranga Lake if it was excavated to a uniform depth of 2 m, and a further 40 weeks to fill Knighton Lake if the bore water was the only source of water and evaporation was maximal for the entire period (Table 15). The Waikato region would almost certainly have rainfall within this period, so filling is likely to be much faster.

Table 15. Estimated time to fill Knighton and Oranga lakes after excavation using only bore water.

	Oranga	Knighton	Both lakes
Area (ha)	0.69	1.01	1.70
Area (m^2)	6900	10100	17000
Volume 1 at mean depth 0.6 m (m^3)	4140	6060	10200
Volume 2 at mean depth 1.5 m (m^3)	10350	15150	25500
Volume 3 at mean depth 2.0 m (m^3)	13800	20200	34000
Evaporative water loss (m^3 day^{-1})	41	61	102
Net inflow (bore addition minus evaporation) (m^3 day^{-1})	134	73	
Time to fill volume 1 in days	31	83	
Time to fill volume 2 in days	77	208	
Time to fill volume 3 in days	103	277	

Ducks and shags

Ducks were counted weekly from June to October 2002, and there were usually more ducks on or near Knighton and Oranga lakes than Chapel Lake (Bryant 2003). Within the survey period numbers were maximal in June, coinciding with duck shooting season, and declined thereafter (Figure 23). Seasonal duck counts on Lake Rotoroa (Hamilton Lake) suggest that at their peak in May there were probably twice the number of ducks that were counted in June (Dickie 1994). Ducks can contribute significant amounts of N and P in their faeces (Dickie 1994), and stir up bottom sediments with their dabbling behaviour.

Shags also frequent the campus lakes. On 1 November 2002 three shags were observed on or near Oranga Lake; one of these shags caught a catfish about 150 mm long during our observations.

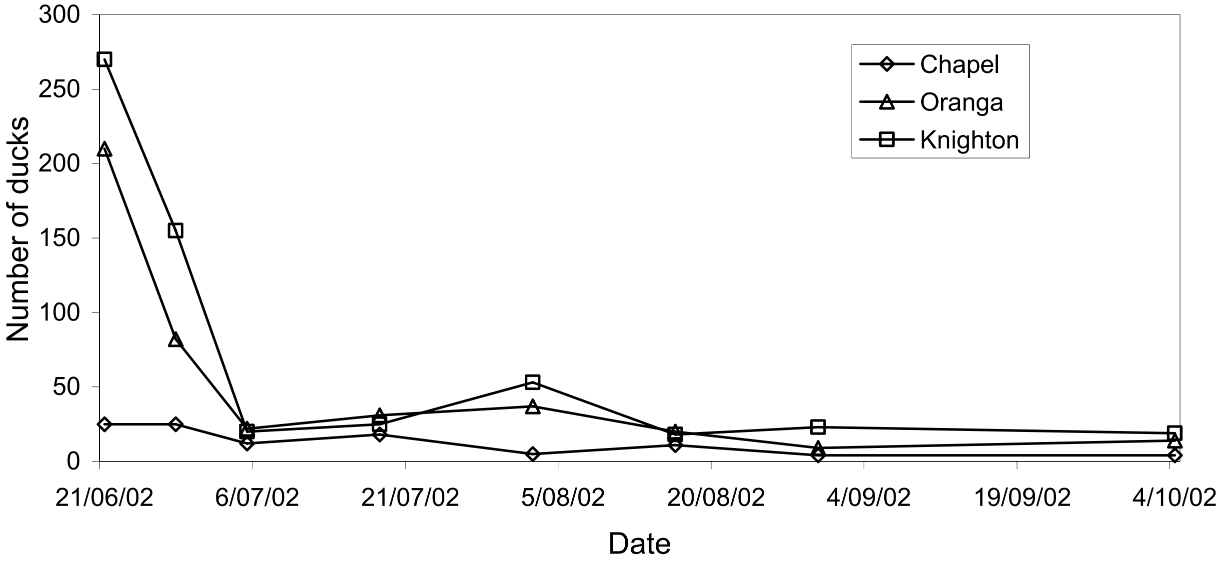


Figure 22. The number of ducks on the campus lakes of the University of Waikato from June to October 2002.

COST ANALYSIS

We analysed the costs of treatments that could be used to alleviate the water quality problems apparent in Knighton and Oranga lakes, and estimated the time that the treatment would last and its risks (Table 16). We assumed that Chapel Lake represents the best water quality possible in the context of the main purpose of the lakes as stormwater detention ponds. However, the water level recedes in summer in Chapel Lake, so addition of clean water would be useful to maintain water level. The rate required to equal evaporative losses of 3 mm day^{-1} is about 13 m^{3} day^{-1}.

We considered several alternatives for algal control. While flocculant dosing might work for a short time, the temperature-induce mixing might resuspend the flocculated material. Ultrasound is an unknown technology in New Zealand, and may fail to control the target algal species. Booming to remove surface algae is time consuming, and only works with a favourable wind. This method cannot be relied on to remove algae when needed. Filtration is expensive and also has a high risk of failure. Resuspension rates might be too high to for this method to be effective. Also, wind can push surface algae away from the intakes for the filtration system. Operations and maintenance costs for filtration would also be considerable. Flushing was the option suggested by the original DSIR consultancy report (Pridmore and Burns 1986). Our analysis suggests that water sufficient for effective flushing is not available.

For macrophyte control, manual removal of curly leaved pondweed has proved very effective and relatively cheap ($3,000 to 6,000 per year). However, it would be desirable not to have to do this. Weed matting appears not to be an option because of the high rates of gas production from the sediments. Grass carp would be an option, but though they relatively cheap to lease, the environmental assessment and potential antagonism from some sectors of the public probably mean that this is not a realistic option. Permission from the Department of

Conservation is required for grass carp release, and the outlet screens would need to be improved and maintained to prevent escape of the carp.

Removal of ducks and fish is one option to reduce an external nutrients input and internal nutrient resuspension. Ducks can add significant amounts of nutrients to lakes, but total removal is probably not acceptable to the public or the local fish and game managers. Catfish removal is an option, though the use of poisons would require a consent from Environment Waikato. Netting in 1998 suggests that this method can remove a reasonable proportion of the catfish, but only with a considerable effort. The catfish biomass in Oranga Lake was greater than the accepted threshold 150 kg ha^{-1}, suggesting that fish removal might improve water clarity. However, there was no obvious improvement in water clarity following fish removal in 1998, probably because the shallowness and strong thermally induced mixing reduced the effectiveness of the fish removal.

Table 16. Costs of potential treatments for Knighton and Oranga lakes to improve water quality.

Aim - to control:	Treatment	Approximate cost (excl. GST) ($)	Duration of treament	Risk of failure	Environmental risk	Comment
Phytoplankton	Flocculant dosing	Fernz to supply	5 years	Moderate	High	pH problems might be unacceptable
Phytoplankton	Ultrasonic cell disruption	14,000 for two units	5 years?	Moderate	Low	Might not control specific algae
Phytoplankton	Booming	3,000	1-2 months	High	Low	Only works with favourable wind
Phytoplankton	Filtration	53,000 plus operating costs	5-10 years	High	Low	Nutrient release still continues
Phytoplankton	Flushing and dilution	3,000 per year for pumping	Indefinite	High	Low	Unlikely to have sufficient flow rate
Macrophytes	Manual removal	3,000-6,000	One year	Low	Low	Cheap and effective if done in Nov-Dec
Macrophytes	Weed matting	30,000 plus installation	5-10 years	High	Low	Gas evolution rates may be too great
Macrophytes	Grass carp	1,600 plus consents	5-10 years	Low	Moderate	Can escape; release controversial
Nutrient recycling	Remove ducks	5,000	1 year	Moderate	Low	Probably socially unacceptable
Nutrient recycling	Remove catfish with poison	10,000	5-6 years	High	High	Probably socially unacceptable
Nutrient recycling	Remove catfish with fishing	5,000	3-4 years	High	Low	Acceptable if eels returned alive
Nutrient recycling	Remove 30 cm sediment	60,000	10	Low	High	Would need to dewater lakes
Phytoplankton and macrophytes	Deepen lakes to 2 m	267,000	20-30 years	Low	High	Would need to dewater lakes

CONCLUSIONS

The principal differences between Chapel Lake and the two shallower lakes (Knighton and Oranga) are that Chapel Lake has clearer water, fewer fish and ducks, and much less deep mixing than the shallow lakes. The likely cause of the lower fish numbers in Chapel Lake is the stratification that periodically lowers dissolved oxygen in the bottom waters to almost zero. These conditions would restrict fish to the shallow edges where dissolved oxygen concentrations were sufficient. The lower catfish abundance in Chapel Lake than in Knighton and Oranga lakes is consistent with fishing in 1996 (Willis 1996).

Thus most of the problems associated with Knighton and Oranga lakes appear to be caused by their insufficient depth. Of all the solutions in Table 16, deepening the lakes would last the longest, and after completion would have the fewest environmental risks. One reservation is that Chapel Lake is also the smallest, most sheltered, and most shaded of the three campus lakes, and some of its differences could be attributed partly to these factors. If Knighton and Oranga lakes were deepened, some smells, fish deaths, and disruption in the vicinity of the lakes would be expected during the dewatering and excavation period.

Deepening Knighton and Oranga lakes is likely to make them react in similar fashion to Chapel Lake, with a similar mixing regime, light extinction coefficient, fish and plankton assemblages. This would reduce the fish populations and growth of curly leafed pond weed, and improve water clarity to the standard of Chapel Lake.

We conclude:

1. That the addition of bore water to Oranga Lake is having no adverse consequences for the water quality of either Oranga or Knighton Lake, and we recommend its continuation to maintain water levels during times of low rainfall. Adding water to Chapel Lake would maintain its level during dry summers.

2. That deepening Knighton and Oranga Lakes would reduce internal nutrient cycling and consequently reduce the nutrients available to support algal growth. These mechanisms of nutrient reduction are:
   - Removal of the soft-nutrient-rich sediment that has accumulated in the approximately 30 years since the original lake excavation;
   - Reduction of the frequency and duration of thermally induced penetrative convection that distributes nutrient-rich pore water from the sediment into the water column;
   - Putting the lake bed out of reach of dabbling ducks, thereby preventing this potential source of nutrient cycling;
   - Reduction of potential bioturbation of bottom sediments by fish, and nutrients from fish excretion. This would occur because lowered concentrations of dissolved oxygen in the bottom waters would reduce fish abundance.

3. That deepening the lakes would also reduce the amount of light penetrating to the lake beds. Light levels below the compensation point for the growth of the troublesome curly leaved pondweed (*Potamogeton crispus*) would virtually eliminate the need for other control measures for pondweed.

4. That without the pondweed, and with the lake bed out of their reach, the habitat would be less suitable for ducks. A reduction in duck numbers would mean less nitrogen and phosphorus input from duck faeces, and less nutrient resuspension by duck dabbling.

Thus we recommend excavation of 1.3 m of the beds of both Knighton and Oranga lakes. The resultant basins would be about 2 m deep. Despite high cost of excavation, this solution has the most chance of success, would fix most of the problems that currently occur, and would be the longest lasting solution.

Finally, as an interim measure, the removal of catfish could be continued. Fish removal was effective in improving water clarity in some Dutch lakes (Meijer et al. 1999), and it is probable that too few fish were removed from Knighton Lake to improve water clarity. Before a commitment is made to the expensive option of deepening the lakes, another attempt could be made to assess the present fish population, and then to remove catfish if the biomass is > 150 kg ha^{-1}. Oranga Lake had an estimated catfish biomass of 200 kg ha^{-1} in 1998, but recent catch rates (Table 10) indicate that abundance might be less than 25% of that estimate. A more soundly based estimate of fish abundance would be very useful for understanding the management options. The Centre for Biodiversity and Ecology Research has a new fish capture tool in the form an electrofishing boat, and this could be highly effective at fish capture and removal.

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