Lake Okareka: Ecological functions of marginal vegetation and the effect of boat lanes

NIWA Client Report: CHC2006-132
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Prepared for

Environment Bay of Plenty

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Executive Summary

In June 2005, NIWA was contracted by Environment Bay of Plenty to assess the effect of boat lanes cut through the marginal vegetation of Lake Okareka on the ecological functions and values provided by the vegetation. Marginal vegetation in lakes is thought to be important in nutrient cycling and protecting water quality, in reducing wave exposure and erosion on shorelines, in preventing submerged weed encroachment into shallow water, and as fish and bird habitat.

Marginal vegetation in Lake Okareka consists mainly of three tall emergent plant species: *Eleocharis sphacelata*, *Typha orientalis,* and *Baumea articulata* (hereafter referred to as eleocharis, typha and baumea). The vegetation currently occurs in scattered bands on the southern, western and north-western shorelines of the lake. A modelling exercise based on wind exposure and shoreline shelter suggests that much of the western area of the lake is suitable for emergent vegetation, and that it has been considerably reduced in extent. Most of the boat lanes have been cut through the largest continuous band of marginal vegetation remaining in the lake, an eleocharis area on the southern shore adjacent to a residential area.

Surveys of the littoral zone confirmed that the dense foliage and litter of the marginal vegetation effectively excluded the submerged weed lagarosiphon, even though the latter formed high cover immediately outside the marginal zone. However, lagarosiphon formed almost 100% cover in the boat lanes, and was rapidly colonising lanes that had been recently formed.

Monitoring of temperature gradients with chains of thermistors confirmed considerable temperature differences between the open water and vegetation. Although we do not yet fully understand all the mixing processes occurring, the temperature data clearly identified that water velocities were lower in the beds than outside and that they were responsible for reducing onshore-offshore mixing rates. This was confirmed by a dye tracing experiment that showed considerable resistance to water mixing in the beds, but rapid short-circuiting of dye movement to the open lake through boat lanes.

We found no evidence that common bullies, the most abundant native fish species in the lake, showed any habitat preference for the vegetation to open areas, and hence no evidence that they were adversely impacted by boat lane creation. Other fish species were not surveyed due to risks associated with interfering with birds. We found that the 7 wetland bird species in the lake showed strong behavioural preferences for the vegetation and were clearly exploiting it for shelter.

Studies of the nutrient cycling in the three main species found relatively low concentrations of nutrients in the plants, and very high nutrient retention within the tissues, with very low concentrations in senescent litter. These data, although preliminary, suggest that the marginal plants are currently experiencing relatively low nutrient inputs from the catchment, that their growth is strongly nutrient (especially nitrogen) limited, and that their productivity and nutrient storage would be likely to increase if nutrient run-off increased. Marginal vegetation appears to be functioning well as a sink of

diffuse nutrient run-off to the lake, and is likely to continue to do so at higher loadings than it is currently receiving.

The studies confirmed that the marginal vegetation of Lake Okareka does support many of the values and functions identified in studies elsewhere. It also provided clear evidence for disturbance of these roles by boat lanes. We confirmed that boat lanes increased encroachment of lagarosiphon into shallow water, and increased onshore-offshore mixing. It is also clear that extensive disturbance of the beds by boat lanes would reduce the nesting habitat of birds, and that the nutrient-stripping capacity of the littoral zone would not function in these areas. The value of marginal vegetation for lake ecosystems needs further recognition, and could be enhanced by minimising the numbers of boat lanes developed, especially on residential shores where nutrient run-off is highest.

1. Introduction

Lake ecosystems are made up of three spatially distinct components: the pelagic zone (surface open waters in the deep part of the lake), profundal or benthic zone (deep waters under the pelagic zone, where light cannot penetrate), and littoral zone (shallow, near-shore waters). Productivity in the pelagic zone is supported by phytoplankton, the microscopic algae that are essential food for pelagic animals, but which also bloom into nuisance proportions when lakes become nutrient-enriched by human eutrophication. In the littoral zone, productivity is supported by a more complex community of large aquatic plants (macrophytes) and their associated epiphytes (algae that grow on the plant surfaces). The deep, dark profundal zone has no plant growth, but has a large biomass of small animals and bacteria that feed on macrophyte and phytoplankton detritus raining down from the littoral and pelagic zones.

All three zones have an important role in controlling overall lake productivity and lake water quality. In clear, oligotrophic lakes with low nutrient (i.e. nitrogen (N) and phosphorus (P)) inputs, pelagic phytoplankton grow slowly and their biomass is kept in balance by small grazing animals (zooplankton). As the nutrient input to the lake increases, any increase in phytoplankton growth is initially restricted by a corresponding increase in zooplankton numbers, and more transport of nutrients into the profundal zone in the detritus. Eventually, however, the phytoplankton growth rate accelerates past that which the zooplankton can cope with, especially as higher nutrient levels favour unpalatable phytoplankton groups such as the bloom-forming cyanobacteria (blue-green algae). The input of pelagic detritus into the profundal zone also increases, until the bacterial growth accelerates sufficiently to deplete oxygen from the deep waters, releasing nutrients that mix back into the pelagic zone thus accelerating even more algal growth. Once lakes reach this state, restoring their water quality is very difficult and expensive.

The shallow littoral zone serving as the interface between the pelagic water and the catchment is able to intercept nutrients entering the lake in surface and ground water, and store them in macrophyte and epiphyte biomass where they are not available to phytoplankton (Wetzel 1990). A healthy littoral zone is therefore an important component of the lake protecting its water quality from nutrient run-off. During an annual cycle of growth, nutrients are incorporated by plants into their new growth. Some of these nutrients are retained in the plant body to support new growth the following year, some leach into the water as dissolved organic matter (DOM), and some are bound up in dead plant litter that is shed into the water and substrate. The amount that becomes available to algal growth depends on how fast bacteria can decompose the litter or DOM and release the N and P back into the water in forms that algae can use. Some of the litter is permanently buried into the substrate and never becomes available to algae. Because macrophyte biomass is more recalcitrant (i.e. 'harder' for bacteria to decompose) than the nutrients the plants took up, littoral macrophyte vegetation protects lake water quality by 'transforming' nutrients from readily bioavailable forms to poorly bioavailable forms (Wetzel 1995). In addition, the roots of macrophytes promote microbial nitrification and denitrification cycles in the soil, allowing nitrogen to be lost from the system as gaseous nitrous oxide (Reddy et al. 1989). Hence, macrophytes have a continuous role in slowing eutrophication and decreasing the rate of water quality decline, even if the area of a lake they colonise and amount of N and P stored in their biomass is stable over time (Wetzel 1995). They can also slow water movement, trapping sediments that run off from catchments, causing them to sink to the lake bed. Understanding how important a role they play in protecting any given lake requires an assessment of their productivity, nutrient uptake, decomposition rate, and nutrient release.

Plant growth forms and species in the littoral zone differ in their distribution and importance in nutrient transformation. The shallowest water (< ca. 3 m depth) is often occupied by tall, emergent plants (see Section 2). These are the most important species in nutrient transformations, as they are very productive and often have very recalcitrant tissues, with high carbon:nitrogen ratios (C:N) and lignin contents (Corstanje et al. 2006). Submerged vascular species grow more deeply (from ca. 2 – 10 m depth), and usually occupy a greater area of the lake, but are less productive and less recalcitrant than the emergent species. They are nevertheless more recalcitrant than algae, and are often important nutrient sinks. Sudden large-scale die-offs of these plants can release large amounts of nutrients into the water and cause algal blooms (Scheffer et al. 1993). The deepest-growing plants of the littoral zone are characean algae (maximum depths as great as 30 m, depending on water clarity), but these have relatively low productivity and are readily decomposed by bacteria.

Nutrient storage is not the only important function of littoral macrophytes in lakes. Their complex, three-dimensional structure provides a large surface area for epiphytes, which support very diverse animal communities. Zooplankton communities are more diverse and productive amongst littoral vegetation than in open water (Duggan et al. 2001), and littoral communities also support many large benthic invertebrates (Kelly and Hawes 2005). Many fish and bird species use macrophytes, especially tall emergent species, for habitat, shelter, and nesting (Innes et al. 1999; Okun et al. 2005). Littoral vegetation is therefore also an important component of lake biodiversity values.

The size, shape and depth of a lake determine the relative sizes of the pelagic, littoral and profundal communities, and this has major implications for how lakes respond to nutrient inputs from the catchment. The proportion of the lake area covered by littoral vegetation can be very high in small, shallow and sheltered lakes, and in these lakes the nutrient status and water quality are strongly tied to cycles of plant growth and biomass turnover. These lakes will initially appear somewhat resilient to nutrient enrichment, as the excess nutrients are bound up in increased macrophyte and epiphyte growth, but tend later to suffer sudden lake-wide mortality and collapse of the macrophytes, leading to sudden nutrient releases, algal blooms and de-oxygenation (Scheffer et al. 1993). Lakes Horowhenua and Omapere are famous New Zealand examples of such collapses.

Since March 2005, NIWA has been carrying out studies to assess the importance of littoral vegetation in the ecology of Lake Okareka. As part of this work, we were contracted by Environment Bay of Plenty to look specifically at the effect of boat lanes that have been cut through tall emergent vegetation on the ecological functions and values of the littoral zone. Three aspects of littoral ecology were identified that could potentially be affected by the boat lanes:

- Mixing patterns: Littoral vegetation can slow horizontal water movement between the open lake and the shoreline, which is beneficial for two reasons. First, it protects shorelines against erosion. Second, slow water movement in the vegetation increases the sedimentation of organic matter and its associated nutrients, further assisting to protect lake water quality. We have used thermistor chains mounted horizontally and vertically within the beds to examine temperature gradients, revealing patterns of water mixing between the littoral zone and open water. We also examined mixing patterns with a dye tracing experiment.

- Weed invasion: Lake Okareka, like many New Zealand lakes, is extensively colonised by exotic submerged weeds – in this case lagarosiphon (*Lagarosiphon major*) and, to a lesser extent, egeria (*Egeria densa*). Unlike the submerged native plant community, tall emergent vegetation is relatively resistant to weed invasion, and therefore has an important function in reducing weed impacts, as shallow waters are where there is greatest human contact with lakes, and greatest habitat value. In this report, we present surveys of the lagarosiphon distribution in and around the emergent vegetation, and how the boat lane development has affected the distribution of lagarosiphon.

- Fish and bird habitat: Lake Okareka is a popular rainbow trout fishery, but also supports large numbers of native fish and waterfowl (Innes et al. 1999). We also report on some brief surveys of the value of the emergent vegetation for fish and bird habitat in the lake.

Our wider FRST-funded research on the functioning of littoral zones involves detailed studies of the importance of their role in nutrient cycling and protecting lake water quality. This work is on-going and involves determining the productivity, nutrient storage, litter production and decomposition of the marginal plants. Although this work is incomplete, in this report we provide some preliminary information on the nature of nutrient-limited growth in the marginal vegetation, and its nutrient storage capacity.

2. Species composition and extent of littoral vegetation in Lake Okareka

2.1. Species composition of the littoral zone

Three tall emergent species dominate the marginal vegetation of Lake Okareka. These species, shown in Figure are *Baumea articulata* (jointed twig rush), *Eleocharis sphacelata* (tall spikerush), and *Typha orientalis* (raupo). There are a few very localised patches of a fourth species, *Schoenoplectus tabernaemontani* (lake club rush), and this species has not formed part of our study. Throughout the remainder of the report, we refer to the three main species as baumea, eleocharis and typha.

Eleocharis is the deepest-growing of the emergent species, often found in lakes to 3 m depth. Although typha can grow to similar depths in very sheltered wetlands, it is more susceptible to wave exposure and tends to be restricted to water < 2 m depth in larger lakes such as L. Okareka. Baumea and schoenoplectus have less physiological tolerance to deep water, and usually occur in water < 1.5 m depth.

Tall emergent species have clonal growth from underground rhizomes, and this allows them to form dense, monospecific bands of vegetation. The vegetation at Lake Okareka is no exception, with most of the marginal vegetation occurring in long, linear bands of one or other of the three dominant species. *Ludwegia palustris*, a sprawling herbaceous plant, occurs in small quantities amongst the emergent stems and on the water surface, and the floating water fern *Azolla* is also common in sheltered areas. Few other plant species occur in association with the emergent vegetation in Lake Okareka. In some lakes, there can be depth zonation, with species such as baumea and typha in water < 2 m depth, and eleocharis > 2 m depth. There are a few areas with such zonations in Lake Okareka, but most shorelines with tall emergent species only have single-species bands from the lake edge to the maximum plant depth.

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Figure 1: The three main tall emergent species of the littoral vegetation in Lake Okareka. Left to right: *Baumea articulata*, *Eleocharis sphacelata*, *Typha orientalis*

Below the maximum depth limit of the tall emergent species, the littoral vegetation down to 7.5 m depth is a community of tall, submerged vascular plants. Lagarosiphon has dominated this community for at least the last 40 years, and still makes up most of the biomass and cover in this zone. Egeria is a relatively recent arrival and still a minor component, but is becoming more widespread. Small amounts of the native species that would have dominated this community before lagarosiphon invasion still occur, especially *Potamogeton ochreatus*. Below this community is the characean algal meadow, which in L. Okareka continues to a maximum depth of 12 m, at which depth light intensities become too low for plant growth.

2.2. Distribution of the tall emergent vegetation and boat lanes

The colonisation of shorelines by tall emergent species depends primarily on slope, exposure and wave action, and to a lesser extent on water clarity (Coops et al. 1994). Steep and exposed shorelines have rocky substrates that are not suitable for these plants, whereas sheltered shorelines allow finer sediment to accumulate and provide habitat for them. In Lake Okareka, tall emergent vegetation is well-developed on the shorelines with shallowest slope, especially the sheltered bays of the southern and north-western shorelines (Fig. 2). Eleocharis is mainly restricted to the lake’s southern bays, but the other species are more widespread. The current distribution is similar to that mapped by Clayton and Wells (1989).

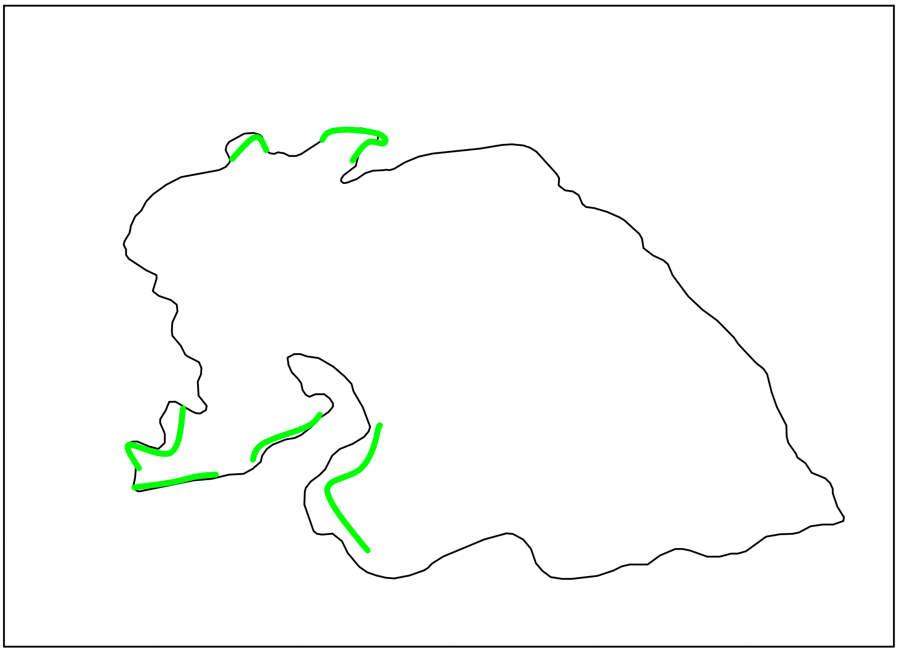


Figure 2: Map of Lake Okareka, showing current extent of the main bands of tall emergent vegetation in the lake. Smaller patches occurring elsewhere not shown.

In many New Zealand lakes, there was considerably more development of tall emergent vegetation in the pre-European vegetation than currently (Tanner 1992). Tall emergent plants typically formed a gradual zonation from the lake into the native terrestrial vegetation, forming shoreline wetlands that acted as buffers between the lake and the catchment. These shoreline wetlands were particularly extensive on flat and shallow shores. Land development has removed many of these wetland areas, and trampling by cattle has often destroyed the emergent vegetation in water up to 0.5 m depth. An indication of the past extent of the vegetation can be gained by comparing the current extent (Fig. 2) with maps of suitable habitat, based on models using exposure and sediment motion.

Figure 3 is a map showing areas of the shoreline that are likely to be suitable for emergent vegetation. The map is generated by the model Lakewave, which uses meteorological data and the shape of the lake to calculate the mixing depth of shoreline waves. This analysis suggests that extensive areas of shallow shoreline that are currently devegetated are suitable for emergent species, and probably supported them in the past. Most of these areas are to the west, because prevailing winds are westerly and hence eastern shorelines are more exposed. It should be noted that, because the model does not take into account the steepness of the land above the water level, it has identified as suitable habitat some shores (e.g. tips of the rocky peninsulas) that are unlikely to support plants. Nevertheless, most of the areas identified in Fig. 3 would be suitable locations for emergent vegetation to occur.

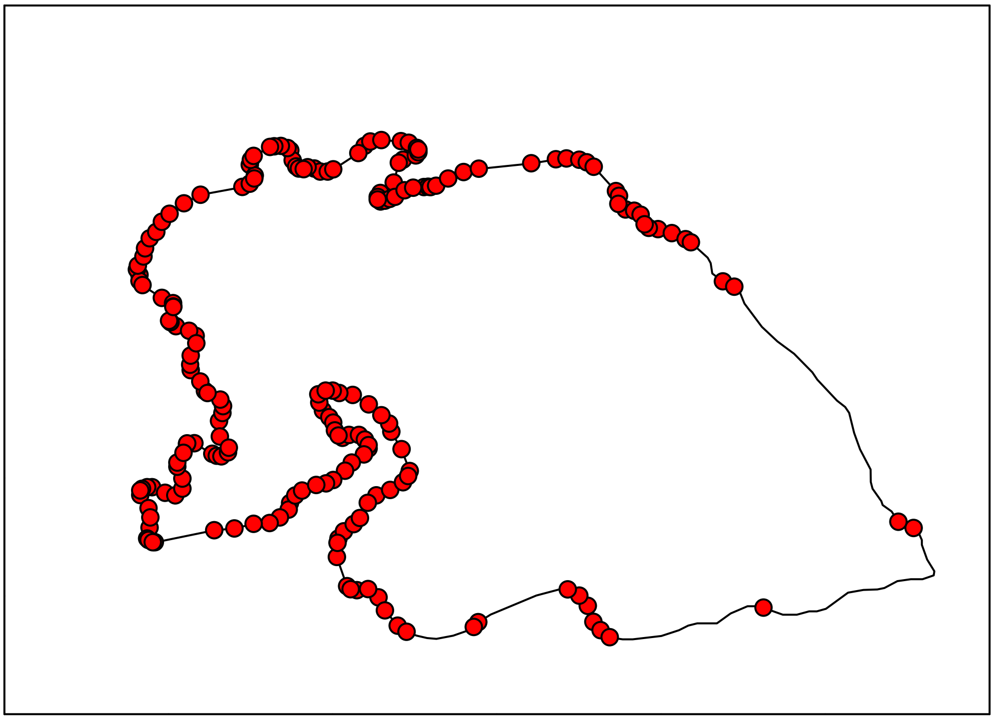


Figure 3: Lakewave modelling analysis of Lake Okareka showing areas of shoreline capable of providing suitable habitat for tall emergent species (c.f. Fig. 2). The plot is based on shape of the lake, wind data we have recently collected from a meteorological station at the lake, and known depth limits of the emergent species.

Most of the current emergent vegetation in the north-western bays is monospecific bands of either typha or baumea, and is adjacent to reserve land with little recent human disturbance or vegetation removal. The bands extend a few metres only from the shore, to the maximum 2 m depth of these species.

Baumea is also common in the southern bays, but eleocharis is particularly dominant here. As a deeper-growing species, it extends over much of the shallow shelf south-east of the peninsula. Most of the boat lanes in the lake are associated with the residential development on this shoreline, and penetrate the eleocharis beds from the open lake through to the shoreline.

3. How littoral vegetation affects the onshore-offshore mixing

Historically, studies of mixing and circulation in lakes have tended to focus on basin-scale motions, and comparatively little is known about the much weaker motions in littoral regions, or about the currents that exchange water between the littoral and the pelagic zones. The same general forcing mechanisms apply to both basin-scale and near-shore motions, e.g., wind stress; horizontal density gradients; inflows from rivers, storm runoff, and groundwater; and rotation of the earth. However, direct measurement of near-shore circulations with current meters is difficult because of the low velocities that generally characterize these flows. Drogues are often unusable near shore because they become grounded or trapped in emergent or submerged vegetation. Use of dye or some other dissolved tracer is often the only practical alternative for observing these flows directly.

Because differences in water density arise as a result of differences in temperature, horizontal variations in temperature from the littoral to the pelagic can be used to infer possible buoyancy-driven circulation between the littoral and pelagic zones. Horizontal temperature structure therefore provides an indirect measure or indication of onshore – offshore water movements.

Some of the general concepts related to littoral-pelagic exchange flows are illustrated in the sketch in Figure 4, emphasizing some features relevant to Lake Okareka, including presence alongshore of emergent vegetation, some of which has been altered by creation of boat lanes.

In the sketch, shallow groundwater flow (SGWF) and storm runoff (SRO) enter the lake in the littoral zone. Where the plants form a continuous band parallel to the shore in the littoral zone, they act as filters for the SGWF and SRO before the flows can reach the pelagic zone. Where the alongshore continuity of the plants has been disrupted by openings, however, the offshore flow can pass primarily through the openings, as they offer a path of lesser resistance to the flow.

Such offshore-directed flows, whether plants are present or not, can also occur in fine weather, under either calm or windy conditions. Under calm conditions, temperature differences between shallower onshore waters and deeper offshore waters create buoyancy-driven circulations (i.e., flows generated by density differences caused by temperature differences). If onshore waters are warmer they will tend to form a surface flow directed offshore, with a compensating onshore flow at depth (dashed arrows in the sketch). This occurs during daylight hours. At night the temperature differences are generally reversed, and cooler onshore water tends to form a density current at depth flowing offshore, with the compensating onshore flow in surface waters. Similar circulations can be generated by winds blowing offshore or onshore, respectively.

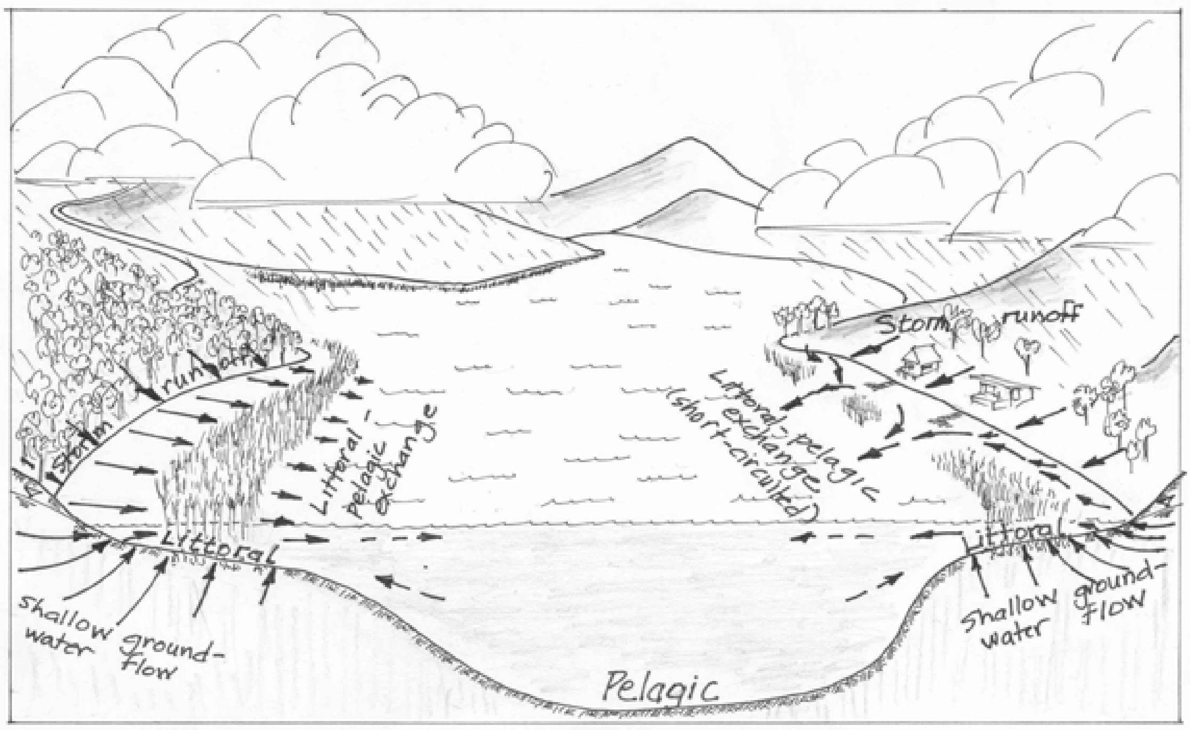


Figure 4: Sketch illustrating some concepts related to the role of emergent plants in exchange flow between littoral (nearshore) and pelagic (offshore) regions.

Emergent vegetation and other tall shoreline plants can modify these buoyancy-driven patterns by shading of the water surface, preventing the penetration and absorption of incident solar radiation in the water column, and thereby reversing the onshore-offshore temperature difference pattern. The observation of a band of *cooler* near-shore temperatures in parts of the shallow marginal vegetation (see Results) was one of the unexpected findings of this study, and serves to emphasize the complexity of physical processes in the littoral, and how little we really know about them.

Recent studies that have investigated the dynamics of onshore-offshore flows have tended to focus on the effects of stronger night-time cooling in shallow waters with no vegetation that results in offshore-flowing density currents (Horsch and Stefan 1988, Stefan et al 1989), or in convective flushing of long continuous bands of emergent vegetation where flow is forced to pass through the vegetation (Nepf 1999, Oldham and Sturman 2001).

4. Methods

4.1. Field programme

Our sampling has been concentrated in two bays (Fig. 5): a small, sheltered bay with baumea and typha vegetation to the northwest, and the eleocharis bay with boat lanes to the south.

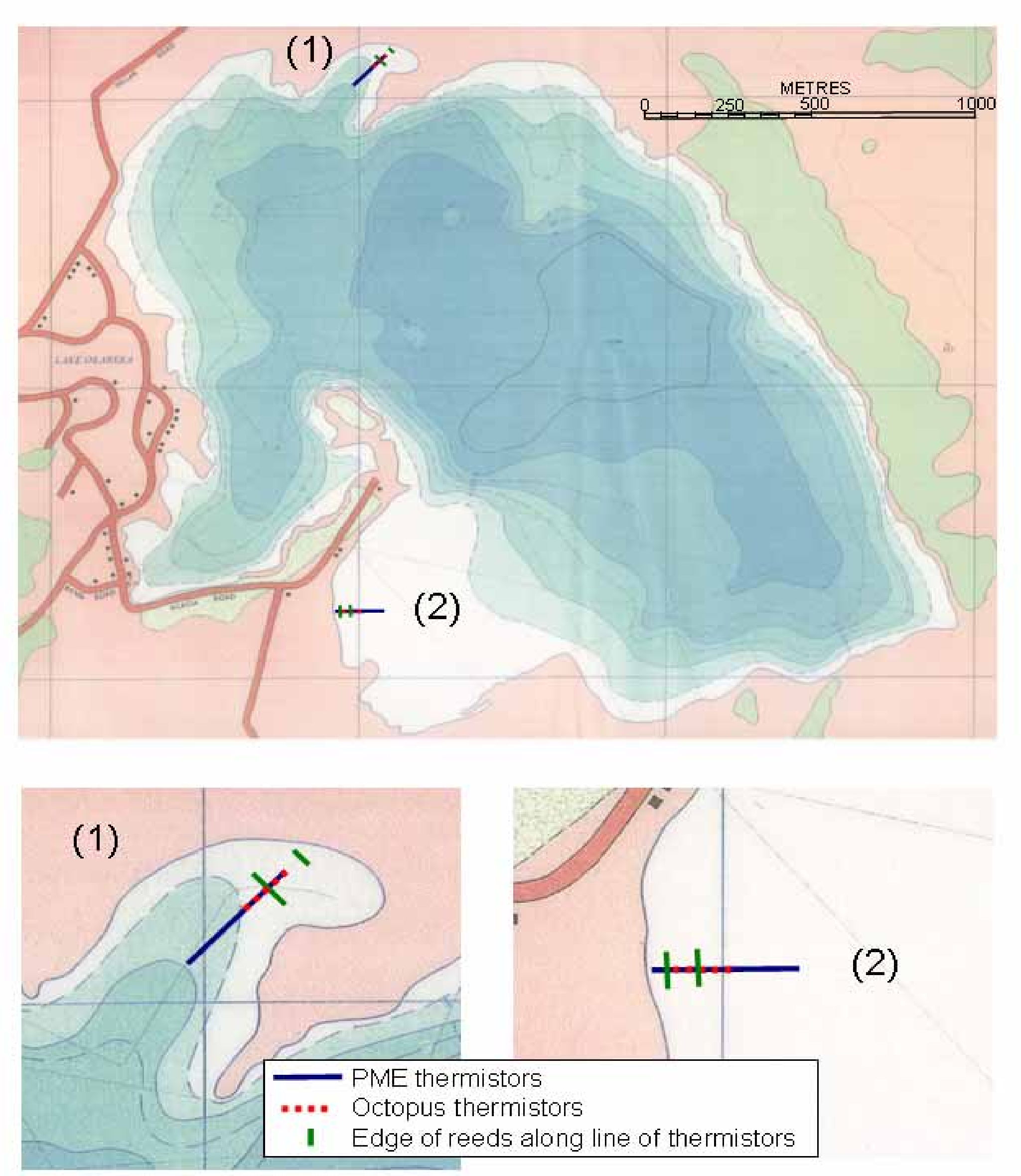


Figure 5: Thermistor sites, PME and Octopus: (1) 15 Mar – 9 Aug 2005; (2) 9 Aug 2005 – 24 May 2006. PME has 41 thermistors over a length of 131 m lying on the lake bed. Octopus has 16 thermistors over 50 m on 6 and 8 vertical lines (1st and 2nd deployments, respectively) .

We are studying plant growth and nutrient storage for all three species at these sites, and have studied mixing patterns with thermistor chains placed in the baumea vegetation of the northwestern bay, and eleocharis vegetation of the southern bay. Studies of fish and bird habitat and lagarosiphon invasion were located around the eleocharis vegetation in the southern bay in November 2005, and May 2006.

In January 2006 a particularly large boat lane clearance was carried out in this area, in which vegetation was dragged from the lake bed, leaving large mats of sediment and rhizome material decomposing on the shoreline. This recent clearance was used as the focus of studies in May 2006.

4.2. Horizontal mixing patterns

4.2.1. Temperatures

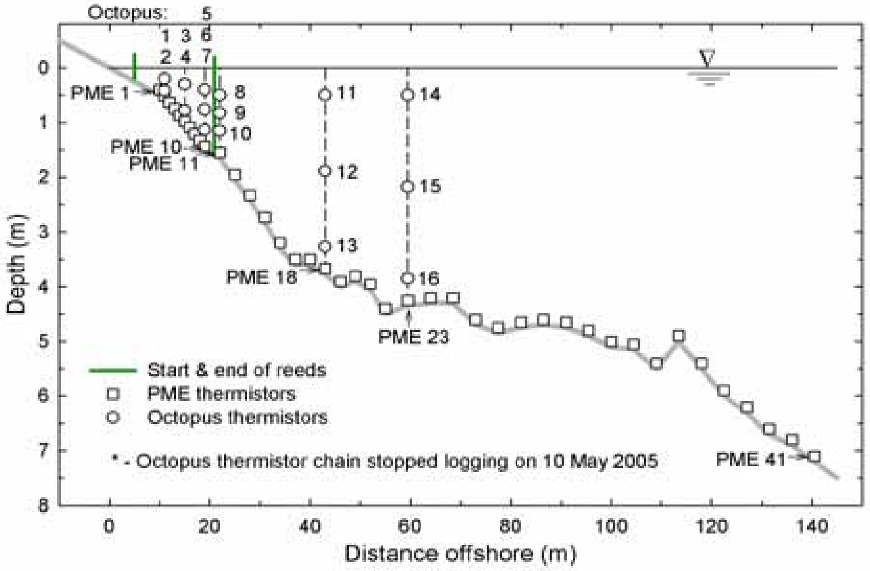
Temperature differences between nearshore waters occupied by vegetation and offshore open waters were measured using two thermistor chains set out to form a horizontal transect through the vegetation and into open water. One chain, approximately 130 m in length with 41 thermistors mounted at spacings varying from 1 m near shore to 4.5 m offshore, was laid along the lakebed to measure bottom water temperatures. This chain was manufactured by Precision Measurement Engineering, San Diego, and is referred to as the PME thermistor chain in this report. The second “chain”, consisting of 2 sets of 8 thermistors, arranged in a branching configuration each at a distance of approximately 25 m from the logger, was manufactured by Richard Brancker Research, Ottawa, and is referred to as the Octopus thermistor chain in this study. The Octopus was configured to measure vertical temperature differences over the water column at several locations along the line formed by the PME chain.

Two deployments were made, the first from 16 March – 9 August 2005 in the northwestern bay, and the second from 9 August 2005 – 24 May 2006 in the ‘eleocharis bay’ bay on the southwestern side of the lake, through the eleocharis beds in which boat lanes had been cut. Locations of the deployments are shown in Fig. 5, and the configurations of the two thermistor chains for each deployment are shown in Figure 6 together with the periods over which data were collected.

4.2.2. Dye studies

Water movements were observed directly on one occasion (16 February 2006) by photographing the path taken by a patch of dye (75 ml Rhodamine WT) released along the line of the submerged PME thermistor chain, on the shoreward side of the eleocharis beds in the southwestern bay where boat lanes had been cut (Fig. 5, deployment 2).

(A) Thermistor deployment 1: 16 Mar - 9 Aug 2005*, Lake Okareka



(B) Thermistor deployment 2: 9 Aug 2005 - 24 May 2006*, Lake Okareka

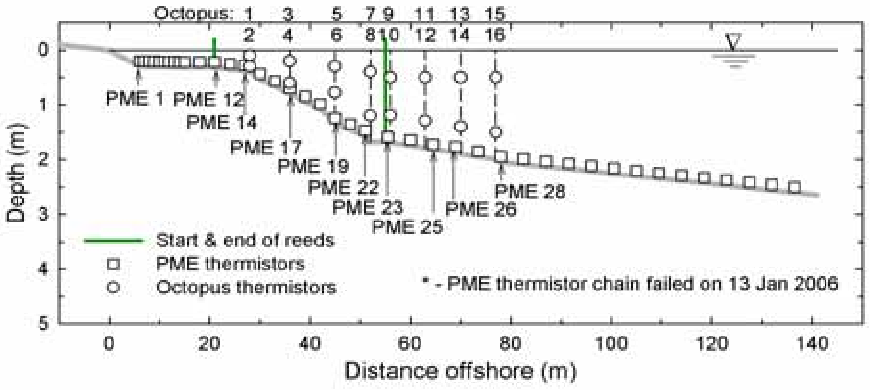


Figure 6: Onshore – offshore cross-section through thermistor line transects for 1st (A) and 2nd (B) deployments. Note that the Octopus did not log after 10 May 2005 for the 1st transect, and the PME chain failed on 13 January 2006 during the second transect.

4.3. *Lagarosiphon major* colonisation

A submerged macrophyte survey was carried out inside and outside of the emergent plant stands, within the two bays and within the boatlanes in the eleocharis bay during November 2005. Submerged vegetation at each site was surveyed in a 2m-wide band, using SCUBA. The maximum and average cover for each plant species was recorded. Cover was expressed as the percent of substrate area covered by each species. A second survey was conducted in May 2006 at the boatlane site formed in January 2006.

4.4. Fish and bird habitat

The NZ Freshwater Fish Database records that at least 4 freshwater fish species are known to reside in the Lake Okareka catchment: koaro (*Galaxias brevipinnis*), common smelt (*Retropinna retropinna*), common bully (*Gobiomorphus cotidianus*), and rainbow trout (*Oncorhynchus mykiss*).

A specific fish sampling exercise was undertaken in the eleocharis bay to compare common bully densities between different habitat types. Common bully is the most abundant fish species and therefore potentially the most affected by the loss of plant material within the boat lanes. Other species were not targeted as they would require sampling methods that pose potential risk of catching waterbirds such as shags, dabchick, and scaup.

For fish surveys, minnow trap lines were set at 6 sites (Fig. 7) within the eleocharis bay. Three habitat types were selected for trapping sites, with two lines per habitat. Sites E1 and E2 were within the eleocharis beds, B1 and B2 within the boat lanes, and S1 and S2 in open water. At each site a line of 6 minnow traps, spaced at 1m intervals were set. All traps were placed at a depth of approximately 2m and left to fish overnight. The traps were removed the following day and catch results recorded.

Lake Okareka features a number of small sheltered bays suitable as habitat for a variety of wetland birds. The extensive eleocharis-dominated vegetation on the western shore of the eleocharis bay (Figs. 2, 7) is likely to provide ideal nesting, roosting, feeding and cover habitat. A brief, semi-quantitative survey of wetland birds was conducted on 5/11/05 in the eleocharis bay. Weather conditions were fine and sunny with little wind. Species, numbers and locations were recorded.

4.5. Nutrient cycling

We have used the method of Daoust and Childers (1998) to estimate the biomass and productivity of the emergent plants. Briefly, this is a non-destructive method that calculates biomass from measurements of shoot density, length and diameter on random samples of shoots, in permanently located quadrats at each study site. It allows repeated measurements in the same area and is less labour-intensive than most other methods for determining productivity. We also harvest the above-ground and below-ground biomass at the time of peak summer biomass (February), which provides a separate determination of productivity and total biomass (including below-ground rhizomes and roots).

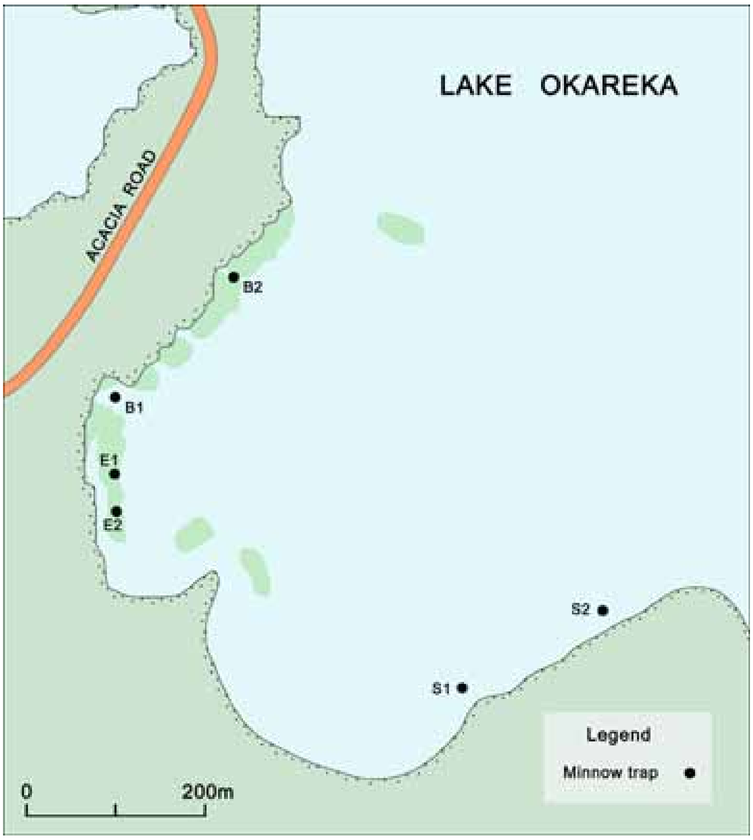


Figure 7: Location of minnow traps for fish sampling exercise in Lake Okareka. E1 and E2 = within eleocharis beds (shown in green), B1 and B2 = within boat lanes, and S1 and S2 = open water sites.

To demonstrate the extent to which the vegetation is nutrient-limited, we present information here on nutrient concentrations in the sediment and in the plant tissue. We collected sediment cores from underneath all three species (two sites per species), and analysed them for total carbon, nitrogen and phosphorus. Live and dead plant material has been collected seasonally and analysed for nitrogen and phosphorus. Methods for soil and plant analysis are those of Blakemore et al. (1987).

We interpret the nature and extent of nutrient limitation from concentrations and ratios of N and P in the tissues, and differences in concentrations in live and dead tissue. The ratio of nitrogen to phosphorus in the live tissue indicates which of the two is growth-limiting, with N:P < 13 indicating N limitation, N:P > 16 indicating P limiting, and ratios between 13 and 16 indicating that either or both may be limiting (Güsewell and Koerselman 2001). The nutrient availability and degree of nutrient enrichment are determined further from two useful measures of nutrient availability – the nutrient resorption efficiency and nutrient resorption proficiency (Shaver and Melillo 1984; Killingbeck 1996). All three measurements are indicators of nutrient conservation in plants. Under low nutrient conditions, plants resorb nutrients from senescing tissue in autumn and store them in belowground tissues for use in the following growing season, but as nutrient enrichment increases they allow more nutrients to be lost in their senescent tissues (Aerts 1996). We calculated these parameters as described elsewhere (Shaver and Melillo 1984; Killingbeck 1996). We also used the N and P concentrations in the tissues and the seasonal changes in biomass to model the seasonal changes in nitrogen and phosphorus storage in the tissues (Daoust and Childers 2004). We used Analysis of Variance and probability plot techniques to identify statistically significant differences in parameters.

5. Results and discussion

5.1. Horizontal mixing patterns

5.1.1. Temperatures

Two weeks of autumn temperatures (1-14 April 2005) from the north-western baumea bay are shown in Figure 8. The strength of diurnal fluctuations was stronger in shallower, surface waters, amplitude decreasing both with depth and distance offshore (compare upper two graphs). The water column was stably stratified at all locations (bottom waters being cooler; see six smaller lower graphs), although there did appear to be periods of instability at night at the most shoreward site (thermistors 1 and 2) when surface temperatures cooled below those of bottom waters. This could be an artefact due to calibration problems with the thermistors, although it is also possible that a “concentration boundary layer” may have existed near the bottom within dense, submerged vegetation, in which higher concentrations of dissolved substances increased the density of water in this layer, stabilizing it against the effects of warmer temperatures and thereby preventing it from mixing vertically with cooler water above the layer. We have some evidence for the occurrence of such boundary layers from dissolved oxygen measurements and conductivity-temperature profiles made during the second deployment in the southwest bay, but this must be treated as a hypothesis requiring further investigation and testing.

At this site both surface and bottom temperatures were coolest during day and night at the shallowest near-shore sites (thermistors 1, 2 and 3, 4); this was probably due to shading effects by the tall baumea vegetation, shoreline trees, surrounding hills and southwest-facing aspect of this site. Groundwater inflow may also have played a role, but we have no information on this. Regardless of the details of the patterns and their causes, however, it is clear that horizontal onshore-offshore temperatures are a persistent feature and that these are strong enough to generate a buoyancy-driven circulation.

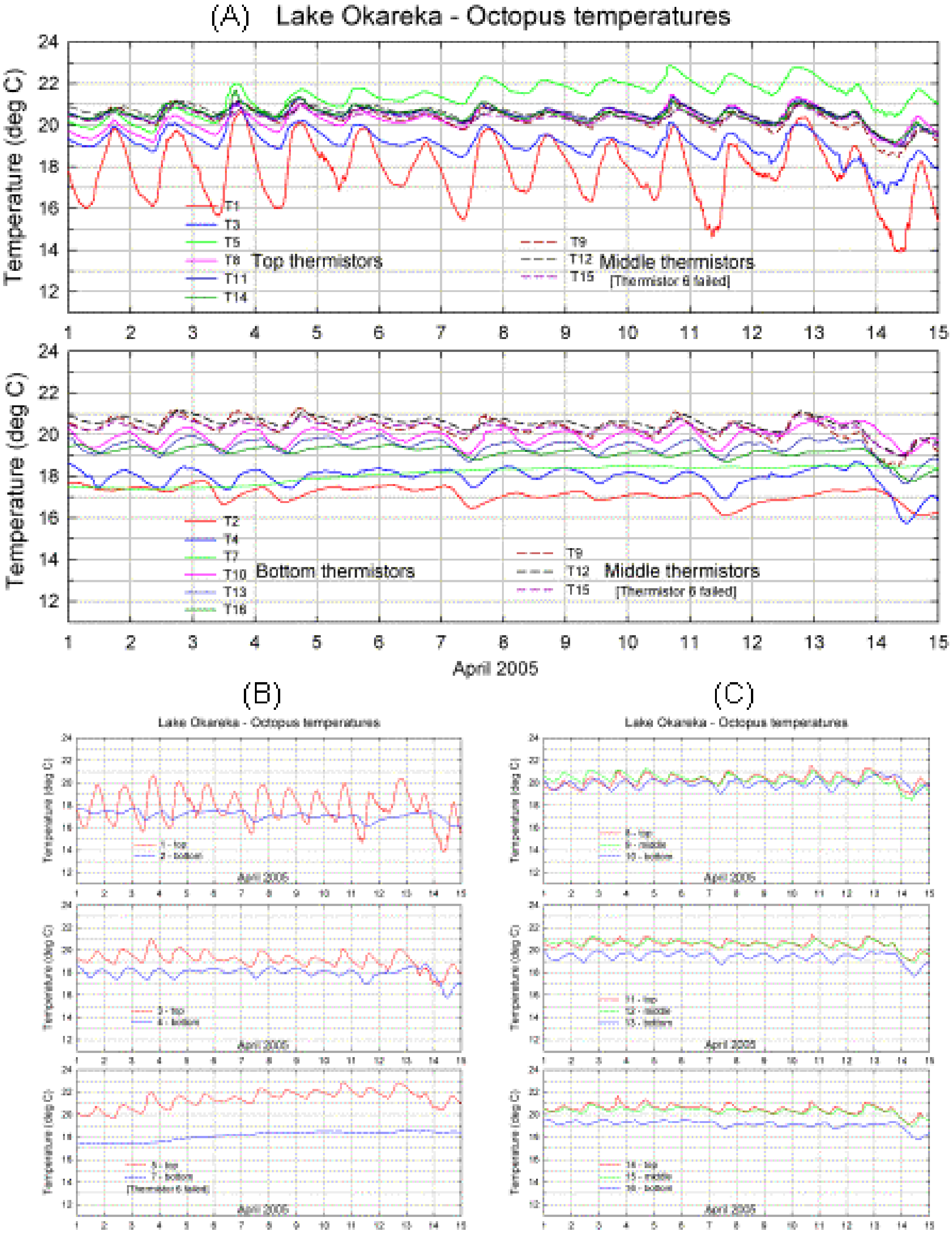


Figure 8: Octopus temperatures, Lake Okareka, northern bay, 1-14 April 2005. (A) All top thermistor temperatures plotted in upper plot and bottom thermistor temperatures in lower plot, with middle thermistor temperatures in both plots; (B) plotted by vertical, for thermistors in vegetation; (C) plotted by vertical for thermistors in open water.

Two weeks of spring temperatures (1-14 September 2005) from the eleocharis bay adjacent to the residential development are shown in Figure 9. Note that the thermistor chains passed through the eleocharis and then into open water, not through a boat lane (the location of the dye release shown by the red ellipse in the upper photograph of Figure 10 is along the line of the thermistor chains). Almost all of the remarks made above about the deployment in the northwest bay (Fig. 8) are applicable to the temperatures shown in Fig. 9. An exception is that in the southwest bay, temperatures were warmest in the shallower waters during the day, and generally become cooler offshore. This is to be expected for an unshaded shoreline with a northeast-facing aspect.

5.1.2. Dye studies

Dye was released in a band of shallow water separating the shoreline from the start of the eleocharis beds in the southwestern bay, at a point midway between two gaps formed by a boat lane and the southernmost extent of the vegetation (Fig. 10).

Weather was calm and warm, ideal conditions for observing the buoyancy-driven circulation described earlier, in which warmer onshore water forms a surface current moving offshore. In this case, the dye patch moved offshore until it encountered the edge of the vegetation. Instead of flowing through the plants, however, the patch split into two parts and flowed parallel to the edge of the vegetation toward the gaps. Our hypothesis is that the gaps provided a path with less resistance flow than through the vegetation. We also hypothesize that in the presence of a longer, continuous band of vegetation, the buoyancy driven flow would have passed slowly through the plants, and that the gaps caused a “short-circuiting” of this onshore-offshore flushing.

In summary, the thermistor and dye studies have confirmed that the emergent vegetation in Lake Okareka does act to slow water movements in the littoral zone and allows differences in temperature to develop within the vegetation compared to the open water. It also has provided evidence that the boat lanes inhibit this feature, acting as a short-circuiting pathway for onshore-offshore exchange. We are continuing these studies to address some of the uncertainties discussed above.

5.2. *Lagarosiphon major* colonisation

During the November 2005 survey *Lagarosiphon major* dominated the submerged macrophyte community immediately on the deep margin of the emergent plant vegetation. Percent cover reached 95% in both bays, with the native species

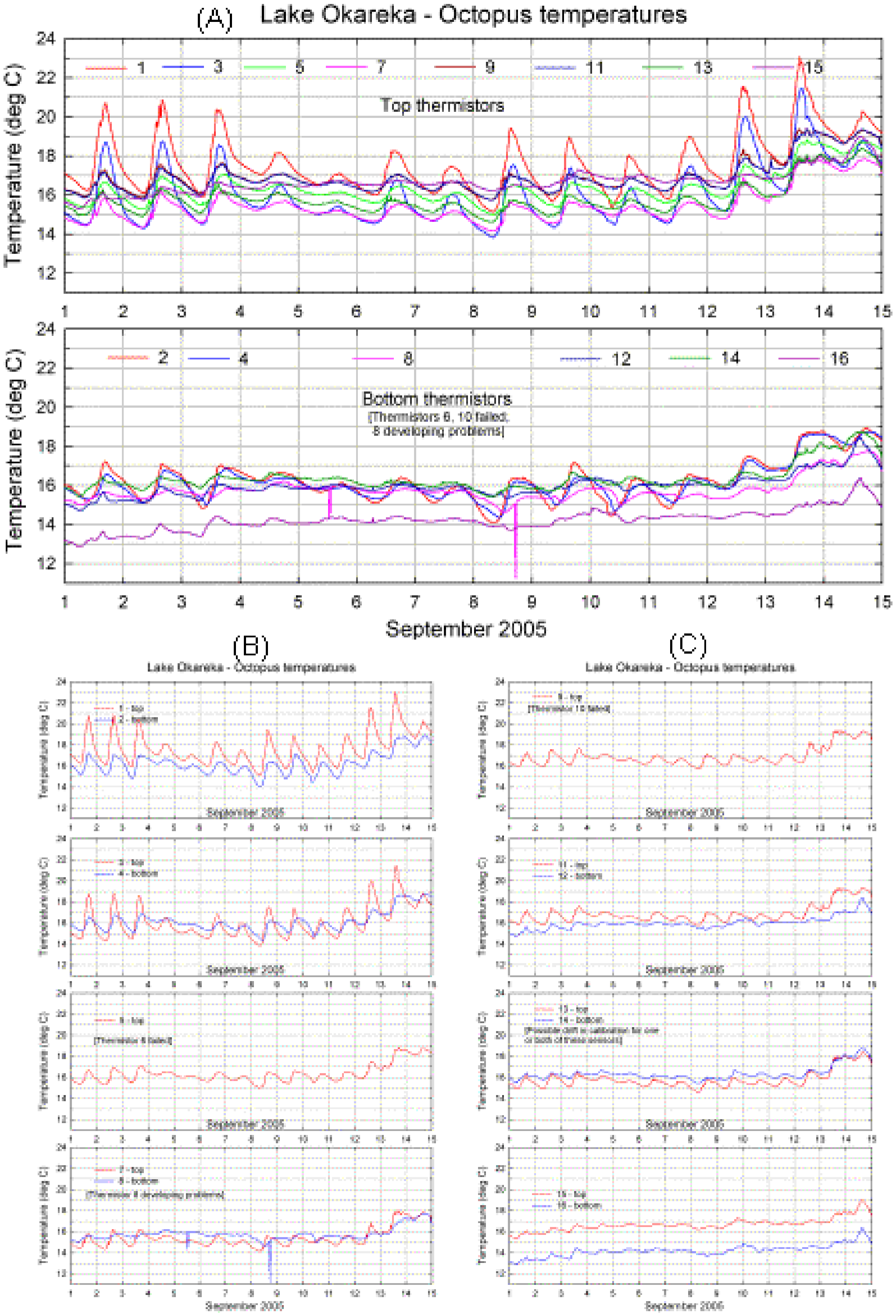


Figure 9: Octopus temperatures, Lake Okareka, southern bay, 1-14 September 2005. (A) All top thermistor temperatures plotted in upper plot and bottom thermistor temperatures in lower plot; (B) plotted by vertical, for thermistors in vegetation; (C) plotted by vertical for thermistors in open water.

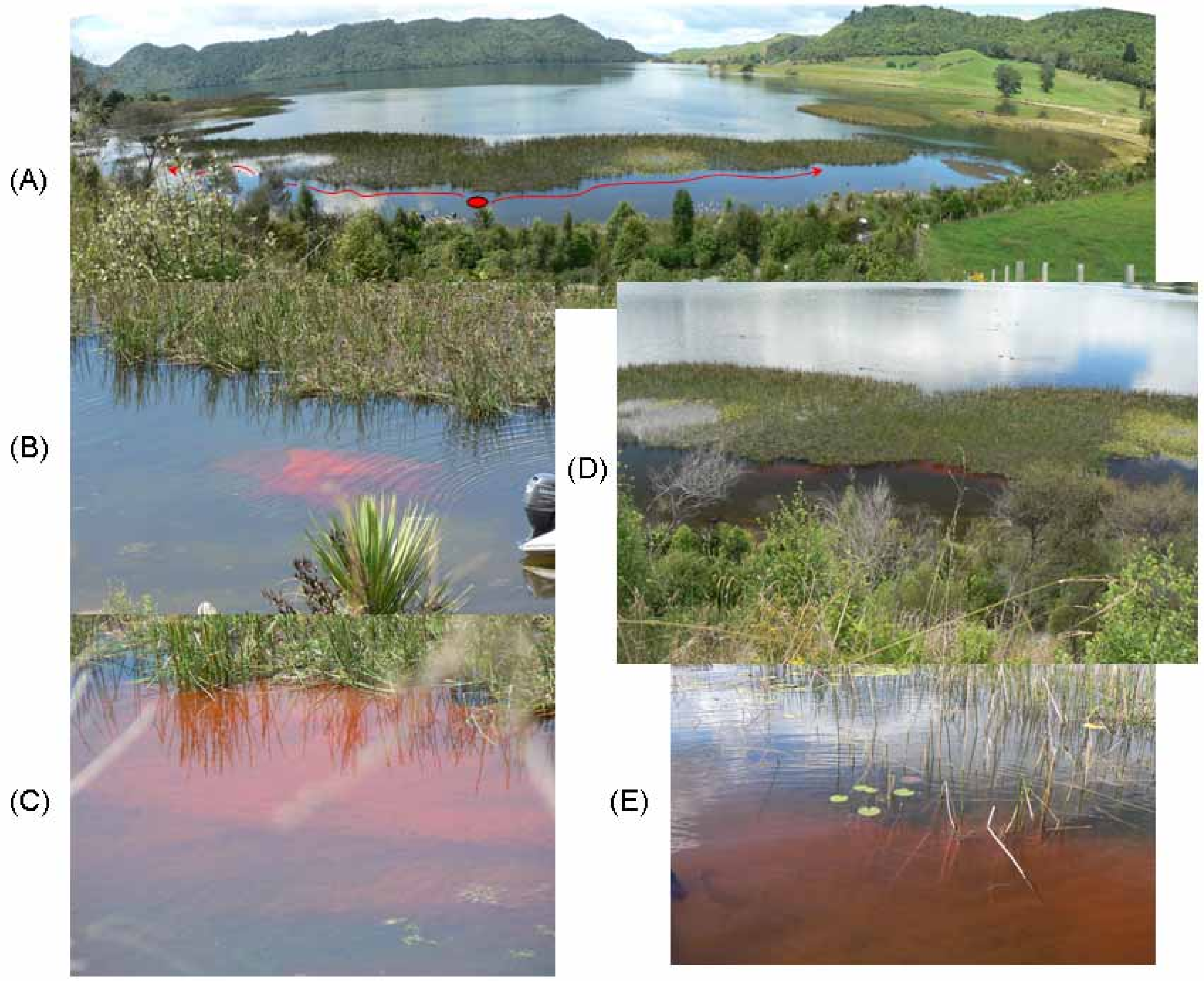


Figure 10: Dye release 16 February 2006 (approximately 75 ml Rhodamine WT), illustrating short-circuiting of onshore-offshore circulation through gaps in the vegetation. (A) Panorama view looking west showing location of the release and the paths followed by the two parts of the dye cloud. Boat lanes have been cut through the vegetation to the left of the northward pointing flow path. (B) Dye patch just after release, before it separated into two parts. (C) Flow moving parallel to the edge rather than through the vegetation, northward moving dye cloud. (D) The dye cloud after separating into two parts travelling parallel to the vegetation in opposite directions. (E) Similar to (C) but farther toward the boat lanes.

Potamogeton ochreatus and *Myriophyllum triphyllum* making up the remainder of the community. Lagarosiphon was also the dominant macrophyte (95%) in the previously established boat lanes. Within the emergent plant stands total macrophyte cover was < 10%, comprising mainly of *P. ochreatus* with <2% lagarosiphon.

Species composition and percent cover remained consistent at all sites during the May 2006 survey, with the exception of just in front of the emergent stand in the NW bay. Egeria, previously confined to further out in the bay, is rapidly displacing lagarosiphon and now makes up 40% of the macrophyte community adjacent to the eleocharis.

At the newly formed boat lane (January 2006 – Fig. 11), previously part of the eleocharis stand, lagarosiphon has rapidly (< 4 months) colonised all available substrate within the cleared site. Percent cover of lagarosiphon within the cleared area was at 100%. A further collapse of the eleocharis stand, adjacent to the cleared boat lane, had occurred between March 2006 and the May survey. Lagarosiphon was rapidly colonising the newly exposed area amongst the remaining dead eleocharis material (Fig. 12).

Figure 11: Top: New boatlane formed in January 2006. Bottom: Mat of rhizome and sediment resulting from boatlane clearance.

Figure 12: Underwater photos of new growth of the invasive weed lagarosiphon colonizing newly cleared areas amongst dead eleocharis in areas recently cleared for boatlanes.

5.3. Fish and bird habitat

In the fish survey, there was high variability in bully numbers within the three habitat zones. There were no obvious trends in the numbers of fish in the three habitats, although catches at sites S1 and S2 (open water) were relatively constant and higher than those at the boat lane or eleocharis sites. It appears that most fish in the lake are generalists and do not have strong habitat preferences.

In the bird survey, 135 individuals of 7 wetland species were observed in the bay (Fig 13). The dominant species were NZ scaup (81 individuals) and black swans (32 individuals). Most birds were scattered around southern and western side of the bay. Only one pair of dabchicks was observed in the survey, but more pairs of this species had been observed during other visits. It is likely that some pairs of this species were hiding or feeding amongst the emergent vegetation at the time of the survey. During the course of the survey, many scaup and all coots swam to the eleocharis beds for cover. Many of the birds using this area are known to favour the shores with jetties and human occupation, possibly because these are located in sheltered areas and may provide food sources (Bright et al. 2004). Hence, birds are not disadvantaged and may even exploit human presence per se and human structures. However, the survey shows that the vegetation is an important habitat resource for them, and strongly indicates that destruction of the eleocharis material by boat lane creation will be deleterious for these species.

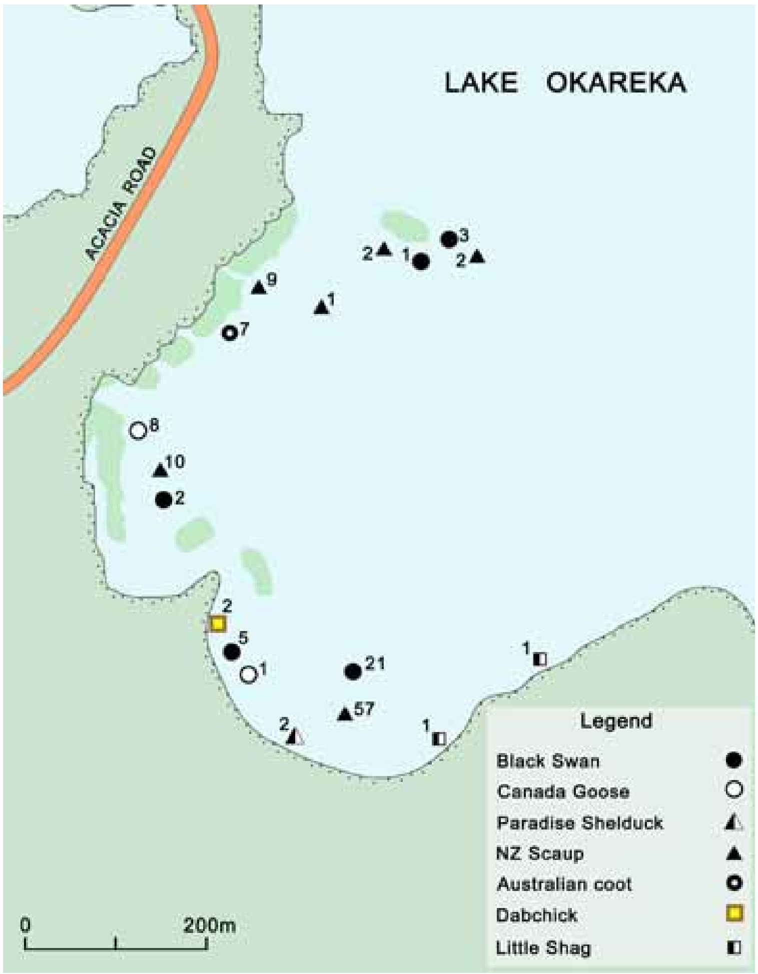


Figure 13: Map showing numbers and locations of bird species recorded during bird survey.

5.4. Nutrient cycling

5.4.1. Sediment nutrient concentrations

The organic matter concentrations and total nitrogen and phosphorus concentrations from the six sites are shown in Table 1. The loss on ignition data were generally low, indicating substrates with low organic matter concentrations (i.e. high mineral content) in all sites. Consistent with this, the N and P concentrations were also relatively low, in the range of typically oligotrophic to mesotrophic littoral sediments. Phosphorus did not differ significantly between sites, but there were differences between sites in nitrogen and therefore N:P ratio. Comparisons of means showed that the eleocharis sites had lower sediment N:P ratios and therefore were more likely to be nitrogen-limiting for plant growth than the other sites. However, the actual degree of nutrient limitation will depend on the nutrient flux from the catchment in groundwater as well as the sediment nutrient availability.

Table 1: Organic matter (% loss on ignition, LOI) and total N and P concentrations in sediment from stands of the three emergent macrophyte species. Mean values shown (*n* = 5 samples) ± 1 standard deviation.

Site	LOI (%)	N (μg mg^{-1})	P (μg mg^{-1})	N:P
Baumea Site1	9.4 ± 2.7	3.4 ± 1.0	0.2 ± 0.0	13.6 ± 2.5
Baumea Site2	1.7 ± 0.2	8.7 ± 4.5	0.6 ± 0.5	14.6 ± 1.8
Eleocharis Site1	3.5 ± 1.9	1.0 ± 1.0	0.1 ± 0.0	6.0 ± 4.7
Eleocharis Site2	5.5 ± 3.5	2.1 ± 2.0	0.2 ± 0.1	9.8 ± 6.6
Typha Site1	5.4 ± 2.6	9.9 ± 8.0	0.7 ± 0.9	18.1 ± 7.8
Typha Site2	15.4 ± 2.7	5.5 ± 2.5	0.4 ± 0.0	13.8 ± 2.3

5.4.2. Plant tissue nutrient cycling

This section presents data on concentrations of N and P in the tissues of the three species, and the nutrient recycling parameters, to assess the degree of nutrient limitation of plant growth, which nutrient (N or P) is likely to be limiting plant growth, and the implications for nutrient storage and loss in litter.

Comparison of the tissue nutrient concentrations showed that there were no significant differences in concentrations of either nitrogen or phosphorus between the two sites for any of the species, so in all analyses we have pooled the data from the two sites for each species.

The main indicator currently used to identify the nature of nutrient limitation in emergent wetland plants is the ratio of N:P in the live plant tissues during summer. Because most plants have higher requirements for N than P, they are usually N-limited unless P availability is very low. The N:P ratios for eleocharis and typha (Table 2) are typical for such plants and indicative of growth limitation by N rather than P (N:P < 13). Phosphorus concentrations > 0.1% in the live tissue (Table 2) are also usually indicative that N rather than P is limiting plant growth (Wilby et al. 2001). For baumea, N:P at approximately 16 together with low concentrations of both nutrients suggest that both nutrients are limiting (co-limitation). The high RE and low RP values (Table 2) are also within the range generally interpreted as indicating that plant productivity is nutrient-limited (Aerts 1996; Killingbeck 1996). The data also indicate that typha is the most strongly nutrient-limited species, as it had significantly higher resorption efficiencies and lower N resorption proficiency than the other species. This is consistent with typha’s general nutrient behaviour – it is a fast-growing, productive species with high nutrient demands, and is more likely to show signs of nutrient limitation at low nutrient supply than the other two species. It is therefore also much more likely to increase its productivity if the nutrient input increases, than the other species (Froend and McComb 1994).

Table 2: Nitrogen and phosphorus concentrations, N:P ratios and resorption parameters for tissue of the three species at peak summer biomass. Mean values shown (*n* = 10 samples) ± 1 standard deviation.

Site	Baumea	Eleocharis	Typha
Live tissue N (%)	0.82 ± 0.17	1.66 ± 0.20	1.40 ± 0.27
Live tissue P (%)	0.05 ± 0.01	0.16 ± 0.02	0.14 ± 0.05
N:P ratio of live tissue	16.6 ± 1.8	10.4 ± 1.8	10.3 ± 2.4
Resorption efficiency			
N (%)	48.5 ± 11.3	44.4 ± 5.1	73.3 ± 9.1
P (%)	65.1 ± 11.7	70.0 ± 7.8	86.6 ± 7.0
Resorption proficiency			
N (%)	0.41 ± 0.08	0.92 ± 0.08	0.36 ± 0.10
P (%)	0.02 ± 0.01	0.05 ± 0.01	0.02 ± 0.01

The concentrations of N and P shown in Table 2 are also considerably lower than these plants can accumulate when they are grown in high-nutrient environments. When grown in wastewater-fed systems and other environments with excess nutrients, concentrations are much higher than in the Lake Okareka material (Table 3). Increases in nutrient input to the littoral zone are likely to increase tissue nutrient concentrations, i.e the nutrient storage capacity of the current biomass of the emergent vegetation is not saturated.

Table 3: Maximum concentrations of N and P accumulated in the tissues of the three species when grown in high-fertility environments*.

	Baumea	Eleocharis	Typha
Nitrogen (%)	2.40	3.17	5.2
Phosphorus (%)	0.87	0.94	0.72

*Data for maximum values compiled from Adcock and Ganf (1994), Tanner (1996), Greenway (1997), and unpublished NIWA data.

Whether the productivity and biomass would increase as well, further enhancing nutrient storage, depends on other possible growth-limiting factors as well as nutrients – especially light and space. Under high-nutrient conditions, growth and biomass of emergent plants tend to increase until very productive, dense stands of plants are formed. At this stage, growth becomes limited by self-shading by the dense vegetation, reducing light availability for shoots within the bed, and no further growth increase occurs with more nutrient input. Under these conditions, plants behave less conservatively with nutrients, their RE decreases and RP increases, and higher concentrations are shed in the senescent tissue (Aerts 1996).

At Lake Okareka, baumea is already approximating this condition, even though its growth is nutrient-limited. Table 4 shows data for shoot density and biomass at our sites, compared against maximum values recorded in high-nutrient environments at other sites with similar water depth. (Density and biomass of all three species decrease with depth (Froend and McComb 1994; Sorrell and Tanner 2000), so comparisons between sites can only be made for plants growing at similar depths.) The shoot density and biomass of this species are already very close to the maximum values recorded. This is consistent with previous observations of its growth patterns – its growth rate and biomass are almost indifferent to nutrient supply: even under high nutrient loadings, it grows very slowly, but still eventually forms dense stands (Tanner 1996). Little further biomass increase is likely in this species.

However, Table 4 also shows that both eleocharis and typha currently have considerably lower shoot densities and biomass than maximum values recorded elsewhere, suggesting they are not yet light-limited and are capable of further biomass increase if nutrient inputs increase. This is particularly so for typha, which is capable of forming much taller, denser canopies than the stands in Lake Okareka.

Table 4: Peak late-summer values for shoot density and biomass for the three species in Lake Okareka, compared against maximum values recorded when growing in high-fertility environments. Lake Okareka data are mean values ± 1 standard deviation, *n* = 6 quadrats; maximum values are ranges compiled from literature sources.*

	Baumea	Eleocharis	Typha
Shoot density (number m^{-2}):			
Lake Okareka	367 ± 61	222 ± 41	33 ± 10
Maximum values	350-450	700 – 1200	70 – 80
Standing biomass (g m^{-2}):			
Lake Okareka	5469 ± 1561	838 ± 231	1852 ± 945
Maximum values	6500 - 7700	1500 – 2000	3000 – 3500

*Data for maximum values compiled from Adcock and Ganf (1994), Froend and McComb (1994), Tanner (1996), Greenway (1997), and unpublished NIWA data.

5.4.3. Current nutrient storage and mechanisms for nutrient removal

Figure 13 compares the total biomass (both above- and below-ground) for the three species, which was greatest for baumea, which is consistent with its ability to form greater biomass under low nutrient supply than the other species. Typha’s higher nutrient concentrations increase its nutrient storage relative to its current biomass, especially in its below-ground tissues. If nutrients increase, this species, which reacts strongly to nutrient availability, is likely to benefit and increase biomass and nutrient storage considerably; eleocharis will also, but to a lesser extent. Note that for all species below-ground biomass is an important part of the nutrient storage, whereas standing dead material currently forms very little of the nutrient pool – but this would increase relative to the other tissues if increased nutrient inputs increased concentrations in the dead tissues.

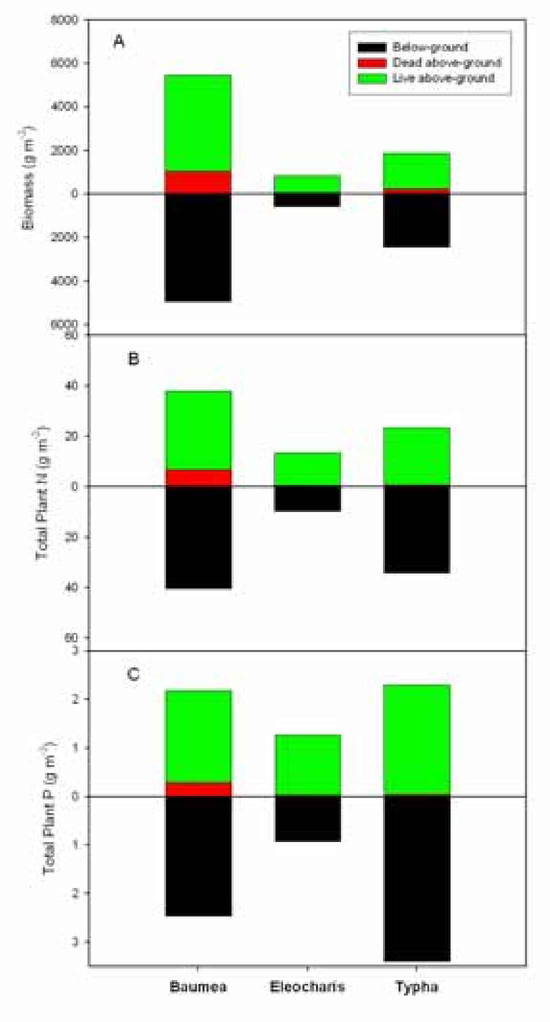


Figure 13: Comparison of the biomass and total nitrogen and phosphorus storage (all in g/m^2) between the three emergent species. Mean values, standard deviations omitted for clarity.

Emergent marginal vegetation is very effective at intercepting diffuse nutrient run-off and reducing the transfer of nutrients from the littoral to pelagic zones of lakes. Overall, the data show that the existing emergent plant stands in Lake Okareka have capacity to increase their nutrient storage in response to increasing nutrient input from the catchment. Also, any significant increase in area colonised by marginal vegetation would also increase the nutrient storage by these plants. Eleocharis, with its greater depth tolerance than the other two species, is the most likely to play a role here.

Under high nutrient inputs, however, much of the nutrient removal and protection of water quality achieved by emergent vegetation is not associated with the amount stored in tissues. Instead, it is the conversion of inorganic nutrients to recalcitrant biomass (see Introduction) and the capacity of emergent species to stimulate microbial nitrification-denitrification cycles and remove N as gaseous nitrous oxide from the system (Reddy et al. 1989) that are the key to long-term removal under high nutrient inputs. At present, the litter released by the vegetation has very low nutrient concentrations, is likely to be highly recalcitrant, and is probably incorporating considerable amounts of nutrients into the sediment rather than the water. We are planning further studies of the decomposition and nutrient cycling processes in the litter in future, but the nutrient concentrations in the tissues and previous studies on similar species (Corstanje et al. 2006) suggest that baumea would be considerably more recalcitrant than the other species.

The typha-willow wetlands around the lake have already been shown to be highly effective in nutrient interception, with both plant uptake and nitrification-denitrification cycles contributing to remove up to 95% of groundwater N (Lusby et al. 1998). Much of the existing marginal vegetation in deeper water, which is the focus of this study, is adjacent to such wetlands and no doubt benefits from it, receiving relatively low nutrient inputs. The data here suggest that its capacity to act as a final polishing stage for the groundwater is not yet saturated, and that it is likely to be playing an important role in this regard.

However, the eleocharis beds we studied are not adjacent to a lake-edge wetland, but instead were offshore of residential development. Of the existing material, they are therefore the most likely to be valuable in nutrient stripping. Our data, although preliminary, suggest they are coping well with any current and historical run-off, including septic tank leachate. Nutrient run-off from residential land is also often higher than undeveloped land because of high surface run-off. The eleocharis beds in this bay, and other marginal vegetation in areas with residential development, should be therefore be particularly valued in the lake. Boat lane development is clearly a threat to any nutrient-stripping role it is performing.

6. Conclusions and management implications

Lake Okareka is a valued amenity for aesthetic and recreational reasons, and our study has shown that the marginal vegetation has an important role to play in maintaining these values, which may not currently be widely appreciated and could in fact be enhanced.

First, we showed that emergent marginal vegetation is able to resist invasion by the aquatic weeds lagarosiphon and egeria, largely no doubt as a combination of the shade they create underwater and the detritus they accumulate amongst their stems. The submerged aquatic weeds are an aesthetic nuisance, and the marginal vegetation restricts them to deeper water where they are less noticeable. The emergent plants are also likely to act as a barrier to mats of floating weed that wash up on shorelines, which is another major aesthetic issue. Eleocharis, which grows deeper than the other species, is particularly beneficial as a weed barrier. The shoreline with the recently established boardwalk and bird-watching facilities is adjacent to the eleocharis bay where we carried out our study, and it is notable that the shallow water between the shoreline and eleocharis has little lagarosiphon, whether growing or washing up. As lagarosiphon is gradually replaced in the lake by egeria, which is a more competitive species in higher nutrient waters and has a denser, surface-reaching growth form, the aesthetic problems are likely to become worse and the marginal vegetation have even more value.

Although our thermistor data are still preliminary, they have clearly identified the presence of horizontal and vertical temperature gradients between the vegetation and open lake, supporting the concept that onshore-offshore mixing is slowed by the plants, with the associated benefits in sedimentation and erosion. The small differences in water temperature that vegetation induces are also likely to be part of the explanation for the high diversity of microfauna associated with species like eleocharis (Duggan et al. 2001).

Although we did not find evidence of common bullies, the most abundant native fish in the lake, preferring the vegetation for habitat, it was clearly playing an important role as bird habitat. In the eleocharis bay, birds were counted in close association with the vegetation and bird behaviour showed a strong tendency for use of the vegetation as shelter from disturbance as well as nesting. Given the tendency for birds to congregate near sites of human habitation, the presence of extensive vegetation for shelter is an important habitat feature under threat from the boat lane creation.

We found that the vegetation currently has very efficient nutrient storage, with high internal nutrient retention and very low N and P concentrations in litter. It appears to be effectively intercepting nutrients in the areas where it is growing, and have the capacity to increase storage in most areas if nutrient input increased. It currently occupies and fulfils this and other functions only in small areas, but our Lakewave modelling suggested that it could probably be re-established elsewhere and the benefits to lake values enhanced. If emergent vegetation could be established over more of the shoreline where it is currently not found as suggested by Lakewave, there could be likely to be significant benefits for protection of lake water quality, especially if this was achieved in areas where there are no shoreline typha-willow wetlands at present. The current large eleocharis bed in the southern bay where most of the boat lanes are being cut is likely to be particularly important for nutrient stripping, being adjacent to a residential area.

Boat lane creation is therefore a threat to these values. Areas with plants removed cannot provide nesting habitat, clearly create significant short-circuiting of water movements, and reduce the nutrient filtering role. As the size of the remaining fragments decreases, they may reduce below a threshold where they are too small to be used at all for nesting. Size of emergent vegetation bands is an important consideration for maximising all their values: frequent openings along their length are likely to have greater effects on their functions than may appear likely from their width alone.

The water quality and amenity value of Lake Okaraka are of great local and regional significance and are being enhanced by a number of initiatives in the management plan. The value of marginal vegetation in lake ecology, and protecting its integrity by minimising boat lane disturbance, should be recognised as part of this process. The work in this project suggests that some co-operative management of boat lane activities to minimise its disturbance to littoral ecology would be valuable for sustaining the multiple values of the lake.

7. Acknowledgements

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