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The Role of Exotic Fish in the Loss of Macrophytes and Increased Turbidity of Lake Wainamu, Auckland

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Approved for ARC Publication by:

Name: Grant Barnes

Position: Group Manager Monitoring & Research

Organisation: Auckland Regional Council

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The role of exotic fish in the loss of macrophytes and increased turbidity of Lake Wainamu, Auckland

D. K. Rowe
J.P. Smith

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National Institute of Water & Atmospheric Research Ltd
PO Box 11-115, Hamilton
New Zealand
Tel: 07 856 7026
Fax: 07 856 0151

Contents

Peer Reviewed by:

Max Gibbs

Approved for release by:

Jody Richardson

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1 Executive Summary

A survey to determine whether koi carp and/or other exotic fish could be responsible for the turbid condition of Lake Wainamu was carried out for the Auckland Regional Council in April 2002. No koi carp were found in the lake despite an intensive and comprehensive netting and trapping programme. Exotic fish present in the lake included perch, goldfish and Gambusia (mosquitofish). Native species included eels (mainly shortfins), common bullies and mullet. Freshwater shrimps were present in the lake, but no crayfish were found there, although they still occur in the tributary streams. Tench, perch, goldfish and Gambusia were not present in the lake in 1979, but the latter three species are now numerous and collectively dominate the fish fauna. Although eels are still abundant, and mullet are still present, it is apparent that populations of other native fish (viz. common bullies, smelt and banded kokopu) have declined, and that this decline occurred after the introduction of the exotic fish now present (viz. perch, Gambusia, goldfish, and tench). The introduction of exotic fish therefore resulted in a decline in native fish biodiversity.

Koi carp are not responsible for the current turbid state of the lake. However, goldfish may have played a role in this, and the exotic fish now present may contribute to the maintenance of turbid conditions. The current cause of the turbidity is likely to be high levels of phytoplankton and 'top-down' predatory effects of fish on zooplankton could be involved in this as much as high nutrient levels. However, re-suspension of silt from the lake bed by fish foraging activities and/or wind-driven subsurface water currents are also possibilities. The sources of turbidity of this lake (e.g. planktonic organisms, or suspended silt, or inorganic particles such as clay) therefore need to be identified as a first step to determining the cause(s) of the problem and restoring this lake's water quality. Recommendations for achieving this are provided.

2 Introduction

The water quality of Lake Wainamu started to decline rapidly after 1995 (Gibbs et al. 1999). Although the exotic plant Egeria densa, was present to a depth of 5.5 m in April 1995, by 1999 the benthic macrophyte community below about 1 m depth had collapsed. Since then, the lake has remained in a turbid state and no macrophyte recovery has been observed.

It is now apparent that this lake has, like many other small dune lakes in New Zealand, 'flipped' from a clear-water, macrophyte dominated state, to a turbid, algal dominated state, and that this change occurred after 1995. One of the factors thought to be potentially responsible was koi carp, a variant of the common carp (Cyprinus carpio). Koi carp have been reported from the lake and were reported from the Waitakere River into which the lake drains in 1995 (New Zealand Freshwater Fish Database). They were not present in the lake during a 1979 survey by the Auckland Acclimatisation Society (Thompson 1979) but may have been illegally stocked into the lake after 1979. If they were not stocked, koi carp from the Waitakere River may have entered Lake Wainamu by moving up the Waiti Stream which drains into the Waitakere River.

Common carp are herbivorous and have an international reputation for increasing the turbidity of lakes (Hanchet 1990). At high densities, they can browse benthic macrophytes to extinction and in shallow lakes, the removal of plant cover results in increased suspension of silt by wind-driven wave action. Also, increased algal production can occur as nutrients formerly locked away in the macrophyte biomass are released into the water column. Carp may also contribute to high turbidity levels in lakes directly by disturbing silt during their benthic feeding activity.

As the disappearance of macrophytes and increased turbidity of Lake Wainamu after 1995 may have been potentially caused by koi carp, a survey was required to determine the relative abundance of this fish in the lake, and if it proved to be abundant, to design ways of reducing it. However, goldfish and Gambusia (mosquitofish) have a similar, albeit less widespread international reputation for causing such problems in lakes (Hurlbert et al. 1972; Richardson et al. 1995; Nagdali & Gupta 2002). Furthermore, other exotic fish species, particularly benthivorous species such as catfish and tench, may increase lake turbidity through their feeding habits which disturb lake sediments. A fish survey in Lake Wainamu was therefore required to determine the relative abundance of all the exotic (and native) fish in the lake and to determine the potential role of such fish in the increased turbidity of this lake.

A survey was carried out for the Auckland Regional Council in April 2002 and in this report, we identify the species of fish present in the lake, note their relative abundance, and discuss their potential role in the decline of Lake Wainamu.

3 Lake Wainamu

Lake Wainamu is on the west coast of the North Island, near Te Henga (Bethell's Beach) Auckland (Fig. 1). It is formed by a large mobile dune across the north western end of a valley (Holland & Rix-Trott 1992). The dune dams three small streams (Wainamu, Plum Pudding, and Houghton's Gully) which feed into the south eastern end of the lake (Fig. 1). The largest of these is the Wainamu Stream, which spills over a series of rock falls just before it enters the lake. The lake's outlet is at its north western end and forms the Waiti Stream which flows along the side of the dune (Fig. 2) into the Waitakere River.

Figure 1
Location map for Lake Wainamu showing its catchment and the outlet and inlet streams.

At the time of this survey the Waiti Stream carried a small flow and was generally braided for much of its length because it flowed over a wide expanse of flat, compacted iron-sand (Fig. 3). Its maximum depth was about 1 cm, except where the channel narrowed and depths of 5-10 cm occurred. Although juvenile migratory fish such as whitebait, eels, and bullies would have no difficulty in accessing the lake via such shallow water, larger fish would, and would only be able to access the lake when flood conditions produced a larger and/or more channelised flow.

Figure 2
The outlet stream at the northern end of the lake

Figure 3
The outlet stream c. 500 m below the lake running along the eastern foot of the dune.

Irwin (1975) stated that the lake is at an altitude of 22 m, however, the mean of 14 GPS fixes in April 2001 was 27 m suggesting an increase in lake level. Locals indicated that the lake level has increased over the past fifty years, but it has not increased by 5 m as this would have more than inundated the base of the falls in the Wainamu Stream.

The lake's area was given as 0.16 km2 (16 ha) and its maximum length at 1.1 km (Irwin 1975). However, Champion (1995) reported its size at 14 ha indicating that it had decreased in area between the 1970s and 1990s. Thompson (1979) recorded a maximum depth of 14.9 m, but the deepest depth recorded in our survey was 12.8 m. Local residents indicated that over the past fifty years or so, the dune has moved south, pushing into the lake and possibly reducing its depth as well as reducing its size.

All catchments in the eastern half of the lake are in native forest and only the north-western catchments were historically farmed. They are now largely retired and native forest is regenerating quickly such that over 95% of the lake's catchment is now in native bush or forest. However, this land use change has been relatively recent as a photograph of the lake taken in 1979 indicates the extent of pasture on its western and eastern sides at this time (Fig. 4). Only a small sector of the lake's north-eastern catchment is now farmed.

Figure 4
Photographs of the lake taken from its south eastern end showing the extent of pasture in the catchment in 1979 and the reversion to native bush by 1999.

The lake is an important recreational asset for locals and is used for swimming, picnicking, walking, and angling. However, its turbid nature detracts from its recreational and scenic values and is creating cause for concern by an active local community (Fig. 5).

Figure 5
Local community notice board noting the decline of Lake Wainamu as an issue to be discussed.

4 Methods

The fish survey of Lake Wainamu was carried out in early autumn, between 15-18th April 2002. Fish tend to inhabitat certain regions of lakes depending on habitat variables such as water depth, shoreline slope, sub-surface reefs or holes, substrate type (e.g. weeds versus sand versus rocks), and the presence of shelter (e.g.; from predators as well as from strong winds). Therefore, to adequately sample fish in lakes, the location of such factors needs to be identified so that sampling can encompass all fish habitats. Acoustic surveys using a high frequency (200 kHz) sounder have proved useful for this as they record water depth, and can differentiate between substrate types such as rock, dense wed beds, and softer weed-free substrates such as sand and silt. They can also reveal the presence of concentrations of larval, juvenile, and adult fish in midwater and so determine whether there are gradients in fish abundance between different regions in lakes. We therefore ran a series of acoustic transects across Lake Wainamu on 15thApril to determine the main features of its bathymetry and to locate the presence of any holes, reefs, weed beds, drop-offs, or concentrations of fish. Each transect was run in a straight line from one side, or end, of the lake to the other, and GPS fixes were taken at each end of each transect to provide a geographical reference point. Boat speed was kept constant. The depths across each transect were recorded on a chart (echogram) and later measured at approximately 5 m intervals along each transect.

Experience with sampling fish in lakes has indicated that different fishing gears are needed to sample different fish species, with some species (e.g. the larger scaled fish) being more susceptible to gill nets, whereas others (e.g. smaller fish, including eels) are better sampled by fyke netting, or traps set on the lake bottom. We therefore used three types of sampling gear. All nets and traps were set each evening (15th, 16th and 17th April) and left until the following morning to catch fish at both dusk and dawn.

Depending on the mesh size used, gill nets are highly selective for specific size ranges of fish. Therefore, we used two 40 m long by 1 m deep, nylon, monofilament, sinking, gill nets each with a mesh size of 160 mm to sample any larger, free-swimming fish present in the lake (e.g. trout, koi carp, mullet, tench etc.). These nets were set on the lake bottom in both shallow (1.5 m), and deep (10-12 m) water on each of the three nights. They were also set perpendicular to the lake edge and across the littoral zone so spanning a range of depths close to the lake edge.

Moderate-sized, free-swimming fish (e.g.; trout, perch, rudd, goldfish, tench) are best sampled using smaller meshed gill nets. We used ten 30 m long by 1.5 m deep, nylon, monofilament, sinking, gill nets, each comprising three 10 m long panels of 60 mm, 90 mm, and 115 mm mesh net respectively. These panel gill nets were set perpendicular to the lake edge, around the margin of the lake. They were set at strategic locations such as off points and drop-offs, and in bays, as well as in shallow and deep water. In general these nets were set in all sectors of the lake. On the second and third nights, two were also set near the middle of the lake at depths of 10-12 m.

Small fyke nets with a mesh size of 5-6 mm have proved useful for sampling a range of the small fish species that inhabit the littoral zones of lakes (e.g. bullies, eels, smelt, inanga, juvenile perch, rudd, catfish etc.). Accordingly, eight fyke nets were set perpendicular to the shoreline around the lake margin on each of the three nights.

Baited G-minnow traps are well suited to sampling the smallest benthic fish inhabiting lakes (e.g. elvers, common bullies, koaro). We placed one trap in shallow water (10-20 cm deep) in the marginal vegetation (mainly Eleocharis and Typha stalks) present in the littoral zone, and one on silt near the lake bottom where the outer margin of the rush beds occurs. These traps were set at six locations on each of the first two nights, with nine locations being fished on the third night. As the mesh size (4 mm) of the minnow traps was too coarse for most Gambusia, dip netting was used to sample and confirm the presence of these fish in the shallow rush-lined margin of the lake.

All nets and traps were inspected each morning and the catches recorded. The fish were identified to species, with red-coloured goldfish being confirmed (and distinguished from rudd) by scale counts along the lateral line. Lengths and weights (where possible) were recorded. Because different sampling gears are used to sample different species, and because catches between gears are not comparable, it is not possible to provide comparative measures of abundance. However, the relative abundance of the fish species present was assessed on a four point scale (i.e. abundant, common, scarce, rare) based on overall catches (by all methods) and the rank abundance of each species was determined on the basis of these data plus knowledge of the species vulnerability to the various sampling gears.

Length frequency distributions were also determined for each species and inspected to see whether one or more age group was present as this indicates the presence of a breeding population in the lake, or for migratory species, whether recruitment from the sea is regular or intermittent.

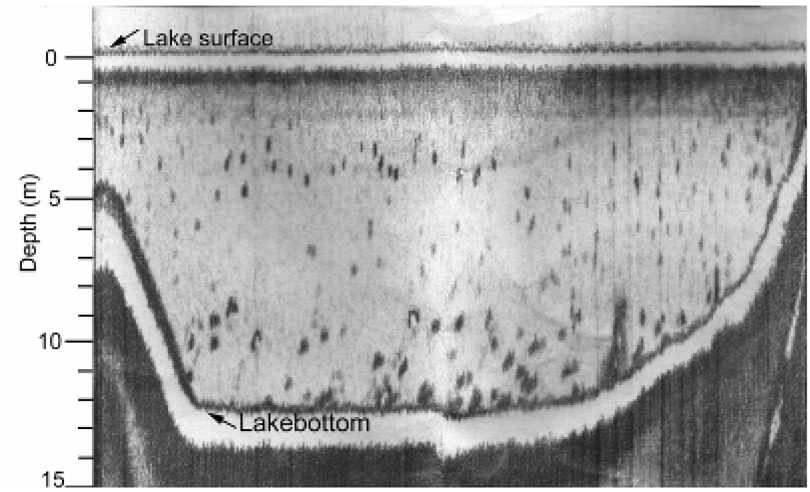
The outlet stream and the three main inlet streams (Wainamu Stream, Plum Pudding stream, and Houghtons Gully Stream) were electric fished to determine the presence of any fish in these fluviatile habitats. A 30 m section of the outlet stream (primarily a run merging into a long pool) just below the lake outlet was fished. Two large pools above the lake and below the falls in the Wainamu Stream were fished, along with a further 6 pools above the falls. Fifteen pools in Plum Pudding Stream, and twelve in Houghton's Gully Stream, each providing optimal habitat for banded kokopu (ie. total canopy closure, a water depth >10 cm, and instream cover) were selected and electric fished. A small tributary stream on the true right of the Waiti stream below the lake outlet and at the same altitude as the lake inlet streams was sampled to provide a control environment for the lake inlet streams. Thirteen pools were selected here that provided optimal habitat for banded kokopu and were also electric fished.

5 Results

5.1 Echosounding and lake bathymetry

An echogram down the main axis of Lake Wainamu from the north west to the south east is shown in Fig. 6. The lake bed descends rapidly from the edge of the sand dune at its western end to a depth of 12 m. It is then relatively flat for two thirds of the lake's length after which the bed gradually rises to the eastern end of the lake. The deepest depth recorded on 15th April 2002 was 12.5 m in the western end of the lake. Large echoes from fish were apparent near the lake bottom indicating that it was oxygenated at this time. In general, fish echoes appeared to be concentrated at depth ranges of 3-5 m and 9-12 m. The larger width of fish echoes at 9-12 m is due to beam spreading with increasing depth.

Figure 6
Echogram from Lake Wainamu showing water depths down the main axis (from the north western to the south eastern end) and the presence of fish echoes mainly at depths of 3-5 and 9-12 m.



The general features of the lake's bathymetry are shown in Fig. 7a & b. Deepest waters occurred in the north western end of the lake and the shallowest waters occurred in the south eastern end where the Wainamu Stream enters the lake. Near the middle of the lake, the bed is relatively flat indicating infilling by sediment or sand. One of the features of this lake was its relatively steep sides (except in the shallower, eastern end), and its correspondingly small littoral zone. No submerged benthic macrophyte beds were evident in the lake, even in the shallow (< 4 m deep) waters of its eastern end.

Figure 7 a.

Preliminary bathymetric map for Lake Wainamu.

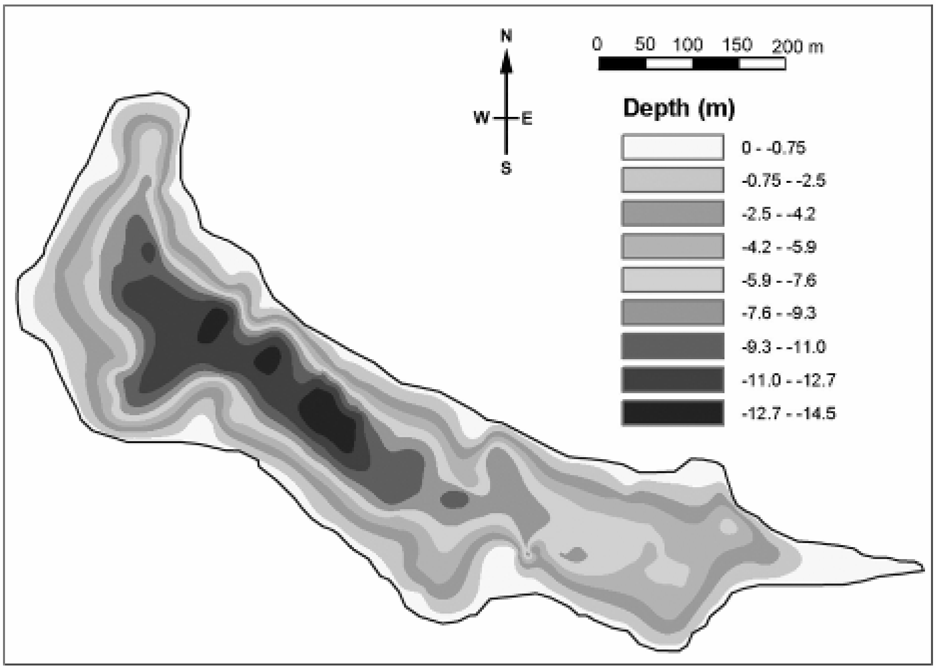
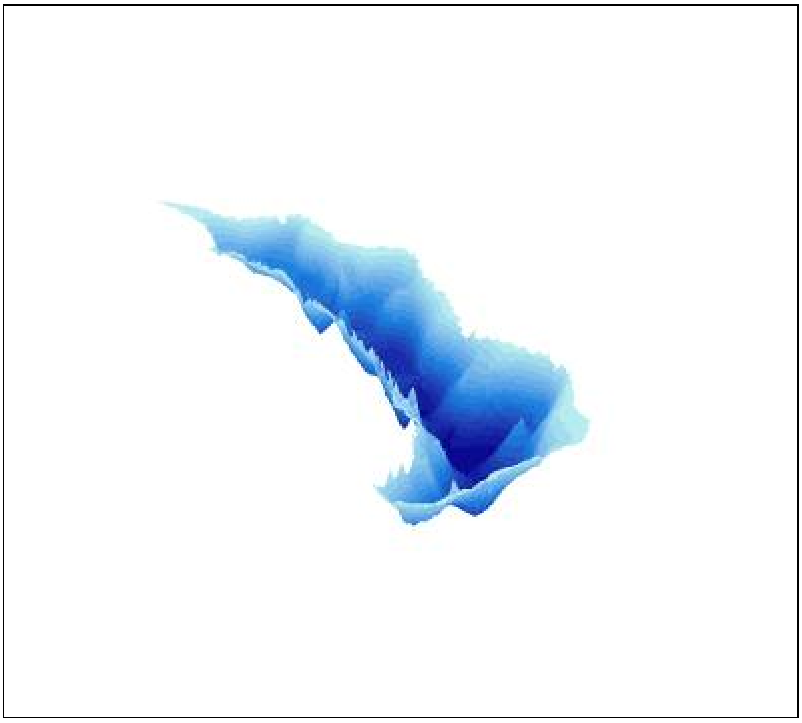


Figure 7b.

Three-dimensional GIS generated bathymetry for Lake Wainamu



Emergent vegetation in the littoral zone comprised a tall, dense, band of raupo (Typha orientalis) in the shallows, and a narrower, fringe of tall spike rush (Eleocharis sphacelata) beyond this. In all bays on the western side of the lake, and in some parts of the eastern shoreline, this littoral margin of rush beds extended 3-5 m out from the lake edge and over water 2-5 m deep, forming a floating sudd. There was a large pocket of water below these sudds, with the sudd providing dense overhead cover for fish. This pocket of water could not be adequately sampled by nets or traps. It was apparent that, at times, parts of these sudds (up to 5 m long by 2 m wide) become detached from the lake edge and are moved around the lake by wind (Fig. 8). They periodically become lodged in the mouth of the outlet stream (Holland & Rix-Trott 1992, Champion 1995). The secchi disc depth for this lake (mean of 3 readings) on 16th April 2002 was 1.25 m.

Figure 8

Photograph of the western end of Lake Wainamu showing a large floating island (sudd) of rushes. This drifted onto the shore of the dune in the foreground.

5.2 Fish species and abundance

Eight species of fish were caught in Lake Wainamu (Table 1), four indigenous and four exotic species. No koi carp, rudd, or catfish were present. No crayfish (Paranephrops planifrons) were caught in the lake (although they were present in the inlet streams and have been reported from the lake), and only a few shrimp (Paratya affinis) were present. Perch were the most abundant species present followed by shortfin eels and goldfish (Table 1).

Table 1.

The species of fish in Lake Wainamu and their relative abundance (4 point scale) and rank abundance (from both catch rates and observations) in April 2002

Common name	Species name	Relative abundance	Rank abundance
Perch	*Perca fluviatilis*	Abundant	1
Shortfin eel	*Anguilla australis*	Abundant	2
Goldfish	*Carassius auratus*	Common	3
Gambusia	*Gambusia affinis*	Common	4
Longfin eel	*Anguilla dieffenbachii*	Common	5
Common bully	*Gobiomorphus cotidianus*	Scarce	6
Grey mullet	*Mugil cephalus*	Rare	7
Tench	*Tinca tinca*	Rare	8

The catches of fish per net type and the total number of fish sampled are shown in Table 2. In general, the panel gill nets sampled more species and more fish than the other fishing methods used. The larger-meshed (150 mm) gill nets caught no fish. The mean catch per unit of effort (CPUE) is also shown, and reflects the greater efficiency of; (a) gill nets for perch, (b) fyke nets for eels, and (c) minnow traps for bullies.

Table 2.

Total numbers of fish (and mean CPUE in brackets) caught in the lake by both species and method.

	Sampling method				
Species	Gill nets	Fyke nets	Minnow traps	Dip net	Total fish
Perch	49 (1.69)	7 (0.32)	----------	---	56
Eels	---------	40 (1.82)	8 (0.18)	---	48
Goldfish	26 (0.90)	1 (0.05)	----------	---	27
Grey mullet	8 (0.28)	----------	----------	---	8
Tench	2 (0.07)	----------	----------	---	2
Bullies	----------	----------	21 (0.48)	---	21
Gambusia	----------	----------	1 (0.02)	24	25
Shrimp	----------	----------	3 (0.07)	---	3
Total fish/net	85	48	33	24	190

Size frequency distributions and length-weight relationships are shown respectively below for perch and goldfish (Figs. 9A, 9B), short and longfin eels (Figs 10A, 10B), and common bullies and Gambusia (Fig. 11).

Figure 9

Perch and goldfish: (A) size frequency distributions; (B) length-weight plots

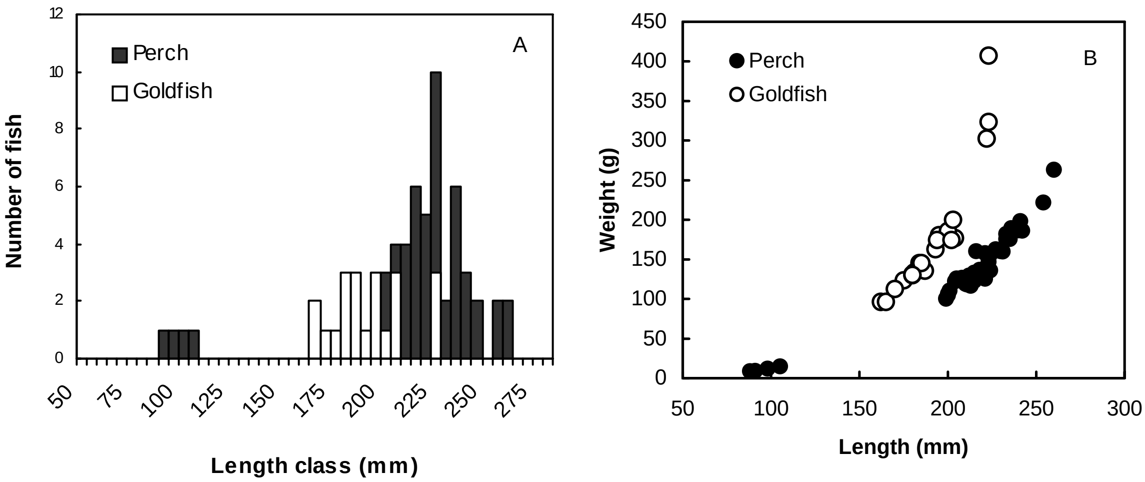


Figure 10

Shortfin and longfin eels: (A) size frequency distributions (B) length-weight plots

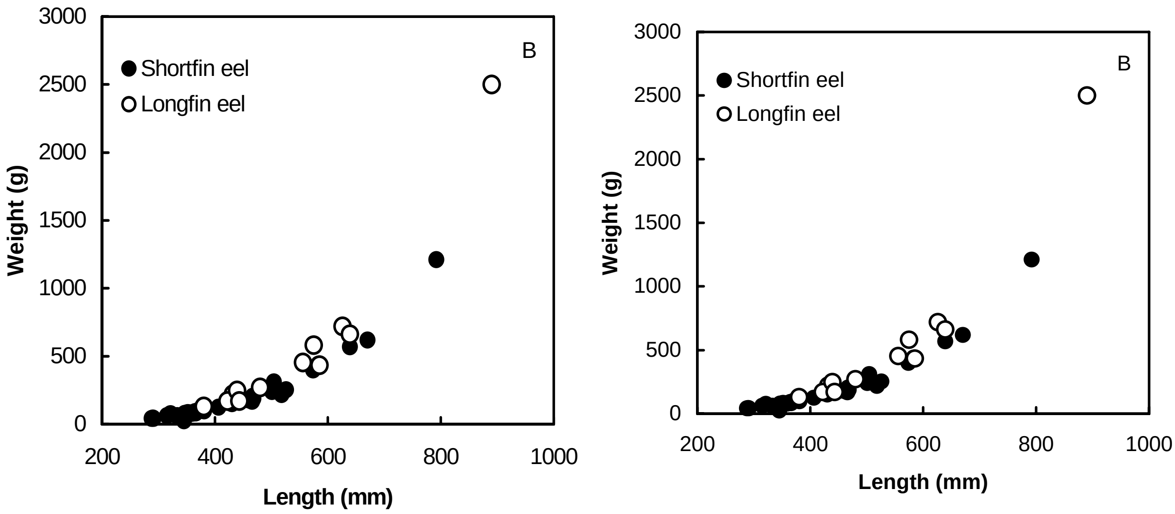
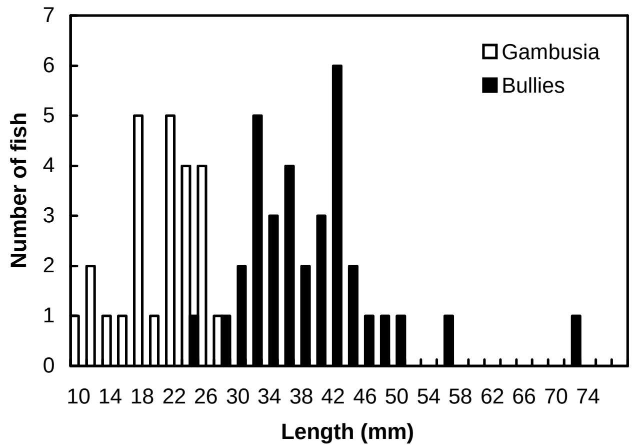


Figure 11
Size frequency distribution for Gambusia and common bullies



Several length cohorts, representing different age classes, were present for perch, goldfish, common bullies and Gambusia. These species are clearly breeding in the lake. However, too few tench were caught to ascertain whether a breeding population is present or not. Both tench were relatively large adults (total length 365 mm and 380 mm) of the same size and hence age, and no juveniles were found. This may indicate a non-breeding population, but tench are notoriously difficult to sample in lakes.

Several age cohorts were present for eels, indicating that regular recruitment from the sea via the outlet stream occurs. The seven mullet caught ranged in size from 417-490 mm and represent one age group.

Adult smelt (length 55-83 mm), common bullies, eels and Gambusia were all found in the outlet stream below the lake (Fig. 2), but few fish were found in any of the three inlet streams. The only fish found in the Wainamu Stream were eels, and only one banded kokopu was found in twelve pools in Houghton's Gully Stream. No banded kokopu occurred in any of the fifteen pools sampled in Plum Pudding Stream. Freshwater crayfish were present in all three streams. In contrast, banded kokopu and longfinned eels were both common in the tributary of the Waiti Stream below the lake, with banded kokopu occurring in 8 of the 13 pools sampled.

5.3 Fish distributions

Mean catch rates (CPUE) for eels and perch in fyke nets showed no significant variation between eastern and western, or northern and southern sectors of the lake (Table 3). There was also no difference in perch catch rates in gill nets between the different sectors of the lake (Table 3). These species showed no evidence of a preference for one side, or end of the lake to any other.

In comparison, goldfish, mullet and tench exhibited clear differences in areal distribution. Goldfish were more abundant on the northern side of this lake and in the eastern end than in the southwestern sectors in both fyke net and gill net catches (Table 3). Mullet were only caught on the southern side of the lake mainly in the western end, whereas tench (two fish) were caught in the shallower north eastern region of the lake.

Table 3.

Mean CPUE by method for the western versus eastern side of the lake, and for the northern versus southern end.

	Fyke net catches (mean CPUE)				Panel gill net catches (mean CPUE)			
Species	South	North	West	East	South	North	West	East
Eels	1.42	1.83	1.67	1.50	-----	-----	-----	-----
Perch	0.33	0.25	0.42	0.16	1.67	2.00	2.00	1.83
Mullet	-----	-----	-----	-----	0.67	0.00	0.50	0.17
Goldfish	0.00	0.08	0.00	0.08	0.42	1.08	0.5	1.00
Tench	-----	-----	-----	-----	0.00	0.17	0.00	0.17

Some differences in depth distribution were also noted (Table 4). Perch were mostly caught in shallower (0-5 m) waters, whereas goldfish were caught in deeper (5-12 m) water. Large goldfish and tench were both caught well offshore at depths of 10-12 m. Most of the mullet were also caught in deeper waters, but these fish are likely to also occur in shallow waters. The predominance of these larger fish in the deep-water ends of nets reflects the fact that they are only caught in the larger meshes and that most nets were set with the largest mesh offshore in deeper water.

The spatial data indicate that adult perch were widely distributed around the lake margins and kept mostly to the shallower waters close to the rush beds. Schools of juvenile perch were also seen in open, shallow waters outside the rush beds. In comparison, goldfish occurred close to the bottom of the lake at depths of 5-12 m and were mostly, but not exclusively, on the more shaded northern side of the lake. Although most were caught close to the littoral zone, others were caught in deeper waters near the middle of the lake. Echograms from the lake (e.g., Fig. 6) indicated that two concentrations of fish were apparent between depths of 3-5 m and 9-12 m respectively. These concentrations of fish echoes are consistent with a near-surface distribution of perch, and a near-bottom distribution of goldfish.

Table 4.

Numbers of fish caught in deep (> 5 m) versus shallow (< 5 m) waters for goldfish and perch on 17th and 18th April 2002.

Depth	Goldfish	Perch	Total
Shallow (< 5 m)	5	25	30
Deep (> 5 m)	16	4	20
Total	21	29	50

6 Discussion

6.1 The fish fauna of Lake Wainamu

There was no evidence that koi carp are present in Lake Wainamu, and it can be concluded that if any are or were present, they are from a very small, non-breeding population. Small non-breeding populations of koi carp have been recorded in other New Zealand dune lakes where they have been (illegally) stocked (Rowe et al. 2000). Failure to breed could occur because the numbers stocked are too few and include only males or females, or because sex-selective mortality occurs in the lake soon after stocking and removes all males or females before breeding occurs.

Koi carp are likely to be breeding in the Waitakere River and juveniles could in theory swim up the Waiti Stream into Lake Wainamu. However, in practice, the sandy substrate and braided nature of much of the stream (Fig. 3) results in a minimal water depth (2 cm) which would prevent all fish, apart from juvenile elvers and migrant whitebait, from moving upstream. Upstream movement by koi carp would only be feasible at times when flood flows channelise the stream creating deeper waters. Little is known about the ability of koi carp to move upstream, however, their preference for still, lowland waters suggests that they are poor swimmers and incapable of penetrating far upstream. To date, the maximum altitude recorded for koi carp in tributary rivers of the Waikato River below Karapiro (e.g. Whangamarino, Maramarua, and Mangatawhiri Rivers) is 12 m (NZ Freshwater Fish database). This suggests that they cannot penetrate far upstream in these rivers and that even small gradients restrict their upstream movement. As Lake Wainamu is at an altitude of 22-27 m, the gradient between the Waitakere River and Lake Wainamu could well be too great for upstream penetration by koi carp.

Grey mullet are likely to be better swimmers than koi carp and it is apparent that their juveniles can, at times, move up the Waiti Stream into the lake.

Several diadromous native species (e.g. longfin eels, shortfin eels, grey mullet) occurred in the lake and so migrate up the Waiti Stream and into the lake. The paucity of mullet indicates that for them, this is a sporadic process, and that recruitment is likely to vary greatly from year to year depending on stream conditions. Thompson (1979) caught 22 mullet in Lake Wainamu in 1979 using gill nets (overnight set) with three mesh sizes (62 mm, 90 mm, and 105 mm mesh). These mullet ranged from 270-485 mm and although three year classes (modes at 280 mm, 420 mm and 480 mm) were apparent, year class strength (number of fish in each age group) varied greatly, again indicating variable recruitment between years. Once in the lake, downstream movement back to the sea to spawn is likely to be limited, resulting in a small, landlocked population of large mullet in the lake.

Shortfinned and longfinned eels were both present in the lake in reasonable numbers and they covered a wide size range indicating that there is little fishing for eels in this lake and a regular recruitment of juveniles.

Thompson (1979) found that the only exotic fish in Lake Wainamu were rainbow trout that had been periodically stocked into the lake. Stocking no longer occurs, and as these trout cannot breed in either the inlet streams (which are too small), or on the lake shore, the population has died out. No perch, goldfish, tench or Gambusia were present in Lake Wainamu in 1979, so it is apparent that these species have all been introduced into the lake since 1980. It is also clear that the introduction of these fish has affected some native fish populations.

For example, common smelt were present in the Waiti Stream within metres of the lake outlet and could readily enter the lake. They are common in many other North Island coastal lakes which they can access. However, none were found in Lake Wainamu indicating that those that do enter the lake fail to survive. Banded kokopu are also likely to have been affected. One adult was seen in Houghton's Gully Stream indicating that the juveniles (whitebait) of this species can enter the lake and migrate through it to tributaries where adult habitats occur. However, no adults were found in the other eleven pools of this stream, or in any of the fifteen pools which provided optimal habitat for this species in Plum Pudding Stream. In contrast, adult banded kokopu occurred in over 60% of the pools of a comparable stream just below the lake. The recruitment of banded kokopu to lake tributaries is therefore now negligible, suggesting that most migrant juveniles are either preyed on by perch in the lake, or that few now enter the lake.

Bullies were common in Lake Wainamu in 1982 (Williams 1982) when trout were still present, but were scarce by 2002 when trout were no longer stocked. In 2002, the mean catch rate (CPUE) for these fish in minnow traps was 0.48 fish trap-1, which is much lower than the range of 7-10 for the comparably shallow, Lake Rotoaira (max depth 13 m), and well below the typical range for larger lakes of 20-30 fish trap-1 (Rowe et al. 1999, 2001). Furthermore, no bullies were caught in the fyke nets set in Lake Wainamu, but the mean CPUE for fyke nets in other comparable dune lakes ranged from 3-8 bullies net –1 night-1 (Rowe 1999). Although dune lakes containing eel populations may have lower numbers of bullies than lakes without eels (Rowe 1999), eels were present in Lake Wainamu in 1982, so cannot account for the current scarcity of the bullies. However, perch also reduce bully numbers in lakes (Closs & Ludgate 2001) and Gambusia can exclude common bullies from shallow weedy habitats in lake margins (D. K. Rowe, pers. obs.). The decline in bullies between 1982 and 2002, and their current scarcity in Lake Wainamu is therefore likely to be related mainly to the presence of perch and Gambusia in this lake.

It is apparent that the introductions of exotic fish, particularly perch and Gambusia, have reduced the diversity of the native fish assemblage in this lake. The exotic fish may also have played a role in the decline of water quality in this lake.

6.2 Fish and the water quality decline in Lake Wainamu

Koi carp were not found in the lake and it can be concluded that a large breeding population capable of browsing out macrophytes and increasing turbidity is not present. This does not exclude the possibility that a large population once existed in the lake and, now that macrophytes are gone, has emigrated or died out. Although this is a possibility, experience with fish populations in lakes and koi carp in New Zealand suggests that it is an unlikely scenario.

Although koi carp were not found in the lake, a number of the goldfish that were present were highly coloured with bright red flanks and fins. This is not the usual coloration for feral populations of goldfish, which are mostly a bronze-black colour. Such highly coloured goldfish could well have been mistaken for koi carp.

It is feasible that the goldfish could be responsible for the increased turbidity. Goldfish have been found to increase the turbidity of Canadian ponds (Richardson & Whoriskey 1982, Richardson et al. 1995), and although no impacts of goldfish on water quality in New Zealand lakes or ponds have been reported to date, this may be because of a lack of data rather than because of a lack of impact. Very high densities of goldfish (in the order of thousands) were recorded in a shallow, turbid cove in Lake Rotoehu (near Rotorua) during tests with underwater explosives (D. Rowe, pers. obs.). This lake later 'flipped' into an algal dominated state.

There were no goldfish in Lake Wainamu in 1979 (Thompson 1979) so they too have been introduced to the lake in more recent times. The bright red coloration of many goldfish present suggests that they have not yet become completely feral. Wild populations don't generally contain 'red-coloured' fish either because it is a recessive gene which is quickly bred out in the wild, or because natural mortality is highly selective for such individuals. The goldfish population in Lake Wainamu may therefore be relatively new. The introduction of Egeria densa to the lake around 1991 (Champion 1995) could well have coincided with the introduction of goldfish and tench (i.e. we suspect that coarse fish and a food base for them may have been introduced at much the same time). The subsequent growth and spread of Egeria would not be checked until the population of goldfish increased and this could take 5 or more years. After this, the browsing activities of large numbers of goldfish may well affect both the Egeria and the lake water quality. The role of high densities of goldfish in precipitating water quality decline in small lakes is clearly in need of more careful examination.

Although the role of exotic fish in precipitating the decline in water quality of Lake Wainamu is speculative, one or more of these species may now contribute to the maintenance of turbid conditions in the lake. Furthermore, browsing and bio-disturbance of sediments by goldfish and/or tench could potentially prevent the regeneration of macrophyte beds from seedlings, even if the turbidity declined and light penetration allowed plant seeds to germinate.

Large populations of planktivorous fish can produce high levels of phytoplankton in lakes resulting in turbid waters. Such fish have been shown to reduce water clarity in overseas lakes through 'top-down' predatory effects on zooplankton. In lakes where large numbers of zooplanktivorous fish occur, the abundance of certain important zooplankton species can be reduced to the point where predation on phytoplanktonic alga is so low that algal densities increase, turbidity increases, and water transparency declines.

Such 'top-down' effects on water transparency have been attributed to Gambusia in small, shallow, ponds and lakes (Hurlbert et al 1972, Nagdali & Gupta 2002). However, Lake Wainamu is relatively deep and Gambusia were confined to the weedy margins of the lake. They are unlikely to extend their foraging much beyond the weed beds because of the increased risk of predation by perch. However, juvenile perch feed on zooplankton and large schools of perch were observed near the surface of Lake Wainamu. Predation on these fish in this lake is likely to be limited because the major predator of such small fish in lakes (i.e. shags) were rare. Only one shag was observed at the lake, and there were no colonies around the lake edge or any visible evidence of their presence (e.g. droppings on jetties or other posts). Juvenile perch numbers could therefore be high in Lake Wainamu and they could potentially reduce zooplankton densities, resulting in a higher algal biomass.

Once macrophytes disappear from lakes, bio-disturbance of lake sediments by fish leading to the greater re-suspension of silt in lake water through wind-driven wave action on shorelines and/or within-lake circulation patterns is also a possibility. This is especially so in shallow lakes where wind-driven circulation currents can reach the lake bed. Both goldfish and tench were caught close to the lake bottom near the middle of Lake Wainamu. This indicates that these benthivorous fish are likely to be foraging on the lake bed. Such activities could well exacerbate wind driven re-suspension of silt by preventing both the growth of plant seedlings and the consolidation of sediments on the surface of the lake bed.

A contributory role for exotic fish in the maintenance of high turbidity in Lake Wainamu, cannot be ruled out, however, the cause of the changed water quality in the lake is probably related to the high nitrate levels that occurred in the water column in late 1995. The timing of water quality changes in this lake (Gibbs et al. 1999) indicated that nitrate levels increased markedly in the winter of 1995 and that this preceded the summer 1996/1997 increase in both phytoplankton (chlorophyll a) and turbidity. Macrophytes were growing to a depth of 5.5 m in April 1995 so their collapse is unlikely to have preceded the increase in nitrate in 1995. This sequence of events suggests that the increased turbidity in the lake after 1995 was mainly biological in origin and was caused by a high annual production of planktonic algae, with the later collapse of macrophytes then exacerbating this.

If the turbidity now occurring in Lake Wainamu is, in fact, created mainly by planktonic algae, then it will be related to one of two factors; either high biological production caused by high nutrient levels, or a reduced cropping of planktonic algae by zooplankton because predation by fish reduces zooplankton numbers (i.e. top-down effects). It is also possible that both these factors could work in tandem with a high algal production rate occurring in winter/spring, and a low cropping rate by zooplankton in summer/autumn. The first step in resolving the problem of turbidity in Lake Wainamu will therefore be to characterise the turbidity in this lake, including seasonal changes in its composition, and to determine whether it is related mainly to plankton, or to some other source (e.g. silt from the lake bed, clay from inlet streams, etc.).

The water in Lake Wainamu in April 2002 was relatively turbid (secchi disk depth of 1.25 m) and yellow/brown in colour. A spot water sample taken in April by Dr I. Hawes indicated that a Dinoflagellate algae (Peridinium sp.) was the dominant species in surface waters. It, together with coloured dissolved organic matter (CDOM) entering the lake from bush catchments, is likely to be responsible for the yellow/brown appearance of the water at this time. It is possible that these factors may have been present in the lake for some time (years?) and responsible for the ongoing turbid conditions. Blooms of this genus occur regularly in Lake Kinneret, Israel (Zohary et al. 1998) and in the Asahi reservoir, Japan (Kishimoto et al. 2001). Monitoring of planktonic algal species composition, as well as of cell densities, will be needed to determine its seasonal prevalence in Lake Wainamu.

7 Recommendations

Recommendation 1. That the type and origin of the suspended particles contributing to the turbidity in Lake Wainamu be identified. Different remediation methods would be required if it is caused by high levels of planktonic organisms, organic silt from the lake bed that becomes suspended in the water column, or inorganic material (e.g. clay) from inflowing stream water, or some combination of these.

> Note. Characterisation of the turbidity in the lake would involve taking a measure of water clarity (e.g. secchi disc depth) and obtaining simultaneous water samples at monthly intervals, to determine seasonal variations in the composition of suspended matter and water colour. This is required to determine the relative influence of: (a) storm events that contribute turbidity from inlet streams; (b) the re-suspension of silt by high winds; (c) planktonic blooms; (d) CDOM and (e) other factors. Laboratory analysis of water samples would require measurement of chlorophyll a, CDOM, suspended solids (including the organic and inorganic fractions), as well as phytoplankton cell densities by species, and zooplankton numbers by species. If, as expected, it emerges that phytoplankton are significant components of the turbidity problem, it will be important to understand where the nutrients fuelling their growth come from. For this reason, we recommend that samples for nutrient analysis be collected from the surface, bottom and 3 main inflows at least every two months. These samples should be analysed for dissolved and particulate nitrogen and phosphorous. Since such analysis is expensive, it may be desirable to preserve them by freezing, until after the first year of sampling. By this time it will be clear as to whether phytoplankton is a key issue in this lake and whether the nutrient data are required.
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> Some of the required data are currently collected quarterly by the ARC, so supplementary data collection and analysis would be required to extend the current ARC monitoring regime. This could be achieved with local help, provided training and equipment are provided. It is possible for a small inflatable dinghy to be readily launched and rowed to a pre-determined, buoyed site where the measurements and water samples could be made, so collection of water samples by boat is possible. In addition a pair of temperature data loggers needs to be installed on the buoy line, near the surface and near the bottom, to determine the frequency and duration of stratification which can lead to oxygen depletion of bottom waters and release of nutrients from sediments.

Recommendation 2. That the data collected as above be collated, reviewed, and analysed after at least one year to determine the main contributors to the turbidity of the lake and to identify the main cause(s) of the turbidity.

Note. The data would indicate whether the turbidity in the lake was caused primarily by a sustained high biomass of planktonic algae throughout the year, or whether other factors are more important, and if so, when. If the main culprit proves to be a high algal biomass, further data collection may be required to confirm the roles of high nutrient levels versus a low cropping rate by zooplankton, or both, in this. Such information will be needed before options to control or reduce the turbidity can be determined.

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