Top down or bottom up? Feasibility of water clarity restoration in the lower Karori Reservoir by fish removal

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Abstract

As part of an overall ecosystem assessment of lower Karori Reservoir, Karori Sanctuary, Wellington, a number of variables are being monitored routinely, including temperature, nutrients, and phytoplankton and zooplankton populations. Ammonium (NH_4) tends to be the dominant species of inorganic nitrogen most of the time except in late winter when nitrate (NO_3) becomes dominant. Total nitrogen concentrations place Karori Sanctuary in a mesotrophic to eutrophic category.

The reservoir has a very unusual fish community that is almost completely one species, European perch. Our preliminary estimate of 20,000 to 22,000 perch in the lower Karori Reservoir, especially the age-0 and age-1 fish that make up over 80% of the population, suggests perch are very likely to have a large effect on the zooplankton size and abundance. We removed approximately 4,000 perch from the reservoir between 12 and 15 February 2007. This represents 18-20% of the total number of fish estimated to be present, and the total weight (72 kg) of removed perch is 8-10% of the estimated total biomass. Age-0 perch may have been under-represented in the catch, given that we caught more age-1 than age-0 perch. Alternatively, the age-1 (2005) cohort may be a particularly strong age class compared to the age-0 (2006) cohort. The small number of age-2 fish caught suggests that survival from age 1 to age 2 is poor.

The dam, spillway, and valve tower structures restrict recruitment of other fish species by acting as a barrier to upstream migration of juveniles from the sea. The reservoir has low numbers of longfin and shortfin eels. The shortfin eels are naturally recruited as this species has not been stocked, but a small number of longfin eels were released in the reservoir. Banded kokopu in the stream between upper and lower reservoirs may be of sea-run origin, or they may be a lake-locked population. This should be tested by otolith microchemistry.

Boat electrofishing is an effective way to catch littoral perch, and night-time boat electrofishing in the reservoir was at least 2-4 times more effective than day-time fishing. Population estimates from day-time fishing were not possible because of the low capture probability, and electrofishing was not effective for limnetic perch. Other methods of estimating perch abundance such as echosounding could be evaluated, and mid-water trawling has the potential to both estimate numbers of limnetic perch and remove fish. Opera house nets were an ineffective way to catch perch.

Fishing by itself is unlikely to eradicate perch from the lower Karori Reservoir. A concerted effort could reduce perch abundance to a point at which their effect on the zooplankton is negligible, but this would require an ongoing effort to maintain a low perch biomass. One way to eradicate perch would be to draw down the lake and poison the fish. The few eels that would be killed by poisoning could be replaced by stocking. Another option worth considering is the introduction of shortfin eels, which would compete with and prey upon perch without growing large enough to prey upon juvenile water birds. The reliance of age-0 perch on cover such as branches in the water suggests that fish aggregation devices might also be explored to control young of the year.

Shortly after perch removal, we observed a reduction in the abundance of the cyanobacterium *Anabaena planktonica* and an increase in total zooplankton abundance. This could be because:

(1) an increase in water temperature stimulated feeding and growth rates of zooplankton; or

(2) removal of zooplanktivorous perch reduced predation pressure on zooplankton.

At this stage, it is not possible to determine the relative importance of each of these processes.

Introduction

The lower Karori Reservoir construction was completed in 1874 to provide a water supply for the growing city of Wellington. The reservoir ceased to function as a water supply in 1992. When the reservoir ceased to function as a water supply, water through-flow also ceased and the retention time increased from 5 days to about 300 days.

The lower Karori Reservoir has been dominated by blooms of the blue-green alga (cyanobacterium) *Anabaena planktonica* from early summer to autumn commencing in 2003-2004 (Smith and Lester, 2006) when the first filaments of *A. planktonica* were identified. Blooms prior to this time tended to be dominated by *A. lemmermannii*. What makes the bloom in the lower Karori Reservoir unique is that *A. planktonica* has remained the dominant species in all blooms in the reservoir since 2003-2004, whereas in many other North Island lakes (e.g. Lake Rotoiti) algal blooms have generally arisen from multiple cyanobacterial species.

Anabaena planktonica shows some adaptive traits that may assist in its dominance. It appears to 'overwinter' well, with moderate populations maintained when the water column is well mixed, and light availability and temperature are low. In the Lower Karori Reservoir, akinetes (spores) were only observed in samples for one week in July 2006 (Cawthron Institute/Waikato University, unpubl. data), which suggests that vegetative cells, whether from the sediments or water column, are largely responsible for initiating biomass increases of this species. Preliminary observations of fluorescence profiles suggest that it is also highly buoyant and, under relatively calm conditions, will aggregate into conspicuous blooms at the water surface.

The extent of *A. planktonica* grazing by zooplankton is unknown, but zooplankton populations are included in the lake assessment. It is possible that high numbers of small planktivorous perch are exerting substantial top-down control on zooplankton populations. Stratification and consequent nutrient release from sediments could have caused the cyanobacterial blooms by a "bottom-up" link whereby increased nutrients increase phytoplankton abundance. Alternatively, a "top-down" trophic cascade driven by the European perch (*Perca fluviatilis*) might be responsible for the cyanobacterial blooms.

Perch were introduced into the reservoir in 1878, and the population is dominated by small, juvenile fish (Smith 2005). Small perch are primarily zooplanktivorous, and have the potential to reduce the size and abundance of grazing zooplankton to the point where the zooplankton are unable to control phytoplankton abundance. Smith and Lester (2006) suggested that the cyanobacterial blooms that have plagued the reservoir appear to be driven by top-down rather than bottom-up effects. Grazing zooplankton in the reservoir were relatively small species, reducing their potential to effectively crop phytoplankton. Research currently taking place on the lake, in conjunction with what is already known about perch populations in the reservoir (Smith and Lester, 2006), suggest that perch could have a major ecosystem-wide impact and may directly and indirectly influence the dynamics of *A. planktonica* populations.

The University of Waikato built, owns, and operates New Zealand's only electrofishing boat. Boat electrofishing offers the opportunity to produce area-based abundance estimates and to systematically compare netting with electrofishing as a removal method for perch. The aim of this study is to assess the feasibility of restoring water clarity and reduce incidences of cyanobacterial blooms in the lower Karori Reservoir by fish removal. The objectives were to:

1. Remove as many perch as possible;
2. Determine the abundance and size distribution of all fish species in the lower Karori Reservoir;

3. Determine abundance of fish in the wetland above the lower Karori Reservoir;
4. Compare efficiency of boat electrofishing during day and night;
5. Compare capture rates and size biases of netting and boat electrofishing;
6. Assess the algal and zooplankton abundance.
7. Assess the feasibility of restoring the water quality by fish removal.

Study site description

From the 936-m long boat track estimated by a boat-mounted global positioning system (GPS) we estimated the perimeter of the lower Karori Reservoir as about 1000 m and the area as 2.34 ha (Fig. 1). The area estimate was made by digitising the area inside the GPS points (Fig. 1; 21,298 m^2). We added 10% to this area to account for the approximately 2 m between the GPS sensor and the shoreline (approximate perimeter 1000 m x 2 m wide = 2,000 m^2) and the bay in front of the spillway (about 200 m^2) where access for the boat was blocked by a trash excluder pipe in the water. The reservoir has an average depth of 8.2 m and maximum depth of about 20 m (Smith and Lester 2006). Specific electrical conductance (i.e., standardised to 20^{o}C) of the surface water was 282 µS cm^{-1} on 12 February 2007.

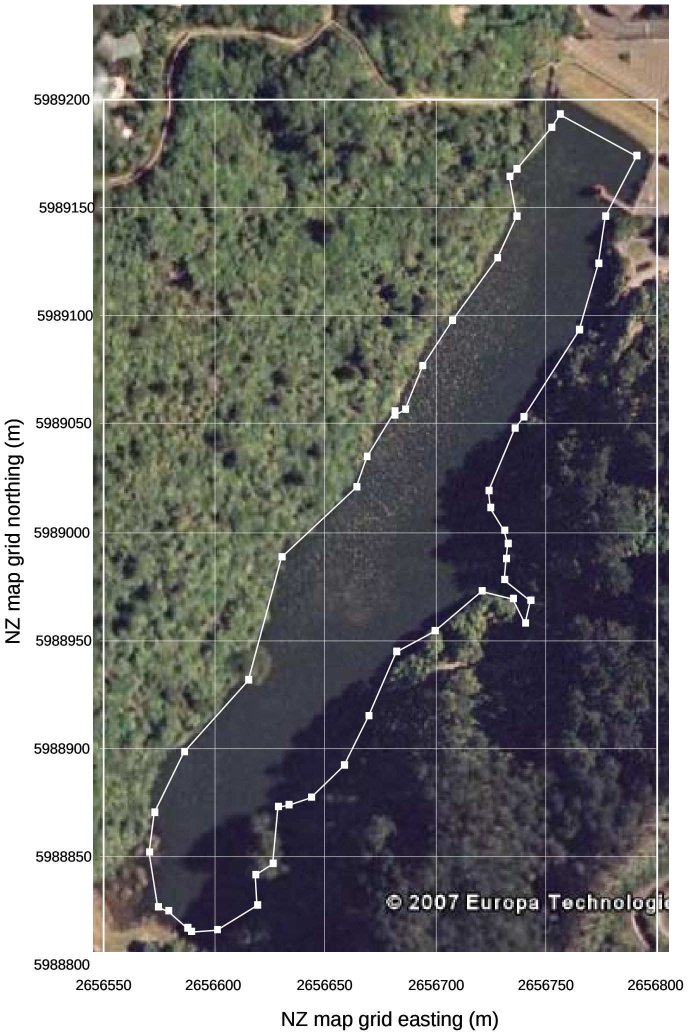

Figure 1. Shoreline of the lower Karori Reservoir as determined by a boat-mounted Lowrance 2400 GPS unit on 12-14 February 2007. Coordinates are the New Zealand map grid. Source

of aerial photograph: Wellington City Council and Europa Technologies, through Google Earth.

Fish removal - Methods

We fished Karori Reservoir between 12 and 15 February 2007 with a combination of netting and boat electrofishing. Netting was carried out with 432 m of 25 to 100 mm stretched-mesh gill nets, 24 2-mm mesh minnow traps, nine 5-mm mesh fyke nets, and 10 opera house nets (Table 1). For boat electrofishing, position and distance fished were recorded with a boat-mounted Lowrance 2400 GPS unit. We electrofished the entire 936 m perimeter of the littoral shoreline in four sectors (K1 to K4 on Fig. 2). We also fished a limnetic lane 118 m long near the valve tower (Centre, K6 on Fig. 2). Perch and brown trout were removed, and native species (longfin eels) were replaced.

We used a 4.5-m long electrofishing boat with a 5-kilowatt petrol-powered pulsator (GPP 5.0, Smith-Root Inc., Vancouver, Washington, USA) powered by a 6-kilowatt custom-wound Honda generator. Two anode poles, each with an array of six droppers, create the fishing field at the bow, with the boat hull acting as the cathode.

Electrical conductivity was measured with a YSI 3200 conductivity meter. Ambient conductivity, i.e., not standardised for temperature, was 252 $\mu S\ cm^{-1}$ and water temperature was $19.5^{o}C$, so we used constant pulsator settings (30% of low range, i.e., 50-500 V direct current, and a frequency of 60 pulses per second) in order to achieve an applied current of 4 A root mean square, which we have previously established produces an effective fishing field (e.g., Hicks et al. 2005).

We assumed from past experience that an effective fishing field was developed to a depth of 2-3 m, and about 2 m either side of the centre line of the boat. The boat thus fished a transect about 4 m wide, which was generally consistent with the behavioural reactions of fish at the water surface. This assumption was used to calculate area fished from the linear distance measured with the global positioning system. Water clarity measured with a black disc viewed horizontally (Davies-Colley 1988) was 0.48 m. We compared day-time and night-time capture rates, and made removal population estimates (White et al. 1982, Armour et al. 1983) at K4 and K5. We fished 100 m^2 of the wetland above the reservoir with a Kainga EFM 300 back-pack electrofisher from 12:30 to 13:20 h, 13 February. All times are given as New Zealand Standard Time.

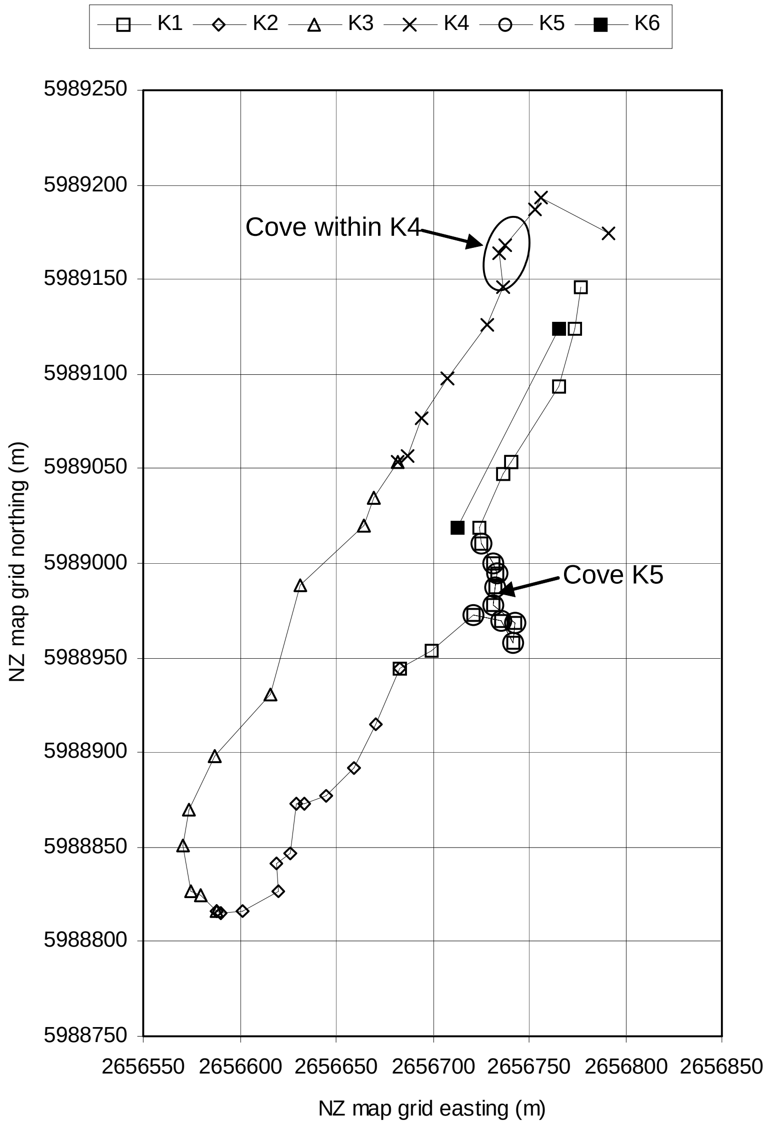

Figure 2. The tracks followed by the University of Waikato's electrofishing boat in the lower Karori Reservoir 12-14 February 2007. Coordinates are shown as New Zealand map grid determined by a boat-mounted Lowrance 2400 GPS unit.

Fish removal - Results

In the reservoir, we caught and removed 3,946 perch weighing a total of 75.0 kg and one adult brown trout (540 mm fork length (FL), 1,660 g). We caught and replaced two longfin eels (534 mm total length (TL) and 479g, and 952 mm TL and 1860 g), and a crayfish (40 mm occiput-carpace length (OCL)) by a combination of netting and trapping in the reservoir (Table 1). 2,280 perch (28.7 kg) were caught by boat electrofishing, and 1,666 perch (46.3 kg) by netting.

In the wetland, we caught 4 shortfin eels (350, 340, 160, and 160 mm TL), 1 perch (145 mm FL), and 1 crayfish (45 mm OCL). Part of the inlet stream was thickly overgrown with trees and shrubs and could not be fished. All eels and crayfish were returned to their location of capture.

Table 1. Perch caught in the lower Karori Reservoir by boat electrofishing and netting between 12 and 15 February 2007.

Fishing method	Net code	Date	Mesh size (mm)	*N* fish	Effort	Units of effort	Catch per unit effort	Mean fish length (mm)
Boat electrofishing by day	K1D/1	12-Feb-07		234	52	mins	4.5	66
Boat electrofishing by day	K2D/1	12-Feb-07		35	33	mins	1.1	110
Boat electrofishing by day	K3D/1	12-Feb-07		67	56	mins	1.2	84
Boat electrofishing by day	K4D/1	12-Feb-07		230	53	mins	4.4	67
Boat electrofishing by night	K4N/1	12-Feb-07		522	62	mins	8.4	99
Boat electrofishing by night	K4N/2	13-Feb-07		291	71	mins	4.1	100
Boat electrofishing by night	K4N/3	14-Feb-07		203	58	mins	3.5	89
Boat electrofishing by day	K5D/1	14-Feb-07		16	23	mins	0.7	96
Boat electrofishing by day	K5D/2	14-Feb-07		105	34	mins	3.1	97
Boat electrofishing by night	K5N/1	14-Feb-07		430	40	mins	10.8	95
Boat electrofishing by night	K5N/2	14-Feb-07		147	45	mins	3.3	99
Boat electrofishing by night	K6N/1	14-Feb-07		0	6	mins	0.0	
Fyke net	FN1/1	15-Feb-07	3	77	9	nets	8.6	67
Gill net	GN1/1	13-Feb-07	100	3	240	m	0.013	359
Gill net	GN1/2	14-Feb-07	100	4	240	m	0.017	322
Gill net	GN1/3	14-Feb-07	100	2	240	m	0.008	345
Gill net	GN1/4	15-Feb-07	100	1	240	m	0.004	376
Gill net	LMN1/1	13-Feb-07	75	16	64	m	0.25	290
Gill net	LMN1/2	13-Feb-07	75	2	64	m	0.03	318
Gill net	LMN2/1	15-Feb-07	75	19	64	m	0.30	272
Gill net	MN1/1	12-Feb-07	25	71	64	m	1.1	109
Gill net	MN1/2	13-Feb-07	25	118	64	m	1.8	102
Gill net	MN1/3	13-Feb-07	25	90	64	m	1.4	103
Gill net	MN1/4	14-Feb-07	25	213	64	m	3.3	99
Gill net	MN1/5	15-Feb-07	25	293	64	m	4.6	102
Gill net	MN2/1	13-Feb-07	25	232	64	m	3.6	106
Gill net	MN2/2	13-Feb-07	25	136	64	m	2.1	107
Gill net	MN2/3	14-Feb-07	25	136	64	m	2.1	103
Gill net	MN2/4	15-Feb-07	25	210	64	m	3.3	99
Gee minnow trap - unbaited, 50% with light	MTU/1	12-Feb-07	2	5	24	nets	0.2	80
Gee minnow trap - unbaited, no light	MT/1	13-Feb-07	2	3	12	nets	0.3	63
Gee minnow trap - cat biscuits, no light	MT/2	13-Feb-07	2	1	12	nets	0.1	106
Gee minnow trap - unbaited, no light	MT/3	13-Feb-07	2	11	12	nets	0.9	65
Gee minnow trap - pilchards, no light	MT/4	14-Feb-07	2	17	24	nets	0.7	67
Opera house net	ONU	12-Feb-07	10	0	10	nets	0.00	
Opera house net	ONB/1	12-Feb-07	10	0	10	nets	0.00	
Opera house net	ONB/2	13-Feb-07	10	1	10	nets	0.10	110
Opera house net	ONP/1	14-Feb-07	10	2	10	nets	0.20	99
Fish found floating after fishing	Floaters	15-Feb-07		3				128
	Total			3946				

The perch ranged between 25 mm fork length (FL; weight 0.15 g) and 405 mm FL (weight 1,108 g), and showed three distinct cohorts between 25 and 160 mm, and a size range of fish >160 mm aged three years and older (Fig. 3). Fish caught by boat electrofishing gave the least biased size distribution, showing a predominance of age-0 and age-1 fish. Netting was more biased towards age-1 perch (Fig. 4). Sizes that defined each cohort were 25-71 mm FL (young of the year, age 0), 74-130 mm FL (age 1), 132-175 mm FL (age 2), and ≥ 179 mm FL (age 3 and older). Net catches of perch showed predictable size selectivity, with larger meshes catching larger fish than smaller meshes (Fig. 5). Weights were measured for 210 perch of a wide size range (Fig. 6), and the weight-length regression equation was

$$Y = 5.780\text{x}10^{-6}\,X^{3.159},$$

where Y = weight in g and X = fork length in mm ($N = 210$, $r^2 = 0.984$, $P \ll 0.001$). Young-of-the-year and age 1 perch dominated the catch. On 15 February, we inadvertently caught 3 New Zealand scaup or black teal (*Aythya novaeseelandiae*) in a 75 mm-mesh mist gill net.

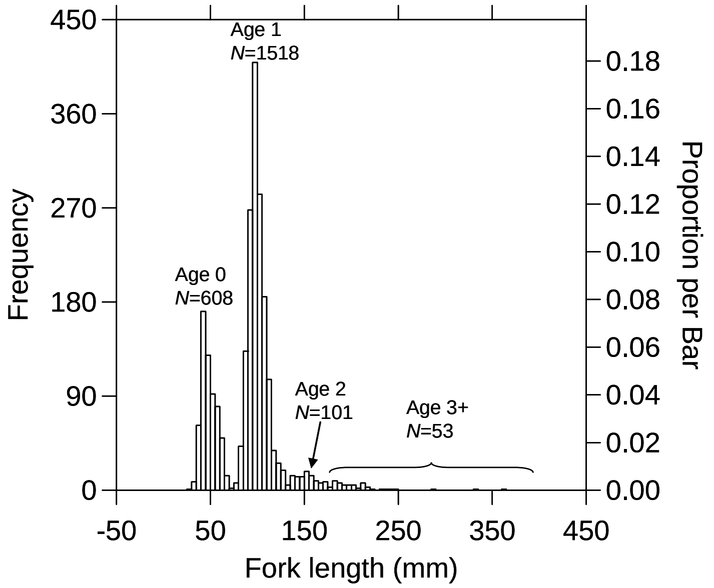

Figure 3. Length-frequency of perch in the lower Karori Reservoir sampled by boat electrofishing 12-15 February 2007 (N=2,280).

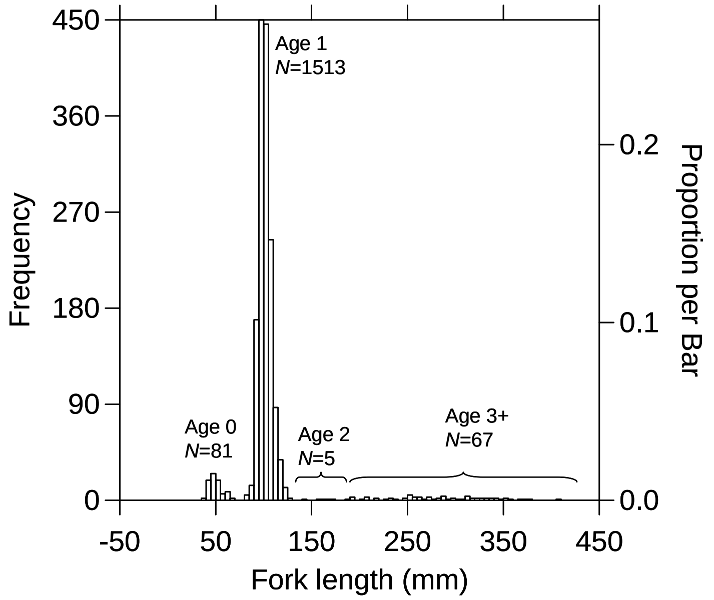

Figure 4. Length-frequency of perch in the lower Karori Reservoir sampled by netting 12-15 February 2007 (N=1,666).

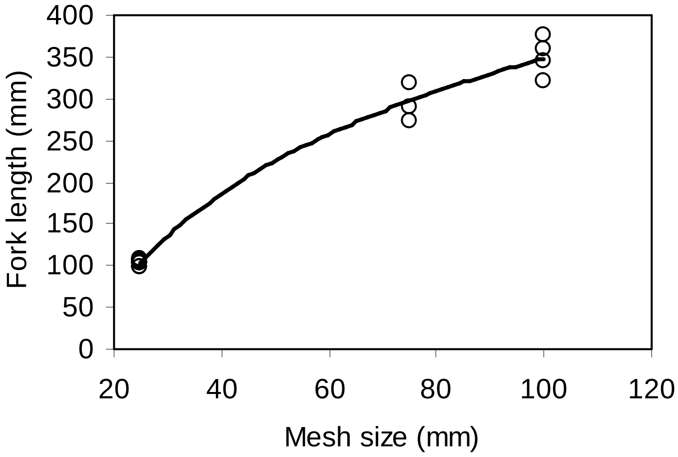

Figure 5. Relationship of perch fork length to stretched mesh size of gill nets set in the lower Karori Reservoir 12-15 February 2007. Fork length in mm = 177 ln(mesh size in mm) – 466, $r^2 = 0.99$, $P = 0.001$.

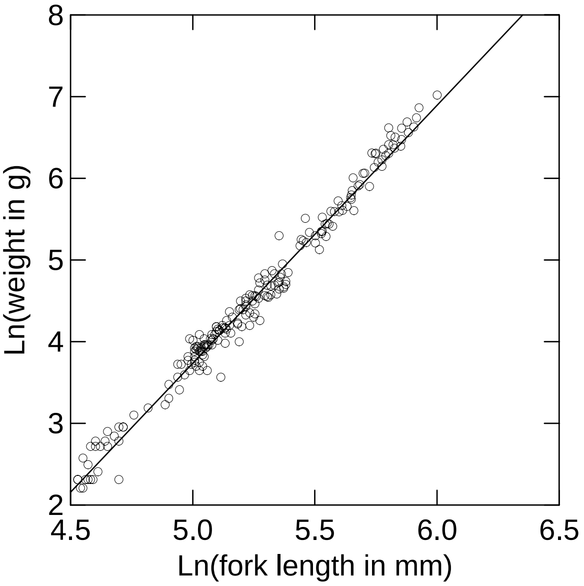

Figure 6. Weight-length regression of perch ($N = 210$) caught on 12-15 February 2007 in the lower Karori Reservoir.

Population estimates from boat electrofishing

Littoral population

In the daytime (15:30 to 16:35 h, 12 February) at section K4 (Fig. 2) (K4D/1 on Table 1), we caught and removed 230 perch (Table 2). That evening after dark (20:32 to 21:46 h, 12 February), we caught 522 perch (K4N/1, Table 1) in the same area (163 m, 652 m^2; Table 2). In successive night time captures, we removed 291 (K4N/2, Table 1) and 203 perch (K4N/3,

Table 1). From the night-time captures, we used the technique of Zippin (1958), as described in Armour et al. (1983) and Hicks (2003), to estimate the population as 1,320 perch (±104, 95% confidence interval). This gave a probability of capture ($\hat{p}$) of 0.39. We also estimated the population size with the program CAPTURE (White et al. 1982) where there were more than two instances of removal at a site. Comparison with the Zippin estimate for the same three passes showed that both methods gave very similar results, with a population estimate of 1,316 perch (±102, 95% confidence interval), $\hat{p} = 0.39$.

In the daytime (10:42 to 11:05 h and 11:11 to 11:45 h, 14 February) at K5, we caught and removed 16 (K5D/1, Table 1) and then 105 perch (K5D/2) from the same area (89 m, 356 m^2). That evening at dusk and after dark (19:15 to 19:59 h and 20:06 to 20:55 h, 14 February) we caught 430 perch (K5N/1, Table 1) and then 147 perch (K5N/2, Table 1). The Zippin removal population estimate was 634 fish (±38, 95% confidence interval) with $\hat{p} = 0.66$.

Extrapolating the lineal density estimates for the littoral of K4 and K5 in Table 2 (8.48-9.51 fish m^{-1}) to the entire 936 m fished perimeter of the reservoir, and applying the 95% confidence intervals, we estimated littoral perch population was 7,541 to 9,498 fish.

These results also show a clear increase in catch rates at or after dusk compared to day-time catch rates. In section K4, night-time catch rates were twice those of day-time rates, and in K5, night-time catch rates were at least four times greater than day-time rates (Table 3).

Table 2. Comparison of day-time and night-time catches of perch by boat electrofishing in the littoral zone of the lower Karori Reservoir, 12-14 February 2007. Total number of fish was extrapolated by applying the upper and lower 95% confidence limits for the population estimates from K4 and K5 to the entire 936 m of shoreline. Population estimated with the removal method CAPTURE (White et al. 1982) for K4 (3 removals) and with Zippin (1958) for K5 (2 removals).

Site	Length (m)	Area (m^2)	Day-time fishing		Night-time fishing			Summation of day and night catch	Estimated shoreline population
			Number caught	Number/ m	Population estimate	95% confidence interval	Estimated density (no./m)		
K1	264	1056	234	0.89					
K2	178	712	35	0.20					
K3	280	1120	67	0.24					
K4	163	652	230	1.41	1320	104	8.10	9.51	8,901
K5	89	356	121	1.36	634	38	7.12	8.48	7,940
K6	118	472			0				

Table 3. Comparsion of day-time and night time capture rates of perch by boat electrofishing in the littoral of lower Karori Reservoir.

Site	Day-time catch (number of fish)	Night-time catch (number of fish)	Night-time removal population estimate	Night-time population estimate plus day-time capture	Day-time probability of capture	Night-time probability of capture	Night-time/day-time
K4, pass 1	230	522	1320	1550	0.15	0.34	2.3
K5, pass 1	16	430	634	755	0.02	0.57	26.9
K5, pass 2	105	430	634	755	0.14	0.57	4.1

Age-specific catch rates

Night-time electrofishing in K5 showed reducing catches between the two passes for perch aged 0, 1, and 2 (K5N/1 and K5N/2; Table 4). From age-specific reductions in catch at K5, we made population estimates (Table 5). Assuming a fished area of 356 m^2, this suggests a density of 0.29 age-0 perch m^{-2}, 1.39 age-1 perch m^{-2}, and 0.11 age-2 perch m^{-2} (Table 5). In area K4, population estimates for age-0 and age-3 perch failed as there was no reduction in catch between the three passes. For age 1 perch, the 3-pass population estimate was 963, or 1.48 age-1 perch m^{-2}, and 0.09 age-2 perch m^{-2}.

Table 4. Age-specific catches of perch by boat electrofishing during day time and night time in the littoral zone of the lower Karori Reservoir, 12-14 February 2007.

Site and pass	Age 0				Age 1				Age 2				Age 3+			
		Length (mm)				Length (mm)				Length (mm)				Length (mm)		
	N	Min	Max	Mean	N	Min	Max	Mean	N	Min	Max	Mean	N	Min	Max	Mean
K1	165	34	71	51	68	89	123	100	1	136	136	136	0			
K3	31	36	64	48	32	88	122	104	0				4	181	246	200
K2	10	40	69	58	20	89	122	101	0				5	213	360	249
K4D/1	152	25	61	45	61	79	124	94	9	133	167	148	8	180	212	198
K4N/1	46	36	63	47	447	77	129	100	21	132	170	150	8	185	216	198
K4N/2	41	38	68	49	225	82	130	102	20	138	175	151	5	181	240	202
K4N/3	53	37	64	46	137	78	129	98	6	134	168	153	7	181	231	197
K5D/1	4	54	67	59	10	84	105	96	1	151	151	151	1	185	185	185
K5D/2	15	41	67	52	81	78	123	98	6	150	170	156	3	179	211	190
K5N/1	67	38	68	46	326	74	125	98	31	132	174	153	6	180	214	194
K5N/2	24	39	60	51	111	80	129	99	6	138	164	152	6	180	332	234
Total	608				1518				101				53			

Table 5. Removal population estimates of perch made from successive captures without replacement during night-time boat electrofishing in lower Karori Reservoir. $\hat{p}$ = capture probability; 95% CI = 95% confidence interval.

A. K5 two-pass removal estimate.

Age class	Number of fish			$\hat{p}$	Population estimate	Variance	SE	95% CI
	K5N/1	K5N/2	Sum (M)					
Age 0	67	24	91	0.64	104	69	8.3	16.6
Age 1	326	111	437	0.66	494	268	16.4	32.7
Age 2	31	6	37	0.81	38	3	1.8	3.6
Age 3+	6	6	12		Failed			
All ages	430	147	577	0.66	653	359	19.0	37.9

B. K4 three-pass removal estimate.

Age class	Number of fish				$\hat{p}$	Population estimate	Variance	SE	95% CI
	K4N/1	K4N/2	K4N/3	Sum (M)					
Age 0	46	41	53	140		Failed			
Age 1	447	225	137	809	0.46	963	858	29.3	59
Age 2	21	20	6	47	0.39	61	117	10.8	22
Age 3+	8	5	7	20	0.07	Failed			
All ages	522	291	203	1016	0.39	1320	2715	52.1	104

Age-1 perch were relatively uniformly distributed around the littoral, except that large numbers were found around the dam face. Age-0 perch were most abundant close to the lake shore, and were particularly abundant in two stream inlets (the cove at K5 and the cove within K4 opposite the valve tower at 41° 17' 27.8100" S 174° 45' 07.6600" E, NZ Map Grid 2656731.20 easting, 5989163.22 northing). Age-0 perch were also very abundant around a single red mapou tree, or red matipo (*Myrsine australis*) lying in the water within the K4 littoral zone (Fig. 5).

Figure 7. Habitat for age-0 perch created by a fallen red mapou tree (*Myrsine australis*) lying in the water within the K4 littoral zone.

Limnetic perch population

Despite its effectiveness in the littoral zone, boat electrofishing failed to catch any fish in the limnetic zone (K6N/1, Table 1). Gill netting was an effective sampling method for limnetic perch, and the most effective mist netting mesh size was 25 mm, which caught 1.1-4.6 fish m^{-1} (Table 1) of mostly age-1 perch (Fig. 3) during sets of 4-24 hours. Larger mesh sizes caught larger but fewer fish (0.03-0.30 fish m^{-1} for 75 mm mesh, 0.004-0.017 fish m^{-1} for 100 mm mesh; Fig. 3). Catch of perch over 4-5 successive captures at the same locations showed no reduction (Table 1). Mist net 1 (MN1) caught 71, 118, 90, 213, and 293, and mist net 2 (MN2) caught 232, 136, 136, and 210 perch in the limnetic zone. The lack of reduction suggests that there are large numbers of limnetic age-1 perch. To estimate total number of perch in the limnetic zone, we assumed that:

1. most of the fish are in the section of the reservoir that is oxygenated to the bed, which represents about 50% of the lake area;
2. subtracting the littoral area (936 m x 4 m = 3,744 m^2) from half the lake area (2.34 ha x 10,000/2 = 11,700 m^2) leaves 7,956 m^2 of available habitat for limnetic perch;
3. the density in the littoral zone (1.39-1.48 age-1 perch m^{-2} and 0.09-0.11 age-2 perch m^{-2}) can be applied to this area;
4. age-0 perch are most likely restricted to the littoral zone by predation, and can therefore be excluded from density estimates for the limnetic zone.

Using these assumptions, there might be 12,968 to 14,405 perch in the limnetic zone, comprising 11,059 to 11,775 age-1 perch, 716 to 875 age-2 perch, and 1193 to 1755 perch of age-3 and older.

Perch biomass estimate for Karori Reservoir

We estimate that the total biomass of perch in the lower Karori Reservoir is 718 to 890 kg, or 307 to 380 kg ha^{-1} (Table 6).

Table 6. Estimated biomass of perch in the lower Karori Reservoir 12-15 February 2007.

	Density		No. fish		Mean weight (g)	Biomass (kg)	
	(no/m)	(no/m^2)	lower estimate	upper estimate		lower estimate	upper estimate
Littoral							
Age 0	1.17	0.29	1,095	1,095	1.3	1.4	1.4
Age 1	5.55	1.39	5,195	5,532	12.3	63.8	67.9
Age 2	0.37	0.09	346	402	46.4	16.1	18.7
Age 3+	0.60	0.15	562	562	266.3	149.5	149.5
Total for littoral			7,198	7,591		230.8	237.6
Limnetic							
Age 0	assumed absent						
Age 1	5.55	1.39	11,059	11,775	12.3	135.8	144.5
Age 2	0.37	0.09	716	875	46.4	33.2	40.6
Age 3+	0.60	0.15	1,193	1,755	266.3	317.8	467.3
Total for limnetic			12,968	14,405		487	652
Total for littoral and limnetic			20,166	21,996		718	890

A review of current water quality status in the lower Karori Reservoir

As part of an overall ecosystem assessment of Karori Sanctuary, a number of variables are being monitored routinely, including temperature, nutrients, and phytoplankton and zooplankton populations. Figure 8 shows a depth-time distribution plot of water column temperature at the Valve House site taken from the thermistor chain, which has temperature sensors positioned at approximately 2 m intervals. The lowest temperature of approximately 7°C occurs in the middle of the year (Fig. 8a). Periods of stratification denoted by vertical colour gradients occur around day 150 and day 216, but are mostly short-lived and suggest that there is substantial vertical mixing through later autumn to early spring. By contrast, temperature in the period early-December to mid-February not only shows the expected warming trend, but also persistent thermal stratification, with a strong temperature gradient between 10 and 15 m (Fig. 8b). Arrows on the temperature profiles in Fig. 8b denote two times when nutrient samples were taken. An arrow on 3 January denotes a time when temperature in the upper 10 m was almost homogeneous at around 16°C, i.e., a surface mixed layer that extends to a depth of around 10 m. Another arrow on 3 February follows a period of rapid warming when temperature was up to 22°C, but only in a very shallow zone within 4 m of the water surface. The significance of variations in temperature on these two days is discussed below, particularly with relevance to distributions of nutrients and chlorophyll *a*.

Figure 9 shows time series of nutrient and chlorophyll *a* concentrations. Ammonium (NH_4) tends to be the dominant species of inorganic nitrogen most of the time except in late winter when nitrate (NO_3) becomes dominant (Fig. 9a). Dominance of ammonium over nitrate in surface waters, as well as consistently elevated levels of ammonium, indicate a low oxidation state associated with recycling of large amounts of organic nitrogen, i.e., a eutrophic waterbody. Brief periods of disparity in ammonium concentrations between surface and bottom samples are likely to be associated with stratified conditions. The very large peak in ammonium concentration on 6 December 2006 may be associated with a deeper sample collection (depth 15 m) than adjacent samples (depth 10 m), i.e., from water that includes an infrequently mixed deeper layer (see Fig. 8b). Sample collection depth is therefore critical to the concentrations that are observed in the deeper sample, particularly as the seasonal thermocline, which separates the surface mixed layer from deeper waters, appears to occur between depths of 10 and 15 m. It is recommended that the deeper nutrient and chlorophyll sample be at precisely 15 m to provide a better indication of concentrations in the deeper water mass in the lower Karori Reservoir.

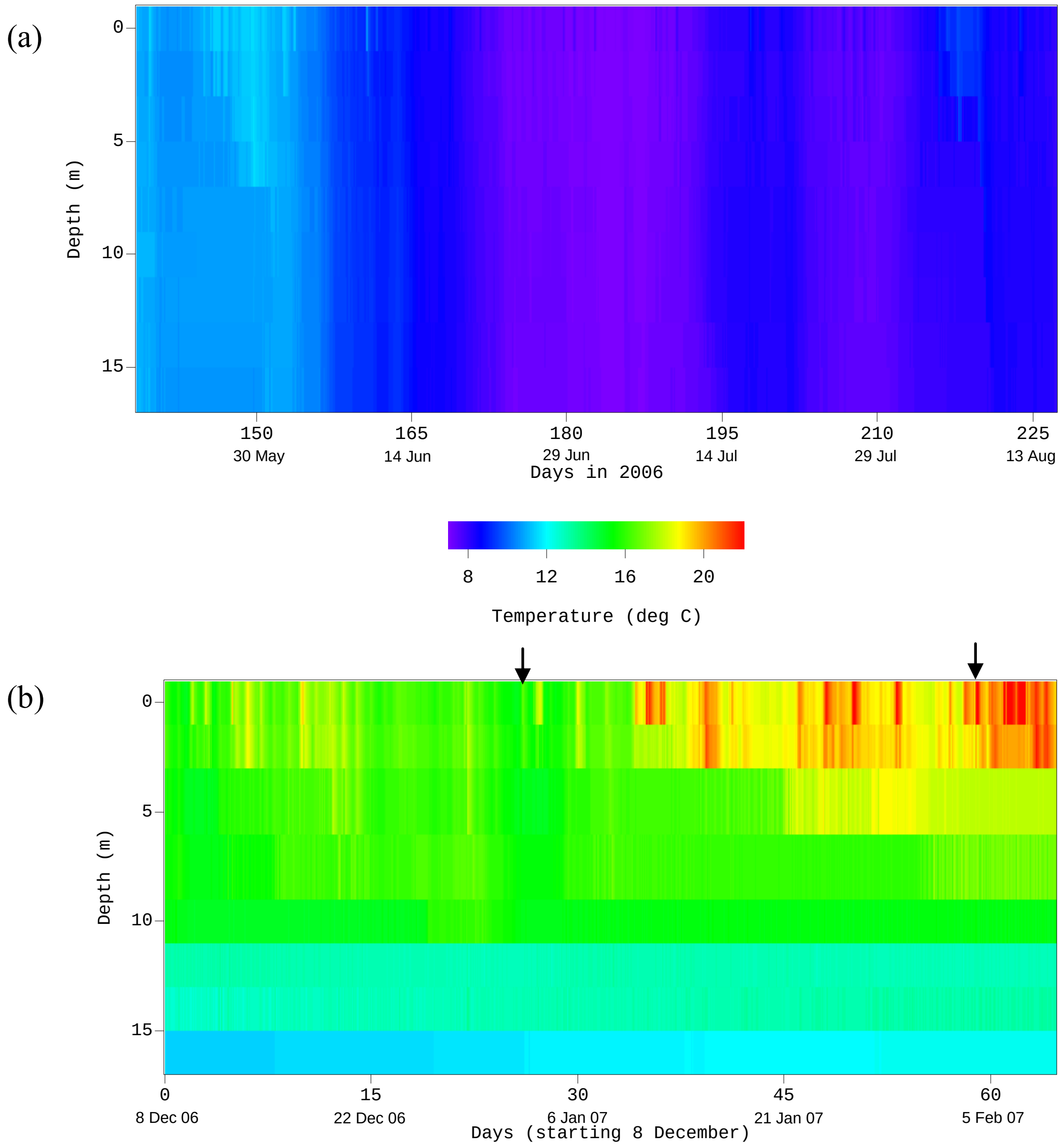

Figure 8. Depth-time distributions of temperature derived from the thermistor chain at the Valve House station of Karori Sanctuary for (a) day 140 (20 May) to day 227 (15 August) 2006, and (b) 8 December 2006 to 10 February 2007. Arrows on the temperature profiles in Fig. 8b denote two of the times when nutrient samples were taken (3 January and 3 February 2007).

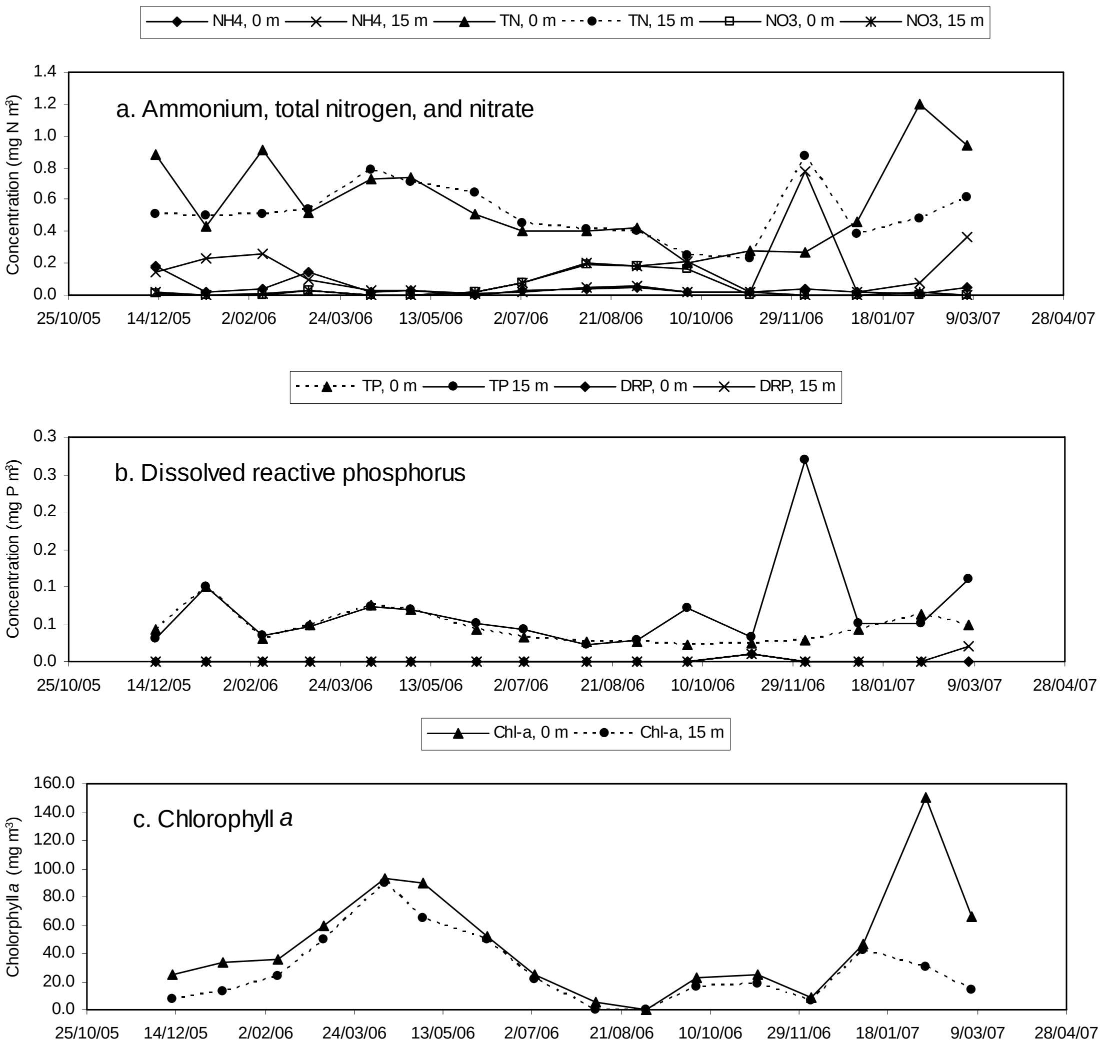

Figure 9. Time series of (a) ammonium, total nitrogen and nitrate, (b) dissolved reactive phosphorus and total phosphorus, and (c) chlorophyll *a* for surface (0m) and deep (10 or 15m) samples at the Valve House station of Karori Sanctuary.

Total nitrogen concentrations place the lower Karori Reservoir in a mesotrophic to eutrophic category. Separation between concentrations of total nitrogen in surface and deeper samples occurs in warmer periods when the water column is likely to be stratified and when nitrogen contained in algal cells is probably responsible for the conspicuous increase in concentration of surface samples. Nitrogen fixation, particularly by large populations of *A. planktonica*, could also elevate total nitrogen concentrations in surface waters. Wood (unpubl. data) has a well developed time series of observations of heterocytes taken during phytoplankton cell counts. There are large numbers of heterocytes (nitrogen-fixing cells) present when densities of *A. planktonica* are high, indicating that nitrogen fixation is likely to be important to the nutrient status of *A. planktonica* and that it could also increase water column total nitrogen concentrations. Another interesting observation for total nitrogen is the steady decrease in surface and deep-water concentrations from autumn through to spring; a similar but reduced magnitude occurs for total phosphorus concentrations. The decrease in total nitrogen may be partly due to denitrification as it occurs in a period of frequent mixing when the oxidation status of the water column is likely to result in higher rates of nitrate production from nitrification, which may be rapidly reduced to nitrogen gas and therefore removed from the analytical determinations of total nitrogen. On the basis of these observations it may be surmised that any action that raised the oxidation status of the water column is likely to be beneficial in removing nitrogen.

Concentrations of dissolved reactive phosphorus (DRP) and total phosphorus are very similar for surface and bottom-water concentrations except for the case of total phosphorus on 6 December 2006 (Fig. 9b). This observation is analogous to that for the different nitrogen species and is likely attributable to the greater sampling depth (15 m) on this date compared with adjacent samples (10 m) around this time. Concentrations of dissolved reactive phosphorus are mostly below detection limits of 0.01 mg L^{-1}; it is therefore suggested that efforts be made to delineate concentrations of 0.005 mg L^{-1} or less in the analytical procedure to add value to this analysis.

For chlorophyll *a* the sampling day with the most marked difference in concentration between surface and bottom-water samples is not 6 December 2006 (cf. nutrients in Fig. 9a and b), but 3 February 2007. The period when this sample was taken is denoted by relatively high temperatures in surface waters but, most importantly, a very shallow surface mixed layer (around 2-3 m) and strong stratification through the upper 10 m. These conditions would favour accumulation of *A. planktonica* cells to high densities in surface waters (see Fig. 8) by allowing them to float with minimal disturbance.

The summer build-up of *A. planktonica* cells in the Lower Karori Reservoir was likely to have been delayed in 2006-7 by a period of exceptionally cold weather for this season. Wellington Airport recorded its coldest monthly mean air temperature since records began and there was very little diurnal heating evident in surface temperatures in the reservoir through December, or of a trend of water warming (Fig 8b) that could be expected for this time of year. Nevertheless, densities of *A. planktonica* became very high at the beginning of February and a bloom was present throughout the perch removal campaign later that month. Immediately following the perch removal, the density of *A. planktonica* fell dramatically, and this fall was accompanied by a large rise in the total zooplankton abundance (Fig. 10).

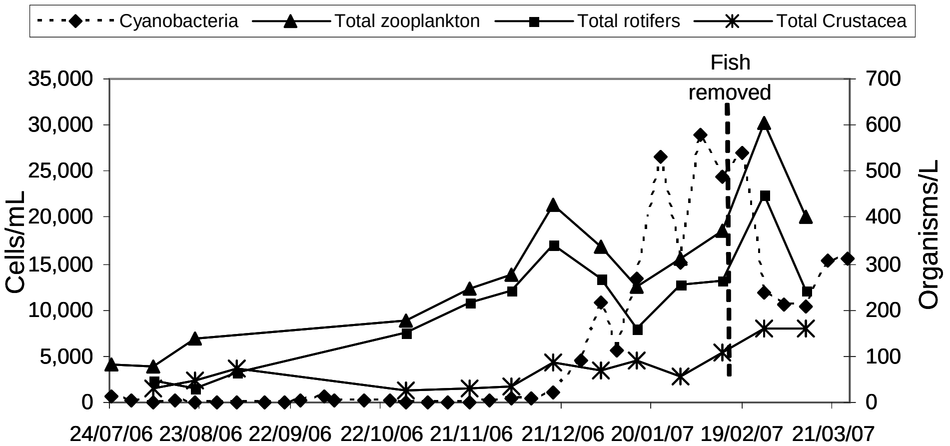

Figure 10. Concentrations in organisms/L of rotifers, Crustacea, total zooplankton (rotifers + Crustacea) and *Anabaena planktonica* cells in cells/mL for 10 m vertically integrated surface samples taken at the Valve House of the lower Karori Reservoir.

Discussion

The fish community

The lower Karori Reservoir has a very unusual fish community that is almost completely one species, European perch. Our estimate of 20,000 to 22,000 perch in the lower Karori Reservoir, especially the age-0 and age-1 fish that make up over 80% of the population, suggests perch are very likely to have a large effect on the zooplankton size and abundance. The approximately 4,000 fish that we removed represent 18-20% of the total number of fish present, and the total weight (72 kg) of removed perch was 8-10% of the total biomass. Age-0 perch may have been under-represented in the catch, given that we caught more age-1 than age-0 perch. Alternatively, the age-1 (2005) cohort may be a particularly strong age class compared to the age-0 (2006) cohort. The small number of age-2 fish caught suggests that survival from age 1 to age 2 is poor.

The dam, spillway, and valve tower structures restrict recruitment of other fish species by acting as a barrier to upstream migration of juveniles from the sea. The reservoir has low numbers of longfin and shortfin eels. The presence of shortfin eels shows that natural recruitment is occurring as none of this species has been stocked. A small number of longfin eels were released in the reservoir (Keith Calder, pers. comm.).The recruitment of banded kokopu found by Mike Joy, Massey University, in the stream between upper and lower reservoirs may similarly be recruited from sea-run juveniles, or they may be a lake-locked population. This should be tested.

Boat electrofishing is an extremely effective way to catch littoral perch, and night-time boat electrofishing in the reservoir was at least 2-4 times more effective than day-time fishing. Population estimates from day-time fishing were not possible because of the low capture probability, and electrofishing was not effective for limnetic perch. Other methods of estimating perch abundance such as echosounding could be evaluated, and mid-water trawling has the potential to both estimate numbers of limnetic perch and remove fish. Opera house nets were also an ineffective way to catch perch. Large mesh gill nets are effective at catching large limnetic perch, but may cause a by-catch of diving birds.

In conclusion, fishing is unlikely to be able to eradicate such a large number of perch from the lower Karori Reservoir. It is possible that a concerted effort could reduce the abundance to a point at which their effect on the zooplankton was negligible, but this would require an ongoing effort to maintain a low biomass. One permanent way to eradicate perch would be to draw down the lake and poison the fish. Few fish of other species would be harmed by this because of their very limited abundance in the reservoir. The reliance of age-0 perch on cover such as branches in the water suggest that fish aggregation devices might also be explored to control young of the year.

Water quality

Large Crustacea (e.g., calanoid copepods) can exert significant grazing pressure on phytoplankton populations. Shortly after perch removal, we observed a reduction in the abundance of the cyanobacterium *Anabaena planktonica* and an increase in total zooplankton abundance (Fig. 10, which could be interpreted in a several ways. This could be because:

(1) an increase in water temperature stimulated feeding and growth rates of zooplankton; or

(2) removal of zooplanktivorous perch reduced predation pressure on zooplankton.

At this stage, it is not possible to determine the relative importance of each of these processes.

The nutrient analysis programme has been valuable in demonstrating the eutrophic nature of the lower Karori Reservoir, the dominance of ammonium amongst inorganic nitrogen species, and the relatively low levels of dissolved reactive phosphorus. These data will be valuable in assessing the outcomes from water quality restoration procedures that target nutrients. For example, aeration, destratification or artificial oxygenation may be considered in order to address nutrient releases from the bottom sediments that are clearly occurring during periods of stratification, most likely as a result of deoxygenation events. An aeration system may provide relatively rapid outcomes in reducing nutrient levels in lower Karori Reservoir, reducing algal blooms in the short to medium-term, and reducing the pool or organic material in the bottom sediments in the medium to long-term. Such a strategy could be used in conjunction with complete fish removal – itself a longer-term impact designed to ultimately increase zooplankton grazing pressure on phytoplankton – and it is quite likely that the two strategies could act synergistically. The present monitoring programme, which leverages a number of different funding sources, is beginning provide a basic understanding of the ecological functioning of the lower Karori Reservoir.

Research currently taking place on the lake, in conjunction with what is already known about perch populations in the reservoir (Smith and Lester, 2006), suggest that perch could have a major ecosystem-wide impact and may directly and indirectly influence the dynamics of *A. planktonica* populations.

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