Fish populations of Lake Ngaroto, Waikato, and fish passage at the outlet weir

CBER Contract Report Number 14

Prepared for the Waipa District Council

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14 November 2001

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EXECUTIVE SUMMARY

1. Lake Ngaroto has a diverse fauna of native and introduced fish. It is the largest of the Waipa lakes, is hypertrophic (i.e., has very high concentrations of plant nutrients), and is highly productive for this reason.

2. In an exhaustive fish survey that used gill nets, fyke nets, and beach seining, 4,317 fish of nine species were caught. The catch included five species of introduced fish. Over 70% of the catch was brown bullhead catfish; rudd, goldfish, a single mosquitofish, and a single koi carp were also caught. In summer, mosquitofish numbers a likely to be very high.

3. Four species of native fish were caught, and of these, shortfinned eels were the most numerous. Common bullies, a few longfinned eels, and a single common smelt were caught, though common smelt and common bullies are expected to be much more numerous in summer.

4. The migratory species in the lake are the eels and common smelt. Eels are always migratory, as they spawn in the tropical ocean. Common smelt may be either migratory or lake-resident, and the single individual caught in this survey had vertebral and gill raker counts diagnostic of a migratory fish. As smelt migrate upstream from the ocean in spring and summer, but are generally absent from freshwaters in winter, the low abundance in August and October 2001 is not surprising.

5. Eels are strong migrators, and can climb rock faces and wriggle through small cracks and crevices during their migration. Common smelt migrate by swimming, and high velocities and free-falling water barriers can prevent their upstream passage.

6. We recommend that to allow upstream passage of swimming species such as common smelt the rebuilt weir has zones with mean water column velocities no greater than 0.5 m s^{-1}, and preferably 0.3-0.4 m s^{-1}. The length of the downstream slope of the weir should be no more than 4 m, and the water depth over the weir should be at least 5 cm during the time of principal upstream migration (August to December).

INTRODUCTION

A weir at the outlet controls the water level of Lake Ngaroto. This weir was installed in 1971 to control water level during the summer period for recreational purposes (Boubée 1977). On 25 June 2000 the Waipa District Council requested an evaluation of the fish populations of Lake Ngaroto in preparation for a consent application for rebuilding of the outlet weir. The objective of this report is to describe the fish populations of Lake Ngaroto, and to consider the requirement for fish passage at the proposed new weir.

Lake Ngaroto is large by comparison with other Waipa lakes, and is a very important recreational area that is used for boating, hunting, and fishing (Vant & Davies-Colley 1988; Boubée 1977). A number of drains enter the lake, with a major inlet at the southeastern end (map reference 27118 63577 on map S15 of the New Zealand map series 260; Figure 1). The outlet flows from the lake at the northwestern end (map reference 27108 63593) and eventually joins the Waipa River 9 km downstream via the Mangaotama Stream. The normal outflow is 200-300 l s^{-1}. During drought conditions, outflows can fall to zero when evaporation exceeds inflows.

Isotopic analyses of phytoplankton and lake sediments in 1982 and 1983 suggested that the lake had recently undergone an increase in productivity. This was inferred from more negative $d^{13}C$ values of the sediments compared to the phytoplankton, which was attributed to forest clearance and current farming practices (McCabe 1985; p172 and p190-191).

THE PROPOSED NEW WEIR

A new weir is proposed to be constructed in the outlet channel to replace the existing weir (Figure 2). The outlet channel varies in width and depth (10m to 3m wide). Near the lake in the likely location of the weir the channel is wide and flat leading to low water velocities at low flows. During heavy rain events the spillway around the weir will come into play. Under typical flow conditions an estimated flow rate will be 0.9-1.2 m^3 s^{-1}. With a weir channel end area of 1 to 1.5 m^2 the average velocity may range from 0.6 to 1.2 m s^{-1}. The flat V shape of the weir top with the rough stone surface will ensure low velocities on the wetted margins (Figure 3). The depth of flow over the weir will vary from 0 mm in a very dry summer period when evaporation exceeds lake inflow to perhaps 300 mm in normal flows and 700 mm in high flows (Bryan Hudson, Waipa District Council, personal communication).

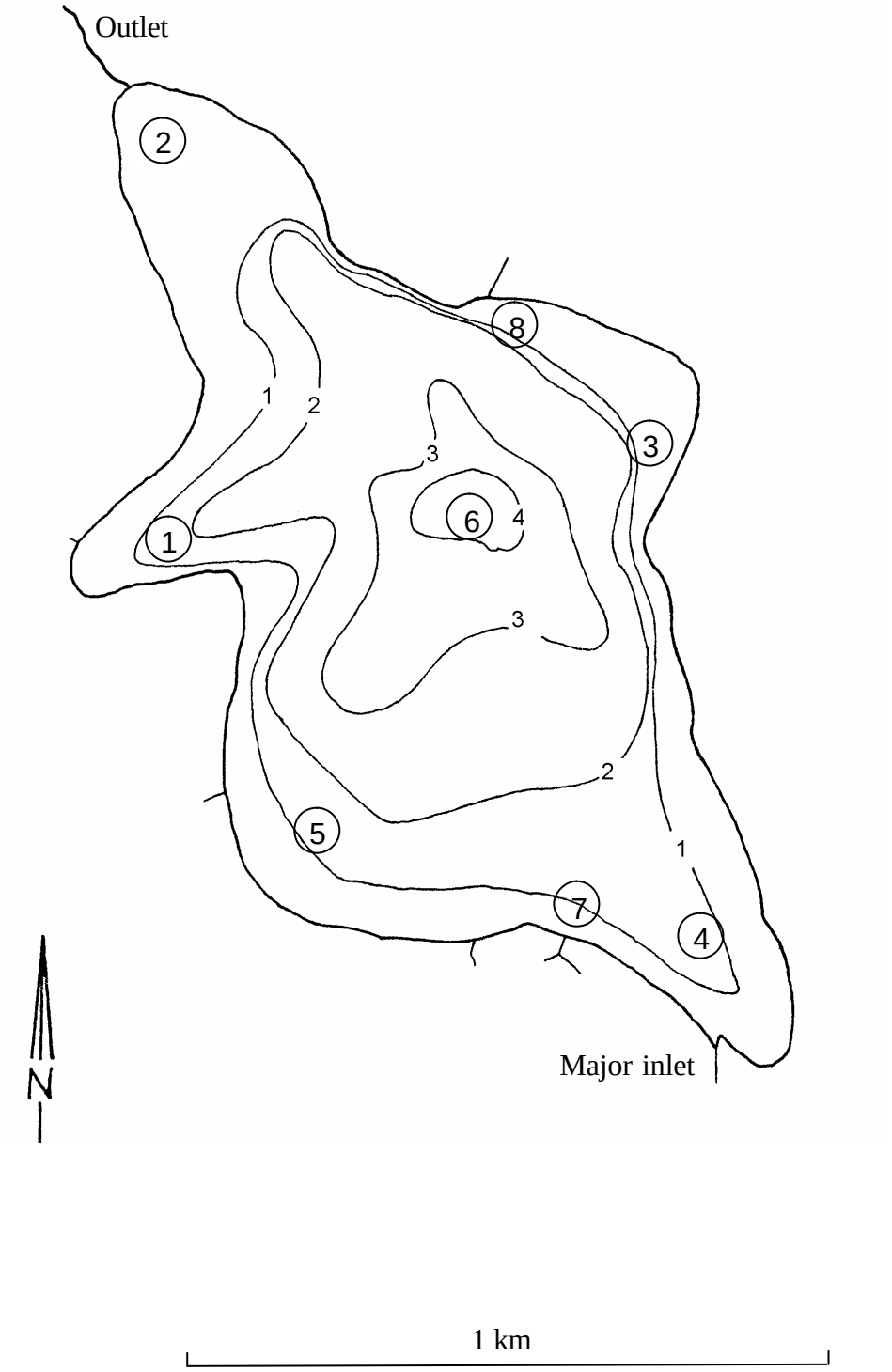

Figure 1. Bathymetry of Lake Ngaroto, showing the location of the sampling sites (circled numbers) and isopleths of depth in metres (after Boubée 1977).

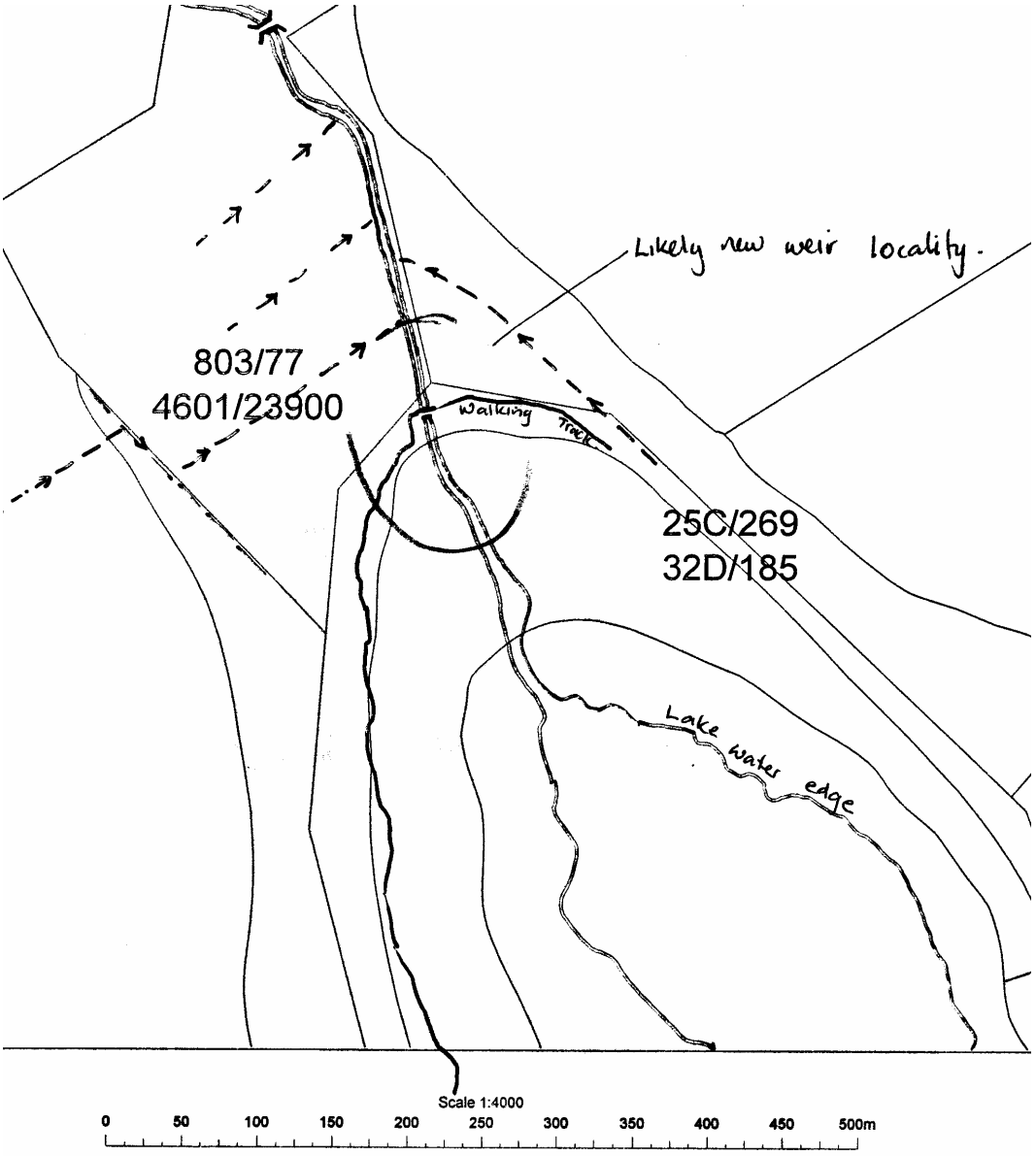

Figure 2. Location of the proposed new weir in the outlet channel of Lake Ngaroto.

Figure 3. The longitudinal section (left) and cross section (right) through the proposed new weir on the outlet of Lake Ngaroto. The downstream face of the weir (left-hand face) will have a slope of 1:10, and the upstream face (right-hand face) will have slope of 1:5.

SITE DESCRIPTION

Lake Ngaroto is a lowland, riverine, peat lake with an area of 1.3 km^2, a maximum dimension of 1.83 km, and a maximum depth of 4 m (Boubée 1977; Lowe & Green 1987a). A large portion of the lake is <2 m deep (Figure 1; Boubée 1977), and the mean depth is 2 m (Duggan 1999; p29). The lake was formed about 16,000 years ago by deposition of alluvium, and unlike some lakes in the Waikato basin, has not been affected by growth of local peat bogs (Lowe & Green 1987b).

The lake has been detrimentally affected by development of its catchment and by the introduction of invasive aquatic macrophytes. The oxygen weeds *Elodea* and *Egeria* were present in 1977, and were documented as problematic for boating (Boubée 1977; Green, no date; p13). Summer pH ranged from 6.6 to 8.7, and Secchi depth was 0.3-1.2 m. Chlorophyll *a* concentration was 11.4-118 mg m^{-3}, and the water was described as weakly to moderately coloured (Vant and Davies-Colley 1988; Green, no date; p31). Its appearance in 1983-1984 was rated as "poor" (Vant and Davies-Colley 1988).

In 1977, dissolved oxygen concentrations at the surface ranged from 122-156% saturation because of oxygen evolution by photosynthesis. However, strong stratification in the summer of 1977 lead to complete oxygen depletion in the bottom 1 m of water (Chapman & Boubée 1977). Usually stratification lasts for only short periods and is broken by wind mixing; in 1997 and 1998 stratification occurred repeatedly between November and May (Duggan 1999. Alkalinity was 0.36-0.43 meq l^{1} (Chapman & Boubée 1977).

The water is highly productive and turbid because of the relatively shallow depth and drainage and seepage of agricultural runoff into the lake (Boubée 1977; Green no date). Water weeds have in the past been controlled with the herbicide Diquat to open waterways for boating (Boubée 1977). Nitrate concentration was 7 g m^{-3}, ammonia concentration was 25 mg m^{-3}, and specific conductance (at 25^{o}C) was 140-152 µSiemens cm^{-1} (Chapman & Boubée 1977). Similar values were recorded in 1997 and 1998 (110-150 µSiemens cm^{-1}; Duggan 1999). The lake is regarded as hypertrophic (Coffey 1987; Duggan 1999; p97), and macrophytes can be excluded for an entire growing season by competition for light with phytoplankton (Coffey 1987). This is probably because of the high total phosphorus concentration (105 mg m^{-3}; Duggan 1999; p29). The lake's optical properties show that

absorbance of photosynthetically active radiation is extreme (Howard-Williams & Vincent 1984; Howard-Williams & Vincent 1985).

The phytoplankton was dominated in summer 1977 by *Melosira granulata* and *Trachelemonas volvocina*; *Melosira distans, Peridinium* sp., and colonial *Pediastrum duplex* were common. At the time when chlorophyll *a* concentration was 11.4 mg m^{-3}, there were 3016 cells or colonies per ml, and 26 algal species. Scums of the cyanobacterium *Microcystis* can form (Chapman & Boubée 1977).

The lake fringe was dominated by a mixed community of raupo (*Typha orientalis*), the rush *Juncus acuminatus*, starwort *Callitriche* sp., gypsywort *Lycopus europaeus*, water primrose *Ludwigia peploides*, and swamp willowherb *Polygonum decipiens.* In shallow areas extensive beds of the native pondweed *Potamogeton pectinatus* grew, and scattered beds of Canadian pondweed *Elodea canadensis*. Stonewort (*Nitella* spp.) and *Ceratophyllum demersum* grew in limited locations. *Elodea* appears to have been introduced from a side drain in about 1968, and by 1973 had become a problem for lake users (Boubée 1977). The zooplankton was dominated by the cladocerans *Bosmina meridionalis* and *Ceriodaphnia* spp. and calanoid copepods (Chapman & Boubée 1977). Lake Ngaroto also supports diverse rotifer populations (Duggan 1999). At the lake edge damselfly nymphs and scattered beds of the freshwater mussel *Hyridella menziesi* were recorded. Net sampling found purse caddis *Oxyethira albiceps*, and the snails *Potamopyrgus antipodarum* and *Physa* sp. Back swimmers and waterboatmen were also present (Boubée 1977).

Lake Ngaroto is an important habitat for wildfowl, and acts as a staging and dispersal area (Boubée 1977).

METHODS

From 21 to 29 August 2001, ten fykes nets with 25-mm stretched mesh were set overnight with their wings extended towards the shore at each of 6 sites (sites 1-6, Figure 1). Offshore from the fyke nets at each site, three 40-m long , 2-m deep panel gill nets were set overnight. Each panel gill net had five panels of monofilament nylon mesh joined end to end. The lengths and stretched-mesh dimensions of the panels were as follows: 6 m of 25-mm mesh, 8 m of 38-mm mesh, 8 m of 56-mm mesh, 8 m of 84-mm mesh, and 10 m of 106-mm mesh.

The gill nets were set for approximately 20 h (about 1430 h to about 1030 h), and fyke nets were set for approximately 24 h (set at about 1500 h). Seine hauls were made during the day onto the beaches at sites 7 and 8. Three hauls were made at site 7, and 2 hauls at site 8. An additional 10 seine hauls were made at site 7 on 29 October 2001. The seine net was 5.3-m long with 5-mm mesh in the wings and a central bag of 3-mm mesh. The net height was 2 m.

All fish caught were measured for length, except for the contents of four fyke nets on 28 August. A subsample of 70-80 fish were weighed at each site. Fish were X-rayed by Hamilton Radiology Ltd with an EPS Instrumentarium Alpha RT at a setting of 24 kV and 0.006 mAs.

RESULTS

Previous fish capture

In 1977, the fish present in the lake were carp (probably *Carassius auratus*), common bullies (*Gobiomorphus cotidianus*), and catfish (*Ameiurus nebulosus*). Eels and grey mullet were speculated to be present; though eels almost certainly were present, grey mullet were probably not present.

Fish capture in August and October 2001

In 2001, a total of 4317 fish were caught in the seven sites around the lake. The majority of fish were captured by overnight sets of fyke nets, but rudd were also caught in panel gill nets (Table 1). The most numerous species were brown bullhead catfish, rudd (*Scardinius erythropthalmus*), and shortfinned eels (*Anguilla australis*; Table 1). The most fish were caught at site 3, and the fewest at site 6, which was in the deepest water. A few goldfish and longfinned eels were caught, and a single koi carp was caught at site 5. Age-0 rudd, common bullies (*Gobiomorphus cotidianus*), one common smelt (*Retropinna retropinna*), and one mosquitofish (*Gambusia affinis*) were caught by beach seining at site 7. The beach seine hauls at site 8 caught nothing.

Table 1. The number of fish caught at seven sites by a combination of fyke netting (10 nets at each site), panel gill netting (three nets at each site) in overnight sets from 21 to 29 August, and day-time beach seine netting on 21-29 August and 29 October 2001.

	Number of fish									
Site	Catfish	Rudd	Shortfinned eel	Longfinned eel	Goldfish	Koi carp	Common bullies	Common smelt	Mosquito fish	Total
Fykes nets										
1	645	39	42	1	0	0	0	0	0	727
2	654	103	39	0	0	0	0	0	0	796
3	916	10	90	3	0	0	0	0	0	1019
4	525	17	27	1	2	0	0	0	0	572
5	385	71	45	1	0	0	0	0	0	502
6	2	0	0	0	0	0	0	0	0	2
Total	3127	240	243	6	2	0	0	0	0	3618
Gill nets										0
1	4	65	1	0	5	0	0	0	0	75
2	0	44	0	0	0	0	0	0	0	44
3	0	54	1	0	9	1	0	0	0	65
4	4	149	0	0	13	0	0	0	0	166
5	5	23	0	0	2	0	0	0	0	30
6	1	39	0	0	11	0	0	0	0	51
Total	14	374	2	0	40	1	0	0	0	431
Beach seine netting										
7	0	243	2	0	0	0	20	2	1	268
Grand total	3141	857	247	6	42	1	20	2	1	4317

Fyke netting

Catch rates of fish in fyke nets were consistent in the littoral sites (1-5), but were markedly lower in the one deep-water site (site 6; Table 2). Catch rates for catfish were 12 times those for rudd and eels, and catch rates for rudd at littoral sites were quite variable.

Table 2. Mean catch rates and one standard error (SE) of brown bullhead catfish, rudd, and shortfinned eels in fyke nets set at six sites in Lake Ngaroto on 21-29 August 2001, showing the mean of means for sites 1-5. *N* = 10 for each site except for site 3, for which *N* = 6.

A. Catch rate per set.

Site	Catch rate (fish net^{-1} 24 h^{-1})					
	Catfish		Shortfinned eel		Rudd	
	Mean	SE	Mean	SE	Mean	SE
1	64.5	13.2	4.2	0.8	3.9	1.3
2	65.4	14.1	3.9	0.8	10.3	3.5
3	91.6	17.1	9.0	2.0	1.0	0.3
4	52.5	11.8	2.7	0.9	1.7	0.7
5	38.5	11.8	4.5	1.1	7.1	1.6
6	0.2	0.2	0.0	0.0	0.0	0.0
Mean of sites 1-5	62.5		4.9		4.8	

B. Catch rate per hour.

Site	Catch rate (fish net^{-1} h^{-1})					
	Catfish		Shortfinned eel		Rudd	
	Mean	SE	Mean	SE	Mean	SE
1	2.69	0.55	0.18	0.04	0.16	0.06
2	2.73	0.59	0.16	0.03	0.43	0.15
3	3.82	0.71	0.38	0.08	0.04	0.01
4	2.19	0.49	0.11	0.04	0.07	0.03
5	1.60	0.49	0.19	0.04	0.30	0.06
6	0.01	0.01	0.00	0.00	0.00	0.00
Mean of sites 1-5	2.60		0.20		0.20	

Gill netting

Catch rates from gill nets were biased towards rudd and goldfish; though small numbers of catfish were caught in gill nets, the majority were caught in fyke nets. The bottom waters at site 6 were almost devoid of fish, but gill net catches of rudd and goldfish higher in the water column imply that the bottom waters at site 6 were probably low in dissolved oxygen.

Table 3. Mean catch rates and one standard error (SE) of rudd and goldfish in gill nets set at six sites in Lake Ngaroto on 21-29 August 2001. Three gill nets were set overnight at each site for about 20 h.

	Catch rate (fish 100 m^{-1} net 24 h^{-1})				Catch rate (fish 100 m^{-1} net h^{-1})			
	Rudd		Goldfish		Rudd		Goldfish	
Site	Mean	SE	Mean	SE	Mean	SE	Mean	SE
1	54.2	8.8	4.2	2.2	2.71	0.44	0.21	0.11
2	36.7	10.2	0.0	0.0	1.84	0.51	0.00	0.00
3	45.0	6.3	7.5	1.4	2.25	0.32	0.38	0.07
4	124.2	14.5	10.8	2.2	6.21	0.72	0.54	0.11
5	19.2	10.8	1.7	0.8	0.96	0.54	0.09	0.04
6	32.5	7.5	9.2	3.0	1.63	0.37	0.46	0.15
Mean	51.9		5.6		2.60		0.28	

Length frequencies

Brown bullhead catfish caught by fyke netting at littoral sites in August 2001 showed three distinct age classes (Figure 4A). Young of the year, which were 10-11 months old at the time, dominated the age structure at sites 1 and 5 (Figure 4B and F). At the other sites, age 2 and 3 catfish were more numerous in the catch than juveniles.

Shortfinned eels in the fyke net catches were relatively large, but this probably reflects the coarse mesh size used rather than an absence of small sized eels (Figure 5). Two size classes dominated the rudd population, and the smaller size class, which were almost certainly age-0 fish, were caught predominantly in the littoral zone by beach seining on 29 October (Figure 6).

The common smelt were 89 and 96 mm fork length (FL), the five longfinned eels were 249-492 mm total length (TL), and the one koi carp was 310 mm FL.

Smelt and bully meristics

Of critical importance to the consideration of fish passage into and out of the lake is whether the common bullies and common smelt are of lake-locked or diadromous origin. Diadromous fish must have access to and from the sea for their migrations. Vertebral and gill raker counts are diagnostic for the origin of common smelt. Diadromous (migratory) smelt have 18-24 gill

rakers, and 56-64 vertebrae, whereas nonmigratory smelt have 24-31 gill rakers, and 49-55 vertebrae (Northcote and Ward 1985).

Vertebrae of the one common smelt retained for analysis were counted from a high-resolution X-ray (Figure 7). The first gill arch was dissected out and a count of 18 gill rakers was obtained. The specimen from Lake Ngaroto was diadromous by these criteria (Figure 8), and therefore had migrated into the lake from the sea. The four bullies that were examined had scales on the nape of the neck forward to between the posterior edge of the eyes, and no head pores. These characteristics are diagnostic of nonmigratory common bullies (McDowall 1990). High-resolution X-rays showed that the bullies had 28-29 vertebrae.

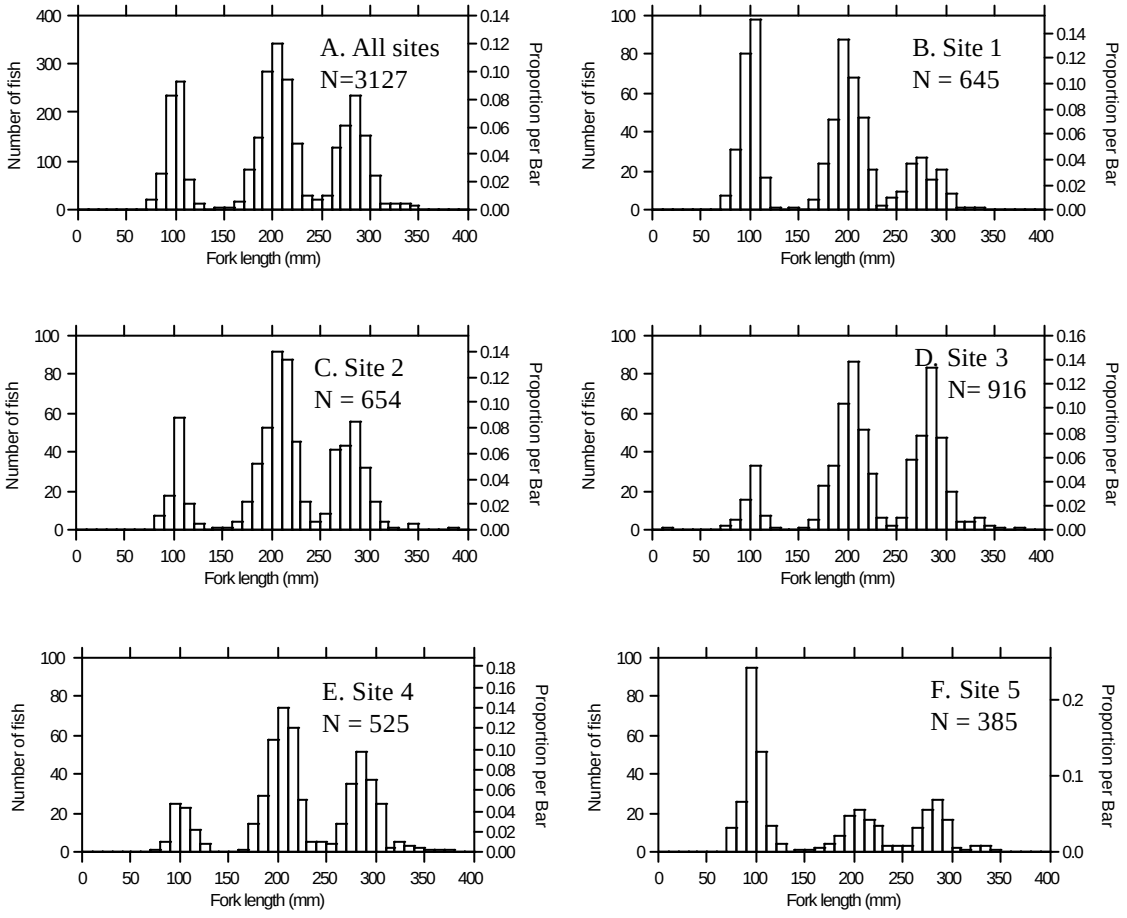

Figure 4. Length-frequency of brown bullhead catfish at six sites in Lake Ngaroto caught in fyke nets on 21-29 August 2001

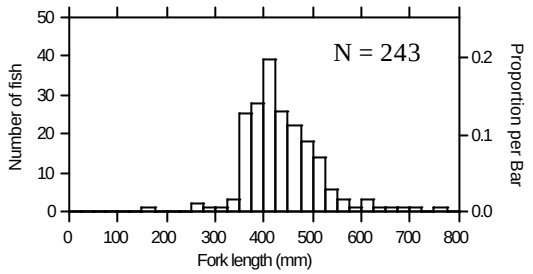

Figure 5. Length-frequency of shortfinned eels at six sites in Lake Ngaroto caught in fyke nets on 21-29 August 2001.

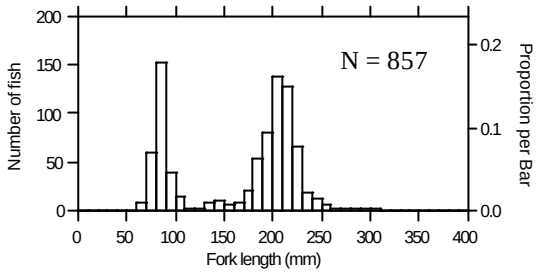

Figure 6. Length-frequency of rudd at six sites in Lake Ngaroto caught in fyke nets on 21-29 August 2001

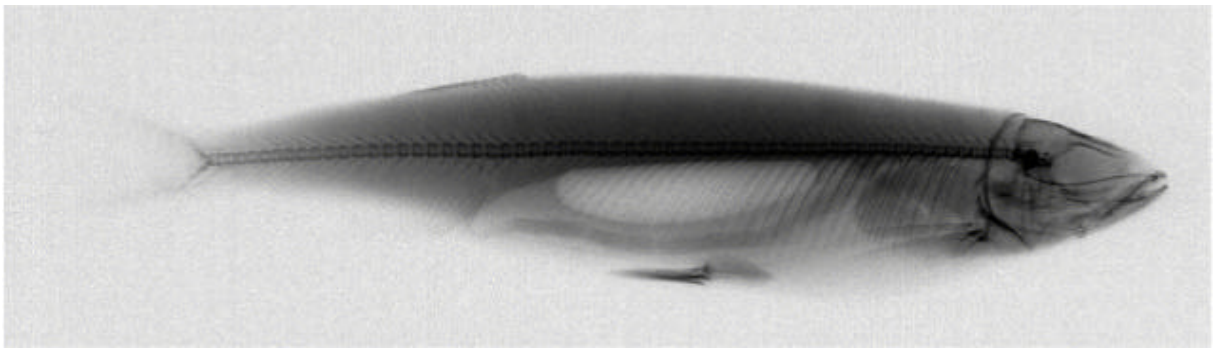

Figure 7. A negative image of a high-resolution X-ray of the 96-mm fork length smelt captured from Lake Ngaroto at site 7 on 29 October 2001.

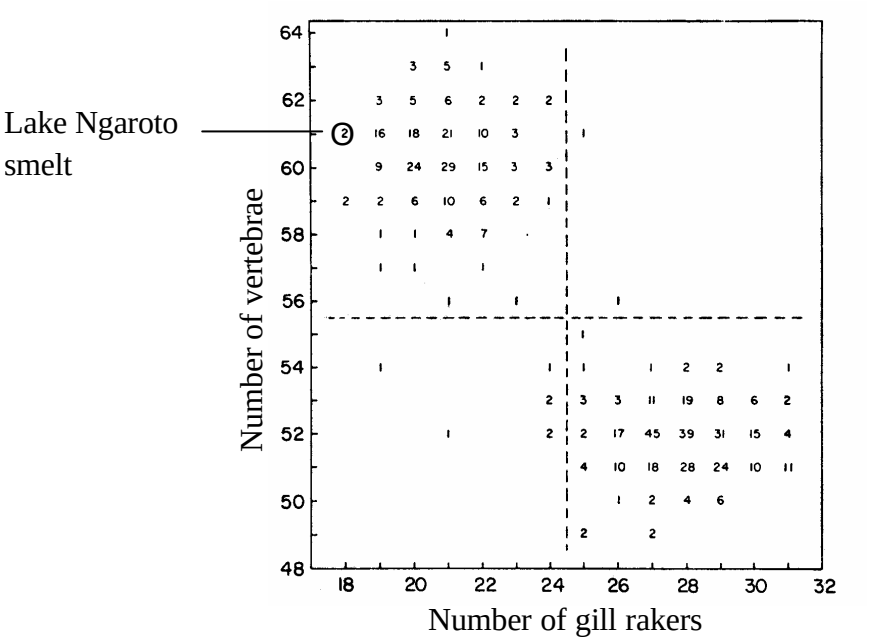

Figure 8. Vertebral and gill raker counts of migratory (low gill raker count) and nonmigratory (high gill raker count) common smelt in the Waikato River and its lakes. The plotted numbers refer to the number of fish with each pair of characteristics (adapted from Northcote and Ward 1985).

Catch rates by weight

Weight-length relationships

Regressions were calculated for weights and fork lengths for catfish, goldfish, and rudd, and total length for eels and common bullies (Table 4).

Table 4. Parameters for the weight-length regressions for of brown bullhead catfish, goldfish, rudd, common bullies, and shortfinned eels caught at six sites in Lake Ngaroto on 21-29 August 2001. $P < 0.001$ for all regressions, $Y = a + bX$, where Y = natural log of weight in g, and X = natural log of length in mm.

		Regression parameters			Length range (mm)	
Species	*N*	r^2_{adj}	*a*	*b*	Minimum	Maximum
Common bullies	20	0.98	-14.05	3.743	24	50
Rudd	640	0.99	-11.54	3.105	62	305
Catfish	445	0.99	-11.43	2.997	80	370
Goldfish	40	0.99	-12.71	3.386	151	341
Shortfinned eel	176	0.92	-13.68	3.072	372	758

Catch rates

The weights of fish measured for length but not weighed were calculated from these regressions. The weights of each species in each fyke net were summed and means and standard errors calculated for each species and site. The mean weight of catfish (7.9 kg net^{-1} set^{-1}) was 10 times that of either shortfinned eels or rudd (Table 5).

Table 5. Mean catch rates and one standard error (SE) of brown bullhead catfish, rudd, and shortfinned eels in fyke nets set at six sites in Lake Ngaroto on 21-29 August 2001, showing the mean of means for sites 1-5. *N* = 10 for each site except for site 3, for which *N* = 6.

Site	Catch rate (g net^{-1} 24 h^{-1})					
	Catfish		Shortfinned eel		Rudd	
	Mean	SE	Mean	SE	Mean	SE
1	5322	1451	742	147	675	249
2	8386	2186	715	176	1631	588
3	15424	3677	1130	382	133	69
4	7280	1772	381	120	254	117
5	3266	1285	691	181	1008	240
Mean	7936		732		740	

DISCUSSION

Fish abundance

Lake Ngaroto has a diverse fish fauna of native and introduced fish. The high productivity of Lake Ngaroto is reflected in the large number of brown bullhead catfish in the catch. These fish prefer highly productive habitats, and are very tolerant of poor water quality. Their excretion and bioturbation when feeding in bottom sediments can increase rates of nutrient cycling, and can contribute to the high productivity.

The commercial eel fishery uses similar fyke nets to those used in this survey, and thus our catches can be compared with previous commercial catch rates. Between 1983 and 1989 the national mean commercial catch rate was 6.5 kg net^{-1} night^{-1} (Annala 1994; p83). Catch rates declined in the 1990s in many locations, mostly due to fishing pressure. In Lake Ngaroto, mean eel catch rates in August 2001 were only 0.73 kg net^{-1} night^{-1}, whereas mean catfish

catch rates were 7.9 kg net^{-1} night^{-1} (Table 5). Cool winter temperatures might have affected eel catch rates, as eels are more active at high temperatures than at low temperatures.

Reproduction and migration

Common smelt and eels migrate upstream to their rearing and adult habitats in spring and summer (Table 6). In autumn, mature eels and smelt migrate downstream, eels to their spawning habitat in the sea and the surviving smelt to their winter habitats. This movement out of Lake Ngaroto probably accounts for the low number of smelt in seine net catches, and suggests that there are few if any lake-resident smelt in the lake. Further sampling is required in summer to be certain of this. It is possible that inanga also migrate into the lake from the sea. If so, their principal upstream migrations are from August to November, but more sampling would be required to establish if inanga use the lake.

Table 6. Seasonal timing of the migrations of common smelt and eels.

A. Upstream migration.

Species	Period of upstream migration												Purpose
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	
Eels - juveniles				■	■	■							To adult habitat
Smelt - juveniles	■	■	■									■	To rearing habitat
Smelt - adults			■	■	■	■							Spawning
Inanga - juveniles	■	■	■	■	■							■	To rearing habitat
Inanga - adults								▪	■	▪			Post-spawning
Common bully - juvenile		■	■	■	■	■							To adult habitat

B. Downstream migration.

Species	Period of downstream migration												Purpose
	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	July	Aug	
Eels - adults				▪▪▪	▪▪▪	▪▪▪	■	■	■				Spawning
Smelt - adults							■	■	■				To winter habitat
Smelt - larvae							■	■	■				To rearing habitat
Inanga - adults							■	■	■				Spawning

Fish passage

Passage is required into and out of the lake for both eels and common smelt. Inanga were not found in the lake, but it is possible that they migrate this far upstream in summer. Downstream passage is unlikely to be a problem as it can occur during periods of high flow over the weir. Upstream passage is not likely to be a problem for the eels, as they are adept climbers, and can wriggle through crevices and over damp surfaces at the water's edge. Upstream passage for common smelt and inanga is a greater problem, as high water velocities can prevent passage of these swimming species. Based on their size at Huntly (58-61 mm; Stancliff et al. 1988), upstream migrants of common smelt and inanga would probably be at least 60 mm long by the time they reach Lake Ngaroto.

Swimming performance

Large fish can swim faster than small fish, but the upstream migrants of many New Zealand native species are small (<100 mm). Tests in a flume suggest that sustained swimming speeds of <0.25 m s^{-1} can be maintained by shortfinned eels, inanga (*Galaxias maculatus*), common smelt, common bullies, banded kokopu (*G. fasciatus*), and grey mullet. Burst speeds of 0.43-0.60 m s^{-1} were observed in these species in fish of 30-73 mm in length, except for 85-96 mm grey mullet, which achieved only 0.25 m s^{-1} (Mitchell 1989).

Swimming can occur as sustained effort, which can be maintained for long periods without fatigue, or in short bursts that can be maintained for only a few seconds (Boubée et al. 1999). Swimming ability has been related to length in the following general formula

$$V_{fw} = a\, L^{b}\, t^{c},$$

Where V_{fw} = the velocity of the fish relative to the water that could be sustained for t seconds by a fish of length L (in metres); a, b and c are coefficients that depend on the fish (Boubée et al. 1999). For inanga and common smelt, a = 5.29, b = 0.63, and c = -0.16 for sustained swimming, and a = 14.4, b = 0.63, and c = -0.43 for burst swimming (Boubée et al. 1999). These coefficients suggest that a 60-mm common smelt or inanga can achieve a sustained swimming speed relative to the water of 0.62 m s^{-1}, and a burst swimming speed of 0.91 m s^{-1} (Figure 9). Burst swimming can be maintained for only about 10 s, whereas sustained swimming can be maintained for longer periods without fatigue.

However, these are swimming speeds that can be achieved relative to the water, and to make forward progress relative to the ground a fish must swim faster than the water velocity. The maximum distance (D_{max}) that can be achieved is related to fish length (L) in metres and water velocity (V) as follows (Boubée et al. 1999):

$$D_{max} = d\, L^{e}\, V^{f}.$$

For sustained swimming, the relationship is

$$D_{max} = 2130\, L^{3.94}\, V^{-5.25},$$

and for burst swimming,

$$D_{max} = 14.4\, L^{0.63}\, V^{-0.43}.$$

According to these relationships, a 60-mm common smelt or inanga could swim 4.0 m upstream against a water velocity of 0.4 m s^{-1} by sustained swimming, and 4.1 m upstream against a water velocity of 0.5 m s^{-1} by burst swimming (Figure 10).

Thus the length of the crest of the weir and exposed downstream face should not exceed about 4 m if velocities are up to 0.5 m s^{-1}, and should be 0.3-0.4 m s^{-1} for easy passage of upstream migrant common smelt and inanga. For small upstream migrants, a shallow water depth of about 5 cm is sufficient. Upstream passage is most important in spring and early summer. This is a preliminary analysis that demonstrates the importance of weir design.

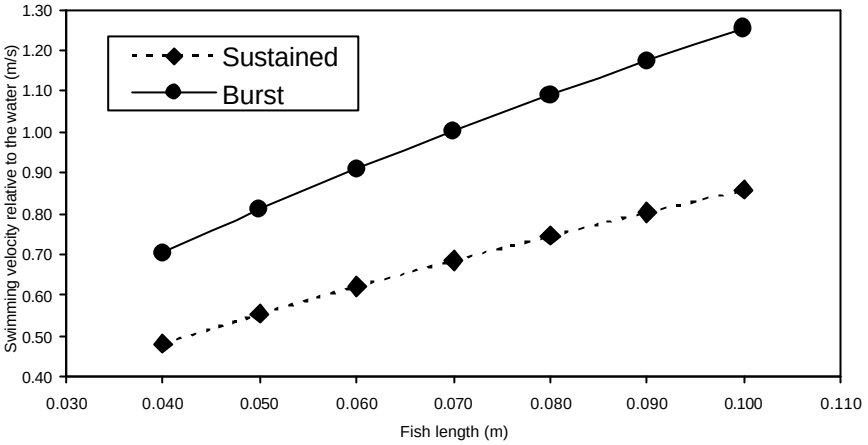

Figure 9. Velocities achieved during sustained and burst swimming relative to the water by common smelt and inanga from 40 to 100 mm fork length calculated from the equations of Boubeé et al. (1999).

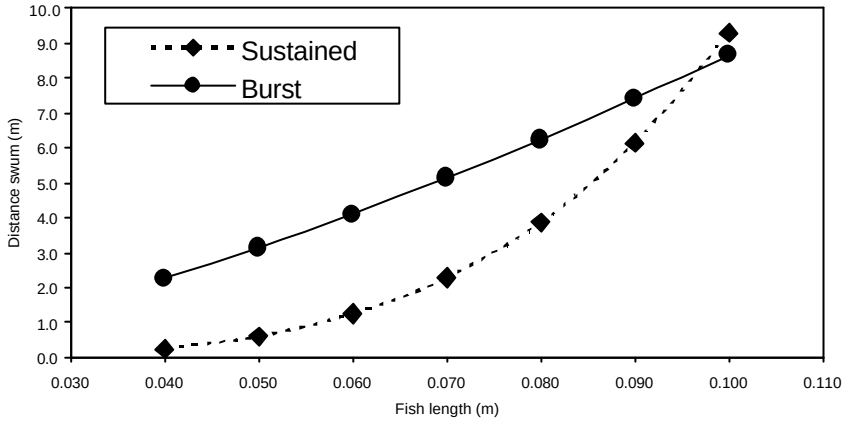

Figure 10. Distances swum during sustained and burst swimming by common smelt and inanga from 40 to 100 mm fork length in 0.5 m s^{-1} velocity calculated from the equations of Boubeé et al. (1999).

ACKNOWLEDGEMENTS

We thank Hamilton Radiology for their help with the fish X-rays.

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