

Factors regulating the downstream migration of mature eels (*Anguilla* spp.) at Aniwhenua Dam, Bay of Plenty, New Zealand

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Abstract The downstream migrations of mature longfinned eels (*Anguilla dieffenbachii* Gray, 1842) and shortfinned eels (*Anguilla australis* Richardson, 1848) were investigated at Aniwhenua Dam on the Rangitaiki River between 1992 and 1998. Migrants were mostly females over 1000 mm total length (TL) with otoliths indicating rapid growth rates. Migrations, which occurred on a few nights each autumn, generally began once water temperatures began to decline and ended when temperatures dropped below c. 11°C. Rainfall and flow increases were found to be key factors triggering migration events. Rainfall exceeding a cumulative total of 40 mm over 3 days accounted for 60% of migrant eels arriving at Aniwhenua. It is proposed that such rainfall triggers could be used as predictors to instigate mitigation

activities that would allow mature eels to proceed uninjured past barriers such as hydro-electric dams.

Keywords eels; dams; fish-passage; fish migration; growth; *Anguilla australis*; *A. dieffenbachii*

INTRODUCTION

The two main species of eels found in New Zealand, *Anguilla australis* (Richardson, 1848) the shortfinned eel and *A. dieffenbachii* (Gray, 1842) the longfinned eel, support important commercial, recreational, and traditional fisheries. The endemic longfinned eel is the top predator in New Zealand fresh waters and penetrates further inland than the indigenous shortfinned eel, which tends to be more lowland in distribution (Jellyman & Todd 1982). Eels are diadromous and must migrate to and from the sea to complete their life cycles. In spring, juvenile eels migrate into rivers from the sea. In autumn, sexually maturing eels begin their migration from feeding areas in fresh water to their spawning areas at sea (Tesch 1977; Moriarty 1978).

Although every major obstruction has the potential to affect eel migration, by far the most disruptive are the hydro-electric dams present, often in series, on many large rivers in New Zealand (e.g., Waikato, Waitaki, Rangitaiki Rivers). The ease with which juvenile eels surmount obstacles has been successfully utilised in elver-pass designs to provide access to productive hydro-reservoirs (Sloane 1984; Porcher 1992; Boubée & Mitchell 1994; White & Knights 1994). Along with manual transfers, these passes have allowed eels to regain access to extensive upstream habitats behind dams (Mitchell & Chisnall 1992; Chisnall & Hicks 1993; Beentjes et al. 1997; Chisnall et al. 1998).

In the North Island of New Zealand, it takes between 30 and 50 years on average before sexually maturing female longfinned eels migrate back to sea (Chisnall & Hicks 1993). This time period is doubled in the cooler South Island lakes (Jellyman 1995). When these eels migrate down stream in an attempt

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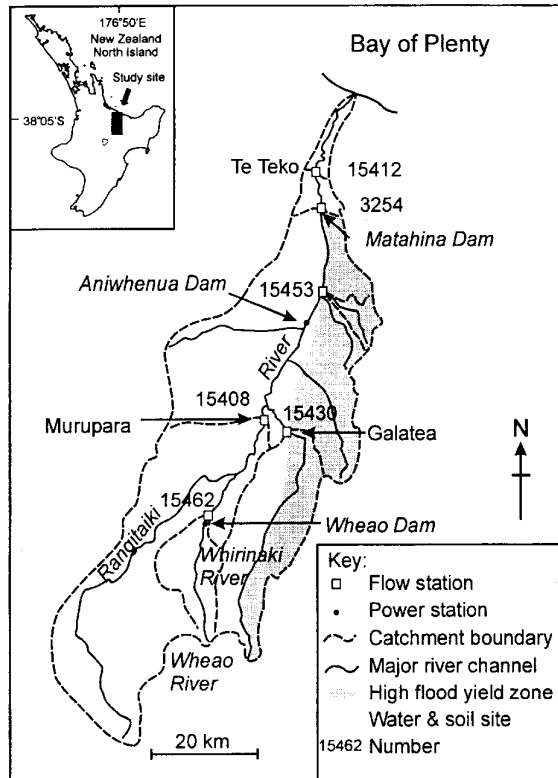


Fig. 1 Map of the Rangitaiki River, Bay of Plenty, New Zealand, showing the location of the hydro-electric dams and recording stations.

to reach spawning grounds, they are inevitably entrained at water intakes associated with hydro-dams. Where the screens are small-meshed (e.g., 30 mm at Aniwhenua Power Station), eels are impinged and suffocated as a result of the water pressure; coarser screens allow eels to pass through to the turbines, but most are mutilated as a result.

In New Zealand, mutilated eels are commonly found below hydro-electric dams during the autumn migration period. Overseas studies (Monten 1964; Larinier & Dartiguelongue 1989; Travade & Larinier 1992; Desrochers 1995) indicate that mortality of fish in turbines is directly related to the size of the turbine and the size of the fish. Elongate fish like eels are most affected, and small turbines cause the most damage. A study of the problem in New Zealand

concluded that turbine survival of the large New Zealand migrant eels was likely to be poor (Mitchell & Boubée 1992).

Monitoring of elver numbers at various elver passes around New Zealand (Jellyman 1994; Moore 1995; Beentjes et al. 1997; Chisnall et al. 1998) suggests that recruitment is now low in comparison with earlier observations (Best 1929; Cairns 1941; Graham 1956). This problem is not confined to New Zealand (Castonguay et al. 1994; Moriarty 1994; Tendron 1994). The impact of damming large rivers, water abstraction, intense commercial fishing, land development and the loss of large areas of wetland have significantly reduced the reproductive output of eels throughout the world. The present high mortality rate of large, pre-spawning female eels

during passage through hydro-dams may represent a serious loss of potential spawners.

Reservoirs can be extremely productive, and eel growth rates obtained in some of the North Island hydro-lakes are unsurpassed (Beentjes et al. 1997). Furthermore, there are indications that upstream habitats predominantly produce female eels (Aprahamian 1988; Chisnall & Hicks 1993), and that fecundity increases with size. Todd (1981b) demonstrated that a 700 mm longfinned eel female carried c. 1 million eggs whereas a 1400 mm fish produced over 20 million. On this basis alone, there is value in allowing large, female longfinned eels living above dams to survive downstream passage.

For the European eel (*A. anguilla*), Lowe (1952), Deelder (1954), and Tesch (1977) related migrations to moon phase, and suggested that floods may be a guiding factor which mechanically aid the eels to move down stream. In New Zealand, similar responses to flood events were recorded by Cairns (1941), Burnett (1969), Todd (1981a), and Palmer et al. (1987). However, apart from Vøllestad et al. (1986), no statistical analysis has demonstrated a connection between these environmental variables and migratory activity and, in New Zealand at least, no attempt has been made to quantify the triggers which may result in an eel migration event.

The purpose of this study, was to identify key environmental variables that regulate the activity of mature eels migrating down stream, so that short duration mitigation activities, such as catch/release operations to transport eels over dams, or water releases at spillways, may be made to coincide with the peak movement of migrant eels.

Site description

The Rangitaiki River arises on the Taupo volcanic plateau and flows north-east into the Bay of Plenty (Fig. 1). It is joined by streams draining the Kaingaroa pumice plains from the west, and by the Wheao and Whirinaki Rivers which arise from the steep greywacke Ikawhenua and Urewera Ranges to the east. The relatively steady flow, and predominantly pumiceous sediments of the main river and western tributaries, differ markedly from the steeper eastern catchments. About 75% of the catchment is covered either by indigenous forest (Urewera National Park and Whirinaki State Forest) or by exotic pine plantations (Kaingaroa Forest).

Few eels have been reported from the western side of the catchment (New Zealand Freshwater Fish Database), and operators of the Wheao Power Scheme on the upper Rangitaiki have never recorded

eels upon their intake screens. In contrast, tributaries like the Whirinaki River, which arise from the Ikawhenua Range to the east are considered by *tangatawhenua* (local Maori) as prime longfinned eel habitat.

There are two major obstructions to eel migration on the Rangitaiki River: the Matahina Dam (completed in 1967), and the upstream Aniwhenua Barrage (completed in 1981). Following concerns expressed by local residents in 1983, a number of groups have manually transferred elvers into the upper catchment, including Lake Aniwhenua. All manual transfers were made using elvers collected at the base of Matahina Dam (Beentjes et al. 1997). Although the elver transfer programme has been highly successful in the lower catchment (Beentjes et al. 1997), it has had limited success in the stocking of the upper catchment (Young 2000). The few large eels that remain accessed the headwaters before the dams were constructed.

METHODS

Migration

An important reason for selecting Aniwhenua Dam for this study is the unusually narrow 30-mm bar spacing on the penstock screens. This retains most migrant eels except small individuals (mostly male shortfinned eels). During 1992, 1997, and 1998, dead adult migrant eels were retrieved from the penstock screens cleaning mechanism and daily counts obtained. On most days, the screens were cleaned in the morning, but during floods, continuous screen cleaning was often necessary. Runs were observed sporadically by station staff during intervening years (1993–96), but few records were kept.

In 1992, all eels were identified measured and weighed, and otoliths extracted from a subsample for ageing. To provide baseline information on the effect of screen spacing on the size distribution of impinged eels, head widths of some of the eels were determined by measuring the circumference of the head at the widest point. In 1997 and 1998, eels were simply separated by the screen cleaner operator into two size categories: (1) female longfinned eels (easily recognisable by their large size and characteristic dorsal fin); and (2) others, which consisted mainly of female shortfinned eels and a few male longfinned eels. A subsample of the eels in both groups was measured and otoliths extracted for ageing. As all freshly killed eels were retained by local Maori for consumption, withholding and/or

mutilating the bodies for collection of additional information such as gonad weight and maturity state was not possible.

In addition to eels collected on the screens in 1997–98, a large capture net of 25 mm square mesh (Mitchell 1996) was stretched across the canal on three flood events, to capture migrants before they became impinged on the screens (1997, 9 March and 10–11 April; and in 1998, 24–26 February). The net was cleared at intervals throughout the night to assess temporal movement patterns. Captured eels were counted, species identified, and transported for release down stream of the lowermost dam at Matahina. The number of eels caught by the net were added to the screen data for analysis of eel movement patterns, i.e., we assumed that most eels not caught by the net would end up on the screens on the same night. Although it would have been desirable to compare head widths of migrants taken from the screens with those captured in the net (1997–98), local Maori volunteers gave priority to liberation of the catches.

Water level and rainfall

To determine if eel migration events were related to rainfall or increased river flow, information collected from the catchment was collated for the periods for which eel movement data were available. Water levels in the upper Rangitaiki River are recorded at the Wheao Power Station (Water & Soil (WS) site 16462, Fig. 1). River levels are also recorded at Murupara (WS site 15408) and below Aniwhenua Dam (WS site 15453). The Whirinaki River is gauged at Galatea (WS site 15430). Rainfall is measured at Murupara, Tarapounamu (near Ruatahuna in the middle of the Ikawhenua Range), and at Aniwhenua Dam.

Moon phase, barometric pressure, and temperature

In addition to comparisons with flow and rainfall trends, eel counts were examined to determine whether lunar moon phase could be correlated with

eel activity, as suggested by eel fishermen (Best 1929), or if the passage of low pressure weather systems affects eel movement (Deelder 1954). For the latter comparison, barometric pressure was obtained from NIWA climate station at Rotorua, c. 50 km west of Aniwhenua Dam.

Several authors have linked water temperature to the start and end of the downstream eel migrations (e.g., Lowe 1952; Todd 1981a; Vøllestad et al. 1986). Water temperature records, collected as part of a separate catchment monitoring programme, were therefore obtained from the Whirinaki River for the periods eel migration data were available.

Age determination

Otoliths of both shortfinned and longfinned eels show alternating concentric transparent and opaque bands; each transparent zone delimits 1 year's growth (Jellyman 1977; Chisnall & Kalish 1993). Otoliths were prepared following the crack-and-burn method (Jellyman 1979) and mounted on microscope slides in silicone rubber sealant (Hu & Todd 1981). Transparent zones (dark when burnt) were counted to determine age. Age was expressed as years spent in fresh water, ignoring the small central zone formed during the oceanic larval phase (Jellyman 1979). When determining age, the width of the opaque zone (growth bands) was also noted and used to determine the habitat where the eel was likely to have spent most of its life (Poole et al. 1992; Chisnall & Hicks 1993).

The relatively small number of eels collected and the constrained length distribution of both eel species meant that growth models could not be readily calculated. However, because most New Zealand growth studies have shown that eel growth is generally linear (e.g., Chisnall & Hayes 1991; Chisnall & Hicks 1993; Jellyman et al. 1995; Beentjes et al. 1997), we used the mean of individual length-at-ages for each species, to provide an estimate of annual growth. Length-at-age = length (mm) – 70 mm (the estimated length of elvers at entry into the lake)/age.

Table 1 Total number of eels and proportion of longfinned eels (*Anguilla dieffenbachii*) (LF) collected from Aniwhenua Power Station, New Zealand, in autumn 1992, 1997, and 1998.

	Feb		Mar		Apr		May		Total	
	No.	% LF	No.	% LF	No.	% LF	No.	% LF	No.	% LF
1992	9	44	0	–	28	36	0	–	37	38
1997	0	–	44	14	62	31	0	–	106	23
1998	91	23	15	7	43	12	22	14	176	19

RESULTS

Migration

A total of 319 eels were collected at Aniwhenua Dam during the 3 years of monitoring. The number of eels collected more than doubled between 1992 and 1997 and increased again between 1997 and 1998 (Table 1). Six or more eels were collected on 17 out of the 34 occasions on which migrants were observed (50%). However, 87% of migrant eels were collected on these 17 nights.

Timing

No difference in migration timing was noted between the two eel species, with both longfinned and shortfinned eels present throughout the autumn migration period (Table 1). On the occasions when the net was set across the intake canal, migrants were first caught c. 0.5 h after dark. Shortfinned eels appeared first, with longfinned eels trapped mostly later in the night.

Two migrations occurred in both 1992 (mid February and early April) and 1997 (early March and early April) (Fig. 2). In 1998, a relatively warm and dry El Niño year, a major run was recorded towards the end of February. This was followed by at least eight minor runs of five or more eels, the last in late May (Fig. 2). In addition to these events, two major eel runs were recorded by station staff; 21–22 February, and 15 April 1994. In 1995, they reported a single large run between 30 March–1 April. Other runs occurred between 1993–96, but records were not kept.

Water level and rainfall

Examination of flow records from the mainstem of the Rangitaiki River (Wheao, Murupara, and Aniwhenua Power Stations) showed that operation of the dams had a major influence on river flows. Therefore, the only natural flow records available were from the Whirinaki River. Eel migration events for 1992, 1997, and 1998 were found to coincide with major increases in flows at this site (Fig. 2). Similarly, all migrations corresponded with rainfall events recorded at each of the three monitoring stations. The relationship with rain events recorded at Aniwhenua is shown in Fig. 3.

Moon phase, barometric pressure, and temperature

No relationships were found between eel migration and moon phase or barometric pressure. However, seasonal changes in temperature seemed to influence

eel migrations, with all events occurring after the summer peak but ending once temperatures dropped below 11°C (Fig. 3).

Size and age structure

Migrant shortfinned eels ranged between 540 and 1350 mm (980–5000 g weight), and longfinned eels between 950 and 1580 mm (3100–15000 g weight) (Fig. 4). Head width of these eels was significantly correlated to total body length: head width = 0.089 length - 51.858 ($n = 28$, $r^2 = 0.702$, $P < 0.001$) (Fig. 5). Age ranged between 7 and 30 years for shortfinned eels ($n = 32$) and 27–61 years for longfinned eels ($n = 18$) (Fig. 6).

The average growth rate was estimated at 85 mm per year for shortfinned eels and 32 mm for longfinned eels. Three growth band-width types (narrow, intermediate, and wide) were apparent in otolith sections. Longfinned eels had mostly narrow and some intermediate banding. In contrast, shortfinned eels had mostly wide banding.

DISCUSSION

Size and age structure

All eels caught by netting the intake canal or collected on the intake screens exhibited morphological indications of physiological changes which are distinguishing features of migrating eels, such as enlarged eyes, elongated head, and black pectoral fins (Hobbs 1947; Todd 1980). However, body colour, often used to characterise sexually mature migrants, was not markedly different from that of feeding eels which are regularly collected from the lake by eel fishermen. All eels collected at Aniwhenua Dam therefore appeared to be migrants, but, as noted by Burnett (1969) it would not have been possible to distinguish these eels from immature eels on the basis of body colour alone. Enlargement of the eye was a more accurate feature. Most eels were over 1000 mm in length, and very few had a head width below 30 mm (Fig. 5). We suspect that all eels with smaller head widths passed between the 30-mm spacing of the intake screens. Based on the size distribution given by Todd (1980) it is likely that migrant eels small enough to pass through the screens would be exclusively male shortfinned eels. However, very few small eels were caught in the 25-mm mesh capture net (all authors pers. obs.), suggesting that few migrant male shortfinned eels are produced in the catchment above Aniwhenua Dam, and that most of the eels migrating down stream were females.

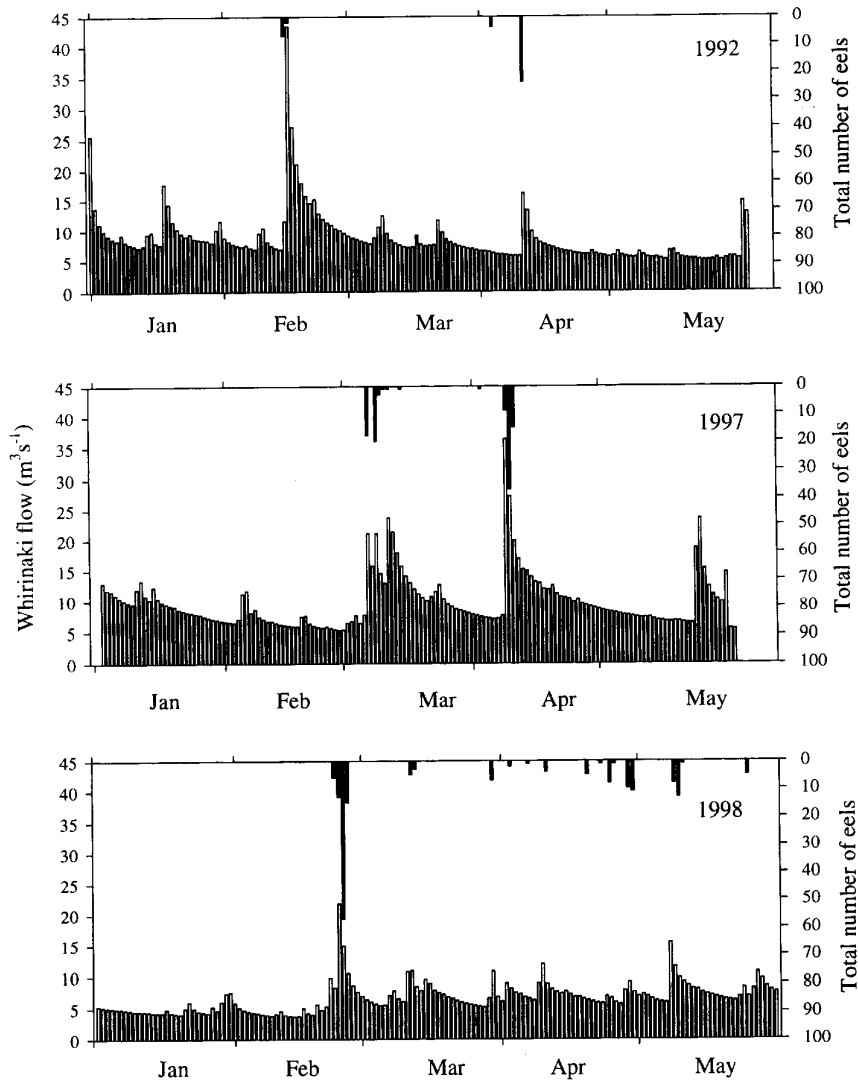


Fig. 2 Variation in flow (open bars) of the Whirinaki River (WS 15410), New Zealand, and number of mature migrant eels (*Anguilla* spp.) collected from Aniwhenua Power Station during autumn 1992, 1997, and 1998 (dark bars).

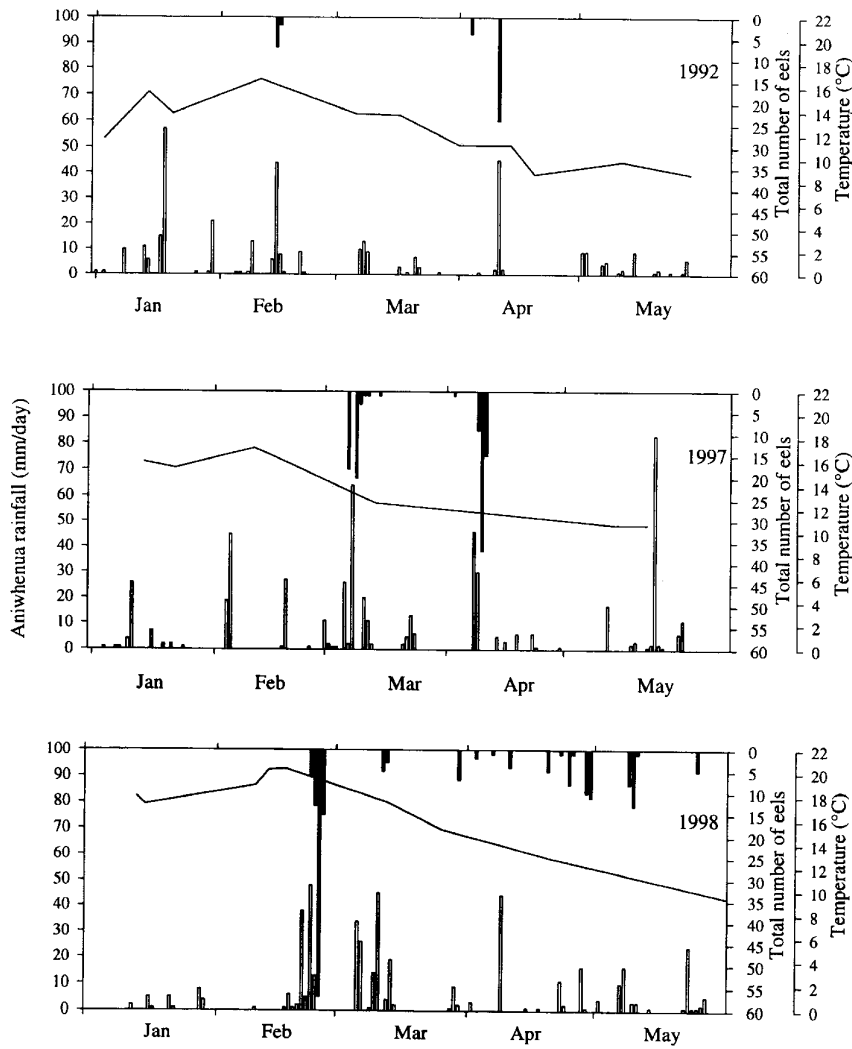


Fig. 3 Comparison of rainfall (clear bars) measured at Aniwihenua Power Station, New Zealand, with the number of mature migrant eels (*Anguilla* spp.) (dark bars) collected from the intake screens during autumn 1992, 1997, and 1998. Temperature records for the Whirinaki River (WS 15410) also shown.

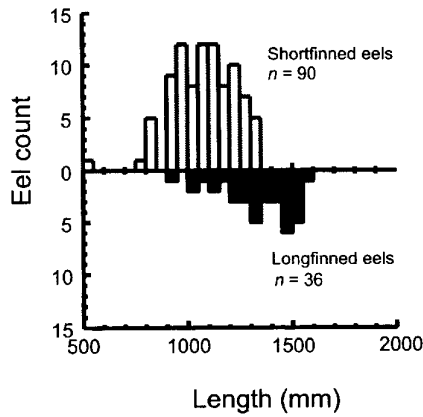


Fig. 4 Length distribution of mature migrant eels (*Anguilla* spp.) collected from the Aniwhenua Power Station, New Zealand, 1992-98.

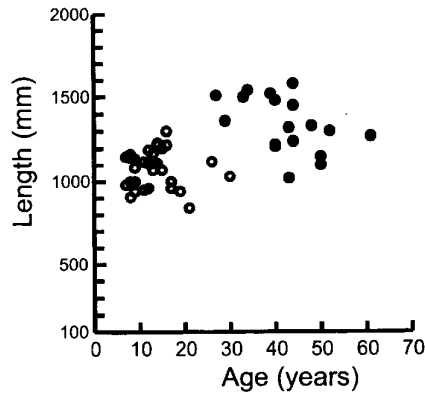


Fig. 6 Length-by-age distribution of mature migrant eels collected from the Aniwhenua Power Station, New Zealand, head pond, 1992-98. Closed circles = longfinned eels (*Anguilla dieffenbachii*) (n = 36), open circles = shortfinned eels (*A. australis*) (n = 90).

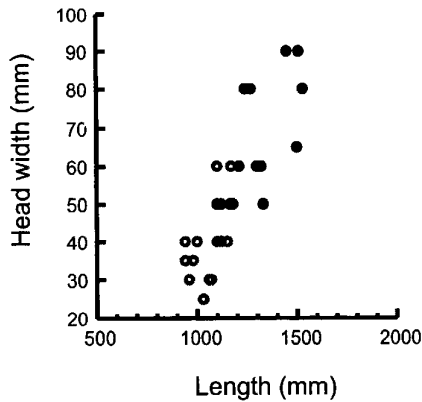


Fig. 5 Plot of head width against total length for eels collected from the Aniwhenua Power Station, New Zealand, 1992-98. Closed circles = longfinned eels (*Anguilla dieffenbachii*) (n = 18); open circles = shortfinned eels (*A. australis*) (n = 32).

The mean size of migrant female shortfinned eels caught at Aniwhenua Dam (mean total length 1085 mm) was large in comparison to published records for the species. For example, of the 256

female shortfinned eels examined by Hobbs (1947), the largest was 1067 mm, whereas Todd (1980) and Burnett (1969) reported 1024 and 810 mm maximum size respectively. Most longfinned eels collected at Aniwhenua Dam were also large, but within the size range reported by McDowall (1990). Nevertheless, the mean size of the longfinned females (1340 mm and 7003 g) was still in the upper quartile of the range given by Todd (1980).

Longfinned eels are one of the largest eel species in the world (Tesch 1977), and can attain a size of almost 2000 mm and more than 50 kg (Potts 1882; Cairns 1941; Graham 1956). Only two other freshwater Anguillid species approach this size, the Australasian longfinned eel (*A. reinhardtii*) (up to 1650 mm and 22 kg, McDowall 1996), and the Chinese spotted eel (*A. marmorata*) (up to 2000 mm and 28 kg, Williamson & Boetius 1993). Since the expansion of commercial eel harvesting in the 1960s, large females have become rare, and the eel catch is now almost entirely composed of immature individuals (Beentjes & Chisnall 1998). New Zealand eels are less fecund than American eels of the same length or weight, and longfinned eels are less fecund than shortfinned eels of the same size (Todd 1981a).

Considering the relatively high reproductive potential of larger female eels, particularly

longfinned eels, ensuring passage and survival of those that exist in catchments above dams may be important for the long-term future of the population.

The mean age of migrant female shortfinned eels from Aniwhehua Dam (13 years) was substantially younger than that reported by Todd (1980) for the Makara Stream near Wellington (19 years), Lake Onoko in the Wairarapa (23 years) or Lake Ellesmere in Canterbury, South Island (24 years). However, the mean age of the mature longfinned eels examined from Aniwhehua Dam (42 years) was similar to that estimated for forested streams in the central North Island (Chisnall & Hicks 1993), and that reported for Makara Stream (34 years) and Lake Ellesmere (49 years) by Todd (1980). These eels were nevertheless considerably younger than those found in Lake Rototiti, a cold, oligotrophic South Island lake, where maturity for female longfinned eels was estimated at 96 years (Jellyman 1995).

Many of the migrants from Aniwhehua not only grew to a large size but also displayed rapid growth. The younger age at maturity and estimated annual growth for shortfinned eels of 76 mm per year far exceeds the less than 50 mm per year recorded at other locations (Jellyman 1977; Chisnall 1989; Chisnall & Hayes 1991; Jellyman et al. 1995; Beentjes & Chisnall 1998). Indeed, it is amongst the fastest growth rates recorded for *Anguilla* species (cf. Helfman et al. 1984a,b; Berg 1990), and similar to that found by Balon (1975) for *A. nebulosa labiata* in Lake Kariba, a hydro-reservoir in Zambia. The rapid growth in the Rangitaiki catchment is probably linked to the low population densities and an abundant food supply (Beentjes et al. 1997; Chisnall et al. 1998).

Three growth-band width types were recognised in the otoliths examined. We attribute these to the three principal habitats available to eels in the Rangitaiki catchment: lake, river (mainly in pasture), and tributary (mainly in forested headwaters). Longfinned eels had mostly narrow and some intermediate banding, suggesting that most came from the upper forested catchment (see Chisnall & Hicks 1993). In contrast, shortfinned eels had mostly wide banding, characteristic of eel growth in lakes.

For longfinned eels, the recorded growth at Aniwhehua Dam was similar to that found by Chisnall & Hicks (1993) in productive streams running through pastures. Despite being slower than shortfinned eels, the growth of longfinned eels was still considerably faster than that expected from the indigenous forest catchment where the longfinned eels are thought to have spent most of their lives.

The age distribution of shortfinned eel migrants was commensurate with eels maturing from the first recorded manual elver releases in 1983. In contrast, the ages of most longfinned eels indicated entry to the catchment before the construction of Matahina Dam. Since the first enhancement trials were made, the numbers of elvers released into Matahina and Aniwhehua Dams have increased each year. Judging from eel catches obtained during a survey of the lakes (Beentjes et al. 1997), survival rates of the released elvers have been high and remarkable growth has been achieved. On this basis, the need to ensure downstream passage for the large number of eels about to mature is imperative.

Timing of migrations

In New Zealand, Cairns (1941), Hobbs (1947), Todd (1981a), and Palmer et al. (1987) reported that the seaward migrations of shortfinned eels take place from February to April, and those of longfinned eels from April to May. At Aniwhehua Dam, all migrations occurred from February to May and we were unable to detect any differences in migration timing between the two species. In contrast, Burnett (1969), who studied the downstream migration of eels in a tributary of the Waimakariri River (Canterbury region of the South Island), found that the migration ran from October to April, with longfinned eels appearing in the trap earlier in the season than shortfinned eels. Similarly, Todd (1981a) reported that on a tributary of the Rakaia River, Canterbury, the largest catches of downstream moving eels were made between October and November. Yet, in two coastal lakes, Lake Ellesmere in Canterbury and Lake Onoko in the North Island, Todd (1981a) found that migrating eels congregated at the outlet between January and June. From his observations, Todd (1981a) postulated that the earlier inland migrations, notably of longfinned eels, could be a mechanism to allow eels to reach the estuary in time to migrate out to sea at the same time as eels are attempting to leave lower catchments. Certainly the fact that eels caught by Burnett (1969) could only be distinguished from immature eels by their enlarged eyes suggest that they were less sexually advanced than the eels caught by Todd (1981a) in coastal areas.

If eels in the Rangitaiki River are migrating later than in other inland waters, it is possible that Lake Aniwhehua causes a migration delay. Deelder (1970) stated that migrations from shallow waters occur earlier than from deeper waters, and that eels congregate near the outlet of lakes waiting for a stimulus to migrate. It is therefore possible that

mature eels leave the upper catchment of the Rangitaiki River early, as in other inland catchments, but remain in Lake Aniwhenua until the necessary trigger (for example rainfall induced increased flows) causes them to move further downstream. Telemetry studies we are currently undertaking may elucidate this.

Temperature

As proposed by Lowe (1952), we found that in the Rangitaiki River most eels migrated downstream in autumn when temperatures were declining. There was no evidence of a threshold temperature initiating migrations as suggested by Tesch (1977). The migrations appear to have ceased once water temperatures fell below 11°C, a temperature limit close to that found by Todd (1981b) and Palmer et al. (1987), who worked in different catchments within New Zealand. Since factors such as day length are also decreasing during the migratory period, it is possible that the link to temperature is purely coincidental. However, given that migrations continued into May during 1998 but ended in April in 1992 or 1997 when temperatures were relatively cooler, it appears unlikely that day length is an influencing factor.

In Tasmania, Sloane (1984) also found that the migration of mature eels was arrested when mean daily temperatures fell below c. 12°C. The situation in both New Zealand and Australia is therefore different to that of Europe where the rate of descent is reported to reach a maximum at 9°C, with few eels migrating at temperatures above 18°C or below 4°C (Vøllestad et al. 1986).

Decreasing temperatures may induce mature eels to migrate down stream in search of warmer water. Haro (1991) reported that the final preferred temperature of mature Atlantic eels was between 17 and 20°C. Although no preferred temperature studies have been made with mature New Zealand eel species, they may also be inclined to migrate down stream in search of higher and more appropriate temperatures to continue gonad development. Gonadal development peaks at 26°C for shortfinned eels and 24°C for longfinned eels (Todd 1981c). The cessation of gonad development in New Zealand eel species held between 9 and 12°C (Todd 1981c), could explain the generally observed end of migration at c. 11°C.

Moon phase and light

It is well known amongst eel fishermen and Maori that mature eels migrate down stream almost entirely

at night, and when the moon is not shining (Best 1929). The phase of the moon probably influences eel migrations more through the effect of light rather than as a periodic effect, since eels will run on the full moon when the water is turbid (Lowe 1952). However, as in many studies (e.g., Eales 1968; Burnett 1969; Todd 1981b; Sloane 1984; Vøllestad et al. 1986) we found no relationship between lunar cycle and downstream movement with, in general, the largest runs occurring on dark stormy nights.

Flow

Increases in water level and flow associated with rainfall in the catchment were key factors determining the downstream migration of mature eels in the Rangitaiki River. The importance of water flow during the descent of mature eels is supported by a number of other studies (e.g., Cairns 1941; Lowe 1952; Burnett 1969; Todd 1981b; Vøllestad et al. 1986). The increased catches of eels when rivers are in flood suggests that flood events may stimulate eels poised to migrate, and increased flows may aid the migration mechanically (Lowe 1952). Between migration events, at the first stage of the migratory phase, Suedäng & Wickström (1997) have suggested that the maturation process can be temporarily arrested and feeding resumed. It is not known whether this occurs in New Zealand.

Migration predictions

The number of eels impinging on the Aniwhenua Power Station screens, appeared to increase between 1992 and 1998. This was probably the result of increased numbers of eels reaching maturity following the restocking of the lake with elvers. The need to predict migration accurately to implement mitigation action is therefore increasing. Although a relationship was found between high rainfall events and/or flow and eel migrations, it is important that a practical trigger be available. Since there can be some delay between rain events, increased river flows and the resulting eel migrations, any predictions based solely on flow would provide less warning of an impending eel run than rainfall, especially in a catchment where water flow is controlled by hydro-generation. Because of this, we chose to try to predict eel migration from rainfall recorded at Aniwhenua Power Station, i.e., records that station staff can readily access. Examination of rainfall records indicated that rain events were of short duration, never lasting more than 2–3 days. A 3-day cumulative total was therefore used. Furthermore, since eel migrations appear to be controlled by

temperature, we also restricted the analysis to the period between maximum summer river temperature and 11°C.

The result of the analysis indicated that, for the 3 years with accurate migration records, if a total of more than 30 mm of rain was used as a trigger, 8 out of the 17 days on which large migrations (>5 eels) occurred could have been predicted (Table 2). On these eight predicted days, 54% of the 319 eels recorded during the study were collected. Better predictions could be obtained using a lower rainfall trigger but this increased markedly the number of false predictions (that is the number of days on which a migration was predicted, but fewer than two eels were recorded). For example, although the same large migrations were predicted using a 30 or 40 mm rain trigger, the number of false predictions declined from 16 days with the 30 mm trigger, to 12 days for the 40 mm trigger. On the 25 days when migrations are predicted from a 40 mm trigger, 60% of the 319 eels recorded during the study were collected (Table 3). Therefore, until additional information becomes available, the use of the 40-mm trigger appears to be a reasonable compromise between protecting migrant eels and maximising power generation at Aniwhenua Dam.

Applying the 40-mm minimum rainfall trigger to the existing records, indicates that eel migrations in 1998 were less accurately predicted than those of 1992 or 1997 (Table 3). In 1998 there were few high rainfall events, and high water temperature extended the migration period. Therefore, it appears that when unusual climatic conditions occur in autumn there will be more occasions when eel migrations will be missed. Nevertheless, when using a 3-day cumulative rainfall of 40 mm for all the years for which migration records were noted (1992, 1994, 1995, 1997, and 1998), it would have been possible to predict 8 of the 12 large (>5 eels) migrations recorded. Over these 5 years, there were a total of 43 days when mitigation action would have been necessary (i.e., c. 9 days per year).

Results of this study indicate that rainfall triggers eel migration and can be used by dam operators as a means of determining when mitigation measures such as catch release operations, or flood gate opening need to be implemented. Trigger levels will be site specific and will be dependent on the level of escapement required. Based on the present study, it appears feasible to predict when the majority of migrant eels proceed down stream. Studies on cost-effective mitigation measures, including physical

Table 2 Number of days on which migrations predicted from rainfall coincided with eels (*Anguilla* spp.) recorded at Aniwhenua Power Station, New Zealand, 1992, 1997, and 1998 eel migration periods combined. Migration period was taken as the number of days between the summer peak water temperature and 11°C. Values in parentheses are the actual number of days on which the number of eels shown were recorded.

No. of eels	No. of days when 3 cumulative days of rainfall (mm) exceeds:					
	10	20	30	40	50	60
>5 (17 days)	17	11	8	8	6	6
2-5 (9 days*)	6	6	5	5	3	1
0-1 (213 days)	43	30	16	12	5	1
Total (238 days)	66	47	29	25	14	8

* One migration of five eels outside the 11°C water temperature limit.

Table 3 Number of days on which migrations predicted from 3 cumulative days of rainfall in excess of 40 mm coincided with eels (*Anguilla* spp.) recorded at Aniwhenua Power Station, New Zealand, 1992, 1997, and 1998 eel migration period. Migration period was taken as the number of days between the summer peak water temperature and 11°C. Values in parentheses are the actual number of eels recorded.

	1992 (37)	1997 (106)	1998 (176*)	Total (319*)
>5 eels	2 (31)	3 (66)	3 (76)	8 (173)
2-5 eel	1 (2)	1 (3)	3 (12*)	6 (17*)
0-1 eel	3	2	7	12
Total days	6 (33)	6 (69)	13 (88)	25 (190)

* One migration of five eels outside the 11°C water temperature limit.

and/or behavioural guiding systems, which allow mature eels to be transferred down stream uninjured, should now be undertaken. Ultimately this will ensure that highly productive hydro-reservoirs, which produce large, fast maturing females, can contribute to the recruitment of the two New Zealand eel species.

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