

Effects of turbidity on the feeding ability of adult, riverine smelt (*Retropinna retropinna*) and inanga (*Galaxias maculatus*)

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INTRODUCTION

The navigation, upstream movement, distribution, predator avoidance, and feeding behaviour of fish can all be affected by increased turbidity in rivers (e.g., Alabaster & Lloyd 1982; Bruton 1985; Lloyd et al. 1987; Newcombe & McDonald 1991; Gregory 1993; Waters 1995; Wood & Armitage 1997). In New Zealand, Ryan (1991) reviewed the effects of sediment pollution on the biota of streams and indicated that, although there was scope for concern, there was not enough information on the effects of suspended solids on native fish to protect the fish fauna.

Protection of indigenous freshwater fish in New Zealand rivers requires identification of the most sensitive species and knowledge of the turbidity limits at which important aspects of their life history are affected. Laboratory tank studies on the juvenile migratory stage of the most common native fish species revealed that the banded kokopu (*Galaxias fasciatus* Gray) was the most sensitive species (Boubée et al. 1997; Rowe & Dean 1998). It avoided turbid waters much over 20–25 Nephelometric Turbidity Units (NTU) whereas other species tolerated higher levels. Furthermore, its feeding rate was reduced in tanks when turbidities exceeded 20 NTU, whereas other species were only affected at much higher levels. Rowe et al. (2000) reported field data to confirm this sensitivity. They found that the reduction in occurrence of banded kokopu between clear and turbid rivers was much greater than for the other common native fish species. Furthermore, adults were less abundant in the remnant, pristine streams of turbid compared with clear rivers indicating that the upstream migration of juvenile recruits may be reduced in turbid rivers. Subsequently, experiments in a natural stream determined that the rate of movement of migrant banded kokopu declined as turbidity levels exceeded 25 NTU (Richardson et al. 2001).

Juvenile banded kokopu therefore provide a useful benchmark species for protecting other indigenous fish in New Zealand rivers. Limits set for

Abstract Laboratory tank experiments indicated that turbidity levels up to 160 Nephelometric Turbidity Units (NTU) did not reduce the feeding rates of adult smelt (*Retropinna retropinna* Richardson), or inanga (*Galaxias maculatus* Jenyns), on *Daphnia* sp. Mean feeding rates were higher for inanga than for smelt. However, the lower rates for smelt were related to the greater variation in individual feeding rates. Specifically, a few fish fed intensively while most did not. As the feeding ability of both species was unaffected by turbidity levels up to 160 NTU, they were less sensitive to turbidity than juvenile banded kokopu (*Galaxias fasciatus* Gray). Juvenile banded kokopu should therefore be used as the benchmark species for setting turbidity guidelines to protect native fish in rivers where this species is present. Both juvenile and adult rainbow trout (*Oncorhynchus mykiss* Richardson) appear to be more sensitive to turbidity than adult inanga and smelt, so should be used as benchmark species in all other waters.

Keywords Retropinnidae; Galaxiidae; NTU; suspended solids; turbidity guidelines; rainbow trout; banded kokopu; rivers

banded kokopu should provide adequate protection for other indigenous species. However, juvenile banded kokopu migrate upstream mainly between September and November (McDowall & Eldon 1980; Stancliff et al. 1988; Rowe et al. 1992) and are rare in most rivers at other times of the year. Moreover, this species does not occur in some Hawkes Bay rivers, nor in many river catchments along the eastern coastline of the North and South Islands (McDowall 1990). This is mainly because streams in pasture catchments provide poor habitat for this species (Rowe et al. 1999) and pasture has largely replaced native forest in these areas. As turbidity limits for juvenile banded kokopu are not relevant for times and places where they are absent, other relatively sensitive fish species need to be identified to provide turbidity limits at such times and places.

Adult smelt and inanga inhabit the lower reaches of most New Zealand rivers (New Zealand Freshwater Fish Database) and such reaches are often more turbid than the upper reaches. Both species have relatively large eyes (McDowall 1990) and are likely to be mainly visual feeders (Cadwallader 1975; Ali et al. 1990). They would therefore be expected to be affected by turbid conditions more than other native species (e.g., Anguillidae, Gobidae) which are mostly benthic feeders. Indeed, Rowe et al. (2000) found that adult smelt and inanga were less common in turbid rivers than in clear rivers. Furthermore, correlations between turbidity level and the mean feeding rates for juvenile migratory smelt and inanga (i.e., $r = -0.81$ and -0.94) were both negative and higher than for other native fish species (Rowe & Dean 1998). These data suggest that smelt and inanga may be the next most sensitive native species to be affected by elevated turbidity levels in rivers.

Rainbow trout (*Oncorhynchus mykiss* Richardson) may also be sensitive to turbidity. A number of studies have investigated the effects of turbidity on this species (Newcombe & McDonald 1991) and it too may be a suitable benchmark species. However, if either smelt or inanga proved to be more sensitive than juvenile rainbow trout, then they should be used for setting turbidity guidelines to protect indigenous fish in New Zealand rivers.

To find the next most sensitive species after banded kokopu, we investigated the effects of turbidity on the feeding ability of inanga and smelt. Specifically, we carried out tank experiments to determine whether turbidity levels up to 160 NTU could reduce the ability of these fish to feed on live

prey. Their natural prey in rivers includes mainly insect larvae, crustacea, and terrestrial insects (Boubée & Ward 1997; Richardson et al. 1997) which are taken on macrophytes, in mid water, and at the water surface respectively. However, although vision is likely to be the dominant means of prey location for inanga and smelt, some native fish use their lateral line senses to detect prey (e.g., Montgomery & Milton 1993; Halstead 1994; Rowe 1999), and the switch from small, active, limnetic prey, to larger, less mobile, benthic prey by a number of fish species in turbid waters (Tippets & Moyle 1978; Rowe 1984; Hecht & van der Lingen 1992) may be related to greater dependence on lateral line detection in turbid waters. To minimise the confounding effects of such non-visual prey detection on feeding in turbid waters, we selected a small, mid water planktonic crustacean, viz. *Daphnia*. Because of their small size (diam. 1 mm), their mid water (as against benthic) distribution, and their movement, *Daphnia* would be more difficult to detect with non-visual senses than natural prey such as dipteran and chironomid larvae. They can be expected to provide a good test of any impairment in visual feeding ability caused by increased turbidity.

In this paper we report the results of tests to determine the effects of turbidity on the ability of adult inanga and smelt to feed on *Daphnia* sp. We then compare the sensitivity of these fish with that of banded kokopu and rainbow trout from studies reported in the literature.

METHODS

Test fish

Adult smelt and inanga were collected from the lower Waikato River in May and June and transported to the laboratory where they were placed in tanks in a light and temperature controlled room (constant 15°C, photoperiod 12 L:12 D). We added filtered sea water (10%) to reduce the incidence of diseases such as white spot and fungal infection which can infect these fish shortly after capture. Although a few fish died during the first 24 h after capture, no further losses occurred. Fish were fed on live *Daphnia* and acclimated to laboratory conditions for 5 or more days before experiments were started. Preliminary tests indicated that 17 h with no food was needed before the stomach was fully emptied so fish were not fed for 24 h before the experiments began.

Apparatus and test protocol

Feeding trials were carried out in a constant temperature and light controlled room during the middle of the day. They were conducted in six polypropylene tanks (33 × 57 × 24 cm) containing 36 litres of water. The sediment used was from the bed of the Waihi Stream in the Waikato River catchment. Physical characteristics are provided by Boubée et al. (1995), and the experimental protocol is described in Rowe & Dean (1998). Basically, fish were placed in the test tanks and acclimated overnight. A measured amount of the stock solution containing a high concentration of suspended solids was added to each tank to produce the desired turbidity level, and an equal quantity of water removed to ensure water volume remained constant. The fish were allowed to acclimate to the test turbidity level for at least an hour before the food was added and the fish were then allowed to feed. Feeding was terminated by removing all fish from the tanks after 30 min.

Turbidity levels tested were 10, 20, 40, 80, and 160 NTU. The remaining tank was used as a clear water (2–4 NTU) control. Turbidities were measured using a Hach 18900 turbidometer in each tank before and after each experiment. Although light aeration was used to maintain dissolved oxygen levels in each tank and to keep the suspended solids in solution, NTU values declined over time. However, the difference was negligible and was less than 3.5% up to the 80 NTU level, and at 160 NTU it averaged 7.2% (range 4.7–11.1%) for smelt and 4% (range 1.8–5.8%) for inanga.

Four to five fish were used in each tank and three replicate trials were run with inanga, and four with smelt. *Daphnia* were sorted using a 1 mm sieve and were all within the range 1–2 mm. The number of *Daphnia* which individual smelt and inanga could eat in 30 min in clear water was determined. As inanga consumed more *Daphnia* than comparable sized smelt, c. 250 *Daphnia* were placed into each tank at the start of each experiment for smelt, and c. 500 were used for the inanga trials. At the end of each trial, each fish was quickly frozen until stomach contents could be examined. The buccal cavity and oesophagus were checked for *Daphnia* and any that were present there were added to those from the stomach. In general, the ingested *Daphnia* were relatively intact so that individual body carapaces could be counted. Where some individuals had been macerated and doubt arose over the number of bodies present, eye spots were used to resolve numbers present.

Data analysis

Relationships between feeding rate and fish size were examined using ANOVA as fish size can be expected to influence feeding rate and may be a covariate influencing effects of turbidity on feeding. Once size effects were excluded, effects of turbidity on feeding rate were examined using two-way ANOVA with turbidity and trial number as categorical variables (Wilkinson et al. 1994).

RESULTS

The mean length of the inanga tested was 62.1 ± 1.1 mm (range 45–85 mm) and for smelt was 69.4 ± 0.8 mm (range 50–100 mm) (Fig. 1A,B). Although the difference in mean size between these species was significant (ANOVA, $F = 27.2$, $P < 0.001$), it was small (7 mm) and there was no relationship between fish size and feeding rate for either species (Fig. 2A,B). Correlation coefficients were both low ($r = 0.03$ for inanga and -0.25 for smelt) and were not significant ($P > 0.10$) so the larger fish did not have a higher feeding rate.

Inspection of the raw data indicated that variation in individual feeding rates (number of prey fish⁻¹) was relatively high for both inanga (mean CV of 46.2%) and smelt (mean CV of 57.4%). This was due in part to some fish not feeding (12.3% of inanga and 7.2% of smelt). For smelt, this was related to fish size as a relatively high proportion (55%) of the largest smelt (>80 mm) did not feed compared with those under 80 mm (3%). Turbidity is unlikely to have suppressed the appetite of these larger fish as a lack of feeding occurred in large fish in three of the four control groups which were not exposed to turbid conditions. For inanga, failure to feed was not related to fish size. All fish that were not feeding were excluded from further analysis on the assumption that their appetite was suppressed by factors other than turbidity.

For inanga, there was no significant difference in the mean size of fish between tanks within each trial or between trials (ANOVA, $F = 1.09$, $P = 0.39$), and there was no overall relationship between mean feeding rate and turbidity (ANOVA, $F = 0.70$, $P = 0.78$). However, mean feeding rates were negatively correlated with turbidity level in all three trials ($r = -0.36$, -0.50 , and -0.83 respectively) and in one of these the correlation was significant ($P < 0.05$). Therefore, the wide variation in individual feeding rates may have masked a small overall effect of turbidity on the feeding of this species.

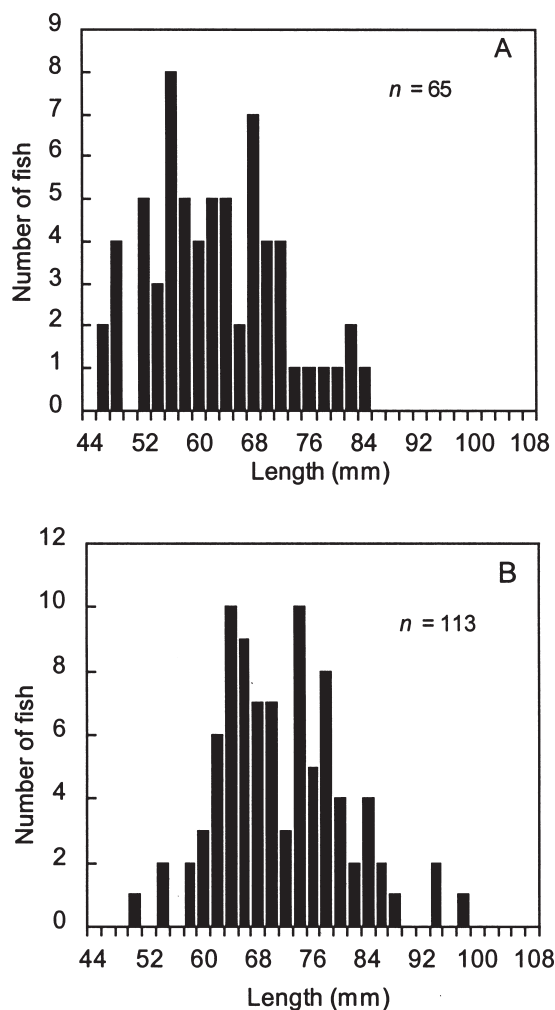


Fig. 1 Length-frequency distributions for the fish used in the feeding trials: **A**, inanga (*Galaxias maculatus*) and **B**, smelt (*Retropinna retropinna*).

The size of smelt did not vary significantly between tanks or trials (ANOVA, $F = 0.85$, $P = 0.63$) and mean feeding rates for smelt were also not influenced by turbidity up to 160 NTU (ANOVA, $F = 0.42$, $P = 0.97$). Mean feeding rates for smelt in the four trials were not consistently or significantly related to turbidity ($r = -0.58, 0.28, -0.14, 0.57$ respectively).

The overall mean feeding rate for inanga dropped by 29%, from 4.9 prey min^{-1} in clear water to 3.5 prey min^{-1} at a turbidity of 20–160 NTU (Fig. 3A). In contrast, the overall mean feeding rate for smelt rose from c. 1.2 to 1.3 prey min^{-1} (Fig. 3B).

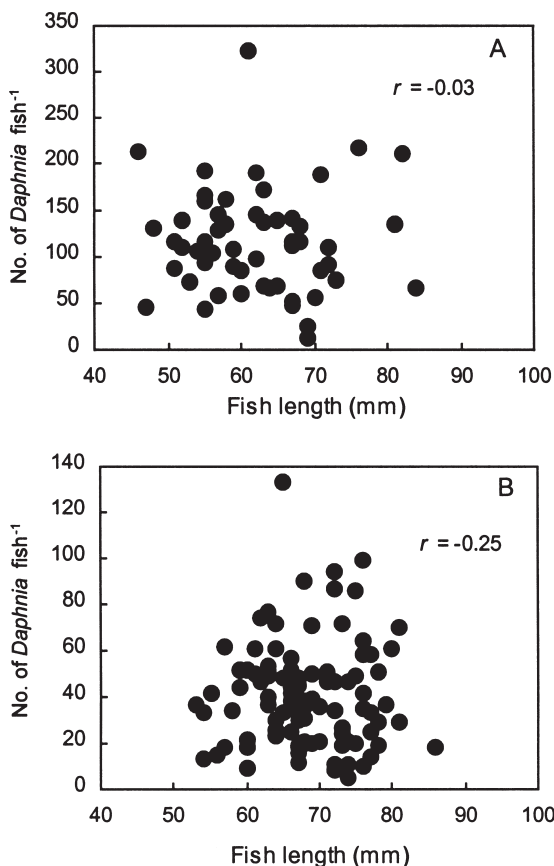


Fig. 2 Relationship between number of prey consumed and fish length for: **A**, inanga (*Galaxias maculatus*) and **B**, smelt (*Retropinna retropinna*).

The overall mean feeding rate differed between these two species (ANOVA, $F = 149$, $P < 0.001$) and was greater for inanga (mean 3.9 ± 0.25) than for smelt (mean 1.3 ± 0.08), despite the larger mean size of smelt.

CONCLUSIONS

The ability of adult smelt and inanga to feed on *Daphnia* was not significantly reduced by turbidity levels up to 160 NTU. Feeding rates may well be reduced at higher levels, however, such conditions are not common or prolonged in many New Zealand rivers (Rowe et al. 2000; NIWA unpubl. data). Furthermore, these fish feed on a wide variety of surface and benthic invertebrates in both turbid and clear conditions (Forsyth & James 1988; Hayes &

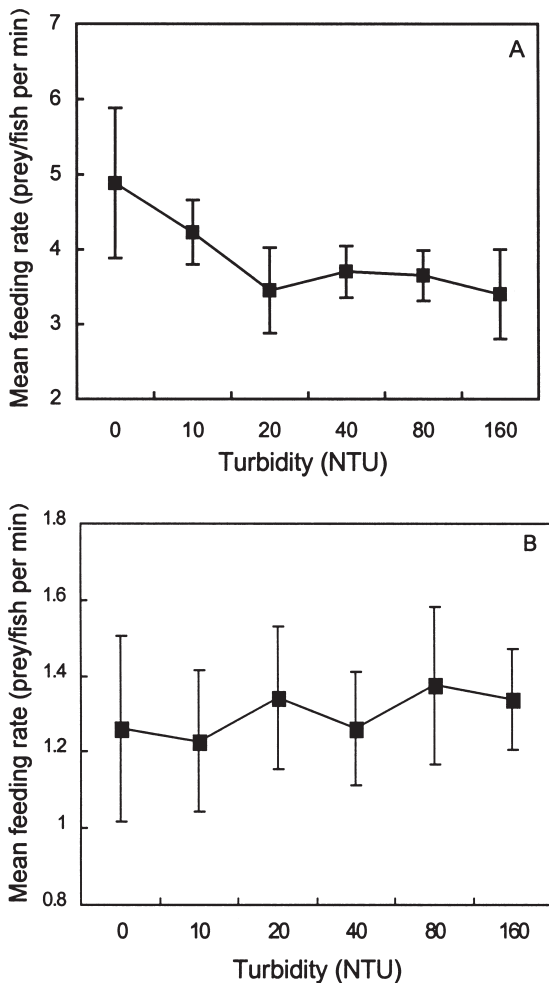


Fig. 3 Overall mean feeding rates (± 1 SE) at each turbidity level for: **A**, inanga (*Galaxias maculatus*) and **B**, smelt (*Retropinna retropinna*).

Rutledge 1991; Boubée & Ward 1997; Richardson et al. 1997). They are therefore well adapted to feeding on a range of prey species in a variety of water quality conditions, and turbidity levels up to 160 NTU are unlikely to prove a major problem for the feeding of these species in natural waters. However, this should not be taken to mean that their abundance will be maintained in turbid rivers. Increased siltation of rivers may reduce food supplies and/or spawning sites and reduce abundance even though turbidity does not affect feeding (Rowe & Dean 1998).

A high proportion (75%) of the larger (>80 mm long) smelt were not feeding and we noted that 67%

of these fish contained either ripe eggs or milt. The feeding rates of mature fish (i.e., with well developed gonads) are often lower than those of immature fish (Metcalf et al. 1986; Rowe & Thorpe 1990; Kadri et al. 1995). The maturation of some smelt may therefore have reduced their feeding rates and this could explain the lack of feeding in some of the larger smelt.

Mean feeding rates for inanga were generally higher than for smelt. This difference was not related to fish size, nor to a longer period of feeding, and it occurred irrespective of turbidity level. It therefore represents either a species-specific difference in feeding efficiency such that inanga consumed more *Daphnia* than smelt over the duration of the trials, or an earlier satiation of smelt, or behavioural interactions among the smelt such that feeding was suppressed in a high proportion of these fish.

Suppression of feeding in a high proportion of smelt seems more likely as there was much wider variation in the feeding rates of smelt than inanga. We noticed that there was often a large difference between the number of prey consumed by a few smelt in each tank and the number consumed by the remaining fish. In a third of all tests with smelt ($n = 24$), the fastest feeding individuals consumed 30% more *Daphnia* than any other fish, whereas in half the tests, these fish consumed 20% more *Daphnia* than all other fish. Thus, there was a strong tendency for a few smelt in each tank to feed rapidly and ingest a high number of prey while the rest fed on comparatively few *Daphnia*. Initially, this difference can be expected to be related to differences in physiology (e.g., appetite) or behaviour (e.g., activity level) between individual fish. However, as prey numbers decline, a reduced encounter frequency can be expected to compound these initial differences.

Although results of the ANOVAs showed that there was no significant effect of turbidity up to 160 NTU on the feeding rate of either inanga or smelt, there was a consistent decline in the mean feeding rate of inanga with turbidity in each trial. This did not occur for smelt and indicates that inanga may be more sensitive to turbidity than smelt. However, the overall reduction in mean feeding rate from 4.9 to 3.5 prey min^{-1} for inanga is unlikely to be ecologically significant.

Inanga and smelt are not as sensitive to turbidity as migrant banded kokopu which showed reduced feeding at 20 NTU (Rowe & Dean 1998). Nor are they likely to be as sensitive to turbidity as rainbow trout. Barrett et al. (1992) found that turbidity levels of 15 NTU reduced the reactive distance of rainbow

trout by 45%, whereas at 30 NTU it was reduced by 80%. This result indicates that the search volume for trout feeding on prey such as *Daphnia* could be expected to be significantly reduced by turbidities of 15–30 NTU. However, a reduced reactive distance or search volume may not result in reduced feeding or a lower growth rate. Fish may change their feeding behaviour to compensate for a reduced visual field. Therefore, effects of turbidity on feeding and growth rate also need to be examined.

Feeding rates for juvenile rainbow trout in turbid waters have not been reported yet, but those for the closely related Lahontan trout (*Oncorhynchus clarki henshaw*) on *Daphnia* declined (by c. 50%) at turbidities of 25 NTU (Vinyard & Yuan 1996). Over periods of 160 days or more, growth rates for rainbow trout were reduced by exposure to 50 mg litre⁻¹ of suspended sediment from coal ash (Herbert & Richards 1963). Similar results were obtained with lime hydroxide suspensions (Sykora 1972). The relationship between suspended solids concentration (SSC) for placer-mining suspensions and turbidity (Lloyd et al. 1987) indicates that an SSC of 50 mg litre⁻¹ would produce a turbidity of c. 48 NTU. Growth rates may therefore be limited by turbidity levels over 48 NTU over long periods. However, preliminary data on rainbow trout parr (D. K. Rowe unpubl. data) indicate that feeding rates are not greatly affected by turbidities from lake bed sediments up to at least 160 NTU.

Turbidity may also influence fish distribution. Avoidance behaviour for juvenile rainbow trout was recorded at SSCs between 66 and 100 mg litre⁻¹ depending on the type of sediment used (Newcombe & McDonald 1991). This equates to NTU levels of c. 23–63 NTU (Lloyd et al. 1987). The turbidity level inducing an avoidance response by smelt is unknown, but that for inanga was over 400 NTU (Boubée et al. 1997). Juvenile trout therefore appear to be more sensitive to turbidity than either smelt or inanga.

Although the precise levels of turbidity that will affect juvenile trout in the wild are uncertain, adult rainbow trout appear to be more sensitive than juveniles. Field evidence that lower turbidity levels affect adult rainbow trout behaviour was provided by Dorgeloh (1995). He found that the trout in a South African reservoir avoided waters with a mean turbidity of 28 NTU and concentrated in clear-water sections of the reservoir where turbidities were around 10 NTU. Moreover, Rowe (1984) found that the main prey for adult rainbow trout in New Zealand lakes changed from schooling smelt in the limnetic

zone to solitary bullies in the benthic zone when secchi disc water transparency declined below c. 3 m. This change may have been related to changes in prey abundance as much as to reduced water clarity, but similar results were obtained for rainbow trout feeding on invertebrate drift versus benthic prey in turbid rivers (Tippetts & Moyle 1978). A secchi disc of 3 m corresponds to a turbidity level of less than 10 NTU (Maslin 1994; R. Davies-Colley pers. comm.) so adult trout feeding behaviour and distribution in the wild may well be affected by turbidities much over 10 NTU.

As rainbow trout are present in many New Zealand rivers throughout the year, and appear to be more sensitive to turbidity than inanga and smelt, they are likely to provide a better species than either smelt or inanga on which to base turbidity guidelines to protect freshwater fish where juvenile banded kokopu are absent. We therefore consider that turbidity guidelines should be set for banded kokopu in waters and at times where their migrations occur, with guidelines set for rainbow trout in remaining locations and times. This strategy will protect most indigenous fish as well as rainbow trout in New Zealand rivers. However, despite a large number of overseas studies on the effects of turbidity on rainbow trout, it appears that good data on the turbidity levels affecting this species in the wild are still lacking.

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