Habitat Preferences
of Brown Mudfish
(*Neochanna apoda* Günther)

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Natasha Katherine Petrove

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"Ironically, it is often not the big and beautiful creatures but the ugly and less dramatic ones which we need the most"

- Douglas Adams, *Last Chance To See*

Abstract

Brown mudfish (*Neochanna apoda*) are one of five non-diadromous mudfish species endemic to New Zealand. They are considered a 'vulnerable' species under human induced gradual decline (Hitchmough et al., 2007; IUCN, 2009). Brown mudfish are the most widely distributed *Neochanna* species in NZ, however, their populations within this range are patchy. A lowland swamp fish species, brown mudfish are historically noted to be found in forested wetland areas, such as kahikatea (*Dacrycarpus dacrydioides*) swamp-forest. Clearance, drainage and modification of around 90% of lowland wetland areas in NZ (McGlone, 2009) has resulted in habitat loss, with populations now found in the widest range of habitat types of all the NZ *Neochanna* species.

Habitat suitability is hard to assess for brown mudfish as they subsist in such a wide range of habitats. Habitat preferences were investigated to determine which habitat characteristics were most influential for brown mudfish. Geographic Information Systems (GIS) data and nationwide records from the New Zealand Freshwater Fish Database (NZFFD) were used for this analysis. Substrate type, rainfall, shading and low slopes were important aspects for sites with brown mudfish present. Sites without mudfish had steep slopes, high elevation catchments, a large substrate size and warm temperatures. Historical land cover and shading were also important in determining brown mudfish distribution. A local study found some GIS variables to be useful for predicting brown mudfish presence, but on-site measures of ephemerality and flowing water were the most important habitat features for brown mudfish.

Brown mudfish are not often found with other fish species and are considered poor competitors (O'Brien and Dunn, 2007), suggesting that presence of other fish species influences brown mudfish presence. Continued wetland modification increases the probability of brown mudfish encountering other species. The ability of brown mudfish to detect shortfin eels (*Anguilla australis*; a natural predator), and the response made once detection occurred, was investigated. Mudfish were presented with a choice between eel odour or neutrally odoured water. The response made varied with mudfish size. The varying responses indicate that brown mudfish are able to detect shortfin eels, and that this is likely to be a learned behaviour.

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Acknowledgements

Finally, many thanks to all the fish – muddies and others – who donated their time and effort to aid in the research and completion of this thesis (to the mudfish especially, who actually gave me some *statistically significant* results), and without whom this project would not have been possible.

Top photo taken by Stella McQueen. All other photos taken by Natasha Petrove

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Chapter One

Introduction

Adult brown mudfish (*Neochanna apoda*) in aquarium   Photo: Stella McQueen

Chapter 1: Introduction

Brown mudfish (*Neochanna apoda*) are one of five non-diadromous mudfish species endemic to New Zealand. They are a small, elongate fish, found mainly in ephemeral wetlands and slow-flowing swampy streams throughout the lower North Island, and on the West Coast of the South Island (Eldon, 1978; McDowall, 2006; O'Brien and Dunn, 2007). Brown mudfish are currently recognised as vulnerable on the IUCN red list of threatened species (IUCN, 2009), and as a chronically threatened species in human induced gradual decline under the New Zealand 'threat of extinction' classification system (Hitchmough et al., 2007). They are under threat from both habitat loss and degradation as a result of drainage schemes, irrigation and development of wetlands. Though currently the most widely spread of the New Zealand mudfish species, the loss of around 90% of swampland in New Zealand (McGlone, 2009) has resulted in severe population reduction for brown mudfish. Continued loss of both actual and potential mudfish habitat is still the biggest cause of decline for all *Neochanna* species in New Zealand (Department of Conservation, 2003; Park, 2002). Despite this, brown mudfish persist in many small wetlands within forest fragments. However, long term survival of the species is precarious as these wetlands are under significant threat from drainage and development as well as further degradation caused by run-off from surrounding land (McDowall, 2006; O'Brien and Dunn, 2007).

The common name 'mudfish' arose due to frequent findings of these fish in the damp mud when land was drained and/or cleared (Günther, 1867; Hector, 1869; Roberts, 1872b). The genus name '*Neochanna*' was given to mudfish by Günther (1867) with '*neo*' meaning 'new', while '*channa*' relates to an Asian fish genus, which contains a species able to tolerate extended periods of drought (O'Brien and Dunn, 2007). The species name '*apoda*' means 'without a foot', and refers to the absence of pelvic fins in this fish. Brown mudfish are cylindrically shaped, with long tubular nostrils and fleshy dorsal and anal fins. They are the most eel-like in appearance of the *Neochanna* species, with the dorsal and anal fins nearly confluent with the caudal fin. Individuals vary greatly in colour, ranging from a dark grey-brown to a lighter, more

sandy brown, and they are often patterned (Figure 1.1). This cryptic colouring is an effective form of camouflage in their natural swamp habitats (Eldon, 1978; Ling, 2001; McDowall, 1980).

Figure 1.1: Adult brown mudfish (*Neochanna apoda*) in natural kahikatea swamp forest habitat, Nga Manu Nature Reserve (Photo: Peter McKenzie)

Brown mudfish usually grow to around 150 mm, but can reach up to 200 mm in length (Eldon, 1978; McDowall, 1980; Phillipps, 1923). They are thought to live for at least 8 years, and possibly longer, although there is limited data regarding the longevity of the species (Department of Conservation, 2003; Eldon, 1978). Adult mudfish are generally nocturnal, whereas fry and juveniles are active during both the day and night. Fry are free swimming, and do not exhibit shoaling behaviour. As they grow bigger they become more cryptic, spending more time in the leaf litter at the bottom of the pools with increased tendency towards nocturnal activity. The fry generally reach a length of approximately 70 mm by the time of their first aestivation (Eldon, 1978; McDowall, 2006).

While brown mudfish are frequently the only species found in their habitat (McDowall, 2006), other species they have been associated with include koura (freshwater crayfish, *Paranephrops planifrons*) (Eldon, 1968; O'Brien and Dunn, 2007), shortfin and longfin eels (*Anguilla australis*/*A. dieffenbachii*) (Eldon, 1968, 1978) and inanga (*Galaxias maculatus*) (pers obs; O'Brien and Dunn, 2007). Other galaxiid species, including giant kokopu (*G. argenteus*), banded kokopu (*G. fasciatus*) and common

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and upland bullies (*Gobiomorphus cotidianus*/*G. breviceps*) have at times also been found with brown mudfish (O'Brien and Dunn, 2007). Habitat loss and degradation throughout New Zealand has resulted in brown mudfish being pushed into more marginal habitats. This has increased interconnectedness with other habitats, such as nearby streams, where other species are abundant. With this greater connectivity, other species are more likely to be able to invade mudfish habitat, which increases the probability of interactions with these species.

The patchy population structure of brown mudfish is at odds with their widespread distribution, which suggests populations should be more numerous. While Phillipps (1923) expressed doubt about the long term survival of the species with loss of forest habitat, current reports indicate that brown mudfish can be found in a wide variety of habitats. Data on brown mudfish habitat preferences is limited, with reports focussing on where they are found, rather than their ideal habitat type.

The aim of this thesis was to investigate habitat preferences for brown mudfish. The main focus was on mudfish populations in the Manawatu and Kapiti Coast, but information was also drawn from nationwide records in the New Zealand Freshwater Fish Database and used GIS data to obtain detailed information on physical habitat features. As brown mudfish are not often found with other fish species, presence of other species may be important in determining the suitability of a habitat for brown mudfish. Interactions of brown mudfish with shortfin eels, their natural predators, were investigated in order to see if brown mudfish exhibited predator avoidance behaviour. Response of mudfish to allelomones emitted by an eel was observed in order to see firstly whether brown mudfish could detect, and secondly if they would respond to, odour from a predator. Information on these two points will help expand knowledge about habitat suitability for brown mudfish, which will aid in the management of this species.

1.1 Study Sites

During the course of this study mudfish trapping was undertaken at several sites in the lower North Island (Figure 1.2). The six sites where mudfish were caught comprise a variety of habitat types, but share some common features. All sites are ephemeral, and in most instances the water is shallow (less than 0.5 metres in depth). All sites contained few or no other fish species. Three of the sites were within native podocarp swamp forest, and had a thick substrate layer of peaty mud, with thick coatings of leaf debris on the surface. The remaining sites each have different defining features, however, at all three of these sites the substrate was primarily relatively compact, bare mud, distinct from the thick peat of the forest sites.
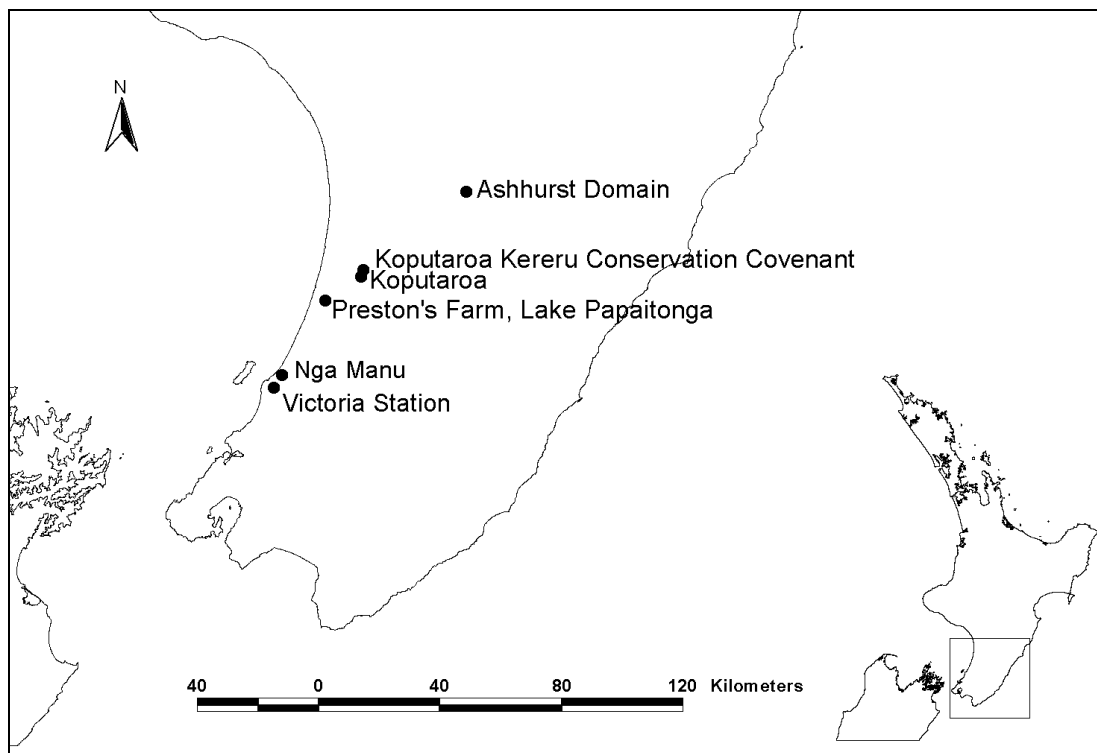
Figure 1.2: Location of the six sites where brown mudfish were trapped during the course of this study

1.1.1 Ashhurst Domain, NZMG 2744300E 6096600N

Ashhurst Domain is one of four city parks owned by the Palmerston North City Council. Native podocarp swamp forest covers part of the reserve (Figures 1.3a, 1.3b). The wetland contains emergent grasses and has a dense surface cover of the aquatic plants *Azolla* and *Lemna*. At this site the water exceeded one metre in places (this is unusual for mudfish, which are usually found in water no greater than 0.5 metres in

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depth; O'Brien and Dunn, 2007). No other fish species were found in this area, but eels are known to be abundant in a permanent part of the wetland nearby.

Figures 1.3a and 1.3b: Brown mudfish habitat at Ashhurst Domain. Water surface is thickly coated with *Azolla* and *Lemna* (Photos: Natasha Petrove)

1.1.2 Koputaroa, NZMG 2709900E 6068400N

This site is situated across the railway line from the Department of Conservation (DOC) reserve at Koputaroa. Vegetation consists of willow trees with emergent grasses, sedges and shrubs (Figures 1.4a, 1.4b). Fallen logs and branches provide cover, but otherwise there is little leaf litter covering the substrate. Few other fish species are present in the area, however inanga and common bullies were each found on one occasion. Eels are known to be present in a nearby stream. While previous surveys have found mudfish within the DOC reserve, which contains a remnant stand of kahikatea, only one was trapped there during the course of this study.

Figures 1.4a and 1.4b: Brown mudfish habitat under willow trees at Koputaroa (Photos: Natasha Petrove)

1.1.3 Koputaroa Kereru Conservation Covenant, NZMG 2710400E 6069400N

Located northeast of the DOC reserve at Koputaroa, this is an open grassland area (Figure 1.5a), which becomes inundated with water from a nearby stream. Water levels here fluctuate greatly; on one occasion the water level decreased twenty centimetres in depth over one trap night. Mudfish were trapped under willow trees (Figure 1.5b) where the substrate was grass and bare mud. No other fish species were found in the same area.

Figures 1.5a and 1.5b: Brown mudfish habitat at Koputaroa Kereru Conservation Covenant. Arrow in fig 1.5b indicates location where mudfish were found (Photos: Natasha Petrove)

1.1.4 Nga Manu Nature Reserve, NZMG 2683500E 6036300N

Nga Manu is a thirteen hectare reserve in Waikanae. Remnant kahikatea (*Dacrycarpus dacrydioides*) swamp forest contains interconnected forest pools populated by mudfish (Figures 1.6a, 1.6b). Shortfin eels are the only other fish species found in the swamp forest. Other galaxiid fish and dense eel populations exist within man-made lakes, and a stream which runs through the swamp forest.

Figure 1.6a: Podocarp swamp forest at Nga Manu; brown mudfish are found in pools of water amongst this vegetation, as seen in **1.6b** (Photos: Rhys Mills)

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1.1.5 Victoria Station, NZMG 2680800E 6032300N

This remnant lowland swamp forest south of Waikanae contains interconnected pools (Figures 1.7a, 1.7b). The peaty mud layer is thick, while the water is shallow; no greater than five centimetres in depth at the time of trapping. No other fish species were found in this area.

Figure 1.7a: Podocarp swamp forest at Victoria Station. **1.7b** shows shallow forest pools at Victoria Station which provide habitat for brown mudfish (Photos: Natasha Petrove)

1.1.6 Lake Papaitonga / Preston's Farm, NZMG 2697900E 6060800N

Brown mudfish were found in two ditches draining farmland on the north-western edge of Lake Papaitonga. One of these ditches was heavily choked with water celery (*Apium nodiflorum*; Figure 1.8a) and *Azolla*. The second ditch contained open water with flax, rushes and other swamp plants growing along the edges (Figure 1.8b). Water here was greater than one metre in depth. Shortfin eels and large numbers of inanga were found at this site.

Figures 1.8a and 1.8b: Brown mudfish habitat at Preston's Farm, Lake Papaitonga (Photos: Steve Aiken)

Chapter Two

Literature Review

General biology of the *Neochanna* species

Adult brown mudfish (*Neochanna apoda*) in aquarium   Photo: Stella McQueen

Chapter 2: Literature Review

General biology of the *Neochanna* species

2.1 Galaxiids, *Neochanna* and distribution

The genus *Neochanna* belongs to the family Galaxiidae, a group of southern cool-temperate freshwater fish (McDowall, 2006). The galaxiids form a major part of the freshwater fish fauna in the southern hemisphere, with more than 50 species currently recognised (McDowall, 2006; Waters et al., 2000). They exhibit a Gondwanan distribution and representatives are currently known on all Gondwanan continents except for Antarctica and India (Waters et al., 2000). Some species are endemic to certain islands or countries in the southern hemisphere, however others, e.g. inanga (*Galaxias maculatus*), are widespread throughout more than one continent (McDowall, 2002).

The genus *Neochanna* consists of six species of mudfish that are currently known. One of these species (the Tasmanian mudfish, *N. cleaveri*) is diadromous, and is found in Tasmania and Victoria, in south-eastern Australia. Of the other five non-diadromous species, four are present on mainland New Zealand (the Northland mudfish, *N. heleios*; the black mudfish, *N. diversus*; the brown mudfish, *N. apoda*; and the Canterbury mudfish, *N. burrowsius*), and the sixth species is found only on Chatham Island (the Chatham Islands mudfish, *N. rekohua*). Phylogenetic analysis of these species indicates that the genus is monophyletic, with a single trajectory of evolution. The Tasmanian mudfish is the basal species in this group, and the five New Zealand species have diverged from this (Waters et al., 2000; Waters and McDowall, 2005).

Two main hypotheses could explain the Trans-Tasman distribution of this monophyletic genus (Waters et al., 2000). As many galaxiid species exhibit a Gondwanan distribution throughout the southern hemisphere the first hypothesis for the distribution of these species is based on plate tectonics. New Zealand is estimated to have become completely separated from Gondwana around 80 million years ago

(Mya) (Laird and Bradshaw, 2002; Waters et al., 2000) and historical marine transgressions since this time mean that New Zealand's freshwater habitats have been limited. For example, in the mid-Oligocene period it is estimated that at least 80% of New Zealand's current land area was submerged. It is therefore unlikely that mudfish would have persisted on mainland New Zealand throughout this time. In addition, phylogenetic analysis of the six mudfish species estimates the divergence between the Tasmanian mudfish and the five New Zealand *Neochanna* species to be around 8-9 Mya (Waters et al., 2000; Waters and White, 1997). By this time New Zealand would have been long separated from the other Gondwanan continents.

An alternative hypothesis for the Trans-Tasman distribution of the *Neochanna* species is oceanic dispersal. Diadromy is an important feature of the galaxiid fish, and possession of a marine larval phase is thought to be a primitive feature in galaxiids (McDowall, 1970, 1993; Waters and McDowall, 2005). Loss of diadromy is considered to be an important mechanism in the cladogenesis of galaxiid species (Waters and McDowall, 2005). Non-diadromous fish also tend to have a far more localised distribution than diadromous species (McDowall, 2002; Waters et al., 2000). Divergence of the mudfish species is estimated to have occurred more recently than Gondwanan connections, so the diadromous habits of the Tasmanian mudfish provide an explanation for the distribution of this genus (McDowall, 2002; Waters et al., 2000).

As all four mainland New Zealand *Neochanna* species are non-diadromous the presence of the non-diadromous Chatham Islands mudfish on Chatham Island is enigmatic to the oceanic dispersal hypothesis. Chatham Islands and Canterbury mudfish have been found to be sister taxa (Waters and McDowall, 2005), suggesting that the common ancestor of these two species was diadromous. Diadromy has, however, subsequently been lost from both lineages. A recent diadromous ancestor for these two species may also explain the retention of pelvic fins, which have been lost in the other New Zealand species (Waters and McDowall, 2005).

2.2 General features of the *Neochanna* species

The *Neochanna* genus was established in 1867 by Dr. Albert Günther after specimens of what is now known as the brown mudfish were collected in Hokitika (Günther,

1867; Hector, 1872; McDowall, 2006). The small fish found during the draining of swamplands on the West Coast of the South Island were often in damp areas with no surface water (Günther, 1867; McDowall, 1997). This gave rise to the belief that this was a fish that lived without the need for water (Hector, 1872), or had a "dislike [for] fresh-water" (Roberts, 1872a). One report gave an account of several fish found when baling water out of trenches following a heavy rainfall, and concluded that the fish had "fallen from the sky" (Roberts, 1872b). These early reports reflected a seemingly common belief of the time: that mudfish lived in areas lacking water, and were free living in the damp mud. These mudfish were classified as part of the family Galaxiidae due to the presence of a posterior dorsal fin, and their lack of scales. However, they were concluded to be different from *Galaxias* species as pelvic fins were lacking; the jaw teeth were small and incisor-like; there were no endopterygoid teeth; the dorsal and anal fins were long and low; the caudal fin was distinctly rounded; and specimens had elongated, tubular anterior nostrils and small eyes (Günther, 1867; McDowall, 1997).

2.2.1 Morphological characteristics

General features defining the genus *Neochanna* include a long, cigar-shaped, scale-less body; relatively small eyes; elongated, tubular anterior nostrils; long and low dorsal and anal fins; and a rounded caudal fin (McDowall, 1997; McDowall, 2006; Waters and McDowall, 2005). The six species now included in *Neochanna* form a transformation series, which ranges from the Tasmanian and Canterbury mudfish, the least specialised, to Northland and brown mudfish, the most specialised. This increased specialisation of the species to the swampy habitats in which they live can be seen in the blunter head; reduced eyes; elongated anterior nostrils; loss of pelvic fins; rounded caudal fins; and cranial reinforcement, features which become more pronounced along the transformation series. The loss of the fairly typical galaxiid morphology possessed by Tasmanian mudfish to a more anguilliform morphology, highly suited to swamp habitats, as seen in Northland and brown mudfish highlights this increased specialisation and change along the transformation series. In the more derived species the fin morphology is also increasingly reduced (first with fewer pelvic rays and then complete loss of pelvic fins) or modified (with dorsal, anal and caudal fins becoming nearly joined) (McDowall, 1997; Waters and McDowall, 2005).

2.2.2 Aestivation

One defining characteristic of the genus *Neochanna* is their ability to aestivate and thus survive in ephemeral wetlands where the surface water dries up over the summer and autumn months (McDowall, 2004, 2006). Drying of these habitats does not involve complete loss of water from the area, rather the loss of surface water, while the substrate remains damp (Eldon, 1978; Gleeson et al., 1999; McDowall, 2004). Aestivation of the *Neochanna* mudfish during this time is not a true aestivation, as the fish do not become entirely torpid, or form a mucous-lined cocoon. Instead these mudfish survive in a state of semi-torpor, breathing through their skin, until the surface water returns to the habitat. At this time they are able to become immediately active (Ling and Gleeson, 2001; McDowall, 1999; McDowall, 2006).

While the Tasmanian mudfish has been observed to form complex burrows during aestivation (Koehn and Raadik, 1991), the New Zealand *Neochanna* species do not appear to burrow, instead wriggling into spaces under logs or holes created by or near to tree roots. In several instances brown mudfish have been found at considerable depths under the surface, after a decrease in the water table (Eldon, 1978; Eldon, 1979a; Reid, 1886). Use of refuges during aestivation appears to be related to fish size. Small fish and fry tend to be found in the detritus on the forest floor, while larger fish are found under logs and tree roots (Eldon, 1978). When there are no suitable places for fish to wriggle down to when the habitat dries, they are frequently found lying on the substrate surface, often on their backs (Eldon, 1978; O'Brien and Dunn, 2007). While the reason for this behaviour is unclear, theories include firstly that the act of rolling increases waste excretion across the skin, aiding rehydration in some way. A second theory is that being on their backs enhances gas exchange efficiency through the thin abdominal skin to vital organs (O'Brien and Dunn, 2007).

It is not known exactly how long *Neochanna* are able to survive drought by aestivating, with reports ranging from several weeks to five months, and possibly longer (Ling, 2001; McPhail, 1999; O'Brien, 2007; Roberts, 1872b). A study of Canterbury mudfish during a drought period found several adult mudfish dead only two weeks after the habitat dried. Other fish were found in locations where they were considered unable to survive much longer (Eldon et al., 1978). Interestingly, eel skeletons have been

found at sites where mudfish were aestivating, suggesting that mudfish are able to cope with extended periods of drought that eels cannot (Eldon, 1979c). Mudfish seem capable of rapidly recolonising an area following the return of water to the habitat. They may either recolonise from a nearby habitat, or from refuges deeper in the substrate (Eldon et al., 1978). The ability to aestivate and thus survive in habitats that are seasonally dry allows *Neochanna* an opportunity to escape predators. It also gives *Neochanna* populations, even those that are depleted in years of severe drought, a competitive advantage over species unable to survive in ephemeral conditions (Ling, 2001).

2.2.3 Response to hypoxia

Mudfish can be found in permanent waters as well as in ephemeral wetlands (Eldon, 1979c). Both these habitats can become isolated resulting in the water becoming hypoxic. Mudfish are able to survive in these habitats by breathing in bubbles of air at the water's surface, unlike other fish species which are unable to cope with low oxygen levels in the water (Eldon, 1979a; McDowall, 1999; McDowall, 2004; McPhail, 1999). This air breathing behaviour could be an adaptation to low oxygen levels rather than drought conditions, but it may also help with breathing during aestivation (Eldon, 1979c; Hicks and Barrier, 1996). The ability of *Neochanna* to cope well with hypoxic waters, in comparison to other fish species, reduces predation and gives *Neochanna* a further competitive edge (Eldon, 1979c).

While able to cope with low oxygen habitats, the need for mudfish to breathe air from the surface when the water becomes hypoxic suggests they are not particularly well adapted to these conditions (McDowall, 1999). This hypothesis is supported by a study which looked at the response of black mudfish to changes in water pH and temperature. The study found that although mudfish are extremely efficient at oxygen uptake in their blood, they are unable to obtain sufficient oxygen from water with a low pH or high temperature (greater than 15°C). In these conditions mudfish were observed to gulp air at the surface (Barrier et al., 1996).

2.2.4 Spawning

Spawning is thought to occur between late autumn and early spring. It appears to be related to environmental factors, primarily the return of water to the habitat following

the dry period (McDowall, 2006; O'Brien and Dunn, 2007). However, there can be great variation in the timing of spawning. For Canterbury mudfish, lack of suitable aquatic vegetation, disturbance of their habitat and poor water quality have been observed to delay spawning. In areas where mudfish populations are established in permanent waters fry are frequently found year round (O'Brien and Dunn, 2007). The total hatching time for eggs is estimated to be around 26 days, depending on temperature, with cooler temperatures resulting in longer development times (Eldon, 1978; Taylor, 1996). Newly hatched fry are around 8-9 mm in length and, while able to survive short periods of drought, need to reach a larger size before being able to cope with lengthy seasonal droughts (Eldon, 1978).

2.2.5 Diet
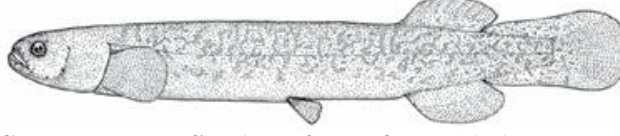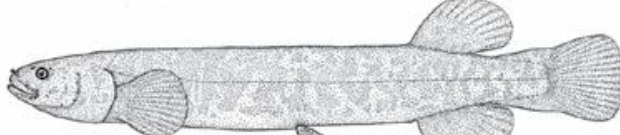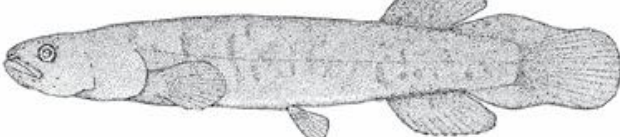
Mudfish eat a variety of small invertebrates. They are opportunistic feeders and their diet is thought to reflect both availability of prey and the ability of the fish to catch various prey species. Copepods are thought to form the main part of the diet of the fry and they are also known to eat cladocera, amphipods and chironomid larvae. Adult fish eat several aquatic invertebrate species, especially dipterans (Eldon, 1978; Eldon, 1979b; O'Brien and Dunn, 2007). However, mosquito and damselfly larvae are two species which mudfish have not been observed to eat, even when they are numerous in mudfish habitat (McDowall, 1990). Earthworms and some terrestrial invertebrates also form a part of the diet, with earthworms seeming to form a large part of the diet immediately after cessation of aestivation (Eldon, 1978; Eldon, 1979b). The high proportion of terrestrial invertebrates in the diet following aestivation is probably due to the high availability of these as a result of movement of terrestrial invertebrates into mudfish habitat during the dry period (McDowall, 1990).

2.3 The six mudfish species

The lack of pelvic fins in the brown mudfish, the first of the *Neochanna* species to be classified, led to much initial confusion in the classification of other mudfish. One of the defining features in the brown mudfish was a lack of pelvic fins, which resulted in the Tasmanian, Canterbury and Chatham Islands mudfish (all of which possess pelvic fins) originally being considered to definitely belong to the genus *Galaxias*. Their features (see Table 2.1), which were in most other ways typically mudfish-like,

eventually led to the inclusion of these three species in *Neochanna*. This genus is now classified as having either reduced or absent pelvic fins (McDowall, 2004; Mitchell, 1995).

Table 2.1: The six *Neochanna* species, in order of discovery/inclusion to the genus, showing main distinguishing features. All species have anterior, tubular nostrils, are able to aestivate, and are found at low altitudes. Diagrams by R. M. McDowall (O'Brien and Dunn, 2007).

Species	*Features*
Brown mudfish (*Neochanna apoda*)	Discovered 1867 • No pelvic fins • Flattened, incisor-like jaw teeth • Strongly developed muscles in head • Found in shallow, swampy habitats with little or no flow
Black mudfish (*Neochanna diversus*)	Discovered 1945 • No pelvic fins • Conical teeth • Found in shallow peaty wetlands with little disturbance and little or no flow
Canterbury mudfish (*Neochanna burrowsius*)	Added to the genus *Neochanna* in 1970 • Small pelvic fins • Found in slow flowing swampy streams, often with permanent water
Tasmanian mudfish (*Neochanna cleaveri*)	Added to the genus *Neochanna* in 1997 • Well-developed pelvic fins • Amphidromous • Found in a wide range of (often ephemeral) habitats, ranging from stagnant pools to slow flowing streams and estuarine areas
Northland mudfish (*Neochanna heleios*)	Discovered 2001 • No pelvic fins • Small eyes • Restricted to a small number of ephemeral wetlands in Northland, NZ, with little or no flow
Chatham Islands mudfish (*Neochanna rekohua*)	Added to the genus *Neochanna* in 2004 • Well-developed pelvic fins • Found in deep, open peat lakes within *Dracophyllum* swampland on Chatham Island

2.3.1 The brown mudfish, Neochanna apoda

Brown mudfish have an anguilliform morphology differing from the more generalised galaxiid morphology seen in the Tasmanian, Chatham Islands and Canterbury mudfish. Due to this, they are considered to be the most specialised of the six *Neochanna* species to the swamp habitats in which they live (Ling, 2001; McDowall, 2006; O'Brien and Dunn, 2007). Early descriptions of brown mudfish are mostly from the Hokitika area on the West Coast of the South Island. They were frequently found by early settlers draining and clearing land for farming (Günther, 1867). Brown mudfish are the most widely distributed of the New Zealand mudfish species, however populations are sporadic. They can be found in Taranaki, Manawatu, Wairarapa and the Kapiti Coast, in addition to the West Coast (see Figure 2.1 for distribution of all New Zealand *Neochanna* species) (McDowall, 2006; O'Brien and Dunn, 2007). This distribution of the fish on both the North and South Islands is a likely result of landbridge connections between the present-day North and South Islands during the Pleistocene (McDowall, 1997; O'Brien and Dunn, 2007).

2.3.2 The black mudfish, Neochanna diversus

The black mudfish was found in the northern North Island in 1945 and added to the genus *Neochanna* at this time (McDowall, 1997). Black mudfish can be found throughout Northland and Waikato (O'Brien and Dunn, 2007). Stokell (1949) described the black mudfish as sharing most of the distinctive features of brown mudfish, but possessing a few different characteristics. These are: conical (rather than compressed) teeth; fewer rays on dorsal and anal fins; more branching of rays on dorsal and anal fins; a shorter mouth; and a more convex profile of the snout (McDowall, 1997).

2.3.3 The Canterbury mudfish, Neochanna burrowsius

Canterbury mudfish are found throughout the Canterbury Plains, and some populations have also been found in North Otago. They are usually found in swampy, slow flowing streams, rather than the still waters favoured by the other New Zealand mudfish species. Canterbury mudfish have small pelvic fins, distinguishing them from the other mainland New Zealand species. Otherwise they have the typical

Neochanna features, such as elongated anterior nostrils, small eyes and a rounded caudal fin (McDowall, 1997; O'Brien and Dunn, 2007).

2.3.4 The Tasmanian mudfish, Neochanna cleaveri

The Tasmanian mudfish is the only diadromous species in the *Neochanna* genus. In appearance they are the most *Galaxias*-like of the mudfish species, possessing well-developed pelvic fins. Tasmanian mudfish are found in Tasmania, Flinder's Island and Victoria. Investigations into the phylogeny of *Neochanna* found the five New Zealand mudfish species to be derived from the Tasmanian mudfish. Tasmanian mudfish have several external similarities to the New Zealand species, and also aestivate (Koehn and Raadik, 1991; McDowall, 1997).
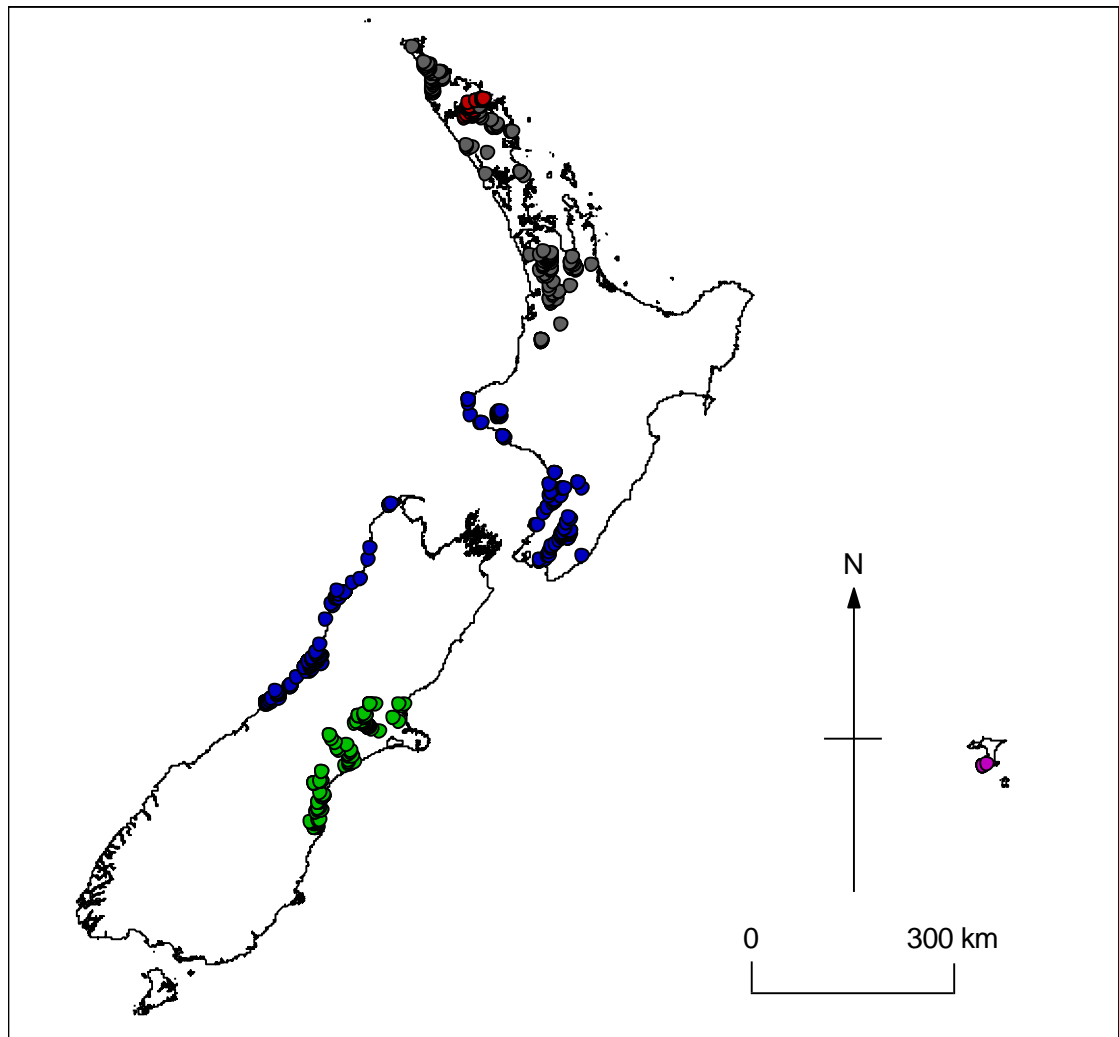
Figure 2.1: Map showing distribution of the five New Zealand *Neochanna* species. Grey dots represent black mudfish; red dots, Northland mudfish; blue dots, brown mudfish; green dots, Canterbury mudfish; and pink dots, Chatham Islands mudfish. Map from New Zealand Freshwater Fish Database.

2.3.5 The Northland mudfish, Neochanna heleios

This mudfish species was recently found in Northland, New Zealand. It has a very localised distribution, and its range overlaps that of the black mudfish, though the two species are not known to co-occur. Northland mudfish lack pelvic fins and can be distinguished from brown mudfish due to the possession of a longer caudal peduncle and fewer caudal fin rays. Northland mudfish differ from black mudfish as they have smaller eyes, a bulbous swelling behind the head (especially prominent in larger individuals), and a mouth extending to the posterior margin of the eye (Ling and Gleeson, 2001).

2.3.6 The Chatham Islands mudfish, Neochanna rekohua

Found in 1994, the Chatham Islands mudfish was not added to the genus *Neochanna* until 2004. This occurred after initial confusion with *Galaxias* species due to its well developed pelvic fins, and moderately forked caudal fin, which is especially prominent in small individuals. The eyes of this species are also much larger than those of other *Neochanna*. Chatham Islands mudfish have to date only been found in two lakes on Chatham Island. These deep peat lakes are more open than the typical habitats in which the mainland New Zealand mudfish species are found (McDowall, 2004; Mitchell, 1995).

2.4 Typical features of *Neochanna* habitat

Loss and extensive modification of lowland wetlands in New Zealand mean it is difficult to compare current habitat use in *Neochanna* species with their historical preferences. Most species still have some populations present in unmodified remnant wetlands, which allows inference of what their historic habitat type may have been. *Neochanna* species are now found in habitats that are generally low-lying, and often ephemeral, with still or slow-flowing water. Some examples of these habitats include swampy and spring fed streams, dams, ponds, lakes, peat bogs, forest puddles, dune swamps and pakihi bogs (O'Brien and Dunn, 2007).

2.4.1 Hydrology

Hydrology, especially water velocity and depth, is one of the most important factors in determining the suitability of a wetland as *Neochanna* habitat. Hydrology is determined primarily by water source, and hydrological preferences appear to be related to fish morphology. The more derived species, brown and black mudfish, which lack pelvic fins, are found predominantly in wetlands with extreme hydrological fluctuations. These extreme conditions can range from no water during summer and autumn months to water with a slight flow during the winter. Water depth in brown mudfish habitats rarely exceeds 0.5 m, and where it does, mudfish are absent from the deeper parts of the wetland. In comparison, Canterbury mudfish tend to inhabit wetlands that contain water year round, although this may range from flowing water during winter to a small pool of still water during summer. They are also often found in areas which have deep pools, some up to 1-2 m in depth (O'Brien and Dunn, 2007). The Chatham Islands mudfish is also found in wetlands that usually contain water year round. The peat lakes inhabited by this species are fairly deep, and are comparatively a much more "open water" habitat than those the other mudfish species live in (Mitchell, 1995; Waters and McDowall, 2005). As mudfish populations can be found in permanent, as well as ephemeral, waters it is possible that the limited ability of other fish species to survive in ephemeral conditions is significant in determining the desirability of mudfish habitat (O'Brien and Dunn, 2007).

2.4.2 Vegetation

The dominant vegetation type in mudfish habitat varies between species. Hydrological regime, disturbance and soil type all play a role in determining vegetation. Canterbury mudfish, which occupy areas that have undergone extensive land clearance and modification (i.e. the Canterbury Plains), tend to be found in drainage ditches and periphery habitat. These areas often contain floating aquatic plants such as *Lemna* and *Azolla*. In contrast, black mudfish are often found in wetlands with little or no disturbance, containing restiad rushes and manuka. Brown mudfish habitat rarely contains aquatic plant species as the mudfish are frequently found in swamp forest areas that are generally unsuitable for aquatic plant growth. In

these habitats trees and shrubs surround the edges of the pools in which they live, providing shading and detritus input (Eldon, 1968; O'Brien and Dunn, 2007).

2.4.3 Water quality

Data regarding water quality and the occurrence of *Neochanna* species is sparse, although they appear to prefer clean, unpolluted water. This means their presence could be a good indicator of wetland health. *Neochanna* abundance has been found to be negatively correlated with high levels of turbidity and nutrients in the water, and pH may also have an influence in determining suitable habitat (O'Brien and Dunn, 2007; Young, 1996). The peaty habitats favoured by black and brown mudfish tend to be more acidic than those in which Canterbury mudfish are found (O'Brien and Dunn, 2007).

2.4.4 Temperature

Neochanna are able to tolerate a wide temperature range. Canterbury mudfish, for example, occur in waters which range in temperature from 0.5°C to 24°C and may freeze during winter. Brown mudfish have also been observed to remain active in pools where ice formed on the surface overnight, while black mudfish often tolerate temperatures of 19°C, or greater. This ability to cope with extreme temperature fluctuations may be important in a species whose habitats dry up during summer, as terrestrial habitats undergo far greater, and more rapid, temperature fluctuations than aquatic habitats (O'Brien and Dunn, 2007).

2.5 Threats to *Neochanna*

The greatest threat to all New Zealand *Neochanna* species, and perhaps also the Tasmanian mudfish, is habitat loss. Around 90% of New Zealand's wetlands have been either lost or modified (Gleeson et al., 1999; McGlone, 2009; Park, 2002). Loss of wetlands is far greater in New Zealand than in most other countries in the world; the next highest estimate of wetland loss is around 60% in the Netherlands and Britain (Park, 2002). Wetlands have very fertile soils, and are therefore highly desirable for conversion to farmland. As a result wetlands are frequently targeted by developers. Many of the wetlands favoured by mudfish were likely to have been around the

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margins of podocarp swamp forest (Eldon, 1968, 1978), much of which has been widely modified, felled for timber and the land cleared for farming. The loss of a significant amount of wetland habitat also means that the wetlands in which mudfish are now found are often small, which makes them highly vulnerable to further draining and development (McDowall, 2006).

In addition, habitat modification can increase vulnerability of the remaining habitat to invasion by other fish species, both native and introduced. Increased competition from other galaxiids, such as kokopu, or from bullies (*Gobiomorphus* spp.) is one result of this habitat modification. Increased predation from eels (*Anguilla* spp.) and competition and predation from introduced species such as brown trout (*Salmo trutta*) or mosquitofish (*Gambusia affinis*) also occurs (Ling and Willis, 2005; McDowall, 1990; O'Brien and Dunn, 2007).

Presence of mosquitofish in black mudfish habitat has been found to reduce population recruitment and growth rate of small mudfish (Ling and Willis, 2005). Mosquitofish are now present in many northern mudfish habitats, and have been observed to show aggression, particularly towards smaller mudfish. They also prey upon mudfish fry, and probably eggs as well (Barrier and Hicks, 1994). Mosquitofish are currently only a problem in black and Northland mudfish habitats, but southern spread of mosquitofish into the range of brown mudfish poses a serious threat (McDowall, 2006). The ephemeral nature of mudfish habitats allows *Neochanna* an advantage over mosquitofish which need to recolonise after the summer months. However, female mosquitofish are able to retain viable sperm over the winter, allowing a single female to rapidly re-establish populations. This ability to rapidly recolonise may counteract the advantages *Neochanna* gain by inhabiting ephemeral wetlands. Problems would arise especially in wetlands that do not completely dry during the summer months, allowing some mosquitofish to remain in the habitat over summer, or in those that become severely flooded during winter, thereby increasing habitat interconnectedness at this time (Barrier and Hicks, 1994; Ling and Willis, 2005).

Birds also play a role in mudfish predation. Bitterns (*Botaurus poiciloptilus*) and white faced herons (*Ardea novaehollandiae*) have been observed to prey upon mudfish. Pukeko (*Porphyrio porphyrio melanotus*) and kingfishers (*Todiramphus sanctus*) may be other potential predators (Eldon, 1978; Hicks and Barrier, 1996; O'Brien and Dunn, 2007). While birds can at times be numerous in *Neochanna* habitats, predation from birds is unlikely to have a significant effect on mudfish populations. In some circumstances predation may be high, but the benthic nature and general cryptic behaviour of adult mudfish reduces this predation risk. In comparison to other threats faced by mudfish, occasional predation from birds is likely to be negligible (O'Brien and Dunn, 2007).

Chapter Three

Habitat

Adult brown mudfish (*Neochanna apoda*) in kahikatea
swamp forest at Nga Manu Nature Reserve   Photo: Peter McKenzie

Chapter 3: Habitat

3.1 Introduction

Habitat loss is the biggest cause of decline for all New Zealand mudfish species (Department of Conservation, 2003). Around 90% of New Zealand's wetland habitats have been lost (McGlone, 2009), and those remaining are under continued threat of degradation. A variety of activities have contributed to this habitat loss, including wetland clearance, drainage, water abstraction, irrigation, channelisation, deterioration of water quality, stock damage and invasion of other species into mudfish habitat (Department of Conservation, 2003; Park, 2002). Brown mudfish are currently considered a 'vulnerable' species under threat of gradual decline (Hitchmough et al., 2007; IUCN, 2009). Continuing habitat loss and degradation contributes greatly to this decline.

It is difficult to determine how abundant brown mudfish were in the past, as historical reports and early descriptions of the species do not clearly indicate whether the fish were common or rare. Reports of large numbers of brown mudfish found when draining swamplands suggest a much more widespread population structure than their current sporadic distribution. A report by Phillipps (1923) notes that the species was then rare, having been found only on "several occasions under white-pine [kahikatea] stumps standing on low-lying heavy blue-clay country subject to flood". Phillipps' report concludes with real concern for the future of the species, adding that with the swamp forest being gradually cleared and swamps themselves drained there was little doubt that the brown mudfish would become extinct.

Reports today note that brown mudfish are found in the widest range of habitats and are considered the least endangered of all New Zealand mudfish species (Eldon, 1968; O'Brien and Dunn, 2007; Phillipps, 1923). While brown mudfish appear to have a versatility allowing them to adapt to new situations and thus survive in a wide range of habitat types, they are potentially under much greater threat than is currently understood. Their persistence in marginal habitats, which are vastly different from historical habitat descriptions, may merely represent survival tactics.

The extensive modification of lowland landscape in New Zealand makes it difficult to draw links between current and historical habitat use by mudfish. Studies regarding habitat are also confounded as remnant wetland areas are likely to be more indicative of areas that are difficult to drain, rather than those which represent ideal brown mudfish habitat. The wide natural range of brown mudfish means regional differences in vegetation type and landscape exist between populations. This may further confound studies regarding habitat as there is a possibility that there may be regional habitat preferences that differ between brown mudfish populations. Comparisons of current and historical reports do, however, highlight some differences between wetland habitats.

3.1.1 Historical findings

Typical reports from the late 1800s and early 1900s regarding brown mudfish described fish found in areas where the land was being (or had been) cleared and drained, rather than in actual wetland areas. The first recorded findings were on the West Coast of the South Island, near Hokitika. Mudfish were often found in areas of swamp land that had no surface water remaining (as a result of either drainage, or the ephemeral nature of the wetland) when that land was being cleared for farmland and roads (Günther, 1867; Roberts, 1872a). The fish were, at times, found deep within the substrate. During trenching in Hokitika several mudfish were found at least 46 centimetres down in damp clay, although there was no surface water (Roberts, 1872b). Brown mudfish were also dug up from gravelly clay, ten feet below the surface, near Rangitikei (Hector, 1869). Other reports describe brown mudfish as being a swamp-forest species. One description of habitat in which they were commonly found was land that was "covered with the usual bush, and in rainy weather was always under water" (Roberts, 1872a). The specimens sent to Dr Günther for classification were found in an area where the town of Kaneiri had been built, but which had been swamp land covered in dense forest less than two years previously (Günther, 1867).

The ability of brown mudfish to aestivate resulted in a number of live mudfish being found in soft clay under tree roots that were grubbed up two years after the land had been drained and cleared. The fish were also "found in great numbers in making new roads through swampy land, but seem to disappear from the land on its being drained
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and cultivated" (Roberts, 1872a). Although found in swampy habitats, brown mudfish were always associated with clean water. The water in these habitats was not always still, with areas often observed to have some (albeit slight) water movement through much of the year. In places where this water movement was present, it was not permanent, as the water would at times become stagnant, or dry up completely (Eldon, 1978).

3.1.2 Recent scientific studies

Brown mudfish usually inhabit ephemeral wetlands, however populations can also be found in permanent waters (Eldon, 1968, 1978). Present-day reports regarding brown mudfish habitat frequently discuss the wide distribution of the species, and their presence in the widest range of habitats of all the New Zealand *Neochanna* species. Six different habitat types were identified during one study on the West Coast of the South Island (Eldon, 1968). These were: forest puddles and swampy areas of varying size, filled with leaf debris; partially cleared kahikatea bogs; borrow pits, where mudfish were found in both flooded and dry pits; dune swamps containing a variety of vegetation; pakihi bogs; and swampy stream backwaters, filled with thick beds of mud and detritus. Although other species were not found in the same locations as the mudfish, on several occasions they were present in pools and streams on the habitat margins.

Although brown mudfish can be found in a variety of habitats, some consistent habitat features have been identified, especially those relating to hydrology. They have not been found in areas where water depth exceeds 0.5 metres. In areas where deeper water is present mudfish have only been found on habitat margins where the water is shallower, if at all, although it is possible this is a reflection of trapping effort rather than a habitat preference of the fish. In deep habitats, where no shallows exist, brown mudfish tend to be absent from the habitat, even when suitable cover is available (Eldon, 1978; O'Brien and Dunn, 2007). Water source is an important contributing factor to the hydrology of a wetland. Wetlands with groundwater sources have the most stable habitats, with fewer seasonal fluctuations. The shallow and ephemeral wetlands often inhabited by brown mudfish are sourced either from rainwater, or

overflow from nearby streams and rivers during floods (Francis, 2000; O'Brien and Dunn, 2007).

Vegetation type and soils are two features often consistent between different brown mudfish populations. They are most frequently associated with podocarp forest, often kahikatea, and are uncommon in beech forests. The soil of wetlands that contain brown mudfish is often slightly acidic, and peaty. This is likely to be a reflection of their lowland distribution (and the presence of peaty soils in lowland wetlands) rather than a specific preference by the mudfish for this soil type (O'Brien and Dunn, 2007). Vegetative cover within the habitat is also important. Cover used by mudfish seems dependent on fish size. Smaller mudfish tend to hide under leaf litter, twigs and sticks, while larger mudfish will occupy holes under tree roots, and large logs (pers obs; Eldon, 1978).

The differences between the early reports from the late 1800s and more recent reports allow an inference of habitat suitability to be applied to habitat descriptions. This chapter focuses on the habitat variables which may influence brown mudfish distribution. With so many deleterious effects on brown mudfish habitat, it is essential that the requirements of this species are determined, enabling this habitat to be protected in the future. While there is a possibility that the habitat characterisations for this study will only provide an accurate reflection of habitat preferences for Kapiti Coast and Manawatu populations, they will provide a baseline for further study. In addition to the smaller scale habitat data gained from surveys of wetlands within the Kapiti Coast and Manawatu, nationwide records from the New Zealand Freshwater Fish Database were also used. This larger scale information will more accurately be able to provide a guide to habitat preferences for all brown mudfish populations. With continued change to wetlands nationwide, there is an increasing importance to know more than just what conditions brown mudfish are able to tolerate. Conservation of brown mudfish depends on the availability of information such as that regarding habitat preferences, especially when it is provided in a way conducive to management and guidance of conservation efforts.

3.2 Methods

Two separate datasets were used to investigate habitat preferences of brown mudfish at both a landscape and micro-scale. Records from the New Zealand Freshwater Fish Database (NZFFD; McDowall and Richardson, 1983) and Freshwater Environments New Zealand River Classification Database (FWENZ; Wild et al., 2005) were used to give an indication of which variables might influence brown mudfish distribution at a large scale. For example, whether soil or weather parameters were consistent across all brown mudfish sites. The second dataset focussed on factors influencing brown mudfish distribution at a local scale only, using data from ten sites sampled during the course of this study.

Two different types of analysis, discriminant function analysis and classification trees, were used to analyse the data. Both can be used as predictive tools as they build a model from the available variables. After this model has been built, a site where the habitat variables, but not fish assemblages, are known could be run through the model to predict whether mudfish could be expected to be present at that site (De'ath, 2002; Joy and Death, 2002; Rice et al., 1983). Both analyses work by differentiating between pre-identified groups in the data (e.g. mudfish or no mudfish; De'ath and Fabricius, 2000; Williams, 1983), however, they give different representations of the data. Discriminant function analysis indicates only the relative importance of each variable, while classification trees are a non-parametric test that provide a more exploratory method of looking at the available data. Values are given for each important variable, identifying a threshold that distinguishes between the groups (De'ath, 2002).

3.2.1 Large scale habitat variables that may influence brown mudfish distribution:

Environmental variables associated with brown mudfish populations at a large scale were investigated for all brown mudfish sites in the NZFFD. Remotely sensed Geographic Information Systems (GIS) environmental variables for the sites were obtained from FWENZ by linking the coordinates at the NZFFD sites with the River Network. The fish dataset included all records from the NZFFD from 1970 to 2008. Less than one percent of these records contained sites where brown mudfish had been.

A large number of the non mudfish records were from sites outside the known range of brown mudfish. As mudfish are a lowland swamp species, comparison of habitat variables at these sites to those of high mountain streams would not draw meaningful conclusions about habitat requirements. To remove this bias an initial reduction of the data was conducted by removing all sites that were of greater elevation and distance inland than the known range of brown mudfish. After this 136 non-mudfish sites (to match the 136 brown mudfish sites recorded in the database) were randomly selected from the remaining records and used in combination with the mudfish sites for all further analysis.

To exclude redundant variables, environmental variables were correlated using Pearson correlations in Microsoft Excel. These highly correlated variables can confound results in analyses, so variables with a Pearson correlation coefficient greater than 0.8, as well as any considered unlikely to be of significant influence to brown mudfish, were removed from the dataset (see Appendix A for a list of environmental variables included in the analysis). Fifty seven variables were used in the analysis. Discriminant analysis was conducted using SAS (proc discrim; 2006) to determine how well environmental variables were able to classify sites based on the presence or absence of brown mudfish and to identify the variables that best separated these two groups. A leave-one-out method of crossvalidation was used to give a robust assessment of the predictive accuracy of the model. Canonical variate analysis was then used to visualise that separation and to rank the relative importance of each variable in distinguishing between groups. As the coefficients of canonical variables can also be biased by correlated variables, the canonical variates were correlated with the environmental variables to avoid any bias.

3.2.2 Local study of variables that may influence brown mudfish distribution:

A second analysis was conducted using only sites from the Manawatu and Kapiti Coast that were trapped during the course of this study. This analysis was conducted in order to investigate factors that may influence brown mudfish distribution using information collected on site. Mudfish were trapped at ten different locations: Ashhurst Domain; Koputaroa Kereru Conservation Covenant; Koputaroa; Lake

Papaitonga; Victoria Station; and five sites within the Nga Manu Nature Reserve. Habitat information from three other locations where no mudfish were found was also included as part of the analysis (see Appendix E for a list of these sites and the species found). As each of these sites was trapped more than once during the course of the study, each individual trapping occasion was included in the analysis, making a total of 135 sites used in the analysis. Habitat information was gained from two different sources. The first was observational data measured at each of the sites. The second added the GIS variables found to be significant at a 95% confidence level for distinguishing between brown mudfish presence and absence in the large scale habitat analysis (section 3.3.1, Table 3.2, Appendix B). These GIS variables were included as part of the dataset in addition to the on site measurements to ascertain how relevant the remotely sensed variables would be in accurately predicting mudfish presence at a site when variables measured at the site were also available for use by the model.

The data was analysed using classification trees in WEKA (Witten and Frank, 2005). To evaluate the models a leave-one-out method of data crossvalidation was used. This process of data analysis allowed the estimation of threshold values for each of the variables associated with presence or absence of brown mudfish, rather than giving only an indication of the relative importance of each variable (as in discriminant and canonical variate analyses). The Area Under Curve (AUC) values were used to assess the validity of the model. An AUC value of 0.7 to 0.8 is considered 'acceptable', while a model with an AUC value greater than 0.8 has 'excellent' accuracy (Hosmer and Lemeshow, 2000).

3.3 Results

3.3.1 Large scale habitat variables that may influence brown mudfish distribution:

When a discriminant analysis was conducted using the 57 GIS environmental variables, only 28 of the sites containing mudfish were incorrectly classified as not containing mudfish. The other 244 (of the total of 272 sites) were all assigned to their correct group (Table 3.1). With only 10.3% of the sites misclassified by the discriminant analysis when using crossvalidated data, a high level of accuracy was shown by the model in predicting the presence or absence of mudfish at a site based on GIS habitat variables.

Table 3.1: Number of observations and percent classified into each of two groups (mudfish present or mudfish absent) by the discriminant analysis, with crossvalidation of the data

		Predicted membership:	
Original grouping:		*Absent*	*Present*
N. apoda:	*Absent*	136	0
	Present	28	108

The canonical variate analysis of the GIS variables found that the hardness of underlying rocks in the catchment was the most important (i.e. had the highest R^2 value) of the variables for effectively distinguishing between sites that contained mudfish and those that did not (Table 3.2). Other variables of importance in creating this distinction were those relating to slope, rainfall, temperature and shading of the site, as well as catchment attributes, such as vegetation cover. Catchment elevation was another important factor in distinguishing between groups.

Table 3.2: R^2 values and F statistics from Canonical Variate Analysis. Values are shown only those variables significant at the $P < 0.01\%$ level. Values for all other variables can be found in Appendix B

Environmental variable	R^2	F statistic	Probability > F
Average hardness of underlying rocks in catchment *	0.46	225.9	<0.0001
Average slope of catchment *	0.31	119.3	<0.0001
Average particle size for catchment*	0.20	69.0	<0.0001
% of catchment in LRI category: Alluvium *	0.19	64.7	<0.0001
Average elevation of catchment	0.13	39.0	<0.0001
% of catchment in LRI category: Peat *	0.12	36.9	<0.0001
Proportion of catchment with slope <30° *	0.12	35.2	<0.0001
Proportion of catchment with slope >30° *	0.10	31.2	<0.0001
Current summer equilibrium temperature	0.09	26.8	<0.0001
Catchment rain days (>10mm/month) *	0.08	24.7	<0.0001
Estimate of current segment shade	0.08	22.6	<0.0001
Maximum segment slope	0.07	18.8	<0.0001
Catchment rain days (>25mm/month) *	0.06	18.7	<0.0001
Variation of annual catchment rainfall *	0.06	17.6	<0.0001
Catchment rain days (>50mm/month) *	0.06	17.3	<0.0001
% of catchment in LCDB category: Tussock *	0.05	14.0	0.0002
Catchment rain days (>100mm/month) *	0.04	12.2	0.0006
Estimate of historic segment land cover	0.04	11.6	0.0008
% of riparian area in LCDB category: Urban	0.04	11.6	0.0008

* Variables are weighted for run-off

The canonical variate analysis plot showed a clear distinction between sites where brown mudfish were present and those where no mudfish were found (Figure 3.1).

1) % of catchment in LRI category: Alluvium *	1) Catchment average hardness of rocks*
2) % of catchment in LRI category: Peat *	2) Average slope of catchment *
3) Catchment with slope <30° *	3) Catchment average of particle size *
4) Catchment rain days > 10mm/month *	4) Average elevation of catchment
5) Current segment shade	5) Catchment with slope >30° *
	6) Current summer equilibrium temperature

Figure 3.1: Position of sites relating to their environmental variables, from Canonical Variate Analysis. The variation is all described by canonical variate 1 (on the X axis), so the Y axis only provides scatter of the points. Sites containing brown mudfish are represented by the open circles, while the closed circles show those without mudfish present. The biplot below the graph indicates the GIS variables most important to each of these two groups.

* Variables are weighted for run-off

In the canonical variate analysis, sites where no brown mudfish had been found were positively correlated with the hardness of underlying rocks (induration) in the catchment; the average slope and elevation of the catchment (steepness); average particle size in the catchment and the equilibrium summer temperature. In comparison, sites containing brown mudfish were most strongly correlated with the percentage of the catchment in the land resource inventory (LRI; LandcareResearch, 2009) categories alluvium and peat. Areas that had a low gradient, the number of rain days

per month with a precipitation greater than 10mm and shading of the area by vegetation were also shown to be important predictors for the presence of brown mudfish.

Table 3.3: Coefficients for correlation between environmental variables with the first axis of the canonical variate analysis. Only variables with coefficients greater than 0.3 are shown. Coefficients for all other variables can be found in Appendix C

	Environmental variable	*Correlation (Can1)*
Mudfish present	% of catchment in LRI category: Alluvium *	-0.49
	% of catchment in LRI category: Peat *	-0.38
	Annual runoff volume from catchment with slope <30°	-0.38
	Catchment rain days greater than 10mm/month *	-0.32
	Estimate of current segment shade	-0.31
Mudfish absent	Average hardness of underlying rocks in the catchment *	0.75
	Average slope of catchment *	0.61
	Catchment average of particle size *	0.50
	Average elevation of the catchment	0.39
	Annual runoff volume from catchment with slope >30°	0.36
	Current summer equilibrium temperature (within segment)	0.33

* Variables are weighted for runoff

3.3.2 Local study of habitat variables that may influence brown mudfish distribution:

Classification tree analysis of the small scale habitat data showed that the presence of an ephemeral wetland was the most important factor for predicting the presence or absence of mudfish at a site (Figure 3.2). The first classification tree came up with the presence of any kind of wetland in the catchment area as the secondary factor. The AUC value for this tree was 0.824, meaning the model had excellent predictive accuracy (Hosmer and Lemeshow, 2000).
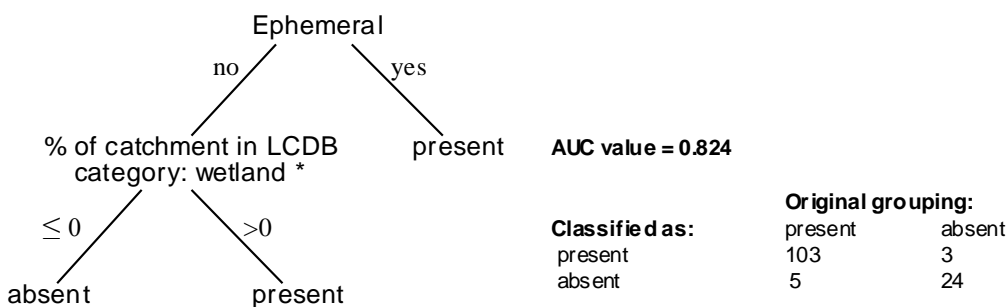
Figure 3.2: Classification tree from analysis of brown mudfish presence/absence data

This first classification tree presented by WEKA contained only two variables as the pruning process of the algorithm had removed the others as not improving the accuracy of the model. While these variables were able to partition the data from the ten sites with high accuracy, by themselves the variables do not give very useful information, as they simply state that if a wetland is present, then mudfish will be present. In order to determine whether any other variables were important in predicting brown mudfish presence, the variable 'percentage of catchment in the Land Cover Database (LCDB) category wetland' was removed from the dataset and the analysis run again. For this next analysis the primary distinguishing variable 'ephemeral' was retained within the dataset. This meant the second classification tree showed whether other variables, for instance those measured on site, would be important in predicting brown mudfish presence when information regarding the ephemerality of the wetland was still available. The second tree also contained only two variables: 'ephemeral' and 'number of catchment rain days greater than 50mm per month' (Table 3.4). The AUC value, and thus accuracy of the model, remained the

same as that of the first tree. The secondary variable of this second tree ('number of catchment rain days greater than 50mm per month') was removed from the dataset to determine any other important variables. This process was repeated until the AUC value decreased, meaning the model became less accurate at predicting mudfish presence. The variables from each of the trees are shown in Table 3.4. Each number corresponds to an individual tree, and the variables replace the secondary variable 'percentage of catchment in the LCDB category wetland' in the tree depicted in Figure 3.2. 'Ephemeral' remains the primary variable for all the trees listed in the table.

Table 3.4: Secondary determinate variables for brown mudfish presence or absence using a classification tree. A total of 12 different trees are represented in this table, with each number denoting a new variable. 'Ephemeral' remains the primary determining variable for all trees, as in Figure 3.2. Each of the variables shown in the table replace '% of catchment in LCDB category: wetland'. Each new tree is built only when the previous secondary variable is removed from the dataset.

Secondary variable (after 'ephemeral')	Rule	AUC value
2) Catchment rain days greater than 50mm/month *	≤0.09 present; >0.09 absent	0.824
3) % of catchment in LRI category: Peat *	≤0.25 absent; >0.25 present	0.824
4) Inanga (*Galaxias maculatus*)[†]	≤2 absent; >2 present	0.824
5) Current winter equilibrium temp. in segment	≤7°C present; >7°C absent	0.824
6) Catchment rain days greater than 25mm/month	≤0.67 present; >0.67 absent	0.824
7) Annual potential evapotranspiration of catchment*	≤1037.72 present; >1037.72 absent	0.824
8) Coefficient of variation in annual rainfall *	≤148 present; >148 absent	0.824
9) Mean minimum July air temp (in catchment) *	≤3.86°C present; >3.86°C absent	0.824
10) Catchment rain days greater than 10mm/month*	≤2.94 present; >2.94 absent	0.824
11) Average hardness of underlying rocks in the catchment *	≤1.68 absent; >1.68 present	0.824
12) % of catchment in LCDB category: exotic forest*	≤0 absent; >0 present	0.824
13a) Average January air temp. in segment	>17.1°C absent; ≤17.1°C then b	0.824
b) Surrounding land: native forest[†]	no, present; yes, absent	

* Variables weighted for run-off

[†] Variable measured on site

The analysis was run again to determine whether the variables in Table 3.4 would remain important predictors of brown mudfish presence in the absence of information about the ephemerality of the site. For this analysis all variables except for 'ephemeral' were retained in the dataset. The classification tree obtained from this

analysis gave the presence of flowing water, the surrounding area in farmland and the summer air temperature as the predicting variables (Figure 3.3). The AUC value for this tree was lower than when information regarding the ephemerality was available, but was still greater than 0.8, meaning the model still had excellent accuracy (Hosmer and Lemeshow, 2000). Knowledge regarding the ephemerality of a wetland may not be essential for predicting the presence of brown mudfish within that wetland, but it does increase the accuracy of the model. In the absence of knowledge about the ephemerality of a wetland, the presence of flowing water can also be a good predictive variable. Both remotely measured GIS variables, and on site measurements were useful predictors of brown mudfish presence at a small scale.
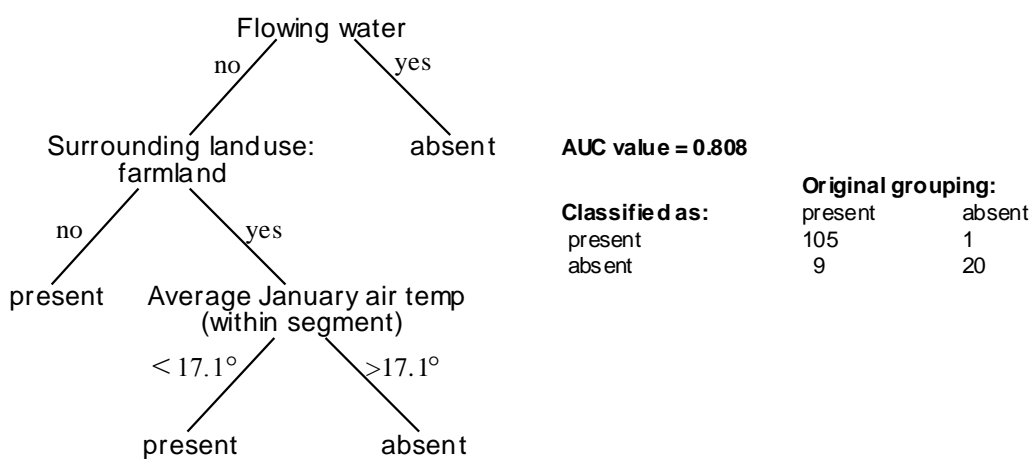
Figure 3.3: Classification tree after 'ephemeral' was removed from the data analysis

If both 'ephemeral' and 'flowing water' were removed from the dataset, but all other variables retained, the AUC value dropped below 0.8, meaning the model gained from this analysis was not very accurate at predicting the presence of brown mudfish.

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3.4 Discussion

The large scale GIS habitat analysis, which used nationwide records from the NZFFD, found the amounts of peat and alluvium in the catchment to be the two most important variables for sites that contained brown mudfish. While peat soils have been associated with brown mudfish before, underlying soil categories were not able to predict presence of black mudfish at a small scale (O'Brien and Dunn, 2007). This raises the possibility that peat soils may reflect only the lowland distribution of brown mudfish, rather than being a habitat feature specifically preferred by brown mudfish. Alluvium may also be a reflection of this distribution, as alluvial deposits build up in areas of slow flowing waters, and could therefore be important in the formation of wetland areas (Leithwick et al., 2003). However, both the large scale analysis and local study found peat to be a feature distinguishing between sites with brown mudfish and those without. All non-mudfish sites in the large scale analysis were at low elevations, and therefore within the potential range of brown mudfish. As peat and alluvium were still the most important features of brown mudfish sites, this indicates that they are habitat features preferred by the mudfish, rather than simply a reflection of their distribution. The small and soft substrates of peat and alluvium (Leithwick et al., 2003) could conceivably be a requirement of brown mudfish habitats, as brown mudfish of all life stages frequently bury themselves under the substrate surface (pers obs.). The negative correlation of particle size with brown mudfish presence supports the idea that the small particle sizes of peat and alluvium are important for brown mudfish.

The intensity of rainfall in the catchment was another feature important to brown mudfish habitats. As wetlands where brown mudfish are found are supplied primarily by rainfall (O'Brien and Dunn, 2007), steady rainfalls throughout the year would be important in maintaining the water levels of the wetland. Two of the secondary selection variables in the local study indicated that in wetlands that were not ephemeral, high amounts of rainfall each month resulted in an absence of brown mudfish. In a wetland with permanent water, high rainfall would likely produce a variable environment, possibly creating flow within the wetland, which brown mudfish are not able to cope well with (Figure 3.3; O'Brien and Dunn, 2007).

Brown mudfish sites were also found to be negatively correlated with variation in the annual rainfall (Appendix C), which emphasises that light, but frequent, rainfalls are preferable for brown mudfish. This indicates a preference for areas that have low disturbance and little flow variation. There was a negative correlation with hardness of underlying rocks in the catchment. In addition to partially determining the geology of downstream areas (due to erosion and sedimentation), the underlying rock type can also have an important influence on flow variability. Hard bedrock results in high levels of runoff, which create high variation in water level and flow, features unsuitable for brown mudfish (Collier et al., 2009). As water velocity is considered a significant limiting factor in brown mudfish distribution (O'Brien and Dunn, 2007), highly variable water flows would be unsuitable for brown mudfish populations.

Catchment elevation was also negatively correlated with brown mudfish presence. This is likely to be related to water source, with brown mudfish resident in areas where the water levels are primarily maintained by rainfall (O'Brien and Dunn, 2007). Sites with a high catchment elevation receive water originating from high mountainous areas, a water source that would be driven by factors such as snowmelt. This would create seasonal variability in flows, resulting in a habitat markedly different from the still or slow flowing, but stable, habitats favoured by brown mudfish.

All New Zealand mudfish species have been found to be able to tolerate a wide range of temperatures, an ability that is likely to be necessary in ephemeral conditions, when temperature fluctuations are far greater and more rapid (O'Brien and Dunn, 2007). However, warm temperatures in both summer and winter were negatively associated with sites where brown mudfish were present. It is possible that the lack of latitude restrictions on the large scale data was driving this preference for cooler temperatures. If some of the randomly chosen non-mudfish sites used in the analysis were located in warmer areas outside the range of brown mudfish this could falsely indicate brown mudfish to be found in areas that have cool temperatures. As the local study indicated that air temperatures greater than 17.1°C in summer and 7°C in winter equated to an absence of brown mudfish at a site, this suggests that while supposedly able to

withstand a wide range of temperatures, brown mudfish do not have a broad tolerance for these conditions, instead preferring cooler temperatures.

There was a negative association with steep slopes, and a positive correlation with those that had low gradients. This may relate to the lowland distribution of brown mudfish as wetlands within this region are not often in steep areas. Shading of an area was a feature significantly associated with the presence of brown mudfish. There has not been much association between brown mudfish and riparian shading (O'Brien and Dunn, 2007), although brown mudfish are often present in forested areas (Eldon, 1978), meaning that this shading variable may simply be reflecting the surrounding vegetation. However, with loss of this swamp forest (Park, 2002) brown mudfish are increasingly being found in more open areas. This means it may not be the shading itself that is necessary for the fish, but instead other factors that exist as a result of the nearby vegetation. These factors could include formation of holes and hollows by tree roots that are utilised by mudfish during aestivation; preventing the substrate from drying out completely during the summer dry period; or regulation of temperature. The latter point may be especially important, as, despite the ability of mudfish to withstand temperature extremes (O'Brien and Dunn, 2007), temperature appeared to be a significant limiting factor in the distribution of brown mudfish populations.

Historical reports frequently note the presence of forest in areas where brown mudfish are found (Roberts, 1872a). It is interesting that estimates of historic segment land cover and historic segment shade were both positively correlated with the presence of brown mudfish at a site, although not strongly so (Appendix C). While more in depth studies are necessary, this provides an indication that past habitats (i.e. presence of swamp forest) are important in determining the current distribution of brown mudfish. If this is the case, it suggests that brown mudfish are now merely surviving in habitats where environmental conditions have changed. This would account for the presence of brown mudfish in such a wide range of habitat types.

The local study found the ephemerality of a site to be the most important factor for determining brown mudfish presence at that site. When information about whether the wetland was ephemeral was not available, then presence of flowing water provided a

good surrogate. Mudfish were present where there was no flowing water, but when flowing water was present, mudfish were found only in a few instances, when other variables were also favourable. Land use of the surrounding area, in particular when it was farmland, was another factor that appeared to influence brown mudfish. Presence of farmland seemed to be a limiting factor for brown mudfish, with mudfish only present in these areas when average summer temperatures in the area were low.

These analyses provide an initial guide to the habitat preferences of brown mudfish. They also indicate the relative importance of various environmental variables to this species. Remotely sensed GIS data, which is available for areas nationwide in New Zealand, was shown to be relevant and useful for predicting presence of brown mudfish even at a small scale, when on site environmental measures were also available. This type of prediction is one method for investigating the relationship of brown mudfish with the environment. Globally, this kind of predictive modelling is becoming increasingly important, especially as environmental pressures, such as climate change and species loss, increase (De'ath, 2002; Guegan et al., 1998). Predictive modelling of species distribution can produce predictive maps of species presence, based on the environmental variables at a site. The availability of GIS data for all of New Zealand means this sort of modelling is readily accessible as a management tool (Joy and Death, 2004). Continued habitat loss and degradation, resulting in decline of brown mudfish populations, makes management of remaining populations essential, in order to prevent further decline of the species.

3.4.1 Summary of key habitat requirements for brown mudfish

From both the local study and large scale habitat analysis, ideal brown mudfish habitat appears to be ephemeral areas with still or slow flowing water. Although most often found in ephemeral areas, brown mudfish can also be found in many areas of permanent water (Eldon, 1968; O'Brien and Dunn, 2007). Soft substrate types with a small particle size, such as peat and alluvium, are other features that appear to be preferred by brown mudfish. There was a positive correlation in the analysis with both shading and historical vegetation cover. This suggests that riparian vegetation is important to brown mudfish, as well as supporting early reports which state that they are a swamp forest species (Roberts, 1872a).

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Presence of brown mudfish was able to be accurately predicted using remotely sensed GIS data, meaning that GIS information can be used as a management technique (e.g. in the form of predictive maps). This would allow the suitability of wetlands as brown mudfish habitat to be evaluated prior to undertaking in-depth surveys in the field. Utilisation of this sort of tool will provide recognition of the habitat requirements of brown mudfish, which is necessary for their population decline to be addressed.

Chapter Four

Response of brown mudfish to the presence of eels

Brown mudfish (*Neochanna apoda*) caught at Koputaroa   Photo: Natasha Petrove

Chapter 4: Response of brown mudfish to the presence of eels

4.1 Introduction

It is essential for prey species to be able to detect and assess predation risks, as failure to detect a potential predator and subsequently engage in an appropriate anti-predator response is likely to result in mortality (Brown, 2003; Lehtiniemi, 2005; McLean et al., 2007). However, predator avoidance is in itself a costly behaviour, as it reduces the time and energy available to spend on other important activities, such as foraging. In order to maximise fitness it is necessary for prey species to respond adaptively to the threat of predation by assessing their level of risk at any point in time. This results in a trade-off between the risks and benefits of predator avoidance behaviour (Brown, 2003; Ferrari et al., 2006). For example, anti-predator responses can be expected to increase with size and proximity of a predator. In some species responses also differ between life stages, with younger animals more inclined to seek refuge when faced with a potential threat (Ferrari et al., 2006).

Usually a combination of sensory cues will be used to detect potential predators, as different cues represent very different levels of risk and information. The two main predator detection methods used by fish are visual and olfactory/chemical cues (Brown, 2003; Lehtiniemi, 2005). Visual cues, while reliable, are also very risky, as the predator will not be detected until it is nearby. Olfactory cues have a lower associated risk, but can also be less reliable (Brown, 2003). However, there are situations in which chemical cues are more reliable than visual cues, such as in densely vegetated areas, in turbid waters, or at night. Olfactory cues are often used as an initial warning of the presence of a predator in the area, but the prey individual will often react only when the predator is also seen (Lehtiniemi, 2005; Mirza and Chivers, 2002). The level of response from a prey individual can vary greatly depending upon its physical state at the time. For example, prey individuals that are hungry may be less likely to respond to a potential threat than those that are satiated (Brown, 2003).

Innate predator recognition usually occurs when the predator and prey species share a long evolutionary history (Kelley and Magurran, 2003; Magurran, 1990). Many fish do not have innate recognition of potential predators and instead learn through acquired recognition of various cues associated with the predator. Both visual cues and predator allelomones can trigger learned recognition. Release of chemical alarm cues by conspecifics and other prey species, which are strongest when they are captured or injured, can also aid in this acquired recognition and elicit an avoidance response from other prey individuals (Brown, 2003). Fish are able to learn recognition of a predator by associating chemical cues with the predator, even if they make no obvious response to the predator's presence (Brown, 2003; Brown et al., 2001). This learned recognition can give the prey individual a lot of information about a potential predator including the size and proximity of the predator, as well as an indication of what the predator has been eating recently (Brown, 2003; Ferrari et al., 2006).

Brown mudfish generally inhabit areas unpopulated by most other fish species as the ephemeral nature of mudfish habitat limits the ability of other species to survive there. Brown mudfish are also considered to be poor competitors (O'Brien and Dunn, 2007). The presence of brown mudfish in these marginal, ephemeral habitats may therefore be more related to the absence of other species in, rather than a preference for, this habitat. The ephemeral nature of mudfish habitat means that predators are not a constant threat, as they can only survive when the habitat is inundated with water, and must recolonise following every dry period (McDowall, 2006; O'Brien and Dunn, 2007). However, brown mudfish are often associated with shortfin eels (Eldon, 1978). Although these predators may be present only sporadically, or in low numbers, some kind of predator recognition and response would still be beneficial for mudfish. As brown mudfish are mostly nocturnal (Eldon, 1978; O'Brien and Dunn, 2007) and inhabit wetlands containing logs, tree roots and detritus, which provide hiding places for both the mudfish and for predators, it is likely that they would use olfactory cues for predator detection. These cues may be either innate or learned. The aim of this study was to test whether brown mudfish could detect and would respond to allelomones emitted by shortfin eels, their natural predator, by moving away from eel odour when it was detected.

4.2 Methods

Brown mudfish were caught in kahikatea swamp forest at the Nga Manu Nature Reserve in Waikanae using 4mm wire mesh Gee minnow traps (G-408M, 2009). Unbaited traps were set overnight, and fish collected the following day. All mudfish caught were used in the trials. They varied in size from 2.5 to 14 centimetres. The mudfish were transferred to 20L buckets containing water and vegetation detritus from their swamp forest habitat to provide cover and minimise stress. They were then transported in the buckets to the choice chamber, which was set up on site. The buckets were topped up with the water used in the trials to help the fish to acclimatise. Once all mudfish had been run through the trials they were returned to the locations where they had been caught.

Shortfin eels were caught in a pond at Nga Manu using a 10mm wire mesh hinaki (Downes, 1918). The hinaki was set overnight near to where the choice chamber was set up. The hinaki was checked the following day and the eels transferred straight into the holding tanks of the chamber. After completion of trials for the day eels were returned to the pond.

Experimental setup

The trials were conducted in a two-chamber choice tank with a lower chamber giving access to both choice chambers (Figure 4.1), similar to those used by Atkinson & Joy (2008) and Baker & Hicks (2003). Mesh funnels allowed mudfish to access the two chambers, but prevented them from returning to the original chamber after making their choice. An eel was placed in one of two holding tanks from which the water then ran into each of the two choice chambers to create an odour in the water. The tank holding the eel was swapped between sides to ensure results reflected a choice by the mudfish to either swim toward, or to avoid, the eel odour rather than a preference for swimming in a particular direction (Agrillo et al., 2009; Versace et al., 2007). The flow rate of the water was $0.034Ls^{-1}$. Water was sourced from an untreated bore water supply at Nga Manu, and therefore did not contain any pre-existing eel odours which may have conflicted results.

Water running through the choice chamber apparatus first ran through the holding tanks, then down through the choice chambers to the lower chamber. This provided the mudfish with a choice of swimming towards or away from the eel odour created by the presence of an eel in one of the two holding tanks (see Figures 4.1a and 4.1b).
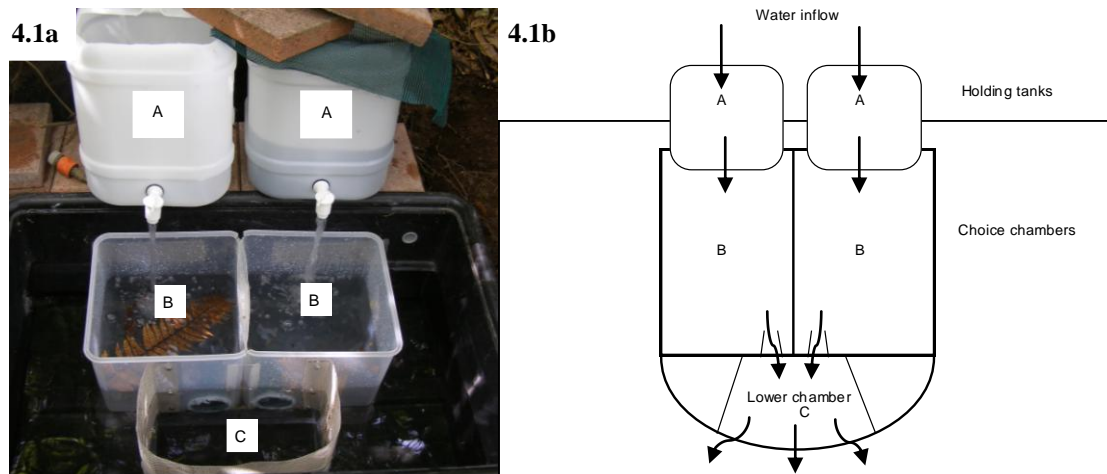
Figure 4.1a: The choice chamber as it was set up for the choice trials. An eel was placed in one of the head tanks (A) for the duration of the trials, creating an eel odour in the water. Mudfish were placed in the lower chamber (C), and could then make a choice to swim into either of the two choice chambers (B). **4.1b:** Diagram showing the water flow through the choice chamber apparatus.

Four or five mudfish were used for each trial, dependent on the number of fish caught each day. The mudfish were placed in the lower chamber for five minutes to allow them to further acclimatise to the water in the apparatus. During this time a barrier was in place across the entrances to the two choice chambers. After five minutes, this barrier was removed and the fish were allowed a further 10 minutes to make a choice. After 10 minutes the position of all the fish was recorded, and the fish were removed from the apparatus. Shade cloth was draped over the apparatus for the entire 15 minute period to minimise stress on the fish, and to avoid their choice being influenced by additional external factors.

Statistical analysis

Chi-square tests were used to determine whether there were any differences in the choice of the mudfish to swim towards or away from the eel odour, as well as to test whether there was a preference for swimming left or right. Analysis of Variance (ANOVA) and chi-square tests were also used to investigate the effects of mudfish size on the choice made by the fish (proc glm, proc freq; SAS, 2006).

4.3 Results

There was no significant preference shown by the fish for either the left or right choice chamber (Table 4.1). This means that the results gained from the trial reflect choices made by the fish, rather than individual behaviour traits for swimming in a certain direction.

Table 4.1: Chi-square analysis of the number of mudfish present in each chamber under various conditions

Effect being investigated	χ^2	d.f.	P value
Influence of direction on choice (i.e. left or right)	0.0169	1	0.8964
Towards eel, away from eel or no choice	81.3294	2	<0.0001
Towards eel or away from eel only	6.1186	1	0.0134

Significantly more fish remained in the initial holding chamber than those which made a choice either to swim towards or to avoid the eel odour (Table 4.1; Figure 4.2). Of the fish that did move significantly more fish chose to avoid the eel, rather than swim towards it (Table 4.1).
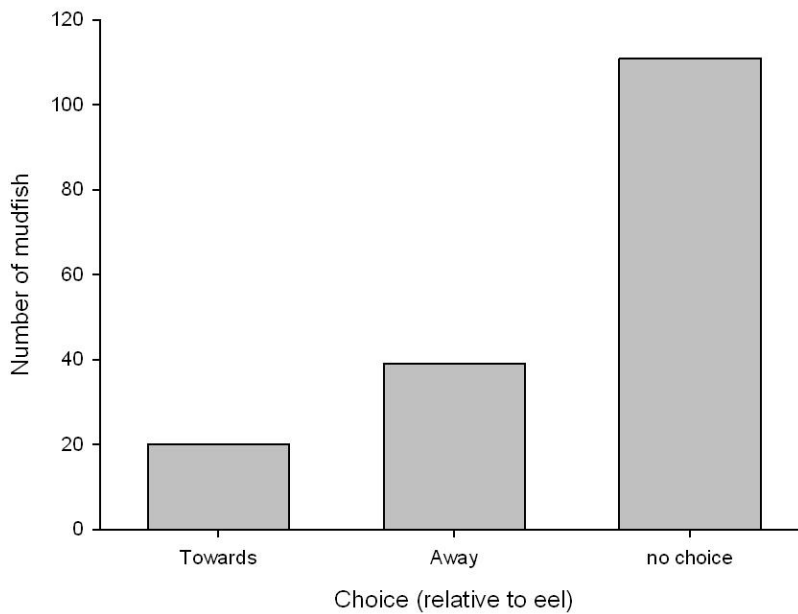
Figure 4.2: Graph showing the number of mudfish that made each of three possible choices

Larger fish (average size 9.93 cm ± 0.63 standard error) were most likely to swim towards the eel odour, while medium sized fish (7.14 cm ± 0.45 SE) tended to swim away from the odour. The smallest fish (5.61 cm ± 0.27 SE) were those most likely to remain in the initial holding chamber, not making a choice either towards or away from the eel (Figure 4.3; $F_{2,167} = 21.4$ P <0.0001).
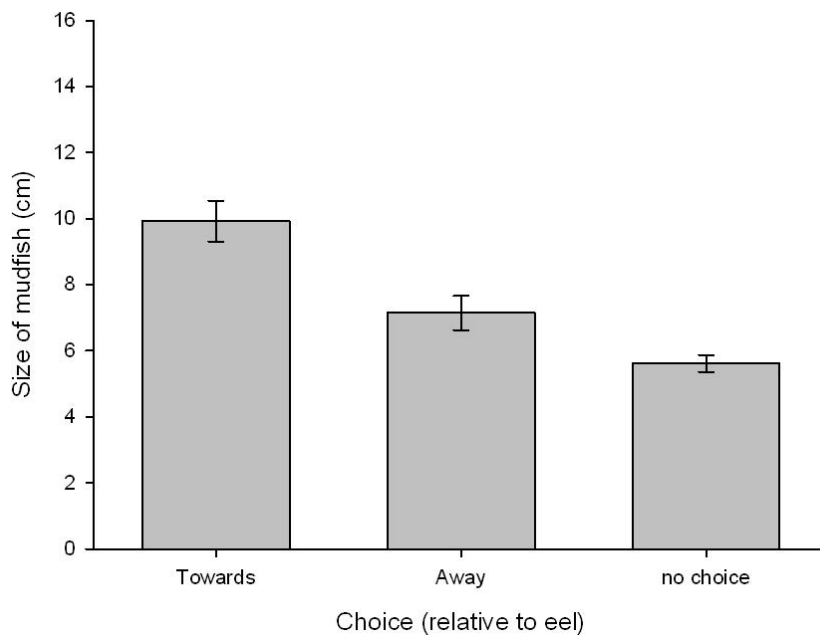
Figure 4.3: Graph showing the average size of mudfish making each choice (towards eel odour; away from eel odour; or no choice) with standard error bars.

Mudfish were grouped into three different size classes using size and age growth curves gained from otolith readings in Eldon (1978) as well as the size data from these trials: those less than or equal to 6cm (likely to be less than a year old); those between 6 and 9cm (older than 1 year, but probably including both immature fish and mature adults); and those greater than 9cm in length (mature adults of a large size). While small and medium mudfish made a significant choice to remain in the initial chamber, rather than making a choice either towards or away from the eel odour, large fish were equally likely to make any of the three choices (Table 4.2, Figure 4.4).

Table 4.2: Chi-square analysis of the choices made by mudfish of each of three size classes

Size class of mudfish	χ^2	d.f.	P value
Small (≤ 6cm)	91.2340	2	<0.0001
Medium (> 6cm, ≤ 9cm)	13.0000	2	0.0015
Large (> 9cm)	0.2105	2	0.9001
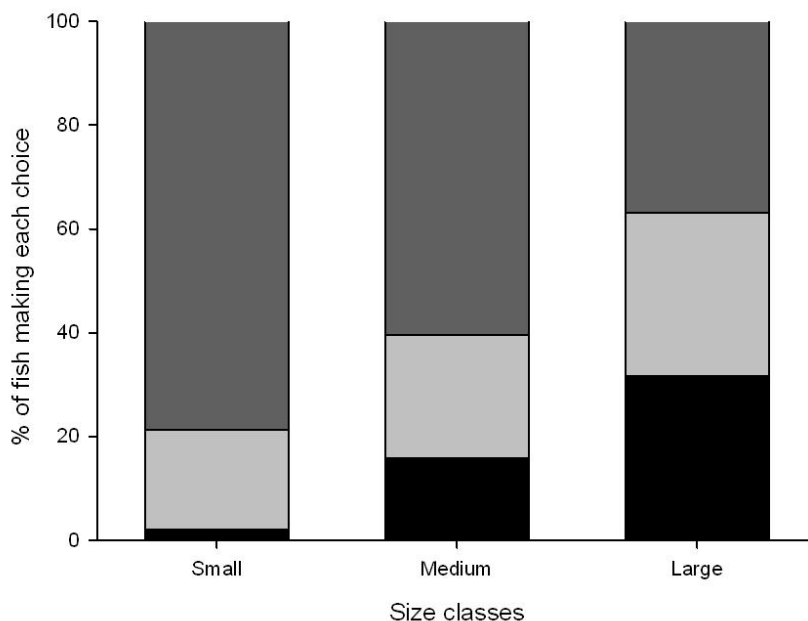
Figure 4.4: Graph showing the percentage of fish in each size class that made each of the three choices. Small fish were those ≤ 6cm; medium fish 6-9cm; large fish > 9cm. Black represents fish that swam towards the eel odour, light grey fish that swam away from the eel odour, and dark grey fish that remained in the lower chamber, i.e. making no choice

When the fish were categorised into size classes the probability of moving from the lower chamber differed between size classes (Table 4.3). When considering only the fish that did move from the lower chamber for each size class, there was still a tendency for the three size classes to respond differently to the eel odour. Small fish had an overall tendency to swim away from the eel odour, while medium and large fish were equally likely to swim either way (Table 4.3).

Table 4.3: Chi-square analysis comparing responses made between size classes

Effect being investigated	χ^2	d.f.	P value
Comparison of size classes: likelihood of moving	21.40	2	0.0001
Comparison of size classes: fish that did move	8.12	2	0.0170
Response of small fish to eel odour	12.80	1	0.0003
Response of medium fish to eel odour	0.6000	1	0.4386
Response of large fish to eel odour	0.0000	1	1.0000

4.4 Discussion

While the majority of mudfish made no apparent response to the presence of eel odour in the chamber, a tendency towards avoidance was seen in those mudfish that did move from the lower chamber. Of the fish that moved, significantly more chose to swim away from the eel, rather than towards it, indicating that mudfish possess an ability to recognise the presence of shortfin eels as a predator through chemical cues. As brown mudfish are a predominantly benthic species, with very cryptic colouring, predator avoidance behaviour may not necessarily result in an overt response from the fish. Some fish species will exhibit a "freezing" behaviour when encountering a predator, involving a shift to a more cryptic posture (Edge et al., 1993; Lehtiniemi, 2005). Brown mudfish do spend time resting on the substrate as part of their natural behaviour (pers obs.), and in this state are extremely difficult to detect unless they move. This experiment did not consider the behaviour exhibited by the mudfish during the trial, instead only recording the location of the fish at the end of the trial period. Mudfish that remained in the initial chamber may in fact have been avoiding predation by adopting a cryptic posture, although as eels have highly effective olfactory senses (Cadwallader, 1975; Jellyman, 1989) "freezing" behaviour is unlikely to be a particularly effective technique for avoiding predation by eels.

Another possible explanation for the apparent lack of response from the majority of the mudfish in the trials could be that the mudfish use allelomones as an initial detection method, but do not exhibit avoidance behaviour until another cue (such as visual detection of the predator) is also detected. This could account for the reaction of fish in the medium size class to the eel odour when they moved from the lower chamber. While these fish are of a size large enough that they can be expected to detect the odour and recognise it as a threat, there is no significant difference in their choice with regards to the odour. Those fish that swam towards the eel may be aware of the presence of the eel nearby, but may not yet judge it to be of sufficient threat to elicit an avoidance response. This behaviour is common in other fish species – where information from two cues is more likely to elicit a response than that from only one (Lehtiniemi, 2005). Brown mudfish may only respond strongly to the presence of a predator when more than one cue is detected, which could explain the lack of response from the majority of the fish in the trials.

Behavioural differences may also be related to the state of individual mudfish. Fish that had recently encountered and escaped from an eel would likely be more sensitive to chemical cues emitted by an eel. In other predator avoidance experiments satiated fish have been found to be more likely to respond to the presence of a predator than fish that are hungry (Brown, 2003). This is presumably due to the fact that the benefits gained from continuing to forage outweigh the risks of predation. If the mudfish used in the trial were hungry, and therefore in search of food, this may have resulted in a lack of apparent response from many of the mudfish. However, if this were the case then they would be moving around foraging, and all fish would be expected to be equally likely to be found in any of the three chambers, with no preference for any of the chambers seen.

Mudfish of different sizes differed in their response to the eel odour. This is reflected in the average size of the mudfish making each of the three choices. The fact that the smallest fish were less likely to overtly respond to the eel odour than larger mudfish (Figure 4.3) implies that predator recognition and avoidance behaviour in brown mudfish may be a learned, rather than innate, behaviour (McLean et al., 2007). This is a common method of predator recognition for many fish species (Brown, 2003). The general absence of response from the smaller fish, fry less than a year old, suggests that they had not yet learnt to recognise shortfin eels as a predator.

If brown mudfish are exhibiting a learned avoidance behaviour to shortfin eel allelomones, then small fish should be least likely to respond to the eel odour while larger mudfish avoid the odour. In this study, however, larger mudfish (average size ten centimetres) appeared more likely to swim towards the odour while medium sized mudfish (average size seven centimetres) were most likely to avoid the eel odour (Figure 4.3). In many fish species, different life stages will respond differently to the detection of a predator. Smaller fish of some species are more inclined to seek refuges when faced with threat of predation. Some fish are also able to determine the size of an approaching predator from its pheromones, and assess whether the predator is of a size to be of significant threat to that individual (Ferrari et al., 2006). This may explain the differing responses of large and medium sized mudfish to the eel odour.

Large eels are not often found in mudfish habitat (pers obs.) so medium sized eels were used in the trials to create an odour. These eels may be less likely to be of significant threat to a large mudfish. If brown mudfish are able to determine the size of an approaching predator from its allelomones, then the large fish may have judged the eels to be of no significant threat to them. While large mudfish were those most likely to swim towards the eel, these fish did not preferentially swim towards the odour. Analysis of the response of large mudfish to the eel odour (Table 4.2, Figure 4.4) showed there was no significant difference between the choices they made, with larger fish equally likely to be found in any of the three chambers. This suggests that large mudfish are acting independently of the eel odour.

Shallow and ephemeral mudfish habitats are not ideal habitat for large eels, as there is a physical access restriction, with eels only able to access the habitat during the winter months when water is deep. This intermittent access, combined with the apparently ambivalent responses shown by the large mudfish, suggests that eels are not always a significant threat to adult brown mudfish. The shallower habitat provides a good habitat for smaller eels and elvers, potentially allowing them to escape competition and predation from larger eels. However, as eels are unable to aestivate, and thus would not survive in ephemeral habitats during the summer dry period, they need to move out of the habitat seasonally.

The behaviour observed by the brown mudfish in these trials indicates that they have the ability to recognise predators through chemical cues. While there was an overall tendency towards avoidance of the eel odour in those fish that did make an obvious response (i.e. moved from the lower chamber), the majority of fish did not move from this initial chamber. In a natural environment the behavioural response of mudfish to allelomones from a predator could be quite different from that which was observed. Presence of hiding places and the presence of conspecific pheromones in a natural habitat are two factors that could have significant effects on the behaviour of the mudfish. Brown mudfish are a naturally cryptic fish, with colouring that makes them extremely difficult to detect in their natural habitat. They are also a predominantly benthic species, spending much of their time on and under the substrate surface. When stationary they blend in with the leaf debris that coats the substrate, and are

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often difficult to detect unless they move. Part of a predator avoidance behaviour for many fish species involves camouflage and/or exhibiting cryptic postures (Edge et al., 1993; Lehtiniemi, 2005). The swamp forest habitat of brown mudfish contains many hiding places, including spaces under logs, tree roots, and within the loose substrate. Observance of the behaviour of the fish throughout the trial, as well as for a period of time prior to exposure to the eel odour may enable conclusions to be drawn regarding behaviour of brown mudfish when exposed to shortfin eel odour.

The presence of pheromones from other mudfish may also affect the response of an individual mudfish to the odour of a predator. While each fish underwent the trial with up to four other mudfish, all these fish received information only from the allelomones emitted by the eel. Alarm cues from conspecifics have been found to elicit much stronger responses in many fish species than when cues from only the predator are available (McLean et al., 2007; Mirza and Chivers, 2002). If conspecific cues from the other mudfish were also available, then the response of mudfish to the eel odour may differ. Further investigation of the responses of brown mudfish to shortfin eels in the presence of conspecific pheromones and alarm cues will allow better inference of the reason for the observed behaviours. When considering size classes, for small fish if conspecific alarm cues trigger learned recognition, and subsequently avoidance, this would result in a larger proportion of small fish swimming away from the odour. For medium fish a change in the proportion of fish swimming away from rather than towards the odour should occur. A significant difference in the proportion of fish making each choice (rather than the equal proportions seen in these trials) would indicate that mudfish respond to predators more strongly when presented with more than one cue. If large mudfish were truly acting without reference to the eel odour, then their responses would be expected to remain the same as those in these trials, with equal preferences for each of the three chambers shown when the fish were presented with other cues.

Chapter Five

General Discussion

Close up of adult brown mudfish (*Neochanna apoda*)   Photo: Stella McQueen

Chapter 5: General Discussion

The loss of around 90% of wetland areas (McGlone, 2009) and 98% of lowland swamp forest (G. Rapson, pers comm.) in New Zealand makes it crucial to better understand the habitat preferences of brown mudfish, a lowland swamp fish species. Brown mudfish are a threatened species currently under human induced gradual decline (Hitchmough et al., 2007). Habitat loss and degradation resulting from activities such as drainage, irrigation and wetland development are one of the major causes of this decline. The historical understanding of brown mudfish as being a species found primarily in kahikatea swamp forest is at odds with more recent reports of brown mudfish as being a species able to tolerate a wide range of environmental conditions. Historical reports express concern that brown mudfish will no doubt become extinct with the loss of lowland kahikatea forest (Phillipps, 1923). In comparison, they are currently considered suited to habitats ranging from forested areas, to open grassy wetlands, to farm drains. Continuing habitat loss and degradation mean that lowland wetlands are now vastly different from their original state.

Landscape and micro-scale analyses of brown mudfish habitat support historical reports, indicating that brown mudfish are a swamp forest fish species. These analyses of various environmental aspects of mudfish habitats showed a correlation of brown mudfish with areas of land historically covered in forest. This suggests that brown mudfish are now present only in areas of previously suitable habitat. This accounts for the sporadic distribution of brown mudfish, even though they have a wide natural range. While clearly able to tolerate a variety of conditions, it is not known to what extent brown mudfish are able to cope with changing environmental conditions before being unable to persist in them any longer. Further deviation of modified wetlands where mudfish are present from their current state may result in loss of this species from even more wetland areas.

There may be some regional differences in habitat preferences of brown mudfish, but the large scale analysis (including records of all brown mudfish throughout New Zealand) had a high level of accuracy in predicting the presence of brown mudfish. In this analysis the environmental characteristics of individual brown mudfish sites in both the North and South Islands was compared to other lowland sites where brown mudfish had not been found. The habitat at the brown mudfish sites was found to be distinctly different from that at the other sites. This suggests that in general there are some specific habitat characteristics preferred by brown mudfish.

Shading, and thus the presence of surrounding vegetation, is one habitat feature of importance to brown mudfish populations. Trees surrounding the habitat provide detritus input to the wetland, which may provide shelter and also a potential food source (in the form of terrestrial invertebrates) for the mudfish. Tree roots also create holes and hollows in the substrate, which may be important for aestivating mudfish. In addition to this, riparian vegetation affects many other physical variables within wetlands. One of these is regulation of temperature within the wetland, a feature potentially of high importance to brown mudfish, which seem to prefer areas with cooler temperatures, both in the summer and winter. This dislike of warm temperatures by brown mudfish is evident despite a documented ability of *Neochanna* species to be able to withstand temperature extremes (O'Brien and Dunn, 2007).

Brown mudfish also appear to require areas that have soft substrates with a small particle size, especially those containing peat and alluvium. Ephemeral areas with still waters were also preferred. The water source of the wetland was another important feature, with those areas sourced by light, but frequent, rainfalls most highly associated with the presence of brown mudfish. Areas that had high catchments or a relatively high flow variability, which would be strongly correlated with variation in rainfall, were not suitable for brown mudfish.

Another detrimental effect of habitat loss, modification and degradation, in addition to reduction of suitable mudfish habitat, is the resulting increase in interconnectedness with other habitats. Brown mudfish are considered to be poor competitors (O'Brien and Dunn, 2007) or may be subject to high levels of predation. Regardless of the

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cause, they are not often found with other fish species. Their ability to withstand ephemeral conditions reduces competition as other species are not able to cope with this seasonal drying of the habitat. However, increased habitat interconnectedness can either result in loss of ephemeral areas (O'Brien and Dunn, 2007) or else make it easier for other species to invade the ephemeral parts of a habitat when surface water is present there. Both of these events would result in an increase of other fish species in brown mudfish habitat which would further reduce habitat suitability through an increase in competition, and potentially also predation. This invasion could involve other native galaxiids or eels, or exotic pest fish, such as brown trout (*Salmo trutta*) or mosquitofish (*Gambusia affinis*).

Shortfin eels, a natural predator of brown mudfish (Eldon, 1979c), are able to move freely over damp ground (McDowall, 1990). Increased interconnectedness of habitat could thus result in a higher number of shortfin eels in areas where brown mudfish are present, as the eels would have shorter distances to travel before reaching mudfish areas. This would result in an increase in the number of eels present in the area. Although not generally found with other fish species, when other species are present, brown mudfish are most often associated with shortfin eels (McDowall, 2006). Trials testing the ability of brown mudfish to detect shortfin eels through chemical cues found not only that they were able to detect the eel, but also suggested that brown mudfish will exhibit anti-predator responses towards shortfin eels. While the nature of this predator recognition and response behaviour needs to be further investigated, it is possible that this chemical recognition of shortfin eels is used by brown mudfish as a method of habitat selection. Chemical cues are used to determine habitat suitability and selection in many fish species (Atkinson and Joy, 2008; Baker and Hicks, 2003; Hale et al., 2009). As brown mudfish are considered to be poor competitors, the presence of large numbers of predators or competing species would produce unsuitable mudfish habitat. This could either result in the mudfish being pushed even further onto the edges of an already marginal habitat, or else, if there was nowhere suitable for the mudfish to retreat to, they may be forced to remain in an area where competition from other species was high. This could lead to decline in population size and recruitment, or result in loss of brown mudfish from that area.

5.1 Mana Island

One of the initial aims of this study was to determine whether the wetlands on Mana Island would be suitable as brown mudfish habitat. If the habitat was found to be suitable, release of brown mudfish into these wetlands to establish a sustainable population there and increase the population range of brown mudfish was to be considered. Unfortunately, no in depth surveys were able to be conducted on Mana Island during the course of this study due to time constraints. However, observations of the wetlands by Mike Joy found them to become completely dry during the summer months in 2007/2008. Eels are occasionally found in the wetlands (G. Timlin, pers comm.), which suggests a year round supply of water was available somewhere on the island, as eels are unable to withstand periods of extended drought (Eldon, 1979c).

Results from the habitat analysis in Chapter Three do indicate brown mudfish distribution to be primarily ruled by the presence of an ephemeral water source. For brown mudfish to remain alive the substrate must remain damp throughout the 'dry' period. Complete drying of the substrate, as observed on Mana Island, would not facilitate the survival of mudfish in that area. Brown mudfish, like eels, can travel over damp ground when necessary (Eldon, 1978), but it is not known how far they will move in search of suitable refuge. Brown mudfish have been observed in many cases to remain lying on the substrate surface in the same position they were in when the water table dropped (Eldon, 1978; O'Brien and Dunn, 2007), which suggests that the duration of the dry period is important in determining the behaviour of the mudfish.

At Koputaroa, one of the sites studied, brown mudfish were frequently found in an area vegetated by willow trees (*Salix* sp.). The substrate in this area tended to be only bare mud, without the thick coating of leaves and other detritus common at the other mudfish sites. This mud was also more compact than that of the swamp forest areas at Nga Manu, Victoria Station or Ashhurst Domain, and was observed to dry so completely one summer that the substrate surface became cracked. Permanent water and damp mud areas were located within a few metres of this area, and the mudfish possibly retreated to this water source during the dry period. Holes and hollows created by the willow roots may also have provided the mudfish a means of moving far enough down into the substrate to remain in damp mud (Eldon, 1978; Eldon, 1979a;
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Reid, 1886), meaning they were not affected by the drying of the upper soil layers. As the Mana Island wetlands are open, with no vegetation within them, mudfish would not be able to use soil loosened by tree roots to aid in burrowing down to damp mud, and would therefore be reliant on an area of permanent water for survival during the summer. If this permanent water was also used as a refuge by eels, it may not be suitable for mudfish to use as a refuge as well, as high numbers of predators in a small area would likely result in a great reduction in the number of mudfish.

Furthermore, while able to survive in a wide variety of conditions, both historical reports and the results from the habitat analysis in this study suggest that brown mudfish are a swamp forest fish species. From these initial observations, comparison of the open Mana Island wetlands to other wetland areas surveyed during the course of this study suggest that Mana Island would not be suitable as brown mudfish habitat. Further, in depth studies over a number of years would enable a conclusive indication regarding this, as they would provide consistent information about the hydrology and weather conditions of the area. GIS variables for the island could also be used to determine habitat suitability. Some recommendations regarding possible ways to determine habitat suitability for brown mudfish are set out below.

5.2 Suggested guidelines for determining habitat suitability

While more work needs to be done to determine how applicable the GIS measurements are to all brown mudfish populations, analysis of sites trapped during this study found the GIS variables to be useful in predicting the presence of brown mudfish at a small scale. I would therefore suggest using these variables to make an initial assessment of habitat suitability. Comparison of GIS variables to those where brown mudfish populations are present allows the features of the wetland to be compared to those known to be of influence to brown mudfish, allowing comparison of wetlands at a large scale. This will also give an indication of the conditions at the site over a longer period of time than could be measured from sporadic or one off visits to the site. This allows analysis of the suitability of yearly conditions at the site, rather than only those at one season. These GIS variables can be used both to assess

the suitability of a chosen wetland, as well as to form a predictive map of where brown mudfish populations can be expected to be (Joy and Death, 2004).

Once an initial indication regarding habitat suitability has been gained, field surveys can be undertaken to further determine either whether mudfish are present, or if the habitat would be suitable for brown mudfish. This should involve assessment of habitat characteristics, such as presence of flowing water, whether the site is ephemeral, interconnectedness with nearby habitats, the surrounding landuse, and nearby vegetation. The presence of other species is also important; large numbers of other fish species would suggest an unsuitable habitat, even if environmental characteristics seem favourable.

5.3 Recommendations for future work:

1) Field surveys of several brown mudfish sites should be conducted to ensure the remotely sensed GIS variables are relevant for predicting brown mudfish presence at a wide range of sites. This would indicate the relative use of these variables as a predictive tool, and enable the creation of a predictive map for brown mudfish throughout their range.

2) Predator detection is essential for prey species, with failure to detect a potential predator and respond accordingly likely to result in mortality (Brown, 2003; Lehtiniemi, 2005; McLean et al., 2007). The ability of brown mudfish to detect their natural predator shortfin eels was investigated using chemical cues. The response of the mudfish to these cues indicated that they do have the ability to recognise predators, and that this recognition is likely to be a learned recognition. As the majority of mudfish in the trials made no apparent response to odour created by shortfin eels, the nature of predator responses in brown mudfish needs to be investigated further. Possible predator response behaviours that could be investigated are listed below.

- Predator detection by brown mudfish could be used only as a direct escape, when the predator is close. In this case, olfactory cues would be expected to be

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used in combination with other cues, such as visual cues. This would result in a stronger response from the mudfish when both cues were available. Overt responses by fish in the trials may have been a result of a recent interaction with a predator.

- As brown mudfish are an extremely cryptic species, hard to detect amongst leaf detritus on the substrate, their response to predators may instead be a 'freezing' response, rather than an overt reaction. This is a method of predator avoidance used by several other fish species (Edge et al., 1993; Lehtiniemi, 2005). The prey detection methods used by eels could also be important in determining the response of brown mudfish to this predator. If shortfin eels detect prey by sensing movement, a cryptic 'freezing' response would be a logical method of predator avoidance.

- Some fish species are able to assess the size of an approaching predator from its allelomones, thus assessing the threat to that fish (Ferrari et al., 2006). A large mudfish may be able to judge the size of a small or medium sized eel as being of no significant threat. The response of mudfish of different sizes to varying sized eels could be investigated to see if responses vary between predators of different sizes.

- Presence of conspecific alarm cues can result in stronger predator response behaviours, as well as triggering learned recognition of a predator (Brown, 2003). The response of brown mudfish to the odour of shortfin eels when conspecific alarm cues are also present could indicate whether this is a learned recognition.

3) Increased interconnectedness of habitats with wetland drainage and development will result in an increased likelihood of brown mudfish encountering other species. To reduce negative impacts on brown mudfish in these areas, and prevent the population from dying out as a result of increased competition and predation, the feasibility of predator exclusions could be investigated. While this may cause initial disruption to the habitat, it is possible that it would prevent the loss of brown mudfish populations in areas where habitat modification has already occurred.

4) Chemical cues can also be used as a means of habitat selection (Atkinson and Joy, 2008). The presence of large numbers of predators in an area could indicate unsuitable habitat. Brown mudfish are considered to be poor competitors (O'Brien and Dunn, 2007), so the presence of other fish species could also make habitat unsuitable. The response of brown mudfish to other fish species (both native and exotic) could be investigated to see if any response is made to the presence of possible competing species.

References and Appendices

Adult brown mudfish (*Neochanna apoda*) caught at
Ashhurst Domain   Photo: Shaun Nielsen

References

Department of Conservation, 2003. New Zealand mudfish (*Neochanna* spp.) recovery plan 2003-13. *Threatened Species Recovery Plan 51*: Wellington, 25p.

Agrillo, C.; Dadda, M.; Bisazza, A. 2009. Escape behaviour elicited by a visual stimulus. A comparison between lateralised and non-lateralised female topminnows. *Laterality 14*: 300-314.

Atkinson, N.K.; Joy, M.K. 2008. Response of *Gobiomorphus hubbsi* (bluegill bully) to odours of conspecific fish in the presence of natural stream odours: does habitat have an influence? *New Zealand Journal of Marine and Freshwater Research 42*: 173-180.

Baker, C.F.; Hicks, B.J. 2003. Attraction of migratory inanga (Galaxias maculatus) and koaro (Galaxias brevipinnis) juveniles to adult galaxiid odours. *New Zealand Journal of Marine and Freshwater Research 37*: 291-299.

Barrier, R.; Hicks, B.; Dean, T.; Ling, N. 1996. Habitat requirements and aerial respiration in the black mudfish. *Water and Atmosphere 4*: 20-22.

Barrier, R.F.G.; Hicks, B.J. 1994. Behavioral interactions between black mudfish (Neochanna diversus Stokell, 1949: Galaxiidae) and mosquitofish (Gambusia affinis Baird and Girard, 1854). *Ecology of Freshwater Fish 3*: 93-99.

Brown, G.E. 2003. Learning about danger: chemical alarm cues and local risk assessment in prey fishes. *Fish and Fisheries 4*: 227-234.

Brown, G.E.; Adrian, J.C.; Patton, T.; Chivers, D.P. 2001. Fathead minnows learn to recognize predator odour when exposed to concentrations of artificial alarm pheromone below their behavioural-response threshold. *Canadian Journal of Zoology - Revue Canadienne de Zoologie 79*: 2239-2245.

Cadwallader, P.C. 1975. Feeding relationships of galaxiids, bullies, eels and trout in a New Zealand River. *Australian Journal of Marine and Freshwater Research 26*: 299-316.

Collier, K.J.; Clapcott, J.E.; Young, R.G. 2009. Influence of Human Pressures on Large River Structure and Function. *Department of Conservation Client Report. CBER Contract Report 95*.

De'ath, G. 2002. Multivariate regression trees: A new technique for modeling species-environment relationships. *Ecology 83*: 1105-1117.

De'ath, G.; Fabricius, K.E. 2000. Classification and regression trees: A powerful yet simple technique for ecological data analysis. *Ecology 81*: 3178-3192.

Downes, T.W. 1918. Notes on eels and eel-weirs (tuna and pa-tuna). *Transactions and Proceedings of the Royal Society of New Zealand 50*: 296-316.

Edge, K.; Townsend, C.R.; Crowl, T.A. 1993. Investigating anti-predator behaviour in three genetically differentiated populations of non-migratory galaxiid fishes in a New Zealand river. *New Zealand Journal of Marine and Freshwater Research 27*: 357-363.

Eldon, G.A. 1968. Notes on the presence of the brown mudfish (*Neochanna apoda* Günther) on the west coast of the South Island of New Zealand. *New Zealand Journal of Marine and Freshwater Research 2*: 37-48.

Eldon, G.A. 1978. The life history of *Neochanna apoda* Günther (Pisces: Galaxiidae) *New Zealand Ministry of Agriculture and Fisheries Research Bulletin No. 19*: 1-44.

Eldon, G.A. 1979a. Breeding, growth, and aestivation of the Canterbury mudfish, *Neochanna burrowsius* (Salmoniformes, Galaxiidae). *New Zealand Journal of Marine and Freshwater Research 13*: 331-346.

Eldon, G.A. 1979b. Food of the Canterbury mudfish, *Neochanna burrowsius* (Salmoniformes, Galaxiidae). *New Zealand Journal of Marine and Freshwater Research 13*: 255-261.

Eldon, G.A. 1979c. Habitat and interspecific relationships of the Canterbury mudfish, *Neochanna burrowsius* (Salmoniformes, Galaxiidae). *New Zealand Journal of Marine and Freshwater Research 13*: 111-119.

Eldon, G.A.; Howden, P.J.; Howden, D.B. 1978. Reduction of a population of Canterbury mudfish, *Neochanna burrowsius* (Galaxiidae), by drought. *New Zealand Journal of Marine and Freshwater Research 12*: 313-321.

Ferrari, M.C.O.; Messier, F.; Chivers, D.P. 2006. The nose knows: minnows determine predator proximity and density through detection of predator odours. *Animal Behaviour 72*: 927-932.

Francis, K.A. 2000. Conservation of the brown mudfish (*Neochanna apoda*) in the Manawatu and Rangitikei regions. Unpublished BSc (Honours) project, Massey University, Palmerston North, New Zealand. 28p.

G-408M. 2009. G-408M GEE's Wire Minnow Trap 1/8" mesh. *www. tackle-factory. com*: 22 June 2009.

Gleeson, D.M.; Howitt, R.L.J.; Ling, N. 1999. Genetic variation, population structure and cryptic species within the black mudfish, *Neochanna diversus*, an endemic galaxiid from New Zealand. *Molecular Ecology 8*: 47-57.

Guegan, J.F.; Lek, S.; Oberdorff, T. 1998. Energy availability and habitat heterogeneity predict global riverine fish diversity. *Nature 391*: 382-384.

Günther, A. 1867. On a new form of mudfish from New Zealand. *Annals and Magazine of Natural History 3*: 305-309.

Hale, R.; Swearer, S.E.; Downes, B.J. 2009. Separating natural responses from experimental artefacts: habitat selection by a diadromous fish species using odours from conspecifics and natural stream water. *Oecologia 159*: 679-687.

Hector, J. 1869. On the Mud Fish (*Neochanna apoda*, Günther), from Hokitika. *Transactions and Proceedings of the Royal Society of New Zealand 2*: 402.

Hector, J. 1872. Notes on the Edible Fishes. *In:* Hutton, F.W. (Editor), *Fishes of New Zealand*. James Hughes (Printer), Wellington: 133p.

Hicks, B.J.; Barrier, R.F.G. 1996. Habitat requirements of black mudfish (Neochanna diversus) in the Waikato region, North Island, New Zealand. *New Zealand Journal of Marine and Freshwater Research 30*: 135-150.

Hitchmough, R.; Bull, L.; Cromarty, P. 2007. *New Zealand Threat Classification System lists 2005*. Science & Technical Publishing, Department of Conservation, Wellington.

Hosmer, D.W.; Lemeshow, S. 2000. *Applied Logistic Regression, 2nd Edition*. John Wiley & Sons, Inc., United States of America.

IUCN. 2009. IUCN Red List of Threatened Species. Version 2009.1. *www. iucnredlist. org*: 2 November 2009.

Jellyman, D.J. 1989. Diet of two species of freshwater eel (*Anguilla* spp.) in Lake Pounui, New Zealand. *New Zealand Journal of Marine and Freshwater Research 23*: 1-10.

Joy, M.K.; Death, R.G. 2002. A discriminant analysis investigation of reference site fish assemblages in the Manawatu-Wanganui region, North Island, New Zealand. *Verhandlungen der Internationalen Vereinigung fur Theoretische und Angewandte Limnologie 28*: 319-322.

Joy, M.K.; Death, R.G. 2004. Predictive modelling and spatial mapping of freshwater fish and decapod assemblages using GIS and neural networks. *Freshwater Biology 49*: 1036-1052.

Kelley, J.L.; Magurran, A.E. 2003. Learned predator recognition and antipredator responses in fishes. *Fish and Fisheries 4*: 216-226.

Koehn, J.D.; Raadik, T.A. 1991. The Tasmanian mudfish *Galaxias cleaveri* Scott 1934 in Victoria. *Proceedings of the Royal Society of Victoria 103*: 77-86.

Laird, M.G.; Bradshaw, J.D. 2002. The break-up of a long-term relationship: the Cretaceous separation of New Zealand from Gondwana. *Gondwana 11 Conference*, pp 273-286. Int Assoc Gondwana Research, Christchurch, New Zealand.

LandcareResearch. 2009. *www.landcareresearch.co.nz/databases/nz/ri.asp*.

Lehtiniemi, M. 2005. Swim or hide: predator cues cause species specific reactions in young fish larvae. *Journal of Fish Biology 66*: 1285-1299.

Leithwick, J.; Wilson, G.; Rutledge, D.; Wardle, P.; Morgan, F.; Johnston, K.; McLeod, M.; Kirkpatrick, R. 2003. *Land Environments of New Zealand - Nga Taiao o Aotearoa*. David Bateman Ltd., Auckland.

Ling, N. 2001. *New Zealand mudfishes: a guide*. Science and Research Publication, Department of Conservation.

Ling, N.; Gleeson, D.M. 2001. A new species of mudfish, Neochanna (Teleostei : Galaxiidae), from northern New Zealand. *Journal of the Royal Society of New Zealand 31*: 385-392.

Ling, N.; Willis, K. 2005. Impacts of mosquitofish, *Gambusia affinis*, on black mudfish, *Neochanna diversus*. *New Zealand Journal of Marine and Freshwater Research 39*: 1215-1223.

Magurran, A.E. 1990. The inheritance and development of minnow anti-predator behaviour. *Animal Behaviour 39*: 834-842.

McDowall, R.M. 1970. The galaxiid fishes of New Zealand. *Bulletin of the Museum of Comparative Zoology, Harvard University 139*: 341-431.

McDowall, R.M. 1980. Guide to freshwater fishes. Part IX family Galaxiidae: The mudfishes. *Freshwater Catch 8*: 14-15.

McDowall, R.M. 1990. *New Zealand Freshwater Fishes: A Natural History and Guide*. Heinemann Reed, Auckland.

McDowall, R.M. 1993. A recent marine ancestry for diadromous fishes? Sometimes yes, but mostly no. *Environmental Biology of Fishes 37*: 329-335.

McDowall, R.M. 1997. Affinities, generic classification and biogeography of the Australian and New Zealand mudfishes (Salmoniformes: Galaxiidae). *Records of the Australian Museum 49*: 121-137.

McDowall, R.M. 1999. Just hanging around for some fresh air, thanks! Survival adaptations of the mudfish. *Water and Atmosphere 7*: 7-8.

McDowall, R.M. 2002. Accumulating evidence for a dispersal biogeography of southern cool temperate freshwater fishes. *Journal of Biogeography 29*: 207-219.

McDowall, R.M. 2004. The Chatham Islands endemic galaxiid: a Neochanna mudfish (Teleostei : Galaxiidae). *Journal of the Royal Society of New Zealand 34*: 315-331.

McDowall, R.M. 2006. Crying wolf, crying foul, or crying shame: alien salmonids and a biodiversity crisis in the southern cool-temperate galaxioid fishes? *Reviews in Fish Biology and Fisheries 16*: 233-422.

McDowall, R.M.; Richardson, J. 1983. The New Zealand freshwater fish database - a guide to input and output. . *Fisheries Research Division Information Leaflet 12*: Ministry of Agriculture and Fisheries, Wellington. *www.niwa.co.nz/our-services/online-services/freshwater-fish-database*.

McGlone, M.S. 2009. Postglacial history of New Zealand wetlands and implications for their conservation. *New Zealand Journal of Ecology 33*: 1-23.

McLean, F.; Barbee, N.C.; Swearer, S.E. 2007. Avoidance of native versus non-native predator odours by migrating whitebait and juveniles of the common galaxiid, *Galaxias maculatus*. *New Zealand Journal of Marine and Freshwater Research 41*: 175-184.

McPhail, J.D. 1999. A fish out of water: observations on the ability of black mudfish, Neochanna diversus, to withstand hypoxic water and drought. *New Zealand Journal of Marine and Freshwater Research 33*: 417-424.

Mirza, R.S.; Chivers, D.P. 2002. Behavioural responses to conspecific disturbance chemicals enhanve survival of juvemile Brook Charr, *Salvelinus fontinalis*, during encounters with predators. *Behaviour 139*: 1099-1109.

Mitchell, C.P. 1995. A new species of *Galaxias* (Pisces: Galaxiidae) from Chatham Island, New Zealand. *Journal of the Royal Society of New Zealand 25*: 89-93.

O'Brien, L.K. 2007. Size-dependent strategies in response to drought by *Neochanna burrowsius*. *New Zealand Natural Sciences 32*: 21-28.

O'Brien, L.K.; Dunn, N.R. 2007. Mudfish (*Neochanna* Galaxiidae) literature review. *Science for Conservation 277*. Department of Conservation, Wellington 88p.

Park, G. 2002. Swamps which might doubtless easily be drained: Swamp drainage and its impact on the indigenous. *In:* Pawson, E.; Brooking, T. (Editors), *Environmental Histories of New Zealand*, pp 151-165. Oxford University Press, Melbourne.

Phillipps, W.J. 1923. Note on the occurrence of the New Zealand mudfish, or hauhau (*Neochanna apoda*). *New Zealand Journal of Science and Technology 6*: 62-63.

Reid, R.C. 1886. *Rambles on the Golden Coast of the South Island of New Zealand*. Colonial Printing and Publishing, London.

Rice, J.; Ohmart, R.D.; Anderson, B.W. 1983. Habitat selection attributes of an avian community: A discriminant analysis investigation. *Ecological Monographs 53*: 263-290.

Roberts, W.C. 1872a. On the Mud-fish (*Neochanna apoda*); an extract from a letter written by S.E. Vollams. *Transactions and Proceedings of the Royal Society of New Zealand 5*: 456-457.

Roberts, W.C. 1872b. On the Mud Fish (*Neochanna apoda*), an extract from a letter written by G.G. Fitzgerald. *Transactions and Proceedings of the Royal Society of New Zealand 5*: 456.

SAS. 2006. *SAS 9.1.3 User's Guide*. SAS Institute Inc., Cary NC.

Stokell, G. 1949. The systematic arrangement of the New Zealand Galaxiidae. Part II. Specific Classification. *Transactions of the Royal Society of New Zealand 77*: 472-496.

Taylor, M. 1996. How native fish spawn on land. *Water and Atmosphere 4*: 23-25.

Versace, E.; Morgante, M.; Pulina, G.; Vallortigara, G. 2007. Behavioural lateralization in sheep (*Ovis aries*). *Behavioural Brain Research 184*: 72-80.

Waters, J.M.; Lopez, J.A.; Wallis, G.P. 2000. Molecular phylogenetics and biogeography of galaxiid fishes (Osteichthyes : Galaxiidae): Dispersal, vicariance, and the position of *Lepidogalaxias salamandroides*. *Systematic Biology 49*: 777-795.

Waters, J.M.; McDowall, R.A. 2005. Phylogenetics of the australasian mudfishes: Evolution of an eel-like body plan. *Molecular Phylogenetics and Evolution 37*: 417-425.

Waters, J.M.; White, R.W.G. 1997. Molecular phylogeny and biogeography of the Tasmanian and New Zealand mudfishes (Salmoniformes: Galaxiidae). *Australian Journal of Zoology 45*: 39-48.

Wild, M.; Snelder, T.; Leathwick, J.R.; Shankar, U.; Hurren, H. 2005. Environmental variables for the freshwater environments of New Zealand river classification. *NIWA Client Report CHC2004.086*.

Williams, B.K. 1983. Some observations on the use of discriminant analysis in ecology. *Ecology 64*: 1283-1291.

Witten, I.H.; Frank, E. 2005. *Data Mining: Practical machine learning tools and techniques, 2nd edition*. Morgan Kaufman, San Francisco. *www.cs.waikato.ac.nz/ml/weka/*.

Young, D. 1996. In search of mudfish. *Forest and Bird*: 14-17.

Appendix A

This appendix contains a list of the 57 environmental variables used in the large scale habitat analysis (chapter 3). These are Geographic Information Systems (GIS) variables from the FWENZ database. Variables initially available for use in the analysis but which were excluded to reduce the amount of information being tested in the analysis are also listed, with the reason for their exclusion from the analysis.

Many of the variables had associated variables calculated to represent run-off from that variable. As most of these run-off weighted variables were highly correlated with their associated variable, in all instances the run-off weighted variable was retained, while the associated variable was removed from the dataset. The logic for this choice is that run-off into waterways is likely to be of greater influence in determining fish community composition. This is especially likely to be the case for brown mudfish, which populate habitats primarily fed by rainfall (O'Brien and Dunn, 2007).

Variables considered unlikely to be of influence in determining the presence or absence of brown mudfish populations (for example, the sinuosity of a stream segment) were also removed from the dataset prior to analysis.

Variables included in the large scale analysis:

1) Average slope of the downstream network

2) Distance to coast from the segment

3) Mean January (summer) air temperature within segment

4) Mean minimum June (winter) air temperature within segment

5) Current summertime equilibrium temperature within segment

6) Current wintertime equilibrium temperature within segment

7) December (summer) solar radiation within segment

8) June (winter) solar radiation within segment

9) Maximum segment slope (based on 30m DEM grid)

10) Average segment slope (based on 30m DEM grid)

11) Estimate of historic segment land cover

12) Estimate of current segment shade

13) Estimate of historic segment shade

14) Percentage of riparian area in LCDB category 1: bare ground

15) Percentage of riparian area in LCDB category 2: exotic forest

16) Percentage of riparian area in LCDB category 3: indigenous forest

17) Percentage of riparian area in LCDB category 5: pastoral

18) Percentage of riparian area in LCDB category 6: scrub

19) Percentage of riparian area in LCDB category 7: tussock

20) Percentage of riparian area in LCDB category 8: urban

21) Percentage of riparian area in LCDB category 9: wetlands

22) Percentage of riparian area in LCDB category other than 1-9: miscellaneous land cover

23) Coefficient of variation in annual rainfall in the catchment (runoff weighted)

24) Average slope of the catchment (calculated from 30m DEM grid; runoff weighted)

25) Mean January (summer) air temperature in the catchment (runoff weighted)

26) Mean minimum July (winter) air temperature in the catchment (runoff weighted)

27) Number of catchment rain days per month greater than 10mm (runoff weighted)

28) Number of catchment rain days per month greater than 25mm (runoff weighted)

29) Number of catchment rain days per month greater than 50mm (runoff weighted)

30) Number of catchment rain days per month greater than 100mm (runoff weighted)

31) Total annual runoff volume

32) Mean annual low flow

33) Annual potential evapotranspiration of catchment (runoff weighted)

34) December (summer) solar radiation in the catchment (runoff weighted)

35) June (winter) solar radiation in the catchment (runoff weighted)

36) Average elevation of the catchment

37) Lake index

38) Percentage of annual runoff volume from catchment with slope < 30° (i.e. low gradient)

39) Percentage of annual runoff volume from catchment with slope > 30° (i.e. steep)

40) Percentage of annual runoff from catchment in the LRI category: alluvium

41) Percentage of annual runoff from catchment in LRI category: glacial

42) Percentage of annual runoff from catchment in LRI category: peat

43) Average calcium content in the catchment (runoff weighted)

44) Average hardness of underlying rocks (induration) in the catchment (runoff weighted)

45) Average particle size in the catchment (runoff weighted)

46) Average phosphorus content in the catchment (runoff weighted)

47) Percentage of annual runoff from catchment in the LCDB category 1: bare ground

48) Percentage of annual runoff from catchment in the LCDB category 2: exotic forest

49) Percentage of annual runoff from catchment in the LCDB category 3: indigenous forest

50) Percentage of annual runoff from catchment in the LCDB category 4: mangrove, riparian, willows & coastal sands

51) Percentage of annual runoff from catchment in the LCDB category 5: pastoral

52) Percentage of annual runoff from catchment in the LCDB category 7: tussock

53) Percentage of annual runoff from catchment in the LCDB category 8: urban

54) Percentage of annual runoff from catchment in the LCDB category 9: wetlands

55) Percentage of annual runoff from catchment in an LCDB category other than 1-9: miscellaneous land cover

56) Average elevation of the segment

57) Total catchment area

Variables not included in the analysis:

- 'Maximum slope of downstream segments' and 'Maximum downstream grid slope'
  As brown mudfish are a non diadromous species populating wetlands, the slope downstream of their habitat is unlikely to have a significant influence on their distribution.

- 'Historic summertime equilibrium temperature' and 'Historic wintertime equilibrium temperature'
  The historic winter temperature was highly correlated with several other variables, and was also considered unlikely to have a significant influence on current mudfish distribution. As the winter temperature variable was removed, the historic summer temperature was also removed for consistency.

- 'Segment sinuosity'
  Brown mudfish are non diadromous, and also resident in wetlands rather than streams, so the sinuosity of a stream segment was considered unlikely to influence their distribution.

- 'Coefficient of variation of annual catchment rainfall'
  The runoff weighted equivalent of this variable was retained.

- 'Mean minimum July air temperature' and 'Mean January air temperature'
  These variables were correlated with the runoff weighted equivalent.

- Number of catchment rain days per month greater than 10mm, 25mm, 50mm and 100mm
  The runoff weighted equivalent of these variables was retained in the analysis.

- Number of catchment rain days per month greater than 15mm, 20mm and 200mm (and their runoff weighted equivalents)
  As all the rain days were highly correlated with each other, only four levels of rainfall were retained in the analysis, representing a spread from light to heavy rainfall.

- 'Annual potential evapotranspiration of catchment'

The runoff weighted equivalent of this variable was retained in the analysis.

- 'December solar radiation in the catchment' and 'June solar radiation in the catchment'
  The runoff weighted equivalent of this variable was retained in the analysis.

- 'Average slope of catchment (calculated from a 30m DEM grid)'
  The runoff weighted equivalent of this variable was retained in the analysis.

- 'Proportion of catchment with slope < 30° (i.e. low gradient)' and 'Proportion of catchment with slope > 30° (i.e. steep)'
  The runoff weighted equivalents of these variables were retained in the analysis.

- Percentage of the catchment in the Land Resource Inventory categories alluvium, glacial and peat
  The runoff weighted equivalents of these variables were retained in the analysis.

- Catchment averages of calcium content, bedrock hardness (induration), particle size and phosphorus
  The runoff weighted equivalents of these variables were retained in the analysis.

- Percentage of the catchment in the Land Cover Database categories 'bare ground', 'exotic forest', 'indigenous forest', 'mangrove, riparian, willows, coastal sands', 'pastoral', 'tussock', 'urban', 'inland and coastal wetlands' and 'miscellaneous land cover'
  The runoff weighted equivalents of these variables were retained in the analysis.

- Percentage of the catchment in the Land Cover Database category 'scrub' (and the runoff weighted equivalent)
  Information was not available for all sites for this variable.

- 'Maximum elevation of segment' and 'Minimum elevation of segment'
  Highly correlated with the average elevation.

- X and Y coordinates of the catchment centroid
  Meaningless to a fish community, as these variables relate only to the position on a map.

- Segment length and Euclidean length
  Not relevant to brown mudfish, who are resident in wetlands, not streams. Size of the wetland would be more meaningful.

- 'Stream order'
  Not relevant to mudfish, which populate wetlands, rather than streams.

- Elevation of upstream and downstream ends of segment (from REC)
  Highly correlated with the average elevation of the segment.

Appendix B

R^2 values, F statistics and Probability > F, showing the ability of the 57 environmental variables to distinguish between sites with mudfish and those without, as gained from the univariate test statistics from the canonical variate analysis in Chapter Three.

Note: 'LRI' stands for 'Land Resource Inventory', a national database of physical land-resource information; 'LCDB' stands for 'Land Cover Database', a digital thematic map of land cover.

Environmental variable	R^2	F statistic	Probability > F
Average hardness of underlying rocks in catchment *	0.4555	225.90	<0.0001
Average slope of catchment *	0.3065	119.31	<0.0001
Average particle size of the catchment*	0.2034	68.95	<0.0001
% of catchment in LRI category: alluvium *	0.1934	64.74	<0.0001
Average elevation of the catchment	0.1261	38.98	<0.0001
% of catchment in LRI category: peat *	0.1201	36.87	<0.0001
Annual runoff volume from catchment with slope <30°	0.1153	35.19	<0.0001
Annual runoff volume from catchment with slope >30°	0.1035	31.19	<0.0001
Current summer equilibrium temperature (within segment)	0.0903	26.81	<0.0001
Catchment rain days greater than 10mm/month *	0.0838	24.71	<0.0001
Estimate of current segment shade	0.0773	22.63	<0.0001
Maximum segment slope	0.0652	18.83	<0.0001
Catchment rain days greater than 25mm/month *	0.0648	18.72	<0.0001
Coefficient of variation in annual catchment rainfall *	0.0613	17.63	<0.0001
Catchment rain days greater than 50mm/month *	0.0602	17.31	<0.0001
% of catchment in LCDB category: tussock *	0.0491	13.95	0.0002
Catchment rain days greater than 100mm/month *	0.0432	12.19	0.0006
Estimate of historic segment land cover	0.0411	11.57	0.0008
% of riparian area in LCDB category: urban	0.0410	11.55	0.0008
Mean January (summer) air temperature (within segment)	0.0393	11.06	0.0010
% of catchment in LCDB category: wetland *	0.0390	10.96	0.0011
% of riparian area in LCDB category: miscellaneous land cover	0.0365	10.22	0.0016
Distance to coast from segment	0.0308	8.59	0.0037
December (summer) solar radiation (in catchment) *	0.0234	6.47	0.0116
Average phosphorus content in catchment *	0.0215	5.92	0.0156
% of riparian area in LCDB category: wetland *	0.0202	5.55	0.0192
Mean minimum July air temperature (in catchment) *	0.0198	5.45	0.0203
June (winter) solar radiation (within segment)	0.0173	4.75	0.0301

Environmental variable	R^2	F statistic	Probability > F
% of catchment in LCDB category: indigenous forest *	0.0155	4.24	0.0405
Total annual runoff volume	0.0156	4.27	0.0396
% of catchment in LCDB category: exotic forest *	0.0155	4.24	0.0405
Annual potential evapotranspiration of catchment *	0.0154	4.22	0.0410
Total catchment area	0.0152	4.16	0.0425
June (winter) solar radiation (in catchment) *	0.0150	4.12	0.0432
% of catchment in LCDB category: pastoral *	0.0150	4.12	0.0432
% of catchment in LCDB category: urban *	0.0137	3.75	0.0537
Lake index	0.0134	3.66	0.0569
% of catchment in LCDB category: miscellaneous land cover *	0.0131	3.59	0.0592
% of riparian area in LCDB category: bare ground	0.0130	3.56	0.0601
Mean annual low flow	0.0125	3.41	0.0659
% of catchment in LCDB category: bare ground *	0.0125	3.41	0.0661
Average calcium content in the catchment *	0.0120	3.28	0.0714
Current winter equilibrium temperature (within segment)	0.0107	2.91	0.0890
Average elevation of segment	0.0105	2.87	0.0916
% of catchment in LCDB category: mangrove *	0.0095	2.60	0.1082
% of riparian area in LCDB category: tussock	0.0083	2.27	0.1335
% of riparian area in LCDB category: scrub	0.0080	2.17	0.1419
% of catchment in LRI category: glacial *	0.0074	2.01	0.1569
% of riparian area in LCDB category: pastoral	0.0059	1.61	0.2049
Estimate of historic segment shade	0.0059	1.60	0.2071
% of riparian area in LCDB category: indigenous forest	0.0052	1.40	0.2377
Mean January (summer) air temperature (in catchment) *	0.0051	1.38	0.2416
Average segment slope	0.0038	1.04	0.3085
Average slope of the downstream network	0.0008	0.23	0.6338
% of riparian area in LCDB category: exotic forest	0.0004	0.11	0.7383
Mean minimum June air temperature (within segment)	0.0001	0.04	0.8461
December (summer) solar radiation (within segment)	0.0000	0.01	0.9196

* Variables are weighted for run-off. For LCDB category variables, this means run-off from this area

Appendix C

Coefficients for correlation between environmental variables with the first axis of the canonical variate analysis in Chapter Three.

Note: 'LRI' stands for 'Land Resource Inventory', a national database of physical land-resource information; 'LCDB' stands for 'Land Cover Database', a digital thematic map of land cover.

Environmental variable	Correlation (Can1)
% of catchment in LRI category: alluvium *	-0.4865
% of catchment in LRI category: peat *	-0.3835
Annual runoff volume from catchment with slope <30°	-0.3757
Catchment rain days greater than 10mm/month *	-0.3203
Estimate of current segment shade	-0.3077
Catchment rain days greater than 25mm/month *	-0.2817
Catchment rain days greater than 50mm/month *	-0.2715
Catchment rain days greater than 100mm/month *	-0.2299
Estimate of historic segment land cover	-0.2243
% of catchment in LCDB category: wetland *	-0.2185
Distance to coast from segment	-0.1943
Average phosphorus content in catchment *	-0.1621
% of riparian area in LCDB category: wetland	-0.1571
Mean minimum July air temperature (in catchment) *	-0.1556
June (winter) solar radiation (in catchment) *	-0.1357
% of catchment in LCDB category: pastoral *	-0.1357
Lake index	-0.1279
% of catchment in LCDB category: miscellaneous land cover*	-0.1267
Average calcium content of catchment *	-0.1211
Average elevation of segment	-0.1134
% of riparian area in LCDB category: scrub	-0.0988
% of riparian area in LCDB category: pastoral	-0.0853
Estimate of historic segment shade	-0.0849
Mean January (summer) air temperature (in catchment) *	-0.0788
Average slope of the downstream network	-0.0321

* Variables are weighted for run-off. For LCDB category variables, this means run-off from this area

Environmental variable	Correlation (Can1)
Average hardness of underlying rocks (induration) in the catchment *	0.7467
Average slope of catchment *	0.6124
Average particle size in the catchment *	0.4990
Average elevation of the catchment	0.3929
Annual runoff volume from catchment with slope >30°	0.3560
Current summer equilibrium temperature (within segment)	0.3325
Maximum segment slope *	0.2824
Coefficient of variation in annual catchment rainfall *	0.2739
% of catchment in LCDB category: tussock *	0.2452
% of riparian area in LCDB category: exotic forest	0.2252
% of riparian area in LCDB category: urban	0.2241
Mean January (summer) air temperature (within segment)	0.2194
% of riparian area in LCDB category: miscellaneous land cover	0.2113
December (summer) solar radiation (in catchment) *	0.1692
June (winter) solar radiation (within segment)	0.1455
% of catchment in LCDB category: indigenous forest *	0.1416
Total annual runoff volume	0.1381
% of catchment in LCDB category: exotic forest *	0.1375
Annual potential evapotranspiration of catchment *	0.1372
Total catchment area	0.1362
% of catchment in LCDB category: urban *	0.1295
% of riparian area in LCDB category: bare ground	0.1263
Mean annual low flow	0.1235
% of catchment in LCDB category: bare ground *	0.1235
Current wintertime equilibrium temperature (within segment)	0.1143
% of catchment in LCDB category: mangrove *	0.1080
% of riparian area in LCDB category: tussock	0.1009
% of catchment in LRI category: glacial *	0.0952
% of riparian area in LCDB category: indigenous forest	0.0795
Average segment slope	0.0686
Mean minimum June air temperature (within segment)	0.0131
December (summer) solar radiation (within segment)	0.0068

* Variables are weighted for run-off. For LCDB category variables, this means run-off from this area

Appendix D

This appendix lists the variables used in the small scale habitat analysis (Chapter 3) with a description of how the data was gained. On site measurements of habitat as well as remotely sensed Geographic Information Systems (GIS) environmental variables were used in the analysis.

Variables measured on site:

- Ephemeral: yes/no
  Personal observations combined with knowledge about the wetland from local residents and/or DOC
- Native forest in the surrounding area: yes/no
  Observations of surrounding area
- Willow (*Salix* sp.) in the surrounding area: yes/no
  Observations of surrounding area
- Farmland in the surrounding area: yes/no
  Observations of the surrounding area
- Aquatic vegetation in the wetland: yes/no
  Observations of the wetland
- Flowing water within the wetland: yes/no
  Personal observations combined with knowledge about the wetland from local residents and/or DOC
- Overall land cover of the surrounding area: urban/pastoral
  Personal observations and information from topographical maps
- Brown mudfish: present/absent

- Number of banded kokopu (*Galaxias fasciatus*) at the site <100mm in length
- Number of banded kokopu (*Galaxias fasciatus*) at the site >100mm in length
- Number of koura (*Paranephrops planifrons*) at the site
- Number of inanga (*Galaxias maculatus*) at the site
- Number of giant kokopu (*Galaxias argenteus*) at the site
- Number of elvers at the site
- Number of eels <200mm at the site
- Number of eels >200mm at the site
- Number of common bullies (*Gobiomorphus cotidianus*) at the site
- Number of whitebait (juvenile *Galaxias* spp.) at the site

NB: All information regarding fish species caught at each site was gained from gee minnow trapping at the wetland.

GIS variables:

- Distance to the coast from site
- Total catchment area
- Mean January air temperature (within segment)
- Current summertime equilibrium temperature (within segment)
- Current wintertime equilibrium temperature (within segment)
- June solar radiation (within segment)
- Maximum segment slope
- Estimate of historic segment land cover
- Estimate of current segment shade
- Percentage of the riparian area in LCDB category 8: urban
- Percentage of the riparian area in LCDB category 9: wetland
- Percentage of the riparian area in LCDB category other than 1-9: miscellaneous land cover
- Coefficient of variation in annual rainfall (runoff weighted)
- Average slope of the catchment (runoff weighted)
- Mean minimum July air temperature in the catchment (runoff weighted)
- Number of catchment rain days per month greater than 10mm (runoff weighted)
- Number of catchment rain days per month greater than 25mm (runoff weighted)
- Number of catchment rain days per month greater than 50mm (runoff weighted)
- Number of catchment rain days per month greater than 100mm (runoff weighted)
- Total annual runoff volume
- Annual potential evapotranspiration of the catchment (runoff weighted)
- December (summer) solar radiation in the catchment (runoff weighted)
- June (winter) solar radiation in the catchment (runoff weighted)
- Average elevation of the catchment
- Percentage of annual runoff volume from catchment with slope < 30° (i.e. low gradient)
- Percentage of annual runoff volume from catchment with slope > 30° (i.e. steep)
- Percentage of annual runoff from catchment in the LRI category: alluvium
- Percentage of annual runoff from catchment in the LRI category: peat
- Average hardness of underlying rocks (induration) in the catchment (runoff weighted)
- Average particle size in the catchment (runoff weighted)
- Average phosphorus content in the catchment (runoff weighted)
- Percentage of annual runoff from catchment in LCDB category 2: exotic forest
- Percentage of annual runoff from catchment in LCDB category 3: indigenous forest
- Percentage of annual runoff from catchment in LCDB category 5: pastoral
- Percentage of annual runoff from catchment in LCDB category 7: tussock
- Percentage of annual runoff from catchment in LCDB category 9: wetland

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Appendix E

This appendix provides information on where fish were caught during the course of this study. All trapping was undertaken using unbaited 4mm mesh Gee minnow traps.

Location	Habitat type	Fish species found
Ashhurst Domain	Native forest; ephemeral; no flowing water	Brown mudfish (*Neochanna apoda*)
Koputaroa Kereru Conservation Covenant	Open, grassy wetland; ephemeral; no flowing water	Brown mudfish (*Neochanna apoda*)
Koputaroa	Willows; ephemeral; no flowing water	Brown mudfish (*Neochanna apoda*)
Lake Papaitonga (Preston's Farm)	Open farmland; permanent; very little flow	Brown mudfish (*Neochanna apoda*) Inanga (*Galaxias maculatus*) Eels (*Anguilla* sp)
Lake Papaitonga * Small tributary on eastern side of the lake	Native forest; ephemeral; flowing water	Banded kokopu (*Galaxias fasciatus*) Giant kokopu (*Galaxias argenteus*) Koura (*Paranephrops planifrons*)
Te Hakari [†] Te Iwi o Ngati Tukohere Trust	Open wetland, surrounded by farmland, but with some fringing of native bush; permanent; no flowing water	Banded kokopu (*Galaxias fasciatus*) Inanga (*Galaxias maculatus*) Eels (*Anguilla* sp) Common bully (*Gobiomorphus cotidianus*) Whitebait (*Galaxias* sp)
Pekapeka Trust [†] Wetland nearby to Te Hakari	Open wetland, surrounded by farmland; permanent; no flowing water	Common bully (*Gobiomorphus cotidianus*)
Nga Manu (two habitat types) **1.** Swamp forest	Native swamp forest; ephemeral; no flowing water	Brown mudfish (*Neochanna apoda*) Eels (*Anguilla* sp)
2. 'Top drain' This was initially dug for drainage, but now is a small stream that runs through the swamp forest	Native forest; permanent; flowing water	Banded kokopu (*Galaxias fasciatus*) Eels (*Anguilla* sp) Common bully (*Gobiomorphus cotidianus*) Koura (*Paranephrops planifrons*)
Victoria Station	Native forest; ephemeral; no flowing water	Brown mudfish (*Neochanna apoda*)

* This tributary of Lake Papaitonga can be accessed from Tarahunga Road, south of Levin

[†] Te Hakari and Pekapeka Trust wetlands are just south of Ohau, off Kuku Beach Road