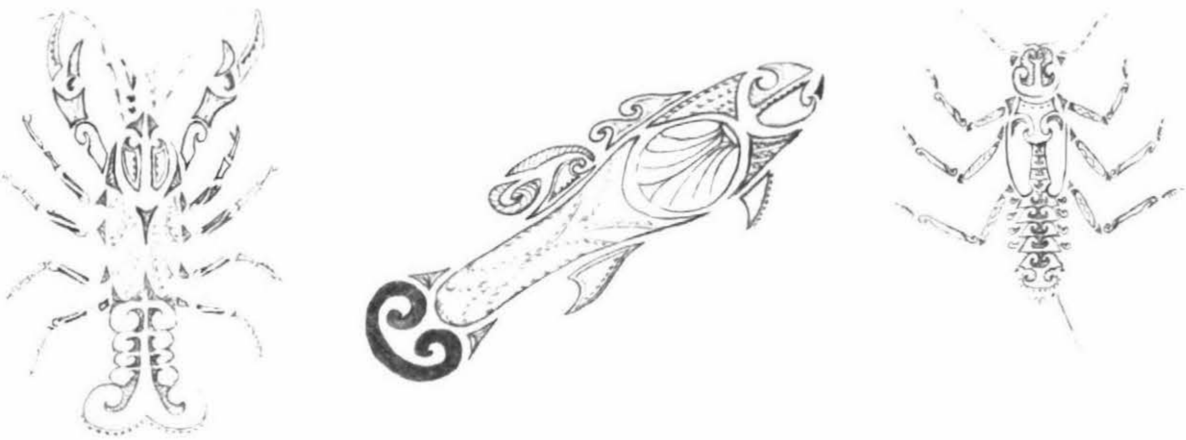
'Rites of passage': biotic and abiotic influences on freshwater fish migration



Drawings by Nicola Atkinson

A thesis submitted in partial fulfilment
of the requirements for the degree of

Master of Science in Ecology

At Massey University,
Palmerston North
By

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2008

Abstract

Assessing the impacts of barriers to native fish migration has in the past been largely subjective due to the difficulties involved in determining whether a species absence upstream of a potential migration barrier is due to a restriction in passage or a consequence of its natural distribution. Now with the increased availability of GIS data and new modelling techniques, accurate models of species occurrences have the potential to be used in the assessment of migration barriers. Consequently, this study uses a predictive model of species occurrence to accurately quantify the passage restrictions caused by 28 structures in the Wellington Region. Comparisons were made between the species observed to be present upstream of a structure and what would be expected to be there in the absence of a barrier. In addition, impacts were quantified in terms of amount of native fish habitat lost and combined with five other metrics to create an index that gauges the priority each structure has for remediation. The application of this method revealed its potential to be used in management decisions but highlighted its reliance on a large amount of data for it to draw statistically robust conclusions. An assessment of the effectiveness of three fish passes was also carried out but revealed that none were successful in facilitating passage.

The ability of bluegill bullies (*Gobiomorphus hubbsi*) to detect and respond to the odour of conspecific fish upstream under neutrally odoured (rainwater) and naturally odoured (stream water) conditions was tested. Bluegill bullies were presented with a choice of two flows of water to move into, one of which contained the odour of conspecific fish. Bluegill bullies displayed a concentration-dependent reaction under neutral water conditions, where they were attracted to low concentrations of conspecific odour but repelled by high concentrations of odour. This result was not consistent under naturally odoured water conditions, where no attraction towards conspecific odour occurred at low odour concentrations and only a weak avoidance of odour occurred at high concentrations. The differences revealed between natural and neutral water trials suggests the use of habitat odours over conspecific odours and casts doubt on previous studies only conducted under neutral conditions.

The longitudinal size distribution of two populations of bluegill bully from Hutt and Rakaia Rivers and one population of torrentfish from Rakaia River was examined. All populations had longitudinal trajectories that showed some increase in size with distance upstream. This increase in size primarily reflects the influence of amphidromous life styles, where juveniles diffuse upstream from the sea. However, a quantile regression analysis revealed differences in growth and migration rate between the two bluegill bully populations; bluegill bullies from Rakaia River grew at a slower rate and showed variation in migration rate within their population that was not evident in the Hutt River population. Null models were also generated for each population to test for the presence of all size classes of fish in the lower reaches of each river. Both bluegill bully populations showed a significant absence of the largest size classes in the lower reaches and differed significantly from the null models. This difference suggests that all individual bluegill bullies continuously move upstream throughout their lives. In comparison, the size distribution of torrentfish closely resembled the null model, indicating that some individuals did not migrate upstream to the same extent as others. The differences revealed between the two bluegill bully populations may be explained through a combination of differences in competition and stability between the Hutt and Rakaia River, while the difference between bluegill bully and torrentfish distributions may be a consequence of different reproductive strategies.

Explanation of text

This thesis is a combination of three individual papers. This format has resulted in some repetition in introductions between chapters. Chapter 3 was published in the New Zealand Journal of Marine and Freshwater Research in June 2008 (42(2): 173-180). Chapter 4 was submitted to the New Zealand Journal of Marine and Freshwater Research in June 2008 and is currently under review.

The experimental manipulations and fish sampling methods have been sanctioned by the Massey University Animal Ethics Committee (protocol No. 07/08).

Acknowledgments

First and foremost, I am grateful to my Supervisor, Dr. Mike Joy. His enthusiasm for ecology and encouragement to question and think critically during my undergraduate degree contributed greatly to my interest in the environment and decision to pursue further study. He eagerly helped me to establish this project early on and always challenged me to achieve beyond my own expectations. I am especially grateful for the prompt and helpful editing, his knack for fooling me into thinking stats was fun, and always finding the time and patience to help me when I needed it.

Thanks also to Dr. Russell Death and the 'stream team' for keeping me on track and helping me find my way through postgraduate study. And to Marty Bonnett of NIWA for digging out a couple of old reports that were of much use in chapter 3.

I am very thankful to my parents who have been unfailing role models throughout my life, always teaching and encouraging me to learn. I couldn't have done this without your support and worldly words of wisdom (even if sometimes they weren't solicited!). A special thanks to Dad, for always taking a keen interest and being up for a good debate. To mum for the encouragement, pointing out spelling mistakes and all those split infinitives!

Thanks to Sian Potier, my brother Brian and Mike and Al for providing me with a bed, nourishment and many laughs during my field work ventures to Wellington. Thanks also to all those who helped out with field work, especially Logan Brown, Hannah Rainforth, Andre Siebers and Mike Joy who endured many hours of fruitless fishing in Hutt River in the middle of winter.

To my fellow students in the ecology department, particularly Lorraine Cook, Esta Chappell, Charlotte Minson and my flatmate Louisa Robertson you guys have been great! Thanks so much for all the fun times, keeping me sane and always providing good advice and an understanding ear to complain to when things weren't going to plan.

To my siblings and good friends who are scattered all over the world, Rachel Atkinson, Brian Atkinson, Mat & Trace Ward, Julia Talbot-Jones, Sian Potier, Anna Mclennan, Pip Sutton and Kathryn Lacey thanks for the unconditional support and tolerating my weird fish obsession, I hope you have found it enlightening!

Thanks to the technical and administrative staff of the ecology department, particularly Barbara Just, Erica Dahya, Carol Nicholson, Paul Barrett, Cleland Wallace and Tracy Harris for always cheerfully helping me out with bits and pieces as I needed them.

A big thanks to the Sir Peter Blake Trust and Massey University for the financial assistance and the Department of Conservation for funding part of this research (contract No. WE0207)

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Chapter 1: General Introduction

Over half of New Zealand's indigenous fish fauna is diadromous, meaning that most species migrate between the sea and freshwater at certain stages in their life cycle. Moreover, because of the relatively restricted range of non-diadromous species the proportion of diadromous species in any one fish community throughout New Zealand is likely to be greater than 75% (McDowall & Taylor 2000). By world standards this level of diadromy is rare (McDowall 1990). In addition, amphidromy[1] is the most prevalent form of diadromy in New Zealand, whereas elsewhere it is virtually absent and anadromy[2] predominates. New Zealand streams and rivers also differ in physical character compared to those in continental USA and Europe where most studies of riverine fish communities have taken place. Comparatively New Zealand rivers are short, turbulent and unstable (Winterbourn et al. 1981). Consequently, the applicability of most overseas research on riverine fish communities to the New Zealand fish fauna is limited.

Embedded throughout much of the literature on New Zealand riverine fish communities is a common theme pertaining to the overwhelming influence that diadromous lifestyles have on all aspects of fish ecology. Diadromy encapsulates influences over a broad geographical range from the marine environment through estuarine habitats, to freshwater environments that can be well inland (McDowall 1993). Consequently, through the acquisition of data on broad scales, it has become highly evident that the migratory requirement of fish has a greater influence on their distribution than the influence of proximal habitats (Jowett & Richardson 1996; Joy & Death 2001). An important implication of this finding is that in order for diadromous species to occupy upstream habitats they must have free passage to and from the sea. Consequently, where barriers to migration exist, upstream habitats will lack diadromous species (McDowall 2008). Such barriers may take the form of natural waterfalls or log jams, or may be a result of manmade structures, such as culverts, weir or dams.

The extent of impacts caused by migration barriers varies from species to species and with the location of the barrier within the river. This variability arises because some species are poor climbers; they have difficulty surpassing small falls and do not penetrate far inland. Other species are highly skilled climbers and have been found above high waterfalls at considerable

[1] Amphidromy is where juvenile migrate into freshwater having spent a brief period at sea as larvae.

[2] Anadromy is where adult fish migrate into freshwater to spawn having spent most of their life at sea.

distances inland (Boubee et al. 1999). Consequently, a small barrier in lowland areas is likely to have a much greater impact on upstream fish communities than a large barrier at a high elevation. However, determining whether or not fish communities upstream of potential barriers are impacted is inherently difficult, as a species absence may be due to the natural limits of its migration, rather than an obstruction to its migration (McDowall 1993). Perhaps not surprisingly, relatively little research has been conducted on quantifying the impacts of migration barriers on New Zealand's native fish fauna (but see Joy & Death 2000).

However, recent improvements in data availability and modelling techniques mean that the extent of each species migration is accurately documented (Joy & Death 2004a; Leathwick et al. 2005). Clear patterns of decreasing abundance (both of species and individuals) with increasing elevation and distance upstream has been formalised into predictive models and biological monitoring tools (Joy & Death 2004b, a; Leathwick et al. 2005). Because such tools are based on distributions that are not limited by barriers, they can indicate what the distribution of fish would be given free migratory access. Subsequently, in chapter 2 of this thesis, a predictive model of species occurrences was combined in a novel approach to determine the impacts of migration barriers. The expected presence of species upstream of a potential barrier was objectively defined and compared to the species that were observed to occur there. This method provided a robust way of determining the impacts of passage restrictions while accounting for the confounding factors that influence a species distribution.

The scale at which the relationships between species distributions and elevation and distance to the sea have been elucidated is broad, often encompassing whole regions or the whole country. Because these relationships are fundamental in the function of predictive models of species occurrences, the scale at which chapter 2 has addressed the influence of migration barriers was also broad. This was pointed out by McDowall (2008) when he noted that the implications of diadromy vary according to the scale at which one addresses the phenomenon. At smaller or larger scales what is perceived to have the greatest influence on fish communities may change.

At a small scale what affects the distribution of species and the extent of their migration within a catchment (outside of the constraints of individual abilities) is not thoroughly understood (David et al. 2002). Often the suitability of habitat has been suggested to influence the distribution of fish within a catchment and drive the upstream migration of individuals (McDowall 1984; Jowett et al. 1996). However, there are a number of examples where the presence of fish does not seem to be mediated simply by the presence of suitable habitat.

McDowall (2000) observed that the presence of torrentfish (*Chemimarrichthys fosteri)* upstream of Lake Coleridge in Rakia River catchment required them to migrate through the extent of Rakaia River, where suitable habitat is prolific, and also through approximately 10km of lake which bears little resemblance to the habitat in which torrentfish are most commonly found. In addition, Rowe et al. (1992) observed river mouth selection by koaro (*Galaxias brevipinnis)* that did not appear to correspond to the presence of suitable habitat, but rather to the presence of conspecifics upstream and suggested that koaro may be responding to chemical cues within the water column.

This use of chemical cues has been well documented overseas, however, there is some controversy as to where the cues originate from; some suggest the use of conspecific odours from upstream (Li et al. 1995; Bjerselius et al. 2000; Fine et al. 2004), while others suggest the use of organic odours that are directly related to upstream habitats (Sorensen & Bianchini 1986). The vast majority of this research has been conducted overseas among anadromous salmonids whose purpose of migration differs from that of amphidromous species that are most common in New Zealand. Despite this difference, limited research on amphidromous species in New Zealand has supported the use of conspecific odours as a navigation cue (Baker & Montgomery 2001; Baker & Hicks 2003), though the conditions under which the experiments were conducted may be too far removed from the natural environment to draw firm conclusions. Subsequently, the influence of chemical cues on migratory fish in New Zealand is yet to be firmly established. To address this knowledge gap, in chapter 3 of this thesis, an amphidromous species (*Gobiomorphus hubbsi*) was tested for a response to the odour of conspecifics under ecologically relevant conditions. These test conditions involved giving bluegill bullies the choice to swim towards or away from the odour of conspecifics in the presence and absence of natural stream odours. A comparison of trials conducted with neutrally odoured rainwater and naturally odoured stream water were used to verify the use of conspecific odours in the presence of habitat odours.

To investigate other influences on migration, conditions under which migration and growth rates differ can be assessed by comparing longitudinal size/age distributions between catchments and/or species. Limited research has shown variation in the patterns of longitudinal size structure. McDowall (1998) cited examples of torrentfish (McDowall 1973; Davis et al. 1983; Bonnett 1986), redfin bullies (*Gobiomorphus huttoni)* (McDowall 1965), bluegill bullies (Davis et al. 1983; Bonnett 1986) and longfin eels (*Anguilla dieffenbachia)* (Strickland 1985) having all size classes present in the lower reaches of rivers with smaller/younger fish becoming increasingly rare with distance upstream. However, Bonnett (1986) showed that only small sizes of bluegill bully were present in the lower reaches of Rangitata River and bigger fish increased in relative abundance with increasing distance inland. Though McDowall's (1998) comment was aimed at highlighting that small/young fish are limited in their upstream penetration, and did not centre on the longitudinal distribution of larger/older fish, the implications of a full size range of fish in downstream reaches (if this exists) may suggest significant variation in the extent to which some individuals migrate upstream. Furthermore, if variation in the presence of large adult fish in downstream reaches exists, both within a species and between species, then an enquiry into the environmental differences in which such distributions occur may help to decipher the factors that affect the upstream migration of diadromous fish at this scale. Consequently, an investigation was carried out, in chapter 4, on the differences in longitudinal size structure of two populations of bluegill bully and one population of torrentfish (*Cheimarrichthys fosteri)*. A number of hypotheses were formed, based on the results of the study and the differences in river characteristics, to explain the variation found.

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Chapter 2: A robust approach in determining impacts of barriers on fish migration; a case study of the Wellington region

ABSTRACT

Assessing the impacts of barriers to native fish migration has in the past been largely subjective due to the difficulties involved in determining whether a species absence upstream of a potential migration barrier is due to a restriction in passage or a consequence of its natural distribution. Now with the increased availability of GIS data and new modelling techniques, accurate models of species occurrences have the potential to be used in the assessment of migration barriers. Consequently, this study uses a predictive model of species occurrence to accurately quantify the passage restrictions caused by 28 structures in the Wellington Region. Comparisons were made between the species observed to be present upstream of a structure and what would be expected to be there in the absence of a barrier. In addition, impacts were quantified in terms of amount of native fish habitat lost and combined with five other metrics to create an index that gauges the priority each structure has for remediation. The application of this method revealed its potential to be used in management decisions but highlighted its reliance on a large amount of data for it to draw statistically robust conclusions. An assessment of the effectiveness of three fish passes was also carried out but revealed that none were successful in facilitating passage.

Keywords diadromy; freshwater fish; migration barriers; predictive models; fish passes

INTRODUCTION

Development of urban areas, forestry and agriculture has resulted in the proliferation of in-stream structures, such as culverts, weirs, and dams. Such structures have the potential to impede the migration of diadromous fish species between the sea and their freshwater habitats (Boubee et al. 1999). Because diadromous species are reliant on upstream habitats to complete their life cycle, any restriction in passage is likely to result in declines in adult stocks or reduced biodiversity (Joy & Death 2001; Baker 2003). Such impacts have been well documented overseas on commercially important species, such as large salmonids (Kareiva et al. 2000; Dauble et al. 2003; Sheer & Steel 2006). However, the applicability of this research to the New Zealand fish fauna is low due to significant differences in behaviour, morphology and swimming techniques (Boubee et al. 1999).

The extent of impacts caused by migration barriers in New Zealand varies from species to species and with the location of the barrier within the river. This variability arises because some species are poor climbers, they have difficulty surpassing small falls and do not penetrate far inland (Baker 2003) (see table 1). Others species are highly skilled climbers and have been found above high waterfalls at considerable distances inland (Boubee et al. 1999). Consequently, a small barrier in lowland areas is likely to have a much greater impact on upstream fish communities than a large barrier that is at a high elevation. However, determining whether or not fish communities upstream of potential barriers are impacted, or whether fish passes are effective in facilitating passage, is inherently difficult, as species absences may be due to the natural limits of their migration rather than an obstruction to their migration (McDowall 1993). Perhaps not surprisingly, the only assessment of passage restrictions that have been carried out in New Zealand, have used largely subjective methods to identify structures that are likely to cause major restrictions in migration (e.g. ARC 2000; EW 2001). Such assessments run the risk of directing mitigation resources (that are often limited) to areas that may naturally lack diadromous species. Furthermore, there are no robust ways of determining whether remediation work is effective.

However, recent improvements in data availability and modelling techniques mean that the extent of each species migration is accurately documented (Joy & Death 2004a; Leathwick et al. 2005). Clear patterns of decreasing abundance (both of species and individuals) with increasing elevation and distance upstream has been formalised into predictive models and biological monitoring tools (Joy & Death 2004b, a; Leathwick et al. 2005). Because such tools are based on distributions that are not limited by barriers, they can indicate what the distribution of fish would be given free migratory access.

Subsequently, this study has used a predictive model of species occurrences in a novel approach to determine the impacts of migration barriers. The expected presence of species upstream of a potential barrier was objectively defined and compared to what species were observed to occur there. This method provides a robust way of determining impacts of passage restrictions while accounting for the confounding factors that influence a species distribution. In addition, the amount of native fish habitat upstream of a potential barrier was quantified and combined with five other metrics in an index to determine remediation priorities. These methods were tested on 13 sites that contained a total of 28 potential migration barriers and three fish passes in the Wellington region. The aims of this research are first, to improve the effectiveness of current assessment methods and second, to develop a protocol which can be used to improve the efficiency of mitigation resources.

Table 1 Fourteen native diadromous fish species found in the Wellington region. Classification of swimming and climbing abilities has been based on data from Boubee et al. (1999) and/ or Baker (2003) and Baker & Boubee (2006). For species that have not had swimming and climbing abilities tested their abilities have been subjectively classified based on general knowledge from relevant literature; an asterisk has been used to indicate such cases. Distance and elevation upstream are maximum values obtained from McDowall (2000).

Fish Species	Swimming ability	Climbing ability	Distance upstream (km)	Elevation (masl)	Type of diadromy
Lamprey *Geotria australis*	Moderate*	Excellent*	230	380	Anadromy[3]
Shortfin eel *Anguilla australis*	Excellent	Excellent	292	835	Catadromy[4]
Longfin eel *A. dieffenbachii*	Excellent	Excellent	314	1150	Catadromy
Smelt *Retropinna retropinna*	Moderate*	Weak*	236	480	Anadromy
Giant kokopu *Galaxias argenteus*	Moderate*	Moderate*	170	250	Amphidromy[5]
Banded kokopu *G. fasciatus*	Moderate	Moderate*	177	550	Amphidromy
Shortjaw kokopu *G. postvectis*	Moderate*	Moderate*	260	520	Amphidromy
Koaro *G. brevipinnis*	Excellent*	Excellent	400	990	Amphidromy
Inanga *G. maculatus*	Weak	Weak	215	230	Catadromy
Torrentfish *Cheimarrichthys fosteri*	Moderate*	Moderate*	235	710	Amphidromy
Redfin bully *Gobiomorphus huttoni*	Moderate	Excellent	266	400	Amphidromy
Common bully *G. cotidianus*	Weak	Weak	313	680	Amphidromy
Giant bully *G. gobiodes*	Weak*	Weak*	21	30	Amphidromy
Bluegill bully *G. hubbsi*	Moderate*	Moderate*	100	480	Amphidromy

[3] Anadromy is where adult fish migrate into freshwater to spawn having spent most of their life at sea.
[4] Catadromy is where adult fish migrate to sea to spawn having spent most of their life in freshwater.
[5] Amphidromy is where juvenile migrate into freshwater having spent a brief period at sea as larvae.

METHODS

Sites

Twenty-eight structures on 13 streams, including three with fish passes, were chosen to analyse their effects on native fish migration in the Greater Wellington Region (Fig .1, see appendix). A wide variety of structures were included in this analysis, both in form (e.g. large dams to small fords, culverts and weirs) and location (from 13 – 250 metres above sea level (masl) and from 0.3 – 24km upstream).

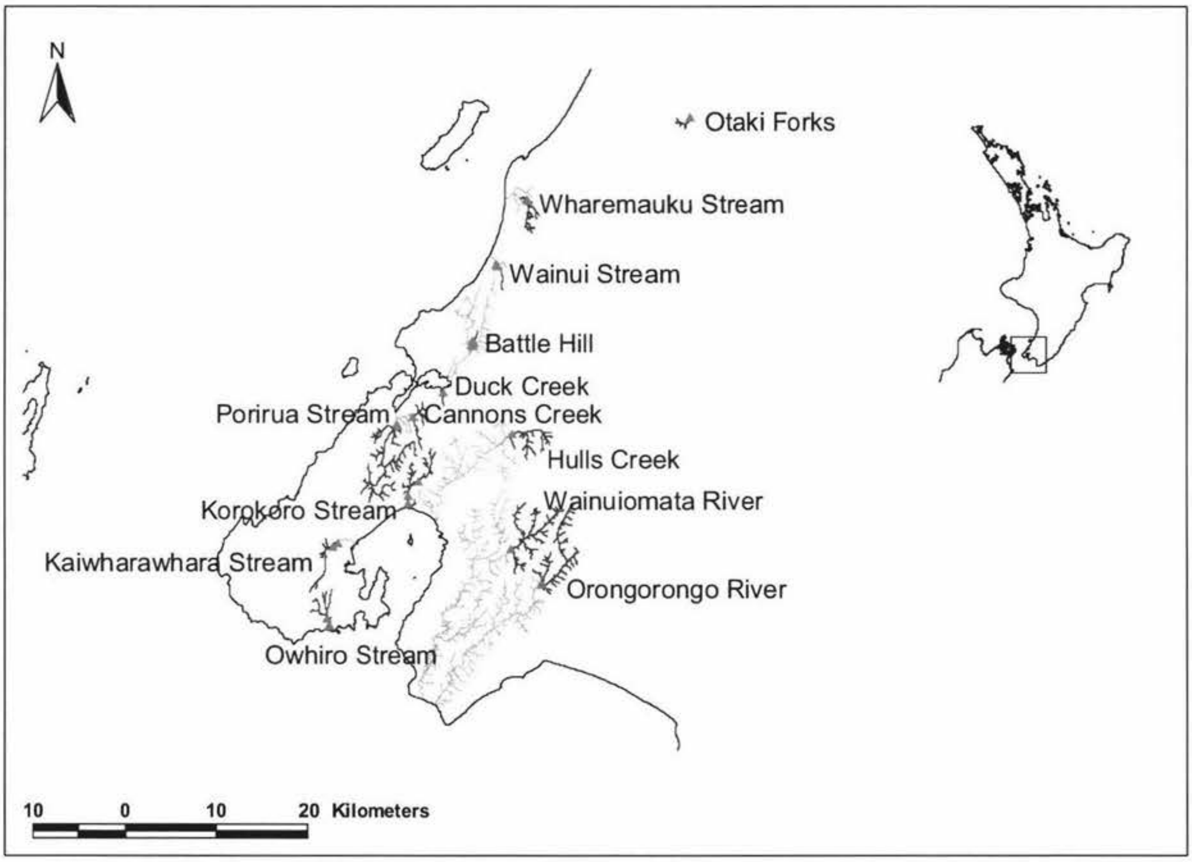

Fig. 1 Site map showing 13 sites and 28 structures (red triangles) that were included in this study. Reaches upstream of each structure are highlighted blue and represent the potential loss of native fish habitat.

Field protocol - structures

Measurements of each structure were taken based on a 'Fish Passage Evaluation Sheet' adapted from Environment Waikato (including length, width, water depth, perch height and undercut length where applicable, see appendix). These measurements were used to assess, subjectively, the likelihood that each structure will restrict migration. Each structure was assigned into one of five categories:

- **no impact** - where the structure poses no significant barrier to the upstream or downstream passage of fish likely to be found in the stream;
- **minimal** - where the structure is likely to inhibit the migration of species with weak swimming and/or climbing abilities;
- **moderate** – where the structure is likely to inhibit the migration of species with moderate swimming and/or climbing abilities;
- **high** – where the structure is likely to inhibit the migration of all species, except those with excellent swimming and/or climbing abilities;
- **very high** – where the structure is likely to inhibit the migration of all species.

At sites where there was more than one structure, the assessment of the most severe structure was used in an overall evaluation of each site.

Field protocol – fish surveys

Presence/absence surveys of fish communities upstream and downstream of each structure were carried out once for each structure between January 2006 and November 2007. Surveys were mostly conducted using electro-fishing methods, however night spotlighting and trapping were carried out in backwaters or deep, slow flowing areas where electro-fishing was not suitable. All surveys above and below each structure aimed to cover all habitat types present. In most cases electro-fishing and/or night spotlighting (depending on which was most suitable) conducted over a 100m stretch was sufficient to cover all habitat types. The three structures that had fish passes installed were monitored on several occasions after their installation (see Hulls creek and Kaiwharawhara Stream in the Appendix for more details).

Records of fish communities from the New Zealand Freshwater Fish Database (NZFFDB) were also extracted for sites on each catchment that the structures were on (only records since 1980 were used, except for structures that were constructed well before this time, such as Morton Dam). These records supplemented the above surveys and were used in the evaluation of existing impacts of the structures.

Data analysis

Estimation of upstream habitat

The amount of fish habitat upstream of each structure was calculated for each fish species using a predictive map of species occurrences (derived from Joy & Death 2004a). For each stream reach upstream of the structure, the probability of occurrence for each species was multiplied by the length of the associated reach to give an estimate of the amount of habitat there is for a particular species measured in kilometres. For example, if longfin eels had a probability of occurrence of 0.6 in a stream reach that was 5km in length, then 3km of longfin eel habitat was present in that reach. This habitat length was calculated for each reach upstream of the structure and summed to give an overall estimate of habitat for each species upstream of the structure. The amount of habitat for each species was then summed to give an overall estimate of the total amount of native fish habitat upstream. If there was more than one structure on the same stream, only the amount of habitat above the most downstream structure was calculated. These habitat estimates are presented both as a proportion of the total habitat present in the catchment and as a proportion of the Wellington region.

Impacts on upstream fish communities

An index of biotic integrity (IBI), developed by Joy & Death (2004b) was one of two indices used to evaluate the existing impacts of each structure on native fish communities. This index was calculated for all sites where fish surveys had been conducted (including those from the NZFFD). The IBI uses the number of species found within six metrics[6] to generate a score between 0 – 60 that reflects the integrity of the fish community or how impacted it is by anthropogenic influences. The IBI accounts for the influence of elevation and distance upstream on the distribution of native fish and therefore is more robust than comparing differences in the number of species above and below each structure. An IBI score of 1-20 indicates poor quality, 20-30 fair, 30-40 good, 40-50 very good, and 50-60 excellent quality. Because the IBI includes species such as banded kokopu and giant kokopu that are known to form landlocked populations when access to the sea is blocked, its ability to detect passage restrictions may be limited if landlocked populations are present.

An observed over expected ratio (O/E) was also calculated for all sites where fish surveys had been conducted. This method compared the occurrence of fish species upstream of the structures (observed values) to predicted values of species occurrence (expected values) that were generated from the predictive model of Joy & Death (2004a). Only diadromous species were included in the analysis and banded kokopu were omitted because of their common ability to form landlocked populations (13 species in total) (McDowall 1993).

The formula below shows how to calculate the O/E ratios. A probability value at which point the species is considered to be present must be determined (a and b). Two such cut-off points were used in this analysis (0.001 and 0.5, a and b respectively). The probabilities of each species over the cut-off value was then summed and divided by the number of species with a

[6] Six metrics were: Native; introduced; benthic riffle; benthic pool; pelagic pool; intolerant.

probability over the cut-off value. This calculation gave the expected value of species present. The number of species observed was then divided by the number of species with probabilities over the cut-off value. This calculation gave the observed value of species present. The observed value was then divided by the expected value to give the observed over expected ratio (O/E) for each probability cut-off. The two O/E ratios from each cut-off were averaged to give an overall O/E ratio. The accuracy of the O/E ratio to detect passage restrictions may have been limited at some sites where the number of species and predictions of occurrence for those species was low.

$$\frac{O}{E} = \frac{\frac{(N/N_{P>a})}{(\sum P_{>a}/N_{P>a})} + \frac{(N/N_{P>b})}{(\sum P_{>b}/N_{P>b})}}{2}$$

N = number of species observed
$N_{P>a}$ = number of species observed with probability > a or b
$P_{>a}$ = probability of species > a or b
a = 0.001
b = 0.5

A student t-test was used to evaluate the difference in IBI and O/E ratio between sites upstream and downstream of all structures combined. In most cases there was not enough data to use this test for every site.

The number of species that were found downstream of each structure but were not found upstream was also counted, but only if that species was also predicted to be upstream.

Priority for remediation

In order to establish the priority for remediation, each site was ranked on a number of attributes that fell into two categories; the potential severity of the structures impact (structure score) and the existing impacts on upstream fish communities (impact score). Three attributes in each of the two categories were averaged and the two categories multiplied to give a final priority score out of 16. The ranking used for each attribute was out of 4, where 1 = least severe or a lowest impact, so that the site with highest total was the site most impacted and had the highest priority for remediation.

The 'structure score' was the average of three scores based on:

1). The classification of each structure into one of five severity categories (see field protocol – structures):
    0 = no impact
    1 = minimal impact

2 = moderate impact
3 = high impact
4 = very high impact

2). The location of the most downstream structure in regard to its elevation:

1= >120masl
2= 80 – 120masl
3= 40 – 80masl
4= <40masl

3). The proportion of native fish habitat in the Wellington region upstream of the most downstream structure at each site:

1 = <0.1%
2 = 0.1 – 0.2%
3 = 0.2 – 0.3%
4 = >0.3%

The 'impact score' was the average of three scores based on:

1). The difference in average IBI scores between sites downstream and upstream of the structure (i.e. average upstream score subtracted from average downstream score)[7]:

0 = <0
1 = 0 – 5
2 = 5 – 10
3 = 10 – 15
4 = >15

2). The difference in O/E ratio between sites downstream and upstream of the structure (i.e. average upstream ratio subtracted from average downstream ratio)[8]:

0 = <0
1 = 0 – 0.15
2 = 0.15 – 0.3
3 = 0.3 – 0.45
4 = >0.45

3). The number of species that were present downstream but were absent upstream and were predicted to be upstream[9]:

0 = 0 species

[7] Joy & Death (2004b) suggested a site could be classified into groups of varying quality, from poor to excellent based on a 10 point range of IBI scores. A change in IBI score of more than 10 points is therefore likely to represent a significant change in quality and this magnitude of difference was used as a reference to set the scoring for this attribute.

[8] Joy & Death (2000) suggested that O/E ratios that fall outside of one standard deviation of un-impacted reference sites are significantly degraded. The standard deviation of all sites below all structures was 0.3 and this magnitude of difference was therefore used as a reference to set the scoring for this attribute.

[9] The average number of species per site was 2.4 ± 0.11 (standard error) and ranged between 0 – 8. The scoring for this attribute was based on these parameters.

1 = 0 – 2 species
2 = 2 – 4 species
3 = 4 – 6 species
4 = >6 species

The 'structure score' and the 'impact score' were then multiplied together to give an overall priority score for each site that had a maximum possible value of 16. Scores of 0 to 4 were designated as 'low priority', 4 to 8 'moderate priority', 8 to 12 'high priority' and 12 to 16 'very high priority'.

RESULTS

Severity of structures

Twenty-eight structures on 13 streams were assessed. The majority of these structures were either culverts or weirs (Table 2) with relatively less dams and fords assessed. Dams had the highest falls and were consequently ranked most severely (Fig. 2). Seven of the nine culverts were perched and on average had a fall height of 0.56m. Fords were the structures least likely to impede migration and had the smallest average fall height of 0.42m.

Table 2 Number and type of structures at each site with the mean fall height for each type of structure ± the standard error.

Site	Culverts	Weirs	Dams	Fords	Other	Total
Battle Hill Farm Forest Park	4	1		1	1	7
Cannons Creek		1				1
Duck Creek	1					1
Hulls Creek		1				1
Kaiwharawhara Stream	1				1	2
Korokoro Stream		1	2			3
Orongorongo River			1			1
Otaki Forks				1		1
Owhiro Stream	1	1		1		3
Porirua Stream		2				2
Wainui Stream	1	2				3
Wainuiomata River			1			1
Wharemauku Stream	1	1				2
Total	**9**	**10**	**4**	**3**	**2**	**28**
Mean fall height (m)	**0.56** ± 0.12	**1.63** ± 0.83	**6.75** ± 2.22	**0.42** ± 0.11	**1.4** ± 0.7	**2.12** ± 0.61

A total of 442km of native fish habitat was estimated to be upstream of the 28 structures detailed above. This habitat comprised 2.1% of native fish habitat in the Wellington region. Porirua stream had the most native fish habitat upstream of any structure, followed by Wainuiomata and Orongorongo Rivers (Fig.3).

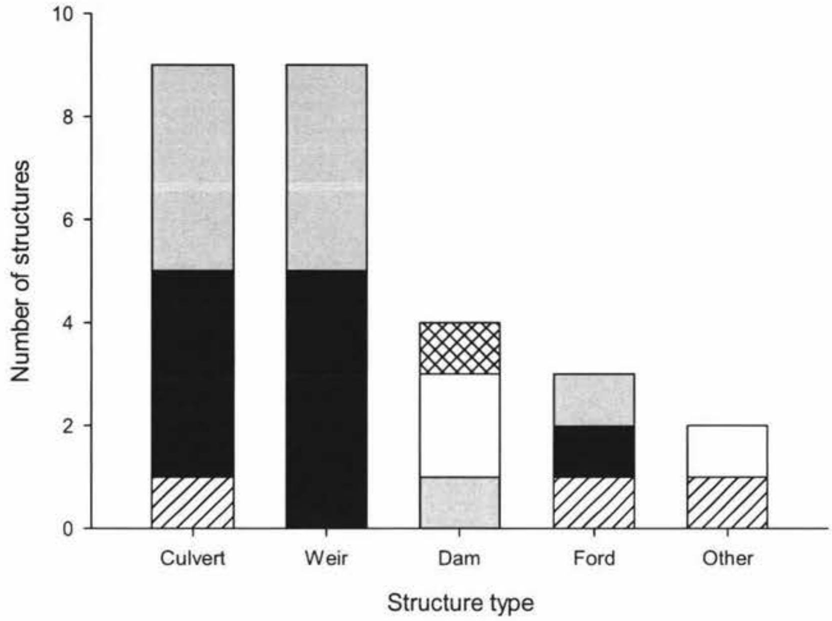

Fig. 2 Types of structures showing the proportion of each that has been classified as having minimal ■ moderate □, high □, very high ⊠ or no impact ▨ on the migration of native fish communities.

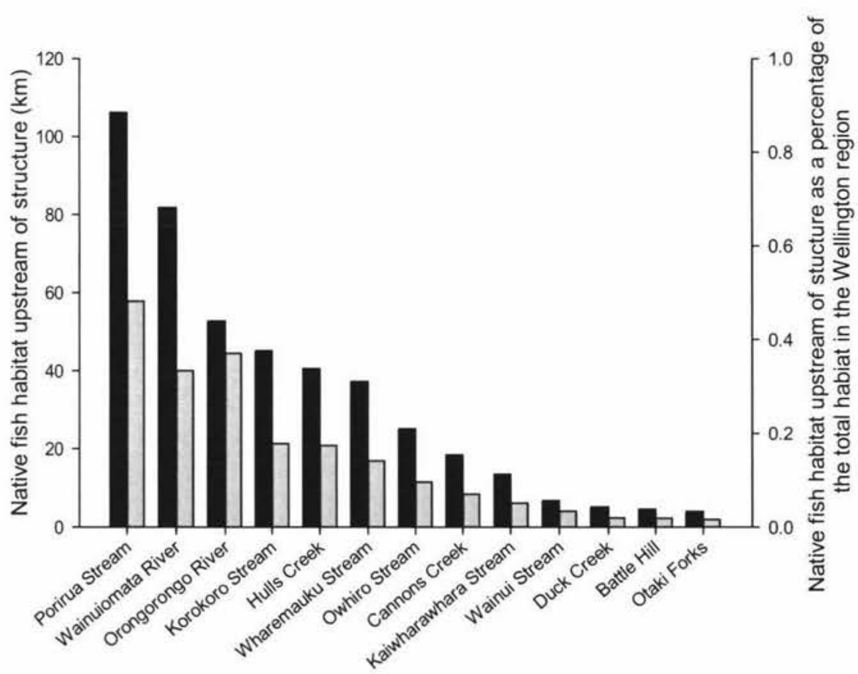

Fig. 3 Amount of native fish habitat estimated to be upstream of each structure measured in kilometres (black bars) and as a proportion of the total native fish habitat in the Wellington region (grey bars). Where more than one structure existed on the same site, estimates have been calculated from the most downstream structure.

The overall structure score ranked the series of structures on Korokoro Stream, Morton Dam on Wainuiomata River and the weirs on Porirua Stream as the most severe structures. The least sever structure was the ford at Otaki Forks (Table 3).

Table 3 Shows the final assessment of the severity of the structures at each site. The barrier score was based on a subjective assessment of each structures potential to be a migration barrier. The location score was based on the elevation of each structure. The habitat score was based on the proportion of native fish habitat in the Wellington region that was upstream of each structure. The ranking used was out of 4 where 1 = least severe or lowest impact.

Site	Barrier score	Location score	Habitat score	Final structure score
Korokoro Stream	3	4	2	3.00
Porirua Stream	1	4	4	3.00
Wainuiomata River	4	1	4	3.00
Cannons Creek	3	4	1	2.67
Orongorongo River	3	1	4	2.67
Wharemauku Stream	2	4	2	2.67
Hulls Creek	2	4	2	2.33
Kaiwharawhara Stream	3	3	1	2.33
Owhiro Stream	2	4	1	2.33
Wainui Stream	2	4	1	2.33
Battle Hill Farm Forest Park	2	3	1	2.00
Duck Creek	1	4	1	2.00
Otaki Forks	1	1	2	1.33

Impacts on fish communities

When data was pooled over the 13 sites, the IBI showed a significant decrease upstream of the structures (Fig. 4) ($t = 3.429$, $P = 0.002$). The O/E ratio also declined on average above each structure, though this difference was marginally statistically significant (Fig. 4) ($t = 2.023$, $P = 0.054$). This reduction in IBI and O/E ratio upstream of structures clearly suggests that the presence of structures downstream is inhibiting the migration of fish species to upstream habitats.

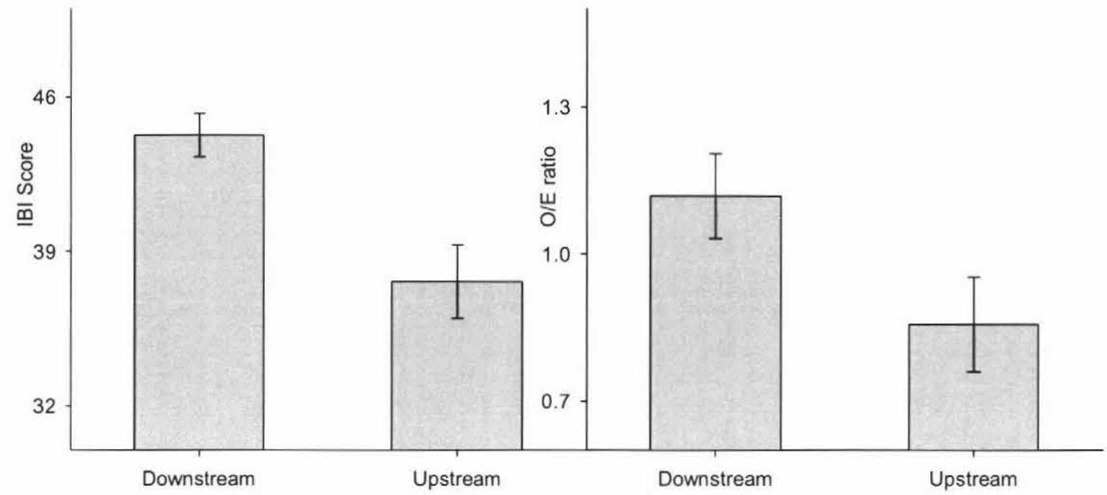

Fig. 4 Average score upstream and downstream of structures for all sites for A). IBI and B). O/E ratio. Downstream sites n = 41, upstream sites n = 39.

The structures on Korokoro stream, Wainuiomata River and Battle Hill appeared to have had the most negative impacts on fish communities as shown by the greatest difference in IBI above and below the structures (fig 5). The difference in O/E ratios upstream and downstream of the structures on each site did not totally reflect those of the IBI (Fig. 5).

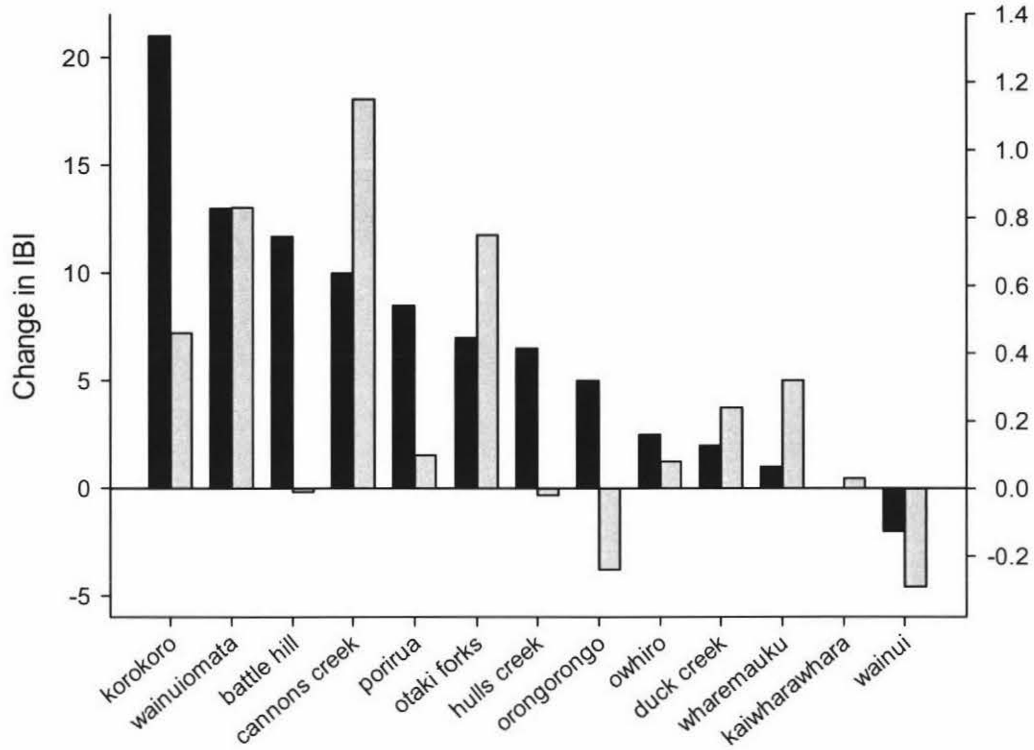

Fig. 5 Difference in average IBI scores (black bars) and O/E ratios (grey bars) upstream and downstream of structures on each site. Values were calculated by subtracting the average index score upstream of the structures from the average index score downstream of the structures.

The number of sites with fish records upstream and downstream of each structure was generally low and unevenly balanced (Table 4). The sites that had the most records were Wainuiomata River, Battle Hill and Kaiwharawhara Stream. These sites will consequently give the most robust conclusions.

The average number of species that were found downstream of a structure but were absent upstream of it was 3.3. The number of species that were absent upstream ranged from zero (Porirua Stream weirs) to six (Morton dam on Wainuiomata River). Common bully, inanga and redfin bullies were the species most frequently absent from upstream sites (Table 4).

Table 4 Number of sites with fish records downstream and upstream of the structures on each stream and the number and type of species that were not found at upstream sites(species also had to be present downstream and predicted to be upstream to be included in this measure).

	Number of sites		Species that were absent upstream	
Site	**Downstream**	**Upstream**		**Total no.**
Battle Hill Farm Forest Park	4	3	Inanga, common bully, redfin bully	3
Cannons Creek	1	2	Inanga, common bully, redfin bully	3
Duck Creek	1	1	Inanga, common bully, redfin bully	3
Hulls Creek	4	3	Inanga, giant kokopu, bluegill bully	3
Kaiwharawhara Stream	4	2	Inanga, giant kokopu, bluegill bully, common bully, redfin bully	5
Korokoro Stream	3	2	Inanga, giant kokopu, bluegill bully, common bully, redfin bully	5
Orongorongo River	3	2	Redfin bully, bluegill bully	2
Otaki Forks	3	1	Shortfin eel, banded kokopu, redfin bully, common bully	5
Owhiro Stream	3	4	Inanga, giant kokopu, common bully	3
Porirua Stream	1	8	-	0
Wainui Stream	2	1	Shortfin eel, giant kokopu, common bully	3
Wainuiomata River	11	7	Shortfin eel, inanga, koaro, redfin bully, bluegill bully, common bully	6
Wharemauku Stream	1	3	Inanga, common bully	2

The final impact score showed that native fish communities are most severely impacted upstream of Morton Dam on Wainuiomata River and the series of weirs and dams on Korokoro Stream (Table 5). Least impacted were those communities upstream of the structures on Wainui Stream.

Table 5 Shows the final assessment of the impacts on upstream fish communities. The IBI and O/E scores were generated by ranking the difference in average index scores from above and below each structure. The species score was generated from ranking the number of species that were present at downstream sites but absent from upstream sites while also predicted to be at upstream sites. The ranking used was out of 4, where 1 = smallest difference or lowest number of species.

Site	IBI score	O/E score	Species score	Final impact score
Korokoro Stream	4	4	3	3.67
Wainuiomata River	3	4	4	3.67
Cannons Creek	3	4	2	3.00
Otaki Forks	2	4	3	3.00
Wharemauku Stream	1	3	2	2.00
Battle Hill Farm Forest Park	3	0	2	1.67
Duck Creek	1	2	2	1.67
Kaiwharawhara Stream	1	1	3	1.67
Hulls Creek	2	0	2	1.33
Orongorongo River	2	0	2	1.33
Owhiro Stream	1	1	2	1.33
Porirua Stream	2	1	1	1.33
Wainui Stream	0	0	2	0.67

Priority for remediation

The priority for remediation was generated by multiplying the final structure score by the final impact score to give a priority score between 0 – 16. Morton Dam on Wainuiomata River, the series of structures on Korokoro Stream and the weir on Cannons Creek scored most highly and therefore had the highest priorities for remediation (Table 6). The structures at Otaki forks, Porirua Stream and Wharemauku Stream were the structures that had the next highest priority for remediation.

Table 6 Shows the priority for remediating each structure. The priority score (out of 16) was calculated by multiplying the final structure score with the final impact score. A score of 0-4 = low, 4-8 = moderate, 8-12 = high and 12-16 = very high priority for remediation.

Site	Priority score	Priority
Cannons Creek	8.00	High
Korokoro Stream	11.00	High
Wainuiomata River	11.00	High
Otaki Forks	4.00	Moderate
Porirua Stream	4.44	Moderate
Wharemauku Stream	5.33	Moderate
Battle Hill Farm Forest Park	3.33	Low
Duck Creek	3.33	Low
Hulls Creek	3.56	Low
Kaiwharawhara Stream	3.89	Low
Orongorongo River	3.56	Low
Owhiro Stream	3.11	Low
Wainui Stream	1.56	Low

Fish passes

Three fish passes were evaluated in this study; one on the weir on Hulls Creek, the other two on structures in Kaiwharawhara Stream (Fig. 6).

The weir on Hulls Creek was approximately 1m in height and was classified as being 'moderately' severe. The fish pass that has been installed is constructed out of large rocks, cobbles and boulders and has built up the stream bed to the level of the weir (Fig. 6a)

The first structure in Kaiwharawhara Stream is a long tunnel (approximately 100m in length) that has a large 1.4m drop at the out flow. This structure was classified to have 'high' severity as a barrier. A zigzag ramp has been installed on the true left of the tunnel outflow to allow passage of fish. Cobbles and gravels have been set into the ramp so that it closely resembles a natural stream bed (Fig. 6b).

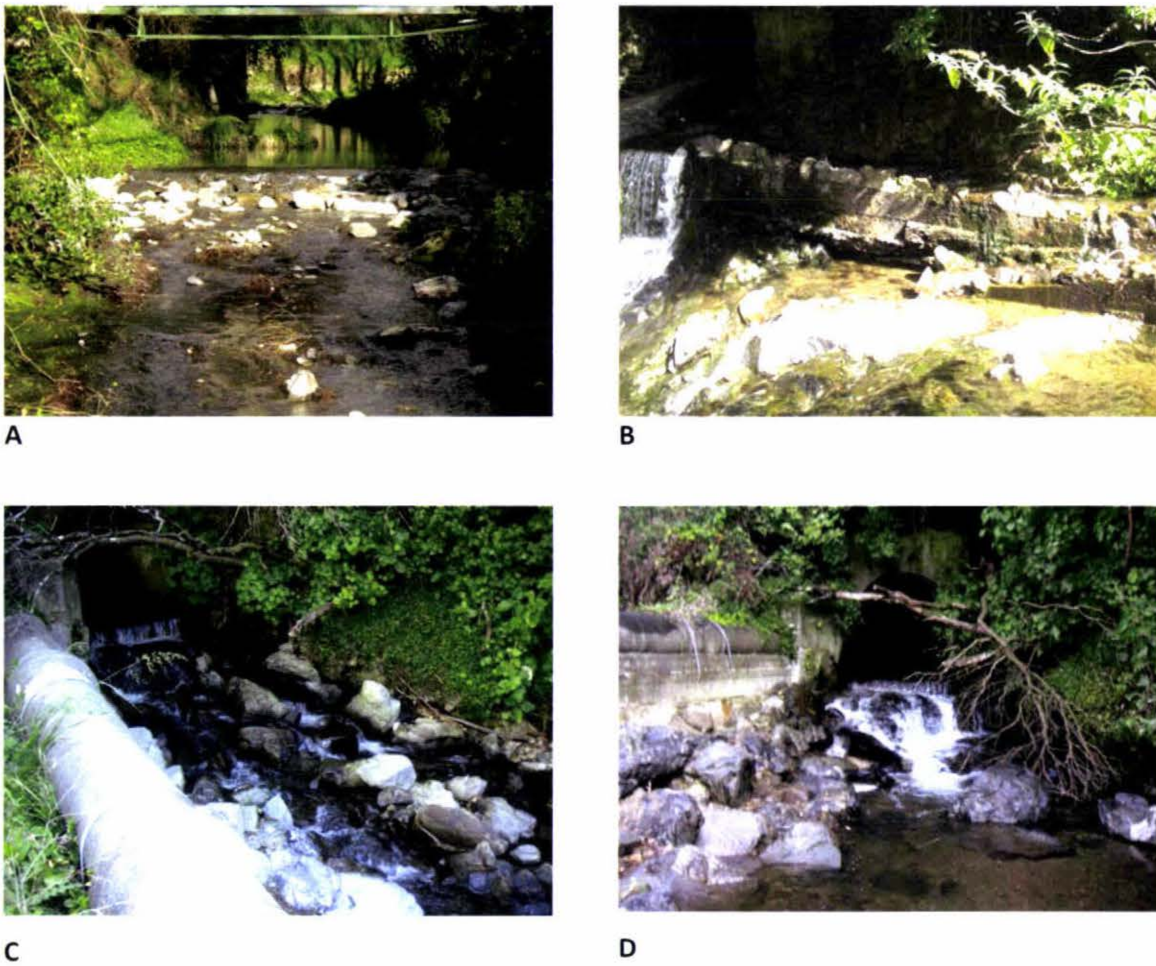

Fig. 6 A. Hulls Creek fish pass. **B**. Fish pass installed on the tunnel structure on Kaiwharawhara Stream. **C.** Fish pass installed on the culvert on Kaiwharawhara Stream two months after it was installed. **D**. Fish pass installed on the culvert on Kaiwharawhara Stream 16 months after it was installed.

The second structure on Kaiwharawhara Stream (upstream of the first structure) is a large culvert that had a small drop and large pool at its outflow. This culvert was classified to have 'minimal' severity as a barrier. The fish pass that was installed filled this pool with large rocks and boulders and raised the height of the stream bed until it was level with the base of the culvert (Fig.6c). This fish pass changed significantly soon after it was installed (Fig. 6d).

Monitoring of fish communities was undertaken once after the installation of the Hulls Creek fish pass in September 2007 and four times after the installation of the fish passes on Kaiwharawhara stream in March, April, May and September 2007.

Longfin and shortfin eels, common bullies and redfin bullies were found above the weir on Hulls Creek before the installation of the fish pass. Despite inanga, giant kokopu and bluegill bullies being predicted to be present upstream of the weir, no additional species were found after the fish pass was installed.

Longfin and shortfin eels, banded kokopu and koaro were found upstream of both structures on Kaiwharawhara Stream before the installation of the fish passes. Despite five other species predicted to be upstream of one or both structures, no additional species were found upstream of either fish pass during any of the monitoring events. However, koaro were found on the zigzag fish pass of the tunnel and between the two passes on one monitoring occasion.

DISCUSSION

To accurately assess the impact of any existing barrier on fish migration it is critical to know the extent of a species distribution in the absence of a barrier. Only then could a robust assessment of impacts be made by comparing the existing distribution with the expected. This study has successfully incorporated such a comparison, through the use of a predictive model, and quantified the potential loss of habitat for each species. These measures may reduce the uncertainty involved in directing mitigation efforts to areas that are naturally unlikely to contain diadromous fish.

The accuracy of the predictive model used was high (Joy & Death 2004a). However, because some sites used to create the model were upstream of potential barriers the use of this model to detect restrictions in passage will underestimate the impact to some degree.

The combined use of the IBI and predictive model in this study has overcome most of the difficulties involved in determining impacts on upstream fish communities. Consequently, it may be possible to establish what realistically constitutes a barrier to diadromous species, rather than basing such an assessment on anthropogenic perception (i.e. subjective assessments of the likelihood that a structure will be a barrier). However, only data of a species presence or absence has been used in this analysis. If a structure impacts a population by reducing its abundance upstream and/or truncating its distribution (due to variation in individual abilities and flows that favour passage) this use of presence/absence data will not detect such impacts. The inclusion of a series of fish survey sites upstream of structures will help to counteract this problem and may indicate whether species distributions are truncated if they are absent from the most upstream sites.

The 28 structures used to test the methods developed in this study were clearly having a negative impact on the migration of native fish species to upstream habitats. However, it was difficult to establish the degree to which each individual structure was inhibiting different species migration. This difficulty arose because of the lack of fish community records in the vicinity of each structure, making any statistical analysis on a per structure basis irresolute due to a lack of statistical power. This finding highlighted this methods heavy reliance on a large amount of data to accurately determine existing impacts.

Most organisations are unlikely to acquire enough data to determine the impact of an individual structure because of the large amount of effort and expense involved. However, the lack of data was counteracted in this study through the use of the 'priority index' which included and equally weighted of a number of attributes that may contribute to gauging the degree of each structures impact. The structure score alone was not a robust measure of passage restrictions as it did not take account of the existing distribution of fish communities. Similarly, the impact score was also unlikely to be robust as it contained too few records of fish communities and relied on presence/absence data. Consequently, the combination of these two measures may give the best indication of migration impacts within realistic limitations.

For example, Porirua Stream scored most highly in terms of structure effects (structure score) because of the combination of a large proportion of habitat upstream of the structures and the lowland location of these structures. However, the final impact score of Porirua Stream suggested a minimal impact on upstream fish communities because there was no species absent from upstream sites (though there was a decline in the average IBI and O/E upstream of the structures). The incongruence of these scores did not necessarily mean that either one was incorrect but rather reflected two different ways in which a structure could be assessed; either by evaluating the importance of the habitat and likelihood of impact, or by evaluating the existing impact on fish communities.

It is also important to consider each structure on an individual basis as there are numerous other factors, usually specific to one or a few sites, which may influence the effectiveness of mitigation work or efficiency of resource allocation. Boubee et al. (1999) suggested that barriers (natural or manmade) upstream and downstream of the structure in question and the timing of migration and flow requirements of the fish species concerned should be considered for all structures before remediation is conducted. In addition, the presence of valuable non-diadromous populations upstream of a structure that may be negatively impacted by the re-establishment of diadromous species should also be considered (e.g. dwarf galaxiid population upstream of Morton Dam on Wainuiomata River, see appendix), as should the quality of the habitat upstream (e.g. Hulls Creek, Korokoro Stream, see appendix) and the difficulty or cost involved in remediating large structures (e.g. Cannons Creek, see appendix). However, a final decision on determining priority may relate to managers' specific goals and will often come down to a decision based on funding commitments.

Fish Passes

Three fish passes were installed and monitored throughout the duration of this study. Two of these passes were installed on structures on Kaiwharawhara Stream the other was installed on the weir in Hulls Creek. Monitoring of fish communities above and below each pass found no additional species upstream of the passes from before they were installed. There may have been several reasons for this.

Firstly, there was a natural fall on Hulls Creek immediately below the weir/fish pass. This natural fall, that was approximately 1.5m in height, was likely to be limiting the species of fish that were able to reach the fish pass to those that were not likely to be restricted by the weir in the first instance. Consequently, this fish pass would not be expected to facilitate the passage of any new species over the weir. In addition, the water quality in Hulls Creek was generally low (Atkinson & Joy unpubl. data). Subsequently, sensitive species, such as giant kokopu, may have been deterred from entering this catchment regardless of whether there was free passage to upstream habitats.

The fish pass on the most downstream structure on Kaiwharawhara Stream was a zigzagged ramp to the side of a large drop at the outlet of a tunnel. While the fish pass itself was well constructed in terms of flow, gradient, and naturalness, its entrance was offset from the main flow. Such placement required fish to leave the main flow in search of an alternative access route upstream. Finding this alternative access may not be an intuitive behaviour for most fish (however one koaro was found on the pass) and may have contributed to its limited effectiveness.

The success of the second pass was dependent on the effectiveness of the first pass. Subsequently, it was difficult to draw any conclusions about its ability to facilitate fish migration. However, it is also important to note that the construction of the second pass on Kaiwharawhara Stream did not withstand high flow events. Much of the original pass was washed away and this subsequently created another drop which is likely to inhibit migration. In addition, a number of large brown trout were found residing within the fish pass. Brown trout are known to predate native fish, so their presence within a fish pass that native species have to move through was likely to be detrimental to native fish populations. Both the erosion of the pass and the presence of trout within it highlighted the importance of designing fish passes to suit the hydrology and ecology of the stream as well as the behaviours and abilities of the fish species that use it.

The main cause of the ineffectiveness of the Kaiwharawhara fish passes was likely to be the tunnel above the first pass. This tunnel constricted the flow of water into a narrow channel which was likely to cause high water velocities over a long distance. This combination of high velocities and long distances was known to cause restrictions in passage for most species (Boubee et al. 1999).

However, finally, the failure to detect a significant change in community structure upstream of the fish passes may be due to an insufficient time between their installation and monitoring. Consequently it may be important to continue monitoring fish passes for several years after their installation.

Conclusions

Robust assessments of migration barriers must compare what species are observed to be present to what would be expected to be present in the absence of barriers. The use of predictive models has allowed such a comparison to be made. In addition, the use of the IBI and the quantification of upstream habitats have overcome most of the cofounded factors that influence the distribution of diadromous fish and allowed an accurate evaluation of barrier impacts to be made. However, the application of these methods to 13 sites in the Wellington region has highlighted the need for a large number of surveys to draw statistically robust conclusions.

Determining priorities for remediation may depend largely on manages' specific goals and funding commitments. However, the inclusion of two major assessments, based on a structure's potential to restrict passage and the existing impacts on fish communities upstream of a structure, may aid in directing an efficient and effective use of mitigation resources. The three fish passes that were found to be ineffective in this study are good examples of where such direction may be needed.

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Chapter 3: Response of Gobiomorphus hubbsi (bluegill bully) to odours of conspecific fish in the presence of natural stream odours: does habitat have an influence?

ABSTRACT

This study tested the ability of bluegill bullies (*Gobiomorphus hubbsi*) to detect and respond to the odour of conspecific fish upstream under neutrally odoured (rainwater) and naturally odoured (stream water) conditions. Bluegill bullies were presented with a choice of two flows of water to move into, one of which contained the odour of conspecific fish. Bluegill bullies displayed a concentration-dependent reaction under neutral water conditions, where they were attracted to low concentrations of conspecific odour but repelled by high concentrations of odour. This result was not consistent under naturally odoured water conditions, where no attraction towards conspecific odour occurred at low odour concentrations and only a weak avoidance of odour occurred at high concentrations. The differences revealed between natural and neutral water trials suggests the use of habitat odours over conspecific odours and casts doubt on previous studies only conducted under neutral conditions.

Keywords navigation cues; odours; diadromy; amphidromy; Gobiidae

INTRODUCTION

Diadromy refers to a migration undertaken by many fish species between the sea and fresh water (McDowall 1992). Many diadromous species select specific freshwater habitats (McDowall 1984) and there is evidence to suggest that these fish species use odours within the water column as a cue to direct them to their favoured habitat (Leggett 1977; Pfeiffer 1982; Sorensen 1992). The origins of these cues are controversial and two major hypotheses have been suggested (Hasler & Wisby 1951; Nordeng 1971). The first hypothesis suggests that the upstream migration of fish is guided by the odour of upstream conspecifics, whose presence may indicate suitable and accessible habitat (Nordeng 1971, 1977; Rowe et al. 1992), whereas the second hypothesis suggests that organic odours, that are directly related to upstream habitats, are used as a cue in stream selection and navigation (Hasler & Wisby 1951). Both of these hypotheses have received experimental support (Selset & Doving 1980; Groot et al. 1986; Quinn & Tolson 1986; Sorensen 1986; Sorensen & Bianchini 1986; Keefe & Winn 1991; Baker & Montgomery 2001a; Baker & Hicks 2003), and therefore may not be mutually exclusive. However, the strongest evidence for the conspecific hypothesis was based on anadromous species (Li et al. 1995; Bjerselius et al. 2000; Fine et al. 2004), whereas the strongest evidence for the habitat hypothesis was based on catadromous species (Sorensen & Bianchini 1986). Subsequently, the relative use of these cues may be different in different fish species and are likely to correspond to the purpose or type of migration (Rowe et al. 1992; Baker & Hicks 2003).

For example, anadromous species migrate into fresh water as adults for the purpose of reproduction where they feed very little and die shortly after (McDowall 1992). Therefore, the odour of juvenile conspecifics that are migrating downstream from spawning grounds, may be well suited as a cue that indicates the presence of the spawning habitat that they seek (Nordeng 1977). In support of the conspecific hypothesis, an anadromous sea lamprey species (*Petromyzon marinus)* demonstrated an attraction to upstream larvae, and unique bile acids secreted from larvae was the substance responsible for this attraction (Li et al. 1995; Bjerselius et al. 2000; Fine et al. 2004). In contrast, catadromous species migrate into fresh water as juveniles for the purpose of feeding, growing and colonisation (McDowall 1992). Thus, they may be aware of cues that indicate an adequate food supply or good quality habitat, and these cues are more likely to relate to attributes of their habitat rather than the presence of conspecifics (Sorensen & Bianchini 1986). In support of the habitat hypothesis, Sorensen (1986) found that elvers of a catadromous eel species (*Anguilla rostrata*) are only weakly attracted to the odours of adult conspecifics and stream odours (such as those created from decaying leaf detritus, submerged stones or aquatic plants) are the preferred cue.

However, the purpose of amphidromous species migration is less clear than the purpose of anadromous and catadromous species migration. Like anadromous species, amphidromous species spawn in fresh water. However, like catadromous species, amphidromous species also move into fresh water as juveniles for feeding, growing and colonisation, having spent a brief period (2-6 months) at sea (McDowall 2007). Thus, the cues that amphidromous species use in stream navigation may be difficult to foresee as both conspecific and habitat cues could indicate the presence of good quality habitat.

Limited research on amphidromous species has shown two species, koaro (*Galaxias brevipinnis*) and banded kokopu (*G. facsiatus)* to have an attraction to water containing the odour of conspecifics under laboratory conditions (Baker & Montgomery 2001a; Baker & Hicks 2003). However, Baker & Montgomery (2001a) and Baker & Hicks (2003) conducted their experiments on amphidromous fish using tap water that is unlikely to contain other fish and habitat odours. Like many laboratory experiments in aquatic chemical ecology, such test conditions are not ecologically relevant to the natural environment and consequently, extrapolation of their conclusions to the natural environment may be tenuous (MacNeil et al. 2000).

This study, tested the response of an amphidromous species, bluegill bully (*Gobiomorphus hubbsi* Stokell, 1959), to conspecific odours in the presence and absence of habitat odours by using neutrally odoured rain water and naturally odoured stream water. The aims of this research were first to determine whether bluegill bullies respond to the odour of conspecifics and secondly to assess whether this response is consistent in the presence of natural habitat odours.

MATERIALS AND METHODS

Bluegill bullies were caught from the lower reaches of the Hutt River, Wellington, New Zealand (174°55'E; 41°11'S), between March and May 2007. All fish were relatively small, with total lengths ranging from 32 mm to 60 mm. Fish were kept in a 12°C temperature control room with a 12 h light to dark cycle and were housed in aerated water sourced from Hutt River. Glass holding tanks, where fish were kept before and after use in experiments, were 91 cm x 38 cm x 45 cm and no more than 100 fish were kept in a tank. A current was created using a submersible pump (Resun®) and fish were fed every 2-3 days on cultured bloodworms.

Two sets of trials were conducted, one used rainwater, the other used water extracted from Turitea Stream in Palmerston North (175°37'E; 40°23'S). Rainwater had a pH of 7.1 and Turitea Stream water had a pH of 7.6. This difference in pH was not expected to have affected the behaviour of fish in the trials.

The rainwater ("neutral water") was assumed to be neutrally odoured with respect to all other fish and stream habitat odours. Rainwater was collected off a rooftop and held in a 10, 000 litre tank before entering the experimental apparatus at a flow rate of 0.22 litre.s^{-1}. The flow was split into two upon entry into two head tanks and was aerated using two battery powered bubblers (Elite™). Out flowing water flowed to waste.

Turitea Stream water ("natural water") was used to test bluegill bullies response to conspecific odours in a natural situation where there is a suite of other fish and habitat odours. Nine species of fish have been found in Turitea Stream, upstream of the water intake (Atkinson & Joy unpubl. data). However, there has not been any record of bluegill bullies in Turitea Stream or the larger Manawatu River catchment, of which the Turitea Stream is a tributary. Landuse in the Turitea Stream catchment is 43% pasture, 26% scrub, 24% native forest, 4% planted forest, and 1% urban upstream of the intake (Snelder et al. 1998).

Stream water was pumped 20 m from the stream channel into the experimental apparatus using a submersible pump (Resun ®) powered by a petrol powered generator (Honda EG1500U). The flow of water into the experimental apparatus was 0.22 litres.s^{-1}, the same as the flow of rainwater in the first set of trials, and was split upon entry into the head tanks. The out flowing water was returned to the stream, downstream of the intake.

Experimental Setup

The experimental apparatus contained a lower chamber (area 319 cm^2, water depth 16 cm) (Fig. 1) which had access to two choice chambers (each holding 11.7 litres). Each choice chamber received water at a flow rate of 0.11 litre.s^{-1} from two identical head tanks (each holding 3.7 litres). The entrance to each choice chamber was created by a mesh funnel that allowed upstream movement of fish only. The walls of the lower chamber were created by fine wire mesh allowing the outflow of water. The whole unit was placed within a tank (83 cm x 45 cm x 30 cm) that had four outflow points spaced evenly along its length allowing a uniform outflow to waste. Outflowing water was not re-circulated through the apparatus. Food colouring was used to assess the flow and mixing of water from one side of the choice chamber and showed no back flow from the lower chamber into the choice chambers.

To acclimatise fish to a change in water before entering the experimental apparatus, fish were placed in a bucket for 20 min with water that was to be used in the subsequent trial.

The head tanks were filled with water and conspecific fish were placed in one of the two head tanks to create an odour in one of the two choice chamber. Trials were conducted with 1, 5, 10, or 20 fish in the head tank which created corresponding "odour concentrations" of 0.03, 0.15, 0.30, and 0.60 fish.$litre^{-1}$.s^{-1}. Once the head tanks were filled, water was allowed to flow through the apparatus. Trials began when the lower chambers had filled and water was flowing out of the lower tank.

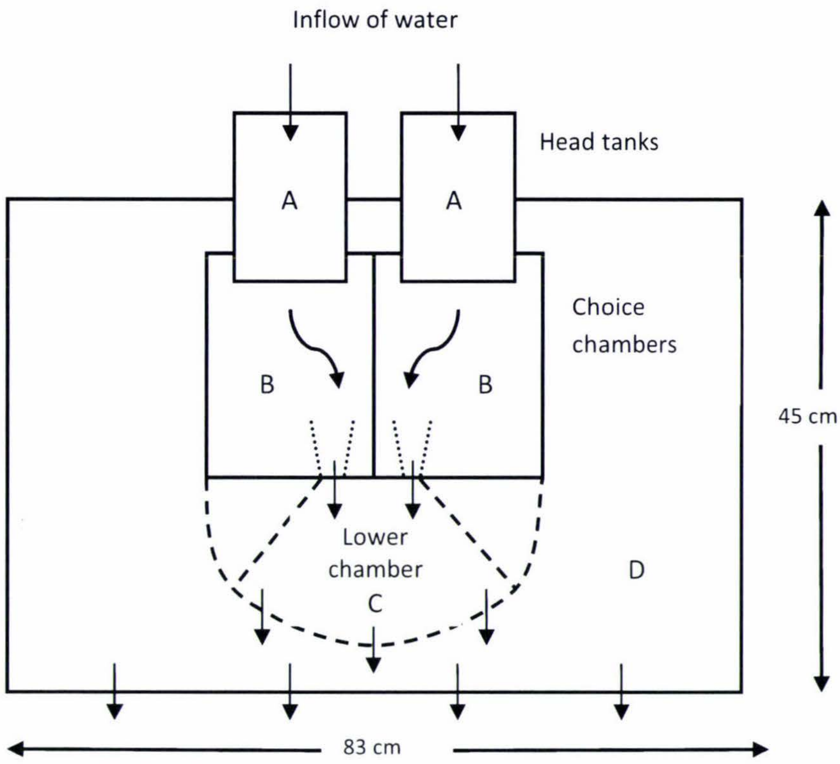

Fig. 1 Schematic diagram of experimental apparatus, consisting of a lower chamber (C) that provides access to two choice chambers (B). Water flows from two head tanks (A), through the choice chambers, into the lower chamber and out. Lower chambers and two choice chambers placed within housing tank (D).

Each trial was conducted by placing bluegill bullies individually into the lower chamber where they could select one of the choice chambers, one of which had an odour of conspecifics. Once the fish had swum into one of the chambers the trial ended and its position was recorded. If, after 10 min, the fish had not moved into either chamber, the trial was ended and the fish was removed. After each trial, the tank was emptied, the side of the odour swapped, and the tank refilled. Fifty trials were conducted for each odour concentration and each fish was used only once. The fish in the head tank were randomly chosen, were not used in any subsequent trials and were changed after every 10 trials to reduce stress. Fifty control trials were also conducted, where neither of the head tanks contained any fish. Each set of trials (four odour concentrations and a control trial, 250 fish) were conducted once using rain water and once using Turitea Stream water (500 fish in total). All trials were conducted outside during daylight hours.

Statistical analysis

All data were compared for significant differences using pairwise Chi-square tests (Baker & Montgomery 2001a), where the expected values, or null hypotheses, were based on the number of fish that did not move upstream in control trials. The number expected to be found in each chamber was then calculated to be half of the total number of fish that did move upstream in control trials.

RESULTS

Control trials, those in the absence of bluegill bully odour, showed fish had no significant preference for either choice chamber under neutrally odoured nor naturally odoured water conditions (Fig. 2, Table 1). Twenty eight and sixteen percent of fish did not move upstream in the control trials using neutral and natural water respectively and these proportions were used as baseline comparisons for subsequent trials.

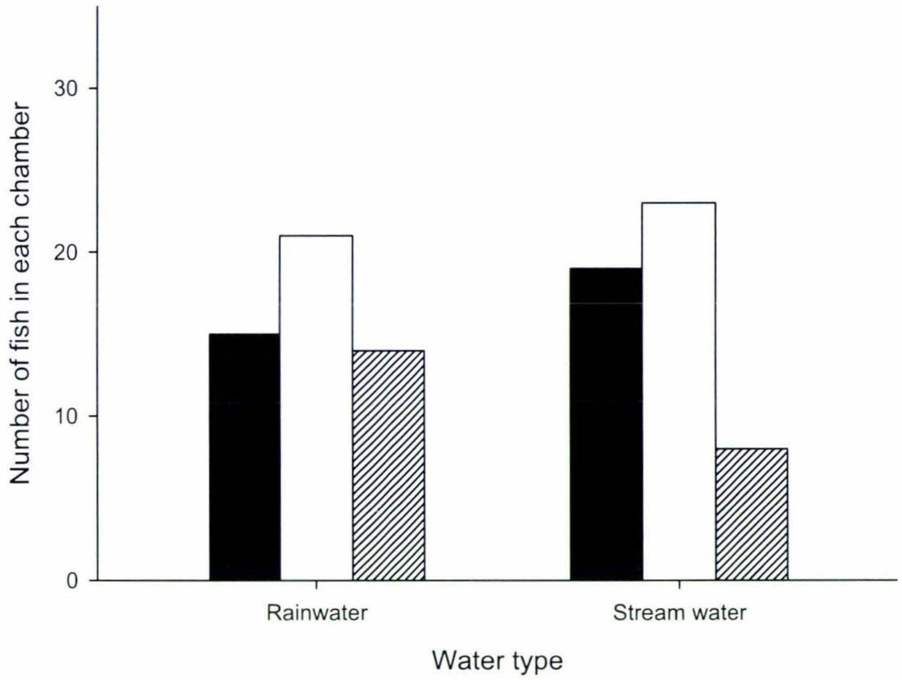

Fig. 2 Number of fish that moved into each choice chamber, or remained in lower chamber when no odour was added for two sets of trials conducted with rain water or stream water. *n* = 50 per water type. Closed bars represent left chamber, open bars represent right chamber, and hatched bars represent lower chamber.

In the neutral water trials, significantly more fish moved into the odour chamber than the non-odour chamber (Table 1, Fig. 3) when a low concentration of odour was created (0.03 fish.litre^{-1}.s^{-1}). In contrast, when intermediate and high concentrations of odour were created (0.30 and 0.60 fish.litre^{-1}.s^{-1} respectively) significantly more fish avoided the odour of conspecifics by moving into the non-odour chamber (Fig. 3, Table 1).

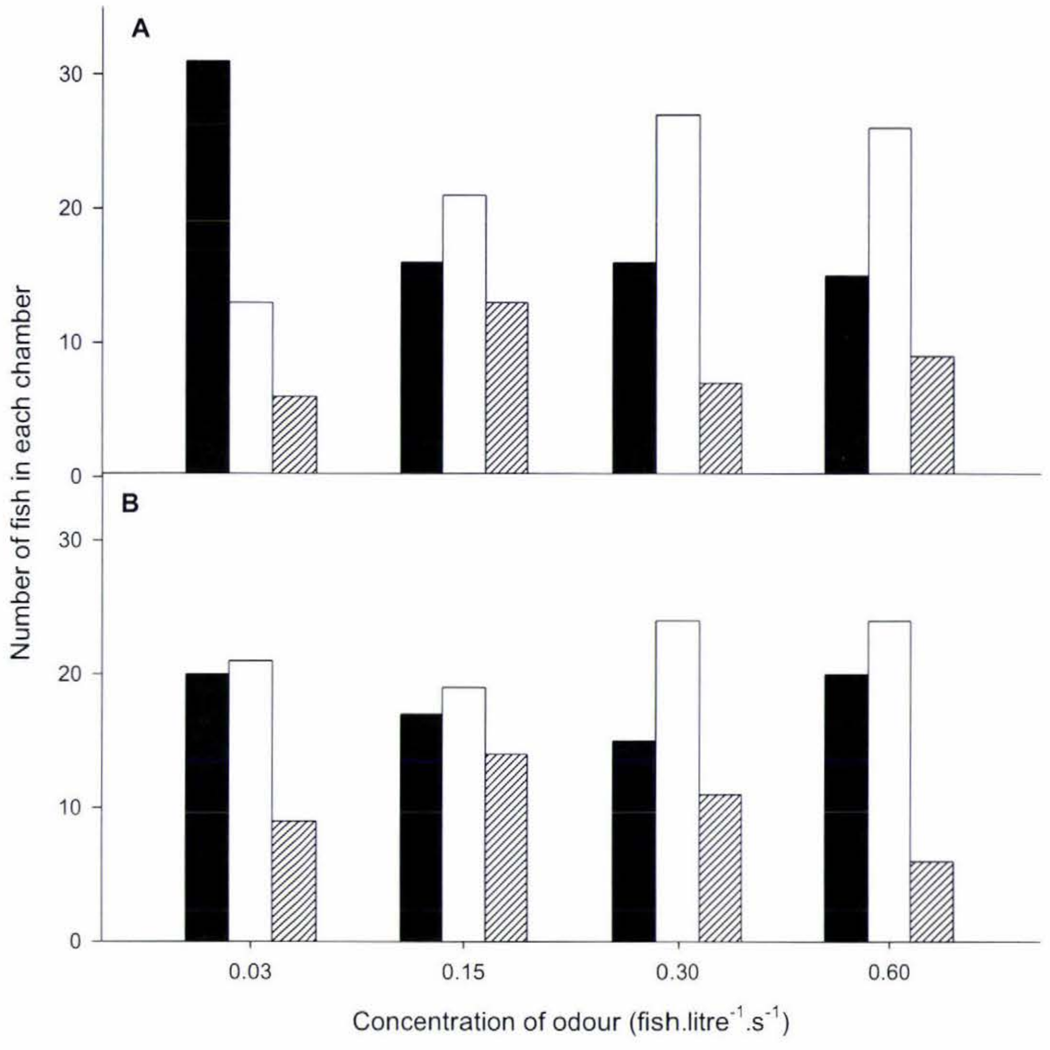

Fig. 3 Number of fish found in each choice chamber under varying concentrations of odour with A. rainwater, and B. stream water. Odour concentrations of 0.03, 0.15, 0.30, and 0.60 fish.litre^{-1}.s^{-1}correspond to 1, 5, 10, and 20 fish in the head tank. n = 50 per odour concentration, per water type. Closed bars represent the odour chamber, open bars represent the non-odour chamber, and hatched bars represent the lower chamber.

In the natural water trials, more fish were found in the non-odour chamber than the odour chamber at all four concentrations of odour (Fig. 3). This pattern was strongest at the highest concentrations of odour (0.30, and 0.60 fish.litre^{-1}.s^{-1}) but was not significantly different from control trials at any concentration (Table 1).

Table 1 Chi-square analysis of the number of fish present in each choice chamber under different concentrations of odour. Note that for d.f=1, the calculated value of chi-square is corrected for continuity. *P* values in bold indicate significance at 0.05.

Experimental group	χ^2	d.f.	P value
Neutral water trials			
Control left versus control right	0.70	1	0.403
Control versus 0.03 fish.litre^{-1}.s^{-1}	15.35	2	**0.001**
Control versus 0.15 fish. litre^{-1}.s^{-1}	0.76	2	0.684
Control versus 0.30 fish. litre^{-1}.s^{-1}	10.25	2	**0.006**
Control versus 0.60 fish. litre^{-1}.s^{-1}	5.84	2	**0.054**
Natural water trials			
Control left versus control right	0.22	1	0.639
Control versus 0.03 fish. litre^{-1}.s^{-1}	0.17	2	0.919
Control versus 0.15 fish. litre^{-1}.s^{-1}	3.72	2	0.156
Control versus 0.30 fish. litre^{-1}.s^{-1}	3.59	2	0.166

Comparison between water types

The influence of conspecific odour on fish behaviour was significantly different when the two water types were compared (Table 2). Under natural water conditions, at the lowest concentration of odour, there was no difference in the number of fish found in either choice chamber. However, under neutral water conditions, at the lowest odour concentration, more than twice the number of fish were found in the odour chamber than in the non-odour chamber (P=0.005, Table 2). At all other odour concentrations (0.15, 0.30 and 0.60 fish.litre^{-1}.s^{-1}), the response of fish in natural trials was similar, but relatively less pronounced, than the response of fish in neutral water trials (Fig. 4).

Table 2 Chi-square analysis of the number of fish present in each choice chamber, comparing rainwater trials (neutral) with stream water trials (natural). *P* values in bold indicate significance at 0.05.

Experimental group	χ^2	d.f.	P value
Control neutral versus control natural	4.40	2	0.111
0.03 fish.litre^{-1}.s^{-1}neutral versus 0.03 fish. litre^{-1}.s^{-1} natural	10.33	2	**0.005**
0.15 fish. litre^{-1}.s^{-1} neutral versus 0.15 fish. litre^{-1}.s^{-1}natural	0.33	2	0.848
0.30 fish. litre^{-1}.s^{-1}neutral versus 0.30 fish. litre^{-1}.s^{-1}natural	2.68	2	0.262
0.60 fish. litre^{-1}.s^{-1}neutral versus 0.60 fish. litre^{-1}.s^{-1} natural	2.82	2	0.244

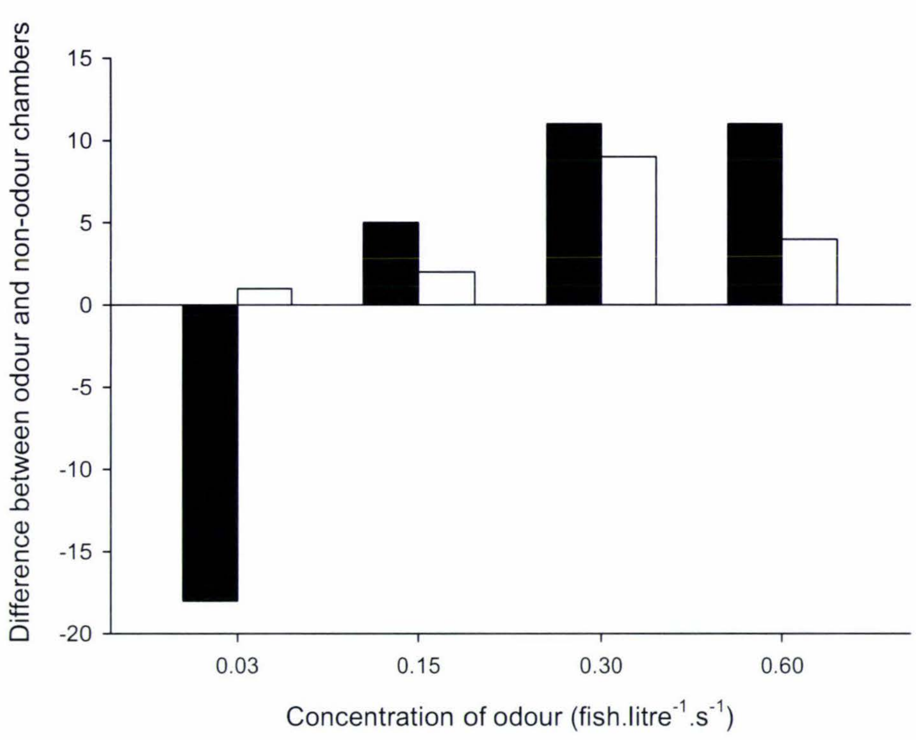

Fig. 4 Number of fish in the non-odour chamber minus the number of fish in the odour chamber for all trials at all concentrations of odour. 0.03, 0.15, 0.30 and 0.60 fish.litre^{-1}.s^{-1}correspond to 1, 5, 10, and 20 fish in the head tank. *n* = 50 per odour concentration, per water type. Closed bars represent rainwater and open bars represent stream water.

DISCUSSION

In the absence of natural stream odours, bluegill bullies were able to detect and react to the odour of conspecifics. This response provides preliminary evidence to suggest that bluegill bullies are able to use the presence of conspecific fish upstream as a cue in upstream navigation. Furthermore, the reaction of bluegill bullies to conspecific odour was concentration-dependent, with an attraction of fish towards weak odours, and an avoidance of fish to strong odours of conspecifics. This result is similar to that of another amphidromous fish species, banded kokopu (*G. fasciatus)*, which also displayed a concentration-dependent reaction to conspecific odours in the absence of natural stream odours (Baker & Montgomery 2001).

In comparison with other amphidromous species, these results reveal differences in behaviour that may be explained in the context of life history preferences. For example, banded kokopu and koaro (*G. brevipinnis)*, show an attraction to conspecifics at low odour concentrations (Baker & Montgomery 2001a; Baker & Hicks 2003). However, at high concentrations of odour, the response of banded kokopu was retarded, in that most fish did not move upstream, whereas the response of koaro did not change (Baker & Montgomery 2001a; Baker & Hicks 2003). In contrast, bluegill bullies actively avoided a high concentration of odour by choosing the non-odour chamber. Bluegill bullies are commonly found at high densities (more than 20 fish were commonly caught per pass of electro-fishing in the lower reaches of Hutt River (Atkinson & Joy unpublished data)) and it may therefore be an advantage to avoid habitats that are already densely populated. In contrast, koaro and banded kokopu are usually found at relatively lower densities (McDowall 1990) and may not be conditioned to any effects of living at high densities; therefore, they may be less sensitive in detecting, and needing to avoid, high concentrations of conspecifics.

In the presence of natural stream odours, the reaction of bluegill bullies was significantly different to their reaction under neutrally odoured water conditions. There was no attraction evident at low odour concentrations in naturally odoured water trials and the level of avoidance at higher concentrations of odour was not significantly different from control trials and weak in comparison to neutral water trials. This result indicates that bluegill bullies may use conspecific odour secondarily to that of natural stream odours, or that there are blocking or muting effects from the Turitea Stream water that impair the ability of bluegill bullies to detect the odour of conspecifics.

Baker & Montgomery (2001b) found that 0.5 μg litre^{-1} of cadmium was sufficient to inhibit the attraction of juvenile banded kokopu to conspecific odours and it is possible that such anthropogenic pollutants are present within Turitea Stream. Palmerston North's water supply and treatment plant is in the headwaters of the stream and the Turitea Stream catchment is predominantly in pasture. Thus, it may be possible that there were pollutants present within the naturally odoured water that interfered with bluegill bullies response to conspecific odours. The potential effects of these pollutants may explain the incongruent results of the two water trials.

If a pollutant had interfered with the detection of conspecifics no trend would be expected in the natural water trials. However, the results of the naturally odoured water trials show a similar trend to the neutrally odoured water trials, but this trend is less pronounced. This similarity between trials may suggest it is unlikely that a pollutant has interfered with the detection of conspecific odours. For this reason, it is likely that bluegill bullies were responding primarily to habitat cues of Turitea Stream. Moreover, when considering the nature of amphidromous species migration, where fish enter fresh water for both colonisation and reproduction, there is potential for differential use of a variety of cues, of which conspecific odour may be only one. The primary use of these cues may relate to specific life history preferences and/or the stage of migration.

To illustrate the highest concentration of odour used in this study on an ecologically relevant scale, 600 fish would have to be present in $1m^3/s$ of flow. The highest density of bluegill bullies encountered in Hutt River equates to 50 fish/m^3/s (calculated from a density estimate of 4 fish/m^2 in a depth of approximately 0.2 m, with an average flow of 0.4 $m.s^{-1}$ (Atkinson & Joy unpubl. data)) and consequently the highest concentration of odour used in this study is unrealistically high. However, the lowest odour concentration used in this study would equate to 30 fish being present in $1m^3/s$ of flow. A density of 30 bluegill bullies/m^3 may still be high, but not unrealistic, particularly when density estimates from single pass electro-fishing are likely to be underestimated (Jowett et al. 2005). It is possible therefore, that the avoidance behaviour of bluegill bullies displayed at high concentrations of conspecific odour is a reaction to stress cues, as reported for Iowa Darters (*Etheostoma exile)* (Wisenden et al. 1995). If this is so, it remains unclear as to why there was only a weak avoidance of high concentrations of conspecific odour in the naturally odoured water trials. However, this anomaly in itself may provide further support for a greater use of habitat cues over conspecific cues rather than avoidance due to stress cues.

This study emphasises the need to conduct experiments in ecologically relevant conditions. It also suggests that the conclusions drawn from previous studies on amphidromous species, that have only used neutral water to conduct their tests, may have premature or unrealistic conclusions without verifying them in a naturally odoured water source.

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Chapter 4 The influence of competition and physical stability on the longitudinal size distributions of bluegill bullies and torrentfish in two large New Zealand Rivers

ABSTRACT

This study examines the longitudinal size distribution of two populations of bluegill bully from Hutt and Rakaia Rivers and one population of torrentfish from Rakaia River. All populations had longitudinal trajectories that showed some increase in size with distance upstream. This increase in size primarily reflects the influence of amphidromous life styles, where juveniles diffuse upstream from the sea. However, a quantile regression analysis revealed differences in growth and migration rate between the two bluegill bully populations; bluegill bullies from Rakaia River grew at a slower rate and showed variation in migration rate within their population that was not evident in the Hutt River population. Null models were also generated for each population to test for the presence of all size classes of fish in the lower reaches of each river. Both bluegill bully populations showed a significant absence of the largest size classes in the lower reaches and differed significantly from the null models. This difference suggests that all individual bluegill bullies continuously move upstream throughout their lives. In comparison, the size distribution of torrentfish closely resembled the null model, indicating that some individuals did not migrate upstream to the same extent as others. The differences revealed between the two bluegill bully populations may be explained through a combination of differences in competition and stability between the Hutt and Rakaia River, while the difference between bluegill bully and torrentfish distributions may be a consequence of different reproductive strategies.

Keywords size distribution; longitudinal; competition; stability; *Gobiomorphus hubbsi*; *Cheimarrichthys fosteri*

INTRODUCTION

A large proportion of New Zealand's native freshwater fish fauna (approximately half) are diadromous. However, the proportion of diadromous species in any one fish community throughout New Zealand is likely to be greater than 75% due to the more restricted range of non-diadromous species (McDowall & Taylor 2000). The most common form of diadromy in New Zealand is amphidromy which results in juveniles migrating upstream from the sea, where they slowly penetrate river systems until they spawn as mature adults and their larvae then drift out to sea (McDowall 2007).

Diadromous species differ in their migratory abilities and instincts and the extent to which they travel upstream (McDowall 1990; McDowall 1993). Thus, the limit of a species penetration is constrained by their individual swimming and climbing abilities coupled with the gradient of the river, while the extent of a species upstream penetration is most often attributed to its search for suitable habitat or 'instinctive migratory drive'(McDowall 1998a).

However, because much research on the distribution of diadromous fish species has been based around the development of predictive models and biological monitoring tools (e.g. Jowett & Richardson 2003; Joy & Death 2004a, b; Leathwick 2005) it has been conducted at the community level on a broad regional or national scale. Consequently, the trajectories of species occurrences (i.e. the average distances and elevations each species can reach) are well documented for each species, but the small scale forces (such as biotic interactions or proximal conditions), that may cause such trajectories, are not so well understood.

Within each species trajectory of occurrence, it is also likely that there are longitudinal trends in abundance and in size/age structure, where abundance declines and smaller/younger fish become increasingly rare with distance upstream (McDowall 1998b, a). Limited research has shown variation in the patterns of longitudinal size structure and few studies have focused on such trends. McDowall (1998a) cites examples of torrentfish (McDowall 1973; Davis et al. 1983; Bonnett 1986), redfin bullies (McDowall 1965), bluegill bullies (Davis et al. 1983; Bonnett 1986) and longfin eels (Strickland 1985) having all size classes present in the lower reaches with smaller/younger fish becoming increasingly rare with distance upstream. However, Bonnett (1986) showed that only small sizes of bluegill bully were present in the lower reaches of Rangitata River and bigger fish increased in relative abundance with increasing distance inland. Though McDowall's (1998a) comment was aimed at highlighting that small/young fish are limited in their upstream penetration, and did not centre on the longitudinal distribution of larger/older fish, the implications of a full size range of fish in downstream reaches (if this exists) may suggest significant variation in the extent to which some individuals migrate upstream. Furthermore, if variation in the presence of large adult fish in downstream reaches exists, both within a species and between species, then an enquiry into the environmental differences in which such distributions occur may help to decipher more precisely the factors that affect the upstream migration of diadromous fish.

This study tests the longitudinal distribution of two amphidromous species, torrentfish (*Cheimarrichthys fosteri* Haast 1874) and bluegill bully (*Gobiomorphus hubbsi* Stokell, 1959).Two populations of bluegill bullies from Hutt and Rakaia Rivers and one population of torrentfish from Rakaia River were tested against a null model that was based on the presence of all size classes of fish in downstream reaches. The aims of this research were first to establish if there was variation both within and between species longitudinal size distributions and secondly to form a hypothesis that could explain such variation.

METHODS

Study Sites

Study sites were located on two New Zealand rivers, Hutt River in Wellington (Fig. 1) and Rakaia River in Christchurch (Fig. 2). Hutt River was surveyed for bluegill bullies on three occasions between June 2007 and February 2008. Data for torrentfish and bluegill bullies from Rakaia River were taken from Davis et al. (1983) for three sampling periods between June 1979 and February 1980.

Hutt River

The Hutt River flows to the south-west from the southern Tararua ranges and flows into Wellington harbour at Petone. Hutt River is about 54km long and has a catchment area of 648km2. The gradient of Hutt River increases with distance upstream and on average rises at 3.0m/km within the longitudinal extent of the sites surveyed in this study. Sites ranged from 4.5 to 38km from the sea and from 8 to 192masl. Rain falls in Hutt River catchment on average 170 days per year. Flooding events are less frequent than in Rakaia River, as assessed by the number of days per year that rainfall exceeds a specific value (Wild et al. 2005). The mean annual flow for Hutt River in 2007 was c. $15m^3/s$ and varied between 3.81 and $499m^3/s$ (GWRC website)

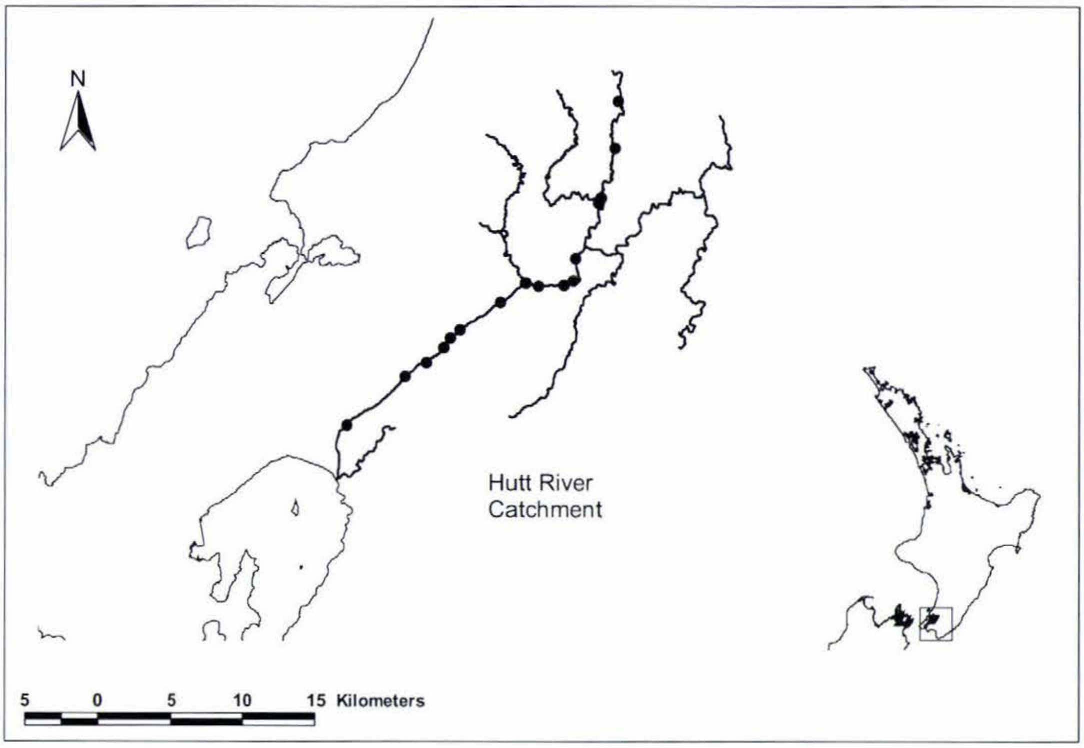

Fig.1 Site map of Hutt River catchment showing 16 survey sites. Streams 4th order and over are shown in black.

Rakaia River

Rakaia River is a braided glacier-fed river that flows to the east coast, south of Banks Peninsula. The bed is highly mobile and is considered unstable (Sagar & Eldon 1983). Rakaia River is about 140km long and has a catchment area of 2626km2. About 60km upstream a gorge divides the river into two distinct parts. Below the gorge the gradient of the river is relatively even with an average fall of 4.6m/km within the longitudinal extent of sites surveyed in this study. Sites ranged from 2km to 50km from the sea and from 10masl to 240masl and were all in the lower part of the river, below the gorge. Rain falls in Rakaia River catchment on average 186 days per year (Wild et al. 2005). The mean annual discharge of Rakaia River was c. $196m^3/s$ between 1958 and 1981 (Bowden 1983). This flow is much higher than that of Hutt River and the flows are also more variable, ranging from $101m^3/s$ to $2319m^3/s$ for the 12 month period between 1979 and 1980 (Sagar & Eldon 1983).

The survey methods used by Davis et al. (1983) were comparable to those used in the Hutt River (details below) where electro-fishing was employed and targeted toward riffle habitats.

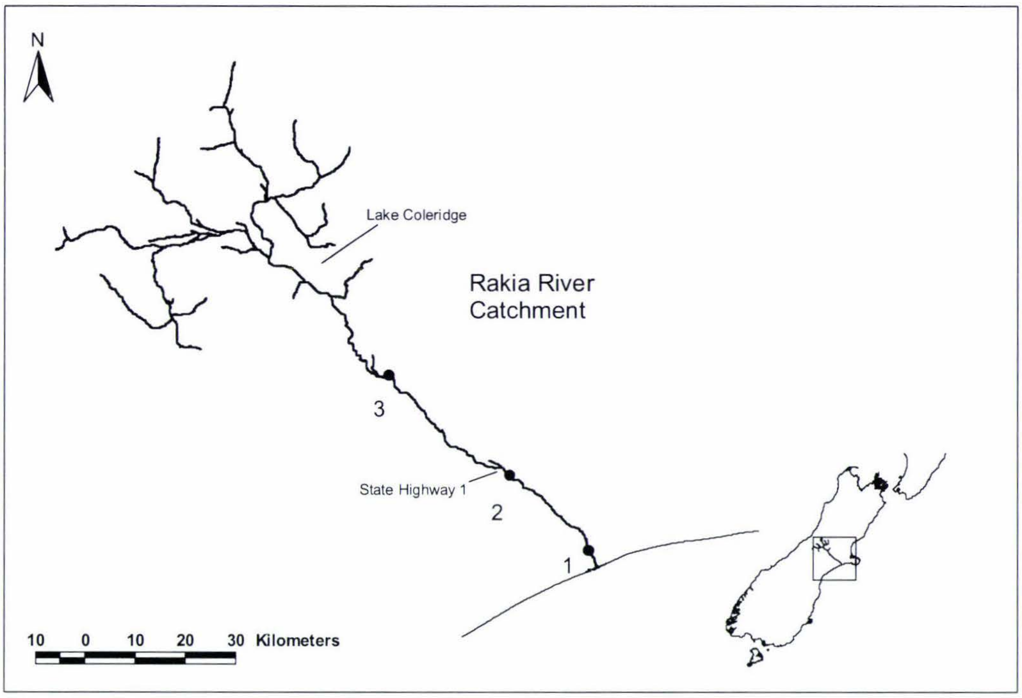

Fig. 2 Site map of Rakaia River catchment showing three survey sites. Streams 4[th] order and over are shown in black.

Sampling Method

Three surveys of Hutt River were conducted in June, November and February of 2007/2008. Single pass electro-fishing was conducted on all sampling occasions and was targeted toward riffle habitats only. A total of 16 sites were surveyed over the three sampling periods: 13 during June survey; 6 during November and 7 in February. Although the intention was to catch and measure at least 20 bluegill bullies at each site, this became difficult to achieve at sites where fish were sparse and on some sampling occasions none were found.

To provide an estimate of growth rate, two fish from each site sampled in June were taken for aging by analysis of their otoliths. However, due to the indistinctiveness of rings this analysis was unsuccessful in both this study and that of Davis et al. (1983).

During the June survey, ten measures of depth, velocity and substrate size were randomly taken for each pass of electro-fishing and associated with those fish that were caught in that pass. This was to assess potential differences in the size of fish due to differences in habitat. However, the low density of fish at some sites meant that the number of passes of electro-fishing that returned no fish increased dramatically and taking habitat measurements from passes that returned only 1 – 2 fish became highly labour intensive. In such cases habitat variables were averaged over the area of riffle that returned the most fish.

Data Analysis

Linear regression was used to investigate the relationship between length of fish and distance and elevation upstream (proc reg procedure of SAS 2000). To rigorously validate this relationship, 10 fold cross-validation was used. This involved holding out 10% of the data and building a model to predict the length of fish based on the remaining 90%. The 10% of data that was withheld was then put into the model to test the accuracy of its predictions by evaluating the error between the predicted and observed values. This was repeated 10 times so that all data were tested.

To explore differences both in length of fish between populations and between real data and null models, analyses of covariance (ANCOVA) were employed, where elevation and/or distance to the sea were used as covariates (proc glm procedure of SAS 2000).

Variation in the relationship between length of fish and distance upstream was investigated using quantile regression because it facilitates analysis of the upper and lower limits of a variable rather than the mean or median (Scharf et al. 1998). This procedure was used because the lower limit of fish lengths may increase at a faster rate than the median or upper limits as smaller/younger amphidromous fish are constrained by an obligatory marine larval stage. The upper limit of fish length may show no increase in length with distance upstream if a proportion of the population remains in the lower reaches of the river. The proc quantreg procedure of SAS (2000) was used to create estimates of the regression slope and intercept at the 25^{th}, 50^{th} and 75^{th} percentiles for all three fish populations (Rakaia River torrentfish and bluegill bullies and Hutt River bluegill bullies).

Null models of longitudinal size distribution were constructed for all three populations. Within these models, fish lengths were created for all sites on the Rakaia River and six sites on the Hutt River based on the range of lengths found for each species over all three sample periods (June, November and February). The RANDBETWEEN function in Excel (2007), was used to generate 100 random lengths for each site. The upper limit of lengths for all sites was the maximum length of fish found in that population, while the smallest length was constrained by the minimum length found at the site that the data was being created for. As a result, the null model depicts a population that has all size classes present at the lowest site, and with increasing distance upstream, the minimum size of fish is constrained by the minimum size that was found at that site over the three survey periods.

Habitat data were analysed using principle component analysis (PCA) to reduce the three variables, depth, velocity and substrate, into a single dimension (proc princom procedure of SAS 2000). This was then regressed against fish length to determine whether the length of fish varied with differing habitat.

RESULTS

The length of bluegill bullies was positively related to elevation and distance from the sea in both Hutt River (elevation: $r^2 = 0.60$ $p < 0.0001$, distance: $r^2 = 0.64$ $P < 0.0001$) and Rakaia River (elevation: $r^2 = 0.40$ $p < 0.0001$, distance: $r^2 = 0.42$ $p < 0.0001$) (Fig. 3). The cross validated regressions confirmed the strength of these relationships showing strong correlations between observed and predicted lengths for Hutt River ($r^2 = 0.63$) and Rakaia River populations ($r^2 = 0.42$) when length of fish was regressed against distance to sea.

Rakaia River bluegill bullies were significantly longer than those in Hutt River but increased in size at a slower rate ($F_{2,1108} = 938.52$) (Fig. 3). On average bluegill bullies from Hutt River increased in length by 30mm over 40km whereas bluegill bullies from Rakaia River increased 17mm over 40km.

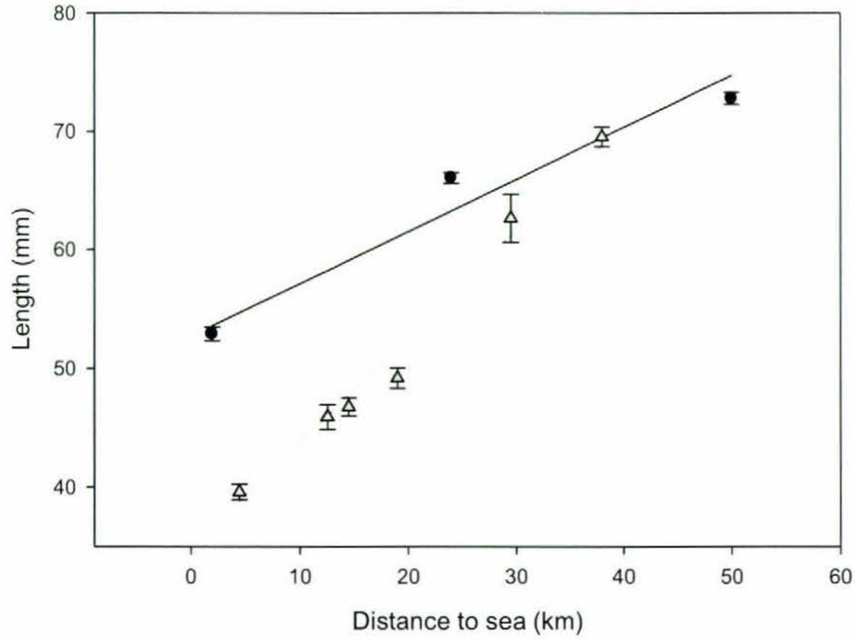

Fig. 3 Length of bluegill bullies in Hutt Δ and Rakaia Rivers ● with distance upstream. Error bars are the standard errors.

The length of torrentfish from the Rakaia River showed no relationship with either elevation (r^2 = 0.065) or distance to the sea (r^2 = 0.064) when all data was combined in the analysis. This assertion was supported by cross validation showing that elevation and distance upstream are weak predictors of torrentfish length (r^2 = 0.062). However, when a quantile regression was employed, the 25th percentile showed a significant increase in length with distance to sea (t = 18.08, $P < 0.001$) while the 50th and 75th percentiles of the length distribution showed no increase in length with distance to sea (t =1.68, $P = 0.093$, t = 1.07 $P = 0.284$ for 50th and 75th percentiles respectively) (Fig. 4). This variation in percentile regression lines suggests that not all torrentfish continue to migrate upstream throughout their lives.

In contrast, all quantile regression percentiles (25th, 50th and 75th) for the two bluegill bully populations showed significant relationships between length of fish and distance upstream (Fig. 4). Each percentile of the Hutt River bluegill bully population had parallel regression lines with similar strong positive slopes (s = 0.85, s = 0.93, s = 0.87 for the 25th, 50th and 75th percentile respectively), whereas Rakaia River bluegill bullies showed the slope of each regression line decreased as the percentiles increased (s = 0.50, s = 0.40, s = 0.29 for the 25th, 50th and 75th percentiles respectively). This variation in the slope of each percentiles regression line indicates that not all bluegill bullies in the Rakaia River migrate upstream at the same rate.

Comparison of length distributions and null models

For all null models, the 25th percentile of lengths showed a significant increase with increasing distance to the sea, whereas the 75th percentile showed no increase in length with distance upstream. The population of torrentfish did not differ significantly from the null model ($F_{1,846}$ = 0.28, p = 0.59) and had full range of sizes at the lowest site (Fig. 5). In comparison, both bluegill bully populations showed an absence of the maximum size classes at lower sites and were significantly different from their null models ($F_{1,1063}$ = 474.83 p < 0.0001; $F_{1,940}$ = 30.84, p < 0.0001 for Hutt River and Rakaia River populations respectively) (Fig. 5).

Habitat variables of Hutt River

The physical characteristics of Hutt River were similar along the studied length of the river. There was no consistent longitudinal variation in depth (r^2=0.002 p=0.63), velocity (r^2=0.001 p=0.74) or substrate (r^2=0.001 p=0.77) among the study sites, though there were significant differences in depth and velocity between some sites ($F_{8,81}$ = 15.36 p > 0.001; $F_{8,81}$= 2.27 p = 0.01, for depth and velocity respectively). PCA reduced the three habitat variables into one dimension, which explained 78% of their variation. The first principle component had

Eigenvalues that were equally comprised of substrate size (0.60) and velocity (0.62) and to a lesser extent depth (0.46). When the first principal component was regressed against fish size it showed there was no habitat partitioning according to the size of fish (r^2 = 0.0009 p=0.22).

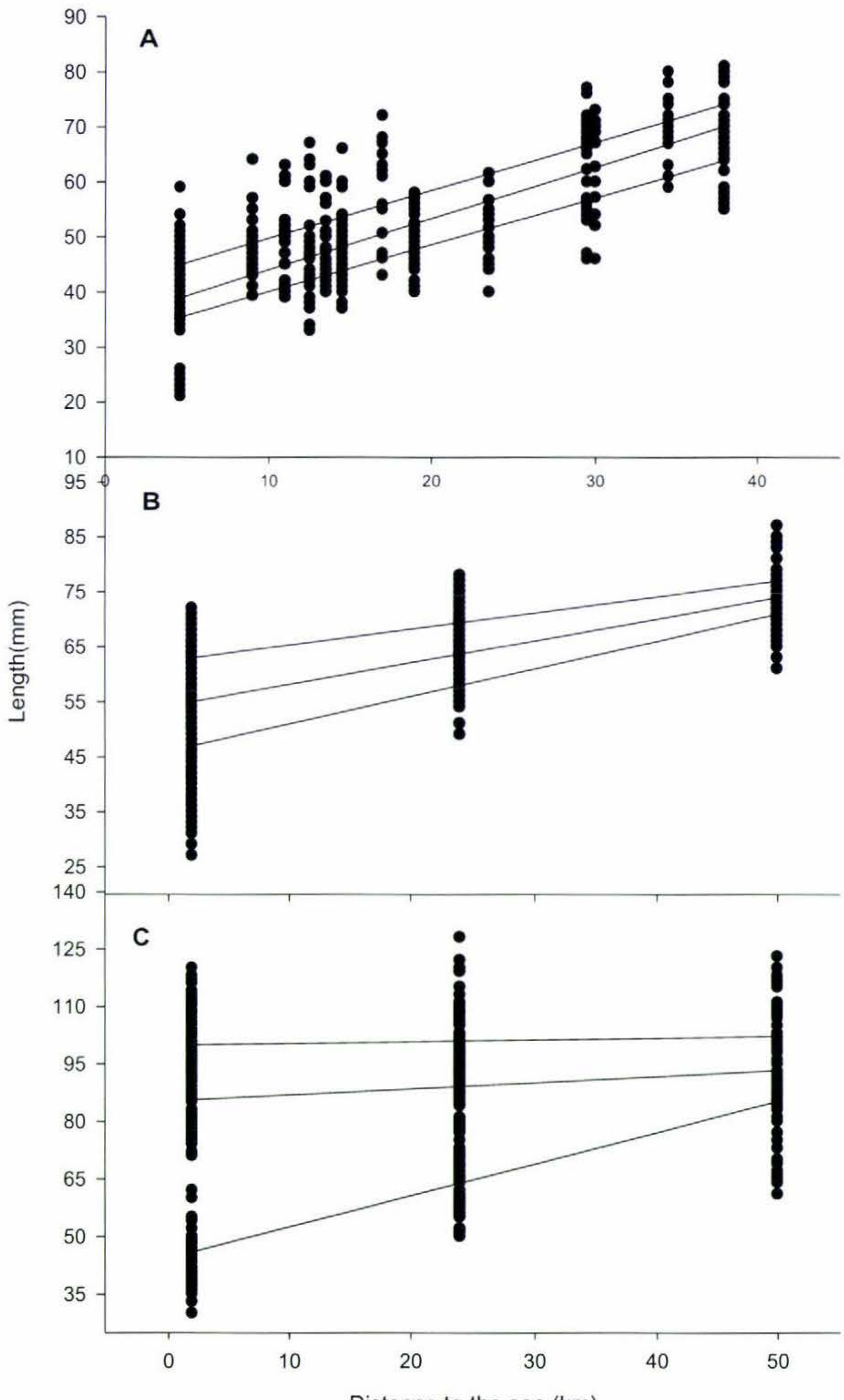

Fig. 4 Distribution of fish lengths with quantile regression lines fitted for the 25th, 50th, and 75th percentiles for A). Hutt River bluegill bullies B). Rakaia River bluegill bullies C). Rakaia River torrentfish

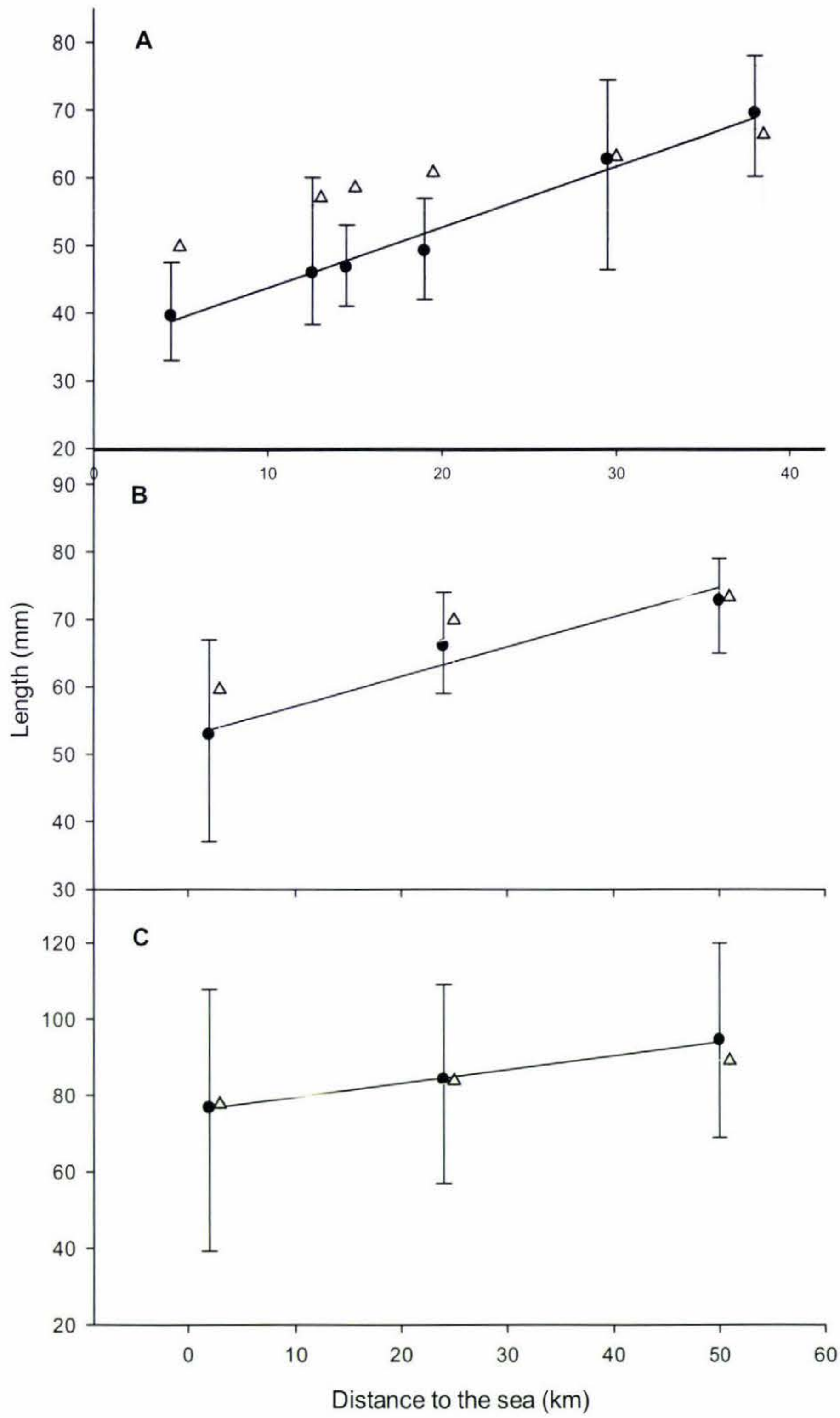

Fig. 5 Longitudinal length distribution of each fish species ● and associated null model Δ for A). Hutt River bluegill bullies, B). Rakaia River bluegill bullies and C). Rakaia River torrentfish. Upper and lower error bars are 90th and 10th percentiles respectively. Null models have been jittered slightly on the X axis for clarity.

DISCUSSION

The size distributions of bluegill bullies in Hutt and Rakaia Rivers were strongly related to their longitudinal position within each river, where length of fish increased linearly with distance upstream. This longitudinal size distribution was primarily shaped by bluegill bullies amphidromous life history, in which an obligate marine larval stage constrains the distance small juvenile fish can penetrate into freshwater (McDowall 1998a). However, in Rakaia River, bluegill bullies grew at a slower rate than bluegill bullies in Hutt River and showed variation in migration rate within their population that was not evident in the Hutt River population. These differences between populations suggest that the longitudinal distribution of bluegill bullies is also influenced by factors outside their life history. Two of these factors, competition and/or physical stability of each river have been hypothesised to account for these differences.

A major competitive difference between these two rivers may be the presence of torrentfish in Rakaia River and their absence in Hutt River. Bluegill bullies and torrentfish were equally dominant in riffle habitats of Rakaia River (Davis et al. 1983), whereas bluegill bullies were the only fish found in the riffle habitats of Hutt River (Atkinson & Joy, unpubl. data). This difference in community structure may result in differences in competitive forces. Both inter and intra-specific competition may exist in Rakaia River and only intra-specific competition may exist in Hutt River. Based on tests conducted in artificial channels with two bully species, Glova (1999) suggested that intra-specific competition was a stronger force than inter-specific competition. If this assertion is applicable to bluegill bullies and torrentfish, then the lack of variation in migration rate of the Hutt River population may be explained by a strong competitive force driving all individuals upstream in search of available habitat and resources. In contrast, a weaker inter-specific competitive force in Rakaia River may allow some individuals to persist longer in one habitat, explaining the variation in migration rate seen among the bluegill bully population in Rakaia River.

However, biotic interactions, such as competition, are usually only important when resources are limited and physical influences, such as flood events, are stable for long periods (Jackson et al. 2001; Boyero & Pearson 2006). Rakaia River has a higher frequency of flood events than Hutt River and is subsequently considered to be less stable. If this instability reduces the potential for competition to exist, then the variation in migration rate among the population of bluegill bullies in Rakaia River may be a consequence of flood events displacing some individuals downstream. In contrast, the downstream displacement of individuals in Hutt River may not be as evident because the frequency of flood events is much lower.

Differences in stability between Hutt and Rakaia Rivers may also explain the differences in growth rate between the two populations. The food source (invertebrate community) for bluegill bullies is likely to recover from disturbance more quickly and have a more constant level of abundance in the more stable Hutt River, than in the less stable Rakaia River (Death & Winterbourn 1995; Death 1996). Subsequently, a more plentiful and more constant food supply in Hutt River means that bluegill bullies there are likely to have a higher growth rate than those in Rakaia River (Molony & Sheaves 1998).

There was also a major difference between torrentfish and bluegill bully size distributions. This difference between species essentially relates to the presence (or absence) of large, presumably older fish in downstream reaches. In ecological terms this difference suggests that all bluegill bullies in Rakaia and Hutt Rivers migrate upstream as they grow and continue this migration throughout their lives. In contrast, torrentfish appear to have at least some individuals that either do not migrate any great distance upstream, or, they subsequently move back downstream after a period of growth.

Scrimgeour (1986) found that the diet of small torrentfish (51-64mm) differed to that of large torrentfish (71-109mm) in composition and size of prey. This resource partitioning between size classes may allow large torrentfish to occupy a niche in downstream reaches that is partially secluded from intra-specific competition with small torrentfish and inter-specific competition with bluegill bullies (if this exits). It is unclear whether this resource partitioning is a passive or active behaviour (Scrimgeour 1986). However, mechanical differences in mouth size may suggest it is at least partially a passive behaviour, since mouth size is linearly related to total length and larger fish were found to consume larger prey (Scrimgeour 1986). Bluegill bullies may be limited in their ability to partition resources among size classes because of their small total size range. Therefore, larger individual bluegill bullies may be forced upstream in search of food resources.

However, the presence of large adult torrentfish in downstream reaches is not likely to be caused by a difference in diet between size classes, particularly if resources are not limited. Male and female torrentfish differentiate themselves spatially along longitudinal gradients; male torrentfish occupy the lower reaches, females occupy the upper reaches and there is a large area of overlap in the middle (Davis et al. 1983; McDowall 2000). Though this segregation is likely to have reproductive implications, and may be a specific reproductive strategy, it is not well understood (McDowall 2000). The ability of torrentfish to partition resources among size classes may simply accommodate this reproductive behaviour allowing large torrentfish to be present downstream.

The longitudinal extent of surveys in Hutt and Rakaia Rivers are probably adequate for bluegill bullies as the upstream penetration of bluegill bullies in New Zealand is modest and few populations have been found to extend beyond 250masl (McDowall 1990). However, torrentfish are known upstream of Lake Coleridge within the Rakaia River catchment at distances of 110km upstream and 507masl (McDowall 2000). McDowall (2000) noted that the presence of torrentfish upstream of Lake Coleridge requires fish to migrate throughout the extent of Rakaia River where suitable habitat is prolific and also through approximately 10km of lake which bears little resemblance to the habitat in which torrentfish are most commonly found. What drives some individuals and not others to carry out this migration is unlikely to be explained by either competition or physical stability but may be, at least partially, be an innate behaviour and/or a response to chemical attractants within the water column (see Atkinson & Joy 2008).

Given that biotic dynamics, such as competition, are intimately linked to variation in abiotic forces (Power et al. 1988), determining if competition influences bluegill bullies and torrentfish distributions, or if competition even exists between these species is inherently difficult and extends beyond the limitations of this study. Similarly determining a single cause for explaining the differences in distributions is highly unrealistic when the environment they occur in is multifaceted. However, it is clear that there are differences both between torrentfish and bluegill bully distributions in Rakaia River and between the distributions of bluegill bullies from Hutt and Rakaia Rivers. The difference between torrentfish and bluegill bully populations primarily relates to specific life history strategies and suggests an innate behaviour or the use of chemical cues to drive the upstream migration in some individuals. In contrast, differences in stability between Hutt and Rakaia Rivers may seem the most important factor in influencing the longitudinal distributions of bluegill bullies as it can provide logical explanations for both the differences in migration rate and the differences in growth rate. Competition, however, while not necessarily absent, does not explain the difference in migration or growth rate as easily.

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Synthesis

This thesis investigated some of the multitude of influences on diadromous native fish distributions in New Zealand's flowing waters. Primarily such distributions are constrained by diadromous movements between the sea and freshwater habitats that create a downstream-upstream trajectory of decreasing abundance and species richness with increasing distance inland. All other factors, whether abiotic or biotic, influence the distribution of fish within this broad pattern; and as such, can either drive or constrain the upstream movement of fish.

On a broad, regional scale, the second chapter of this thesis quantifies the constraints of migration caused by physical barriers, using a predictive model to ascertain what the upstream distribution would have been in the absence of migration barriers. The strength and practical application of this chapter lies in improving the assessment and characterisation of migration barriers and consequently the decisions to direct effective remediation work. However, precisely how migration barriers impact fish communities are not well understood i.e. if a barrier limits the number of individuals that can migrate upstream, does this reduction in abundance affect the extent of migration upstream, recruitment of juveniles, and/or the reestablishment of communities if barriers are removed? In order to answer, or understand any of these questions, it is pertinent to understand the factors that drive or constrain the migration of individuals at a smaller scale.

Consequently, the third chapter of this thesis investigates the relative influence of chemical cues on habitat selection processes used by one amphidromous fish, the bluegill bully. Previous tests of chemical attraction or avoidance for amphidromous species in New Zealand showed that banded kokopu and koaro were attracted to water containing odours of conspecifics. This research suggested that the reestablishment of fish communities upstream of barriers may be limited without the translocation of conspecific fish to extirpated habitats. However, this earlier research did not take account of other naturally occurring stream odours that may equally affect the upstream migration of fish. The tests of bluegill bullies, in chapter 3, shows that the selection of migration paths based on the presence of conspecifics was confused or overridden by the presence of natural stream odours. In addition, an avoidance of high concentrations of conspecific odours was also displayed by bluegill bullies in this experiment, suggesting that the distribution of fish may be mediated by a response to high densities.

Both biotic and abiotic influences on fish distribution were considered in chapter four by looking at non random patterns of size distribution of two riffle dwelling species, the bluegill bully and torrentfish, over a river's elevation and distance continuum. Significant differences in longitudinal size structure were found both between bluegill bullies and torrentfish populations in the same river and between bluegill bully populations from different rivers. Because the size of fish also indicates age, and therefore time, the differences in size structure that were found suggest differences in migration rate both between species and among species. This scrutiny resulted in the development of a number of potential explanations for the differences in patterns found; namely a response to differing levels of competition, which may differentially fuel the upstream migration of populations, and/or differences in physical stability of each river, which may differentially constrain the upstream migration of fish. Consequently, this chapter highlighted the complexity of potential drivers of fish distribution that require further investigation.

The complex interconnected organisation of the influences on the distribution of diadromous fish that were investigated in this thesis are depicted in figure 1. At a small, single catchment scale, at low elevations, the abundance and species richness of fish communities is potentially at its highest. This high density may result in competition which could drive the upstream migration of individuals. Individuals may also use chemical cues to avoid habitats with high densities or find favoured habitats. Physical disturbance of rivers, particularly the frequency of high flows, may constrain the upward movement of fish by periodically displacing them downstream during floods. However, the relative force of these small scale influences is likely to change with distance upstream. This is because abundance and species richness declines with distance upstream so it is unlikely that competition will drive the upstream movement of fish at this point. Chemical attractants, whether they be habitat related and/or conspecific related, may then become important drives of migration. Physical disturbance is still likely to constrain migration at high elevations.

On a broad, regional scale, the fine resolution of influences at small scales is lost and consequently what causes the upstream migration of fish may be perceived as 'instinctive migratory drive'. At low elevations, this influence of 'instinctive migratory drive' may be relatively less apparent than the influence of migration barriers that inhibit or truncate the upstream migration of species and individuals. This is because the extant of a barrier's impact depends on the number of species and individual's migration it inhibits. Consequently, with reductions in abundance and species richness with distance upstream, the relative importance of migration barriers is reduced, and instinctive migratory drive may become a more important influence.

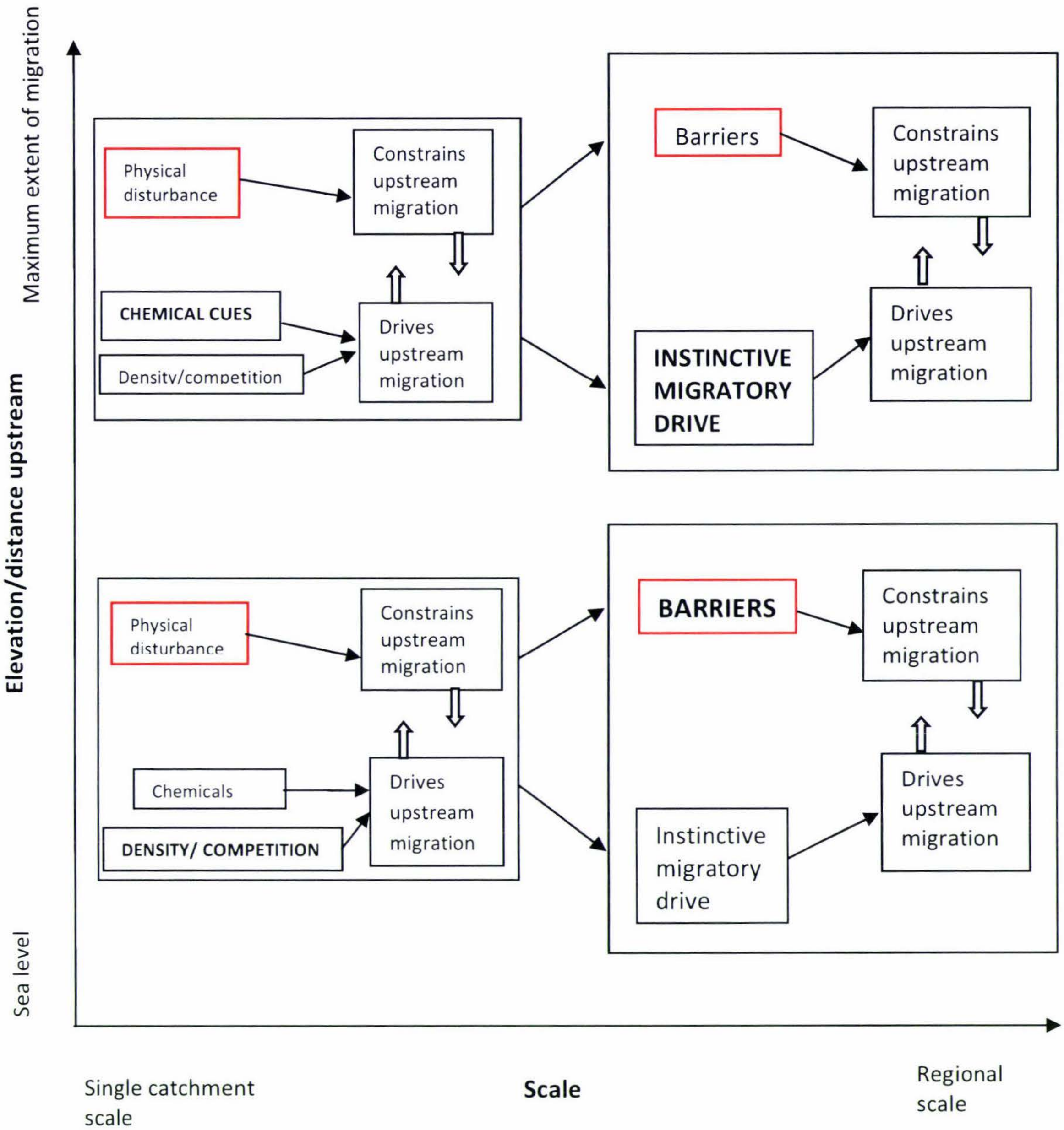

Fig. 1 Dynamic representation of influences on the distribution of diadromous fish investigated in this thesis. Influences coloured red separate abiotic influences from biotic influences (black box) and bold type indicates the relative importance of influences at each scale and distance inland (bold type indicates most important influence).

Appendix – Details of potential migration barriers in the Wellington Region

1.0 Battle Hill

Table 1.0 Location details of seven structures at Battle Hill Farm Forest Park

Location: Tributary of Horokiri Stream, Battle Hill Farm Forest Park, Paekakariki Hill Road			
Easting	2673012	Distance upstream	5.4km
Northing	6014310	Elevation	55masl
Number of structures assessed	7	Known barriers downstream	Yes – weir (2671928 6012465)

Table 1.2 **Battle Hill – Ford, structure # 1**

Structure	Ford
Construction	Gravel
Inlet water depth	Flat – 0.14m
Outlet water depth	Pooled – 0.33m
Height	0.56m
If perched - undercut	0.15m
Width relative to stream	Narrower
Known barriers upstream	Yes
Known barriers downstream	Yes – weir (see above)
Likely severity of structure	Moderate
Flow condition in which barrier will be most severe	Low flows

Fig. 1.0 Ford, Battle Hill structure 1

Table 1.3 **Battle Hill Culvert, structure # 2**

Structure	Culvert - pipe
Construction	Plastic
Diameter	0.30m
Length	5m
If perched - height	0.45m
If perched - undercut	n/a
Inlet water depth	Flat - 0.08m
Outlet water depth	Perched - 0.05m
Alignment	Straight in, straight out
Known barriers upstream	Yes
Known barriers downstream	Yes
Likely severity as a barrier	Moderate
Flow condition in which barrier will be most severe	all flows

Fig. 1.1 Culvert, Battle Hill structure 2

Table 1.4 Battle Hill – Culvert, structure # 3

Structure	Culvert - double pipe
Construction	steel
Diameter	0.40m
Length	10m
If perched - height	n/a
If perched - undercut	n/a
Inlet water depth	Flat - 0.15m
Outlet water depth	Flat - 0.10
Alignment	Straight in, straight out
Known barriers upstream	Yes
Known barriers downstream	Yes
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	High flows

Fig. 1.2 Double pipe culvert, Battle Hill structure

Table 1.5 Battle Hill – Culvert, structure # 4

Structure	Culvert - pipe
Construction	concrete
Diameter	0.60m
Length	5m
If perched - height	n/a
If perched - undercut	n/a
Inlet water depth	Flat - 0.05m
Outlet water depth	Flat - 0.10m
Alignment	Straight in, straight out
Known barriers upstream	no
Known barriers downstream	Yes
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	Low flows

Fig. 1.3 Culvert, Battle Hill structure 4

Table 1.6 Battle Hill – Weir, structure # 5

Structure	Weir
Construction	concrete
Width relative to stream	narrower
Height	0.90m
If perched - undercut	n/a
Inlet water depth	Pooled – 0.70m
Outlet water depth	Flat - 0.08m
Alignment	Straight in, straight out
Known barriers upstream	Yes
Known barriers downstream	Yes
Likely severity as a barrier	Moderate
Flow condition in which barrier will be most severe	low flows

Fig. 1.4 Weir, Battle Hill structure 5

Table 1.7 Battle Hill – Culvert, structure # 6

Structure	Culvert - pipe
Construction	concrete
Diameter	0.35m
Length	5m
If perched - height	0.30m
If perched - undercut	n/a
Inlet water depth	Pooled - 0.43m
Outlet water depth	Perched - 0.08m
Alignment	Straight in, straight out
Known barriers upstream	Yes
Known barriers downstream	Yes
Likely severity as a barrier	Moderate
Flow condition in which barrier will be most severe	all flows

Fig. 1.5 Culvert, Battle Hill structure 6. Note outflow of water from bank on left

Table 1.8 Battle Hill – Earth dam, structure # 7

Structure	Earth dam with fish pass
Width relative to stream	narrower
Length	2.3m
If perched - undercut	n/a
Inlet water depth	Pooled – 0.70m
Outlet water depth	Pooled - 0.60m
Alignment	Straight in, straight out
Known barriers upstream	no
Known barriers downstream	Yes
Likely severity as a barrier	None
Flow condition in which barrier will be most severe	Most flows

Fig. 1.6 Earth dam, Battle Hill structure 7

Table 1.9 Distance of suitable native fish habitat upstream of structure 1. Calculated for native fish species found in Horokiri Stream catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of structure 1**	**Proportion of catchment above structure 1**	**Proportion of Wellington region above structure 1**
Longfin eel	2.25	6.58	0.025
Shortfin eel	1.33	6.51	0.021
Torrentfish	0.00	0.00	0.000
Inanga	0.40	9.22	0.014
Banded kokopu	0.00	0.00	0.000
Common Bully	0.06	1.45	0.006
Redfin bully	0.56	2.04	0.019
Lamprey	0.00	0.00	0.000
Smelt	0.00	0.00	0.000
Total	**4.60km**	**3.78%**	**0.019%**

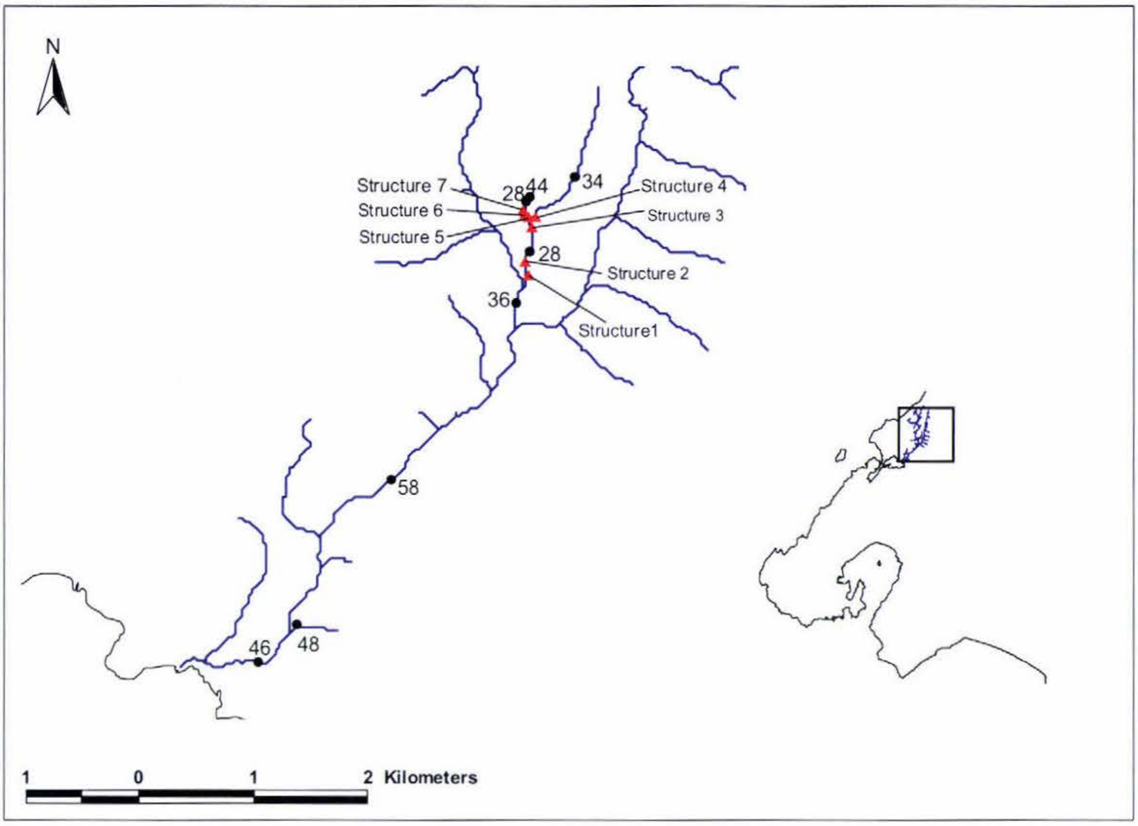

Fig. 1.7 Map of seven potential migration barriers at Battle Hill Farm Forest Park (red triangles) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 1.10 Number of sites where each fish species was found in relation to the location of structures with average IBI and O/E scores ± standard error.

Fish species present	Below (/4)	Between structure 2 & 3 (/1)	Above structure 6, left tributary (/2)	Above structure 4, right tributary (/1)	Total sites (/8)
Longfin eel	4	1	2	-	7
Shortfin eel	3	1	2	1	7
Torrentfish	1	-	-	-	1
Inanga	3	-	-	-	3
Banded kokopu	-	-	1	1	2
Common Bully	3	-	-	--	3
Redfin bully	3	-	-	-	3
Lamprey	1	-	-	-	1
Smelt	1	-	-	-	1
Total spp.	**8**	**2**	**3**	**2**	**8**
Mean IBI	**47** ± 4.5	**28,** n=1	**36** ± 8	**34,** n=1	**40** ± 3.7
Mean O/E	**1.13** ± 0.13	**1.05,** n=1	**1.60 ± 0**	**0.23,** n=1	**1.12** ± 0.16

- The combination of seven structures present a number of barriers in the form of falls (structures 1, 2, 5 and 6), undercuts (structure 1) and velocity barriers (structures 2, 3 and 6) that are likely to impede the passage of most species.
- Three species that were found downstream of the culvert were not found upstream of it, despite being predicted to be found there.
- A rock ramp has been placed below structure 6 in an attempt to remediate the perched height of the culvert. The water flows through the rocks instead of over (see photo). This remediation work has increased the severity of the barrier.
- Structure 7 has had a fish pass installed. However, fish are unlikely to reach this fish pass due to the multiple barriers below.
- More fish surveys needed upstream and downstream of structures to strengthen conclusions
- Banded kokopu population upstream of structure 3 is likely to be a landlocked population. Analysis of strontium in their otoliths could confirm this assertion.

Table 1.11 Summary of results

Final structure score (/4)	2
Final impact score (/4)	1.67
Priority for remediation	**Low**
Priority score (/16)	**3.33**

2.0 Cannons Creek

Table 2.0 Location details and measurements of grading weir at Cannons Creek.

Location: Keneperu Stream, Warspite Ave, Cannons Creek, Porirua East

Easting	2666522	Distance between weirs	2m
Northing	6006385	Inlet water depth	Channelled – 0.12m
Distance upstream	3km	Outlet water depth	Channelled - 0.25m
Elevation	28masl	Alignment	Straight in, straight out
Date assessed	12/06/2008	Known barriers upstream	Yes - culvert
Structure	Series of 9 weirs	Known barriers downstream	Yes - culvert
Construction	Concrete	Likely severity as a barrier	High
Width relative to stream	Narrower	Flow condition in which barrier will be most severe	All flows
Height of each weir	1m		

Fig. 2.1 Series of 9 grading weirs

Fig. 2.2 Downstream of weir

Fig. 2.3 Upstream of weir

Table 2.1 Distance of suitable native fish habitat upstream of weir. Calculated for native fish species found in Keneperu Stream catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of weir**	**Proportion of catchment above weir**	**Proportion of Wellington region above weir**
Longfin eel	5.11	7.67	0.056
Shortfin eel	3.52	8.94	0.056
Koaro	0.20	5.20	0.010
Banded kokopu	2.44	9.87	0.153
Redfin bully	2.83	10.10	0.097
Common Bully	0.07	2.36	0.007
Giant kokopu	1.47	7.62	0.196
Inanga	2.85	16.19	0.102
Total	**18.49km**	**9.13%**	**0.070%**

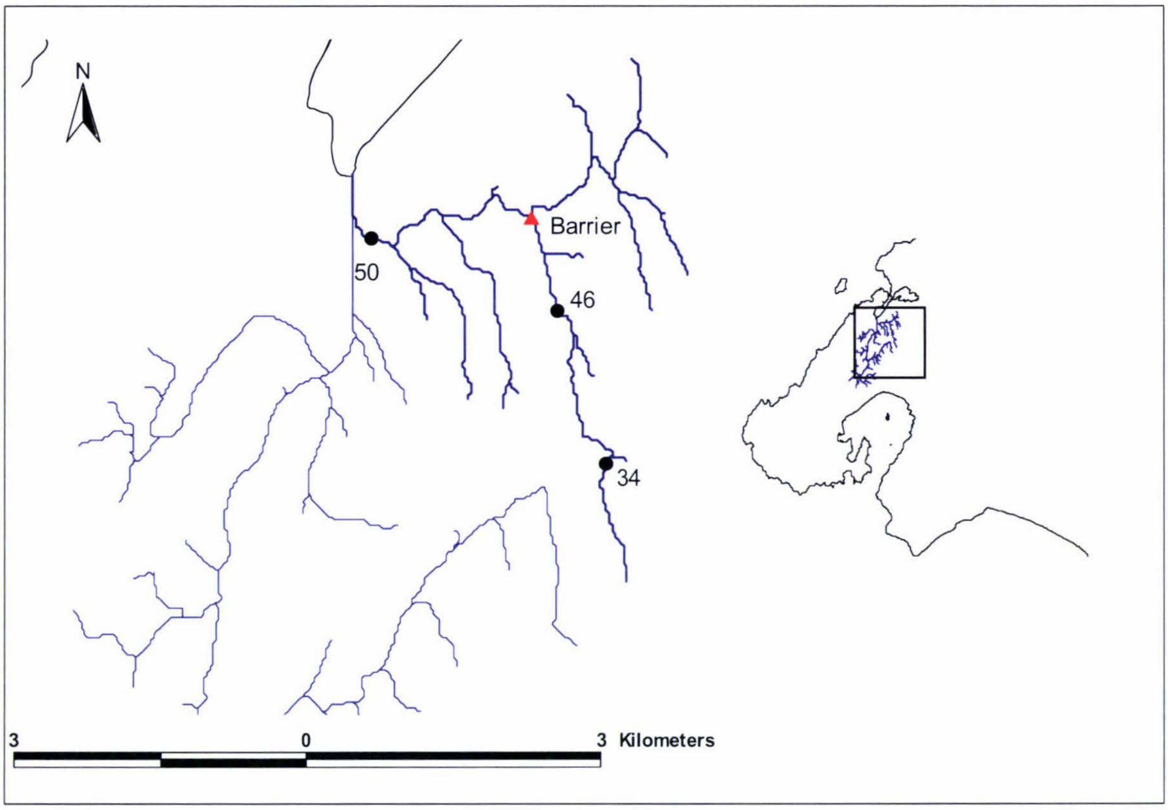

Fig. 2.4 Map of potential migration barrier at Cannons Creek (red triangle) and sites where fish surveys have been conducted (black dot). Each fish survey site is labelled with an IBI score generated from the species present.

Table 2.2 Number of sites where each fish species was found in relation to the location of the weir with average IBI and O/E scores ± standard error.

Fish species present	Below weir (/1)	Above weir (/2)	Total sites (/3)
Shortfin eel	1	1	2
Longfin eel	1	1	2
Giant kokopu	1	1	2
Banded kokopu	-	2	2
Inanga	1	-	1
Common Bully	1	-	1
Redfin bully	1	-	1
Total spp.	**6**	**5**	**6**
Mean IBI	**50,** n=1	**40** ± 6.0	**43** ± 4.3
Mean O/E	**1.50,** n=1	**0.35** ± 0.35	**0.73** ± 0.34

- The extensive channelization and culverts above and below the grading weir coupled with the weir itself present both velocity and climbing barriers for the vast majority of native species.
- Three species that were found downstream of the culvert were not found upstream of it, despite being predicted to be found there.
- The shallow water depth in the channels and series of weirs may hinder the downward migration of eels.
- Likely that the population of banded kokopu and giant kokopu upstream of weirs are landlocked.
- More fish surveys needed upstream and downstream of structures to strengthen conclusions
- There may be considerable difficulty and cost involved in remediating such an extensive structure.

Table 2.3 Summary of results

Final structure score (/4)	2.67
Final impact score (/4)	3.00
Priority for remediation	**High**
Priority score (/16)	**8.00**

3.0 Duck Creek

Table 3.0 Location details and measurements of grading weir at Cannons Creek.

Location: Unnamed tributary of Duck Creek, James Cook Drive, Whitby

Easting	2669767	If perched - height	n/a
Northing	6009040	If perched - undercut	n/a
Number of structures assessed	1	Inlet water depth	Pooled - 0.58m
Distance upstream	500m	Outlet water depth	Flat - 0.15m
Elevation	13masl	Alignment	Curved in, curved out
Date assessed	13/06/2008	Known barriers upstream	Yes - culvert
Structure	Culvert - pipe	Known barriers downstream	no
Construction	concrete	Likely severity as a barrier	minimal
Diameter	1.2m	Flow condition in which barrier will be most severe	most flows
Length	Approx. 30m		

Fig. 3.0 Outlet of culvert on a tributary of Duck Creek

Fig. 3.1 Inlet of culvert on a tributary of Duck Creek

Table 3.1 Distance of suitable native fish habitat upstream of the culvert. Calculated for native fish species found in Duck Creek catchment and as a percentage of the total catchment using predictive model and REC database

Fish Species	Upstream of culvert	Proportion of catchment above the culvert	Proportion of Wellington region above culvert
	Kilometres of suitable fish habitat		
Longfin eel	0.48	3.89	0.005
Shortfin eel	0.17	1.61	0.003
Giant kokopu	1.67	23.83	0.223
Koaro	0.00	0.06	<0.001
Inanga	0.40	6.56	0.014
Banded kokopu	1.55	18.26	0.097
Common Bully	<0.01	<0.00	<0.001
Redfin bully	0.88	14.71	0.030
Total	**5.16km**	**8.90%**	**0.020%**

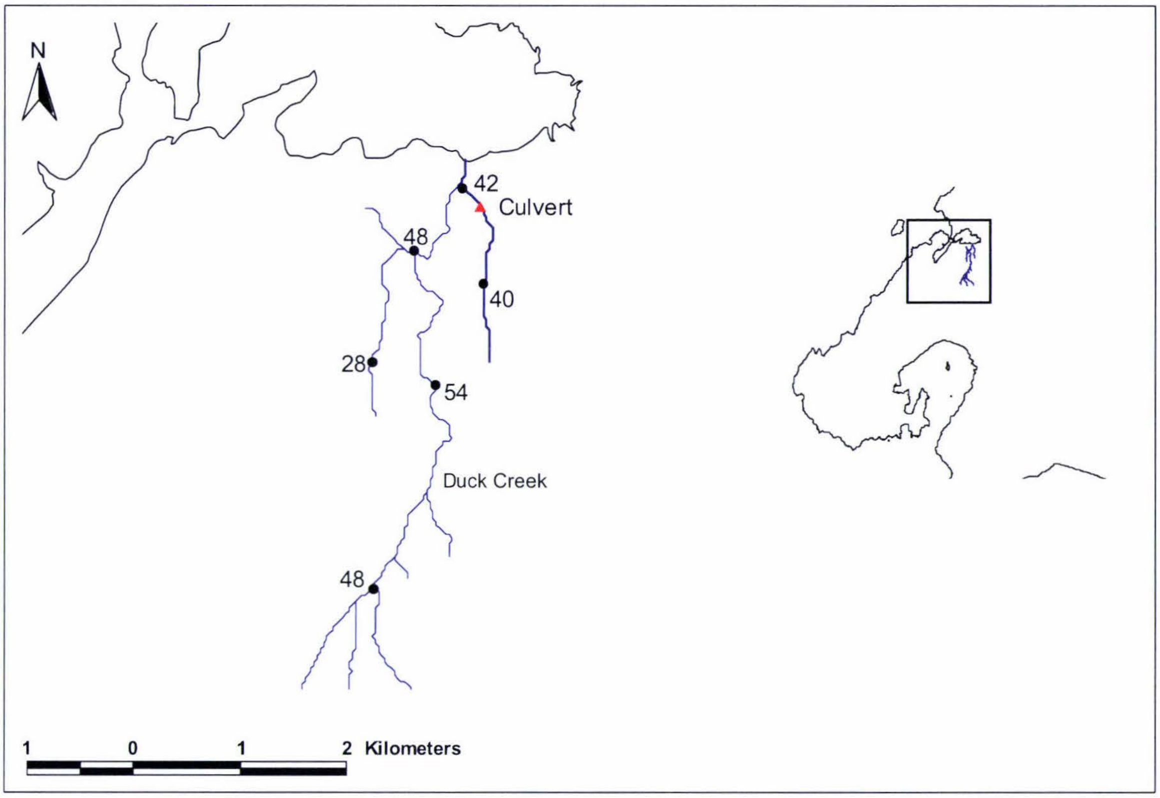

Fig. 3.2 Map of potential migration barrier on a tributary of Duck Creek (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 3.2 Number of sites where each fish species was found in relation to the location of the culvert with average IBI and O/E scores ± standard error.

Fish species present	Below (/1)	Above (/1)	Total sites (/2)	Duck Creek (/4)
Longfin eel	1	1	2	1
Shortfin eel	-	-	-	4
Giant kokopu	-	-	-	2
Koaro	-	-	-	1
Inanga	1	-	1	2
Banded kokopu	-	1	1	2
Common Bully	1	-	1	1
Redfin bully	-	-	-	2
Total spp.	**3**	**2**	**3**	**7**
Mean IBI	**42,** n=1	**40,** n=1	**41** ± 1.0	**44** ± 5.7
Mean O/E	**0.76,** n=1	**0.52,** n=1	**0.64** ± 0.12	**1.15** ± 0.16

- A lack of resting areas in a culvert of this size may be a barrier for species with weak swimming abilities particularly when flow velocity is high.
- The pile of rubbish at inlet grill may impede fish passage (Fig. X)

- Three species that were found downstream of the culvert were not found upstream of it, despite being predicted to be found there.
- More fish surveys needed upstream and downstream of structures to strengthen conclusions.
- Diversity of fish species in the tributary with the culvert is low at both sites above and below the culvert suggesting that the whole tributary may be impacted in some way. It is likely that this impact is a reflection of water quality rather than passage restrictions.

Table 3.4 Summary of results

Final structure score (/4)	2.00
Final impact score (/4)	1.67
Priority for remediation	**Low**
Priority score (/16)	**3.33**

4.0 Hulls Creek

Table 4.0 Location details and measurements of weir in Hulls Creek.

Location: Hulls Creek, tributary of Hutt River, Eastern Hutt Road, Silverstream

Easting	2677351	Inlet	pooled
Northing	6004532	Outlet	Pooled
Number of structures assessed	1	Alignment	Straight in, straight out
Distance upstream	14.9km	Barriers upstream	Yes - culvert
Elevation	32masl	Barriers downstream	Yes - natural fall about 200m downstream of weir
Date assessed	April 2006	Likely severity as a barrier	Moderate
Structure	Weir	Flow condition in which barrier will be most severe	Most flows
Construction	Concrete	Date fish pass installed	Sept. 2007
Width relative to stream	Same	Date of monitoring upstream of fish pass	Nov. 2007
Height of weir	1m		

Fig. 4.0 Weir on Hulls Creek

Fig. 4.1 Fish pass over weir at Hulls Creek

Table 4.1 Distance of suitable native fish habitat upstream of weir. Calculated for native fish species found in Hutt River catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of weir**	**Proportion of catchment above weir**	**Proportion of Wellington region above weir**
Longfin eel	12.12	2.01	0.133
Shortfin eel	5.59	3.70	0.089
Inanga	5.95	7.00	0.213
Common Bully	2.84	6.89	0.282
Giant kokopu	10.25	15.02	1.366
Redfin bully	3.84	0.91	0.132
Giant bully	0.00	0.00	0.000
Bluegill bully	0.04	0.13	0.025
Total	**40.62km**	**2.95%**	**0.174%**

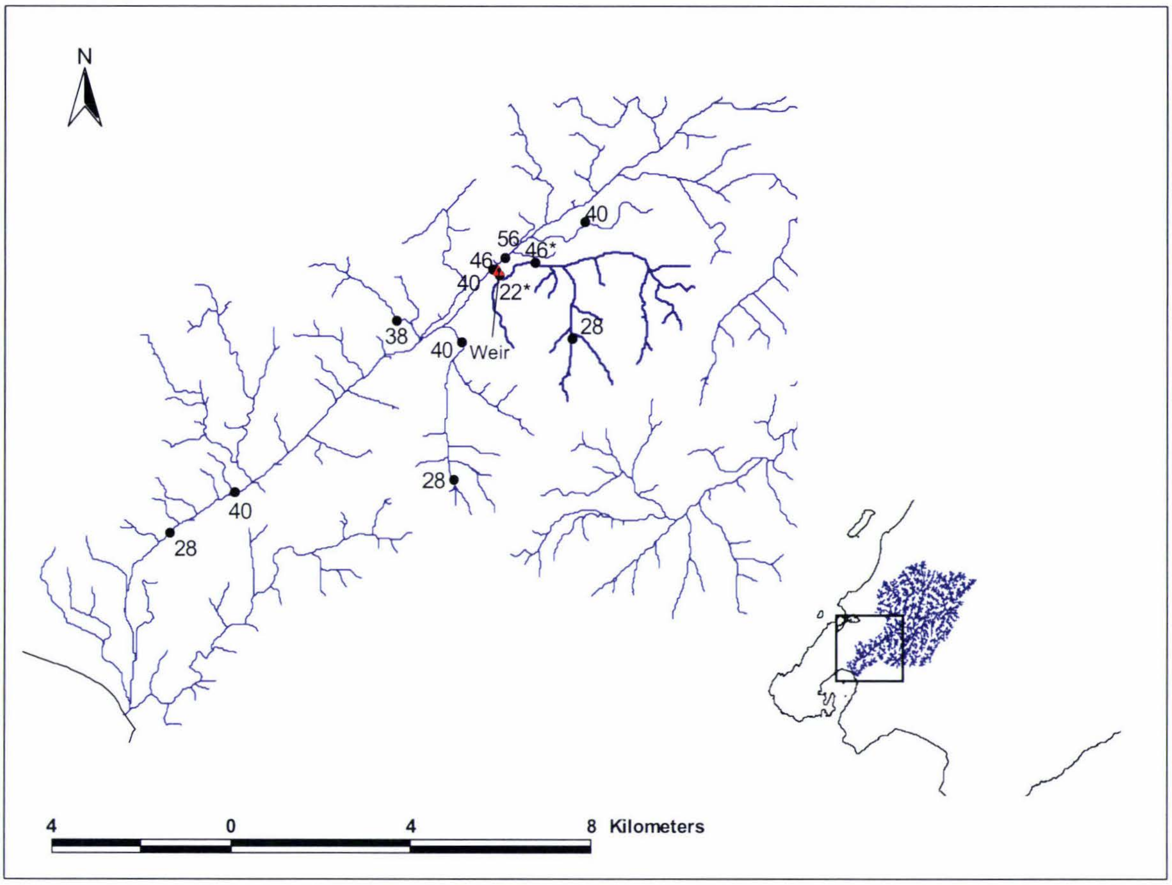

Fig. 4.2 Map of potential migration barrier in Hull Creek (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present. * indicates sites that were surveyed after fish pass was installed. There was no change in species present so the IBI scores remained the same for these sites.

Table 4.2 Number of sites where each fish species was found in relation to the location of the weir with average IBI and O/E scores ± standard error.

Fish species present	Below weir (/4)	Downstream tributaries (/3)	Above weir (/3)	Total (/10)	Above weir after fishpass installed (/2)	Tributaries upstream on Hutt River (/2)
Longfin eel	2	3	1	5	-	2
Shortfin eel	1	2	2	5	2	2
Inanga	2	-	-	2	-	1
Common Bully	2	1	1	4	1	-
Giant kokopu	-	-	-	-	-	1
Redfin bully	2	-	1	3	1	1
Giant bully	1	-	-	1	-	-
Bluegill bully	1	1	-	2	-	1
Total spp.	**7**	**4**	**4**	**7**	**3**	**6**
Mean IBI	**38.5** ± 3.7	**35.3** ± 3.7	**32** ± 7.2	**35.6** ± 2.6	**34** ± 12	**48** ± 8.0
Mean O/E	**0.65** ± 0.21	**0.76** ± 0.17	**0.67** ± 0.16	**0.67** ± 0.07	**0.63** ± 0.28	**0.87** ± 0.15

- Height of weir likely cause a moderate restriction on fish passage.
- Three species that were found downstream of the weir were not found upstream, despite being predicted to occur there.
- No additional species were found upstream of the weir after the installation of a fish pass
- Fish pass may be ineffective due to the presence of a natural barrier immediately below the pass and/or because of the generally low water quality of Hulls Creek
- More fish surveys needed upstream and downstream of fish pass to strengthen conclusions.

- **Table 4.3** Summary of results

Final structure score (/4)	2.67
Final impact score (/4)	1.33
Priority for remediation	**Low**
Priority score (/16)	**3.56**
Effectiveness of fish pass	**Low**

5.0 Kaiwharawhara Stream

Table 5.0 Kaiwharawhara tunnel, structure 1, Hanover

Easting	2658190
Northing	5992561
Distance upstream	2.5km
Elevation	42masl
Structure	Tunnel
Diameter	1.5m
Length	100m
If perched - height	1.4m
Inlet water depth	Flat – 0.2m
Outlet water depth	Pooled – 0.67m
Alignment	Straight in, curved out
Barriers upstream	Yes – culvert
Barriers downstream	Unknown
Likely severity as a barrier	High
Flow condition in which barrier will be most severe	all flows
Date fish pass installed	Dec. 2006
Date of fish pass monitoring	March, April, May, Sept. 2007

Fig. 5.0 Tunnel on Kaiwharawara Stream (structure 1) with zigzag fish pass to the right of tunnel entrance.

Table 5.1 Kaiwharawhara Culvert, structure 2, Churchill Drive, Wilton

Easting	2657700	Outlet water depth	Pooled - 0.40m
Northing	5992200	Alignment	Curved in, straight out
Distance upstream	5.2km	Barriers upstream	Yes
Elevation	102masl	Barriers downstream	Yes
Structure	Culvert - arch	Likely severity as a barrier	Minimal
Construction	concrete	Flow condition in which barrier will be most severe	All flows
Diameter	1.8m		
Length	150m	Date Fish pass installed	Dec. 2006
If perched - height	0.35m	Date fish of pass monitoring	March, April, May, Sept. 2007
Inlet water depth	Flat - 0.10m		

Fig. 5.1 Culvert on Kaiwharawhara Stream (structure 2), photo taken 16 months after fish pass was installed.

Fig. 5.2 Culvert on Kaiwharawhara Stream (structure 2), photo taken 2 months after fish was installed.

Table 5.2 Distance of suitable native fish habitat upstream of structure 1. Calculated for native fish species found in Kaiwharawhara Stream catchment and as a percentage of the total catchment using predictive model and REC database

Kilometres of suitable fish habitat			
Fish Species	**Upstream of structure 1**	**Proportion of catchment upstream of structure 1**	**Proportion of Wellington region upstream of structure 1**
Longfin eel	4.81	39.15	0.053
Shortfin eel	0.32	27.71	0.005
Giant kokopu	1.87	46.84	0.250
Inanga	1.34	55.74	0.048
Common Bully	0.01	14.21	0.001
Redfin bully	2.04	30.17	0.070
Bluegill bully	<0.01	<0.01	<0.001
Banded kokopu	3.07	55.35	0.192
Koaro	0.08	4.59	0.004
Total	**13.54km**	**39.85%**	**0.051%**

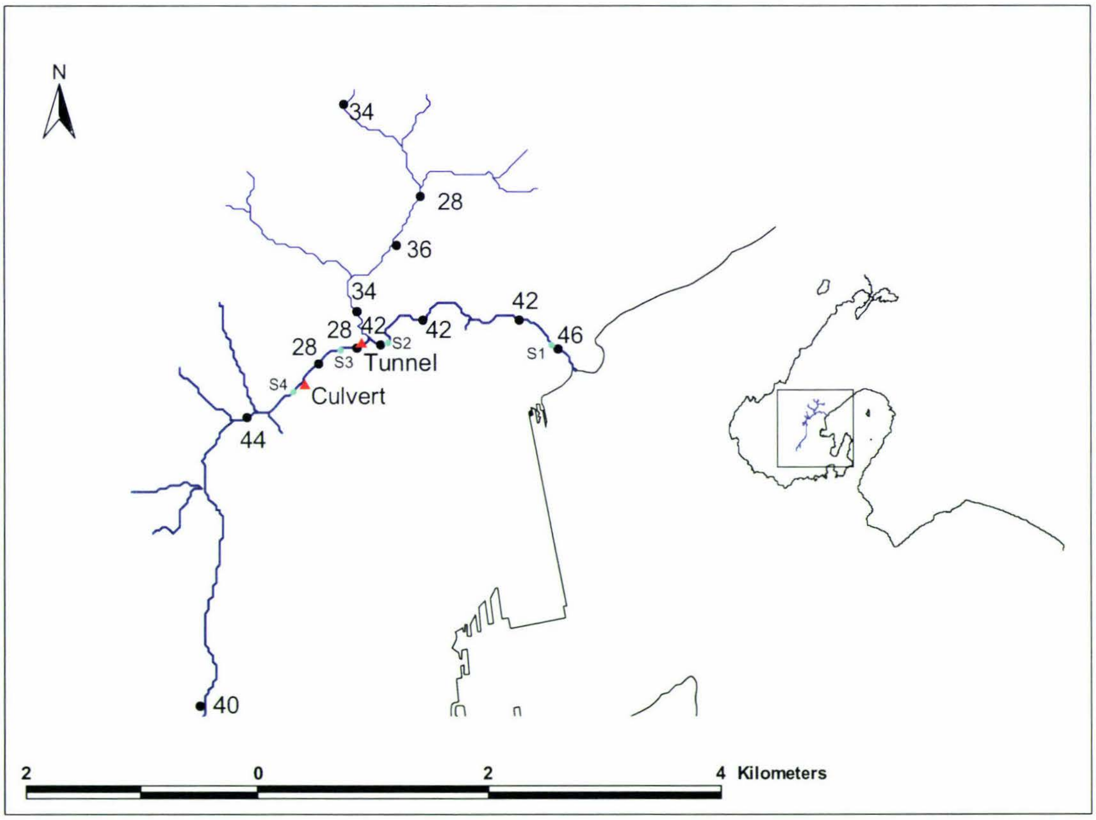

Fig. 5.3 Map of potential migration barrier in Kaiwharawhara Stream (red triangles) and sites where fish surveys have been conducted before the installation of fish passes (black dots). Each of these fish survey site is labelled with an IBI score generated from the species present. Sites surveyed after installation of fish passes are labelled S1-S4 (green dots).

Table 5.3 Number of sites where each fish species was found in relation to the location of the structures with average IBI and O/E scores ± standard error.

Fish species present	Below structure 1 (/4)	Between structures 1 & 2 (/2)	Above structures 1 & 2 (/2)	Total (/8)	Adjacent tributary (/4)
Longfin eel	4	2	1	6	2
Shortfin eel	3	-	1	4	-
Giant kokopu	1	-	-	1	-
Inanga	1	-	-	1	-
Common Bully	1	-	-	1	-
Redfin bully	4	-	-	4	-
Bluegill bully	2	-	-	2	-
Banded kokopu	-	-	1	1	-
Koaro	1	-	1	2	2
Total spp.	**8**	**1**	**4**	**9**	**2**
Mean IBI	**43** ± 1	**28** ± 0	**43** ± 2	**39** ± 2.4	**33** ± 1.7
Mean O/E	**1.40** ±0.19	**1.28** ± 0	**1.39** ± 0.6	**1.37** ± 0.14	**0.66** ± 0.10

Table 5.4 Number of sampling occasions that fish species were found above and below fish passes on Kaiwharawhara Stream.

Fish species present	Below fish pass 1 at site S1 (/2)	Below fish pass 1 at site S2 (/2)	Between passes 1 & 2 at site S3 (/4)	Above fish pass 2 at site S4 (/4)
Longfin eel	2	2	4	4
Shortfin eel	-	-	-	-
Giant kokopu	1	-	-	-
Inanga	2	-	-	-
Common Bully	-	-	-	-
Redfin bully	2	2	-	-
Banded kokopu	1	1	-	2
Koaro	-	1	2	-
Total spp.	**5**	**4**	**2**	**2**
Mean IBI	**49** ± 3.0	**44** ± 2.0	**32** ± 2.3	**34** ± 3.5
Mean O/E	**1.45** ± 0.25	**1.02** ± 0.11	**1.44** ± 0.11	**0.64** ± 0.37

- Structure 1 likely to be a major barrier to the migration of most species. Structure 2 a less severe barrier but dependant on passage passed structure 1.
- Long shallow culvert of structure 2 may inhibit downward migration of eels.
- Five species found downstream of the structures were not found upstream of them despite being predicted to be there.
- Upstream population of banded kokopu likely to be landlocked.
- The IBI and O/E indices may be limited in their ability to accurately reflect any potential impacts of restricted migration due to complications in their methodologies.
- Fish passes installed on both structures but no additional species were found upstream after their installation.

- Entrance to fish pass 1 is off set of main flow requiring fish to move away from main flow. This behaviour may be counterintuitive and contribute to the ineffectiveness of the pass
- Much of fish pass 2 has been washed downstream not withstanding flood events.
- More fish surveys needed upstream and downstream of fish pass to strengthen conclusions
- **Table 5.5** Summary of results

Final structure score (/4)	2.33
Final impact score (/4)	1.67
Priority for remediation	**Low**
Priority score (/16)	**3.98**
Effectiveness of fish pass	**Low**

6.0 Korokoro Stream

Table 6.0 Korokoro Stream weir, structure 1, Cornish St.

Easting	2665971
Northing	5996811
Distance upstream	0.6km
Elevation	14masl
Structure	Weir
If perched - height	0.77m
If perched - undercut	n/a
Width relative to stream	same
Inlet water depth	Flat - 0.20m
Outlet water depth	Pooled - 0.50m
Alignment	Curved in, straight out
Barriers upstream	yes
Barriers downstream	no
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	Low flows

Fig. 6.0 Korokoro Stream weir, structure 1

Table 6.1 Korokoro Stream dam, structure 2, Cornish St.

Easting	2666018
Northing	5997714
Distance upstream	1.7km
Elevation	16masl
Structure	Dam
Length of dam face	9m (sloping)
If perched - height	1.0m
If perched - undercut	n/a
Width relative to stream	narrower
Inlet water depth	Pooled – 0.81m
Outlet water depth	Pooled – 0.40m
Alignment	Straight in, straight out
Barriers upstream	Yes
Barriers downstream	Yes
Likely severity as a barrier	Moderate
Flow condition in which barrier will be most severe	All flows

Fig. 6.1 Korokoro Stream dam, structure 2

Table 6.2 Korokoro Stream dam, structure 2, Cornish St.

Easting	2667138
Northing	5999303
Distance upstream	4.5km
Elevation	70masl
Structure	Dam
Total height	8m
Width relative to stream	narrower
Inlet water depth	pooled
Outlet water depth	pooled
Alignment	Straight in, curved out
Barriers upstream	No
Barriers downstream	Yes
Likely severity as a barrier	High
Flow condition in which barrier will be most severe	All Flows

Fig. 6.2 Korokoro Stream dam, structure 3

Table 6.3 Distance of suitable native fish habitat upstream of structure 1. Calculated for each native species found in the Korokoro Stream catchment and as a percentage of the total catchment and Wellington region using predictive model and REC database.

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of structure 1**	**Proportion of catchment**	**Proportion of Wellington region**
Shortfin eel	3.37	82.03	0.054
Longfin eel	16.58	92.50	0.182
Koaro	2.76	93.91	0.138
Inanga	0.76	87.16	0.027
Common bully	0.24	55.73	0.024
Giant bully	0.00	0.00	0.000
Bluegill bully	<0.01	87.55	0.001
Redfin bully	15.09	93.12	0.518
Giant kokopu	6.36	88.49	0.847
Total	**45.17km**	**90.93%**	**0.178%**

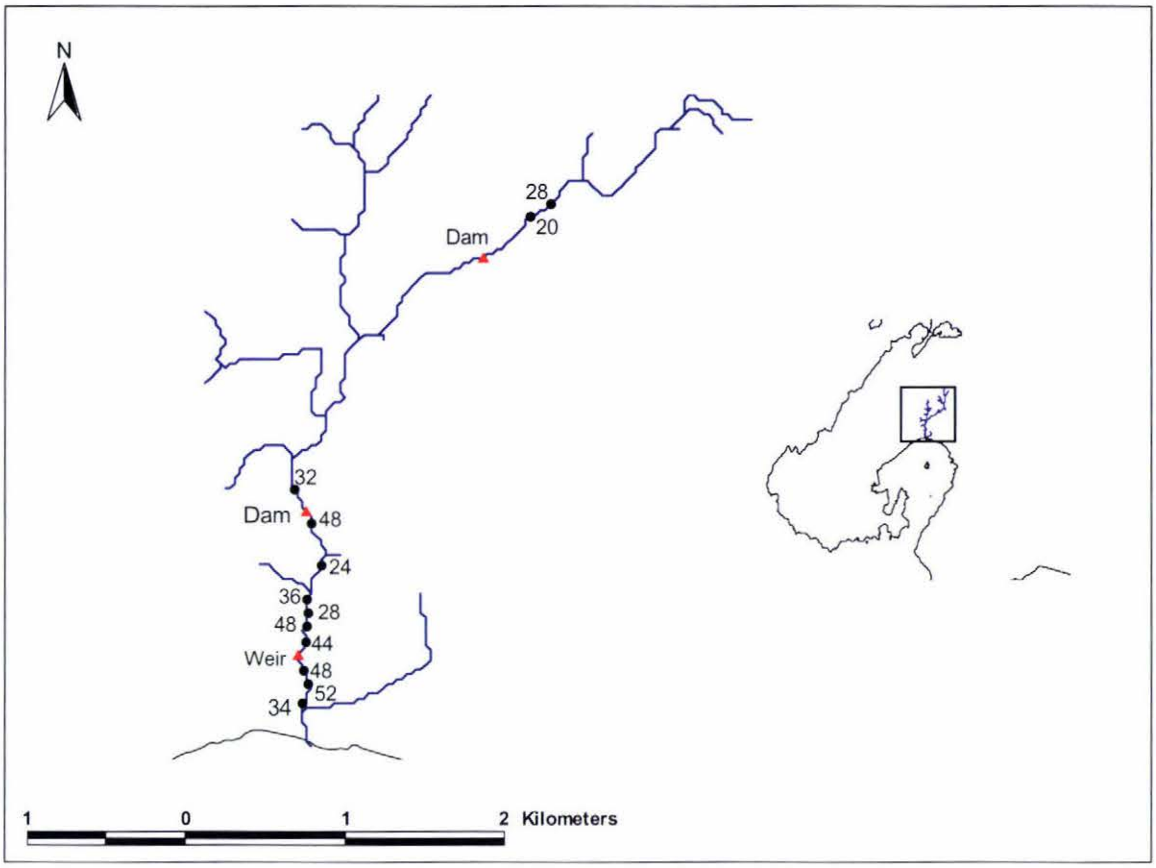

Fig. 6.3 Map of potential migration barriers on Korokoro Stream (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 6.4 Number of sites where each fish species was found in relation to the location of each structure with average IBI and O/E scores ± standard error.

Fish species present	Below structure 1 (/3)	Between Structure 1 & 2 (/6)	Between structure 2 & 3 (/1)	Above structure 3 (/2)	Total (/12)
Shortfin eel	2	4	-	2	8
Longfin eel	3	5	1	2	11
Koaro	2	2	1	1	6
Inanga	2	2	-	-	4
Common bully	2	3	-	-	5
Giant bully	1	-	-	-	1
Bluegill bully	3	4	-	-	7
Redfin bully	3	6	1	-	10
Giant kokopu	-	1	-	-	1
Total spp.	**8**	**8**	**3**	**3**	**9**
Mean IBI	**45** ± 5.5	**38** ± 4.2	**32**, n=1	**24** ± 4.0	**37** ± 3.1
Mean O/E	**1.19** ± 0.19	**1.05** ± 0.15	**0.98**, n=1	**0.73** ± 0.01	**1.03** ± 0.09

- Structure 1 may be a climbing barrier to those species that have weak swimming and climbing abilities. Structure 2 is likely to restrict the migration of most species. The passage of most species past structure 3 is extremely unlikely.

- Due to the structures close proximity to the coast, 91% of the native fish habitat in Korokoro Stream catchment is upstream of structure 1.
- Quality of habitat upstream of structures likely to be high due to proportion of native scrub and forest in catchment.
- Five species were found downstream of the structures but were not found upstream of them, despite being predicted to be there.
- No passage restrictions appeared to be caused by structure 1. Structure 2 appeared to restrict inanga, common bullies, bluegill bullies and giant kokopu. Structure 3 appeared to restrict redfin bullies.
- More fish surveys upstream and downstream of structures are needed to strengthen conclusions.

Table 6.5 Summary of results

Final structure score (/4)	3.00
Final impact score (/4)	3.67
Priority for remediation	**High**
Priority score (/16)	**11.00**

7.0 Orongorongo Dam

Table 7.0 Orongorongo dam, Orongorongo Water Supply Catchment Area. Note that a site visit was not conducted for this structure and most of the details below have been obtained from Taylor & Kelly (2003).

Easting	2680500	Height of dam	3.5m (sloping)
Northing	5988000	Inlet water depth	Unknown
Distance upstream	24.3km	Outlet water depth	Unknown
Elevation	250	Alignment	Unknown
Date assessed	-	Barriers upstream	Unknown
Structure	Dam	Barriers downstream	Unknown
Construction	Concrete	Likely severity as a barrier	High
Width relative to stream	Unknown	Flow condition in which barrier will be most severe	All flows

Fig. 7.0 Orongorongo River dam

Table 7.1 Distance of suitable native fish habitat upstream of dam. Calculated for each native species found in Orongorongo River catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of dam**	**Proportion of catchment upstream of dam**	**Proportion of Wellington region upstream of dam**
Longfin eel	28.38	34.14	0.311
Redfin Bully	7.99	16.73	0.274
Bluegill Bully	0.88	11.82	0.493
Koaro	15.50	17.75	0.774
Total	**52.74km**	**23.38%**	**0.371%**

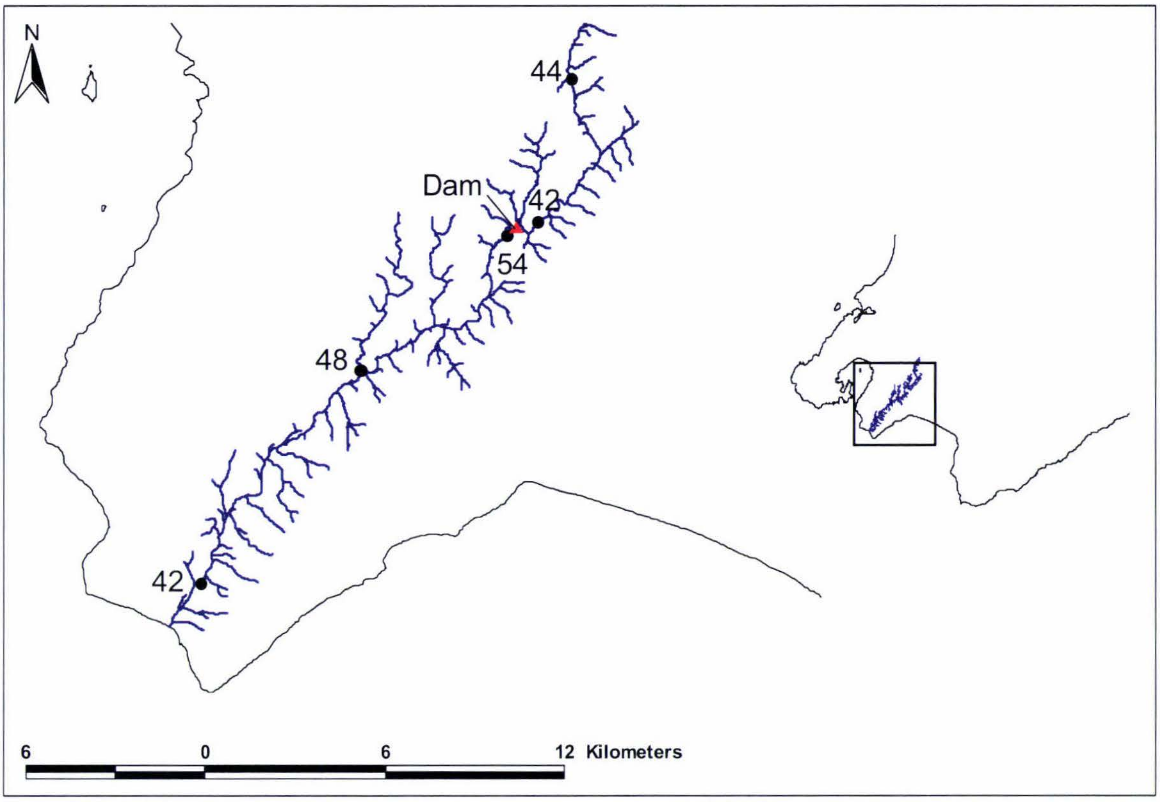

Fig. 7.1 Map of potential migration barrier on Orongorongo River (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 7.2 Number of sites where each fish species was found in relation to the location of the weir with average IBI and O/E scores ± standard error.

Fish species present	Below dam (/3)	Above dam (/2)	Total (/5)
Longfin eel	3	2	5
Redfin Bully	3	-	3
Bluegill Bully	1	-	1
Koaro	3	2	5
Total spp.	**4**	**2**	**4**
Mean IBI	**48** ± 3.5	**43** ± 1.0	**46** ± 2.3
Mean O/E	**1.16** ± 0.03	**1.40** ± 0.22	**1.10** ± 0.09

- Few native species are likely to be able to surpass the dam. However, the inland location of the dam may lessen the severity of impact.
- Two species that are found downstream of the dam were not found upstream of it despite being predicted to be there.
- O/E ratio may be limited in is ability to detect an impact due to the low number of species included in its analysis.

- More fish surveys upstream and downstream of dam are needed to strengthen conclusions.

Table 7.3 Summary of results

Final structure score (/4)	2.67
Final impact score (/4)	1.33
Priority for remediation	**Low**
Priority score (/16)	**3.56**

8.0 Otaki Forks

Table 8.0 Otaki Ford, Otaki Forks Road, Otaki

Easting	2696507	Height of drop	0.5m
Northing	6039194	Inlet	Flat
Distance upstream	16.5km	Outlet	Perched
Elevation	162masl	Alignment	Straight in, straight out
Date assessed	March 2006	Barriers upstream	Unknown
Structure	Ford	Barriers downstream	Unknown
Construction	Concrete	Likely severity as a barrier	Minimal
Width relative to stream	Wider	Flow condition in which barrier will be most severe	Most flows

Fig. 8.0 Ford on unnamed tributary of Otaki River.

Table 8.1 Distance of suitable native fish habitat upstream of ford. Calculated for each native species found in the otaki river catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of ford**	**Proportion of catchment upstream of the ford**	**Proportion of Wellington Region upstream of the ford**
Shortfin eel	0.03	0.08	<0.001
Longfin eel	1.41	0.38	0.015
Torrentfish	0.00	0.00	0.000
Giant kokopu	0.22	6.68	0.030
Shortjaw kokopu	0.00	0.00	0.000
Banded kokopu	0.56	3.12	0.035
Redfin Bully	1.66	0.66	0.057
Common bully	0.03	0.18	0.003
Koaro	0.09	0.02	0.004
Total	**3.99km**	**0.33%**	**0.016%**

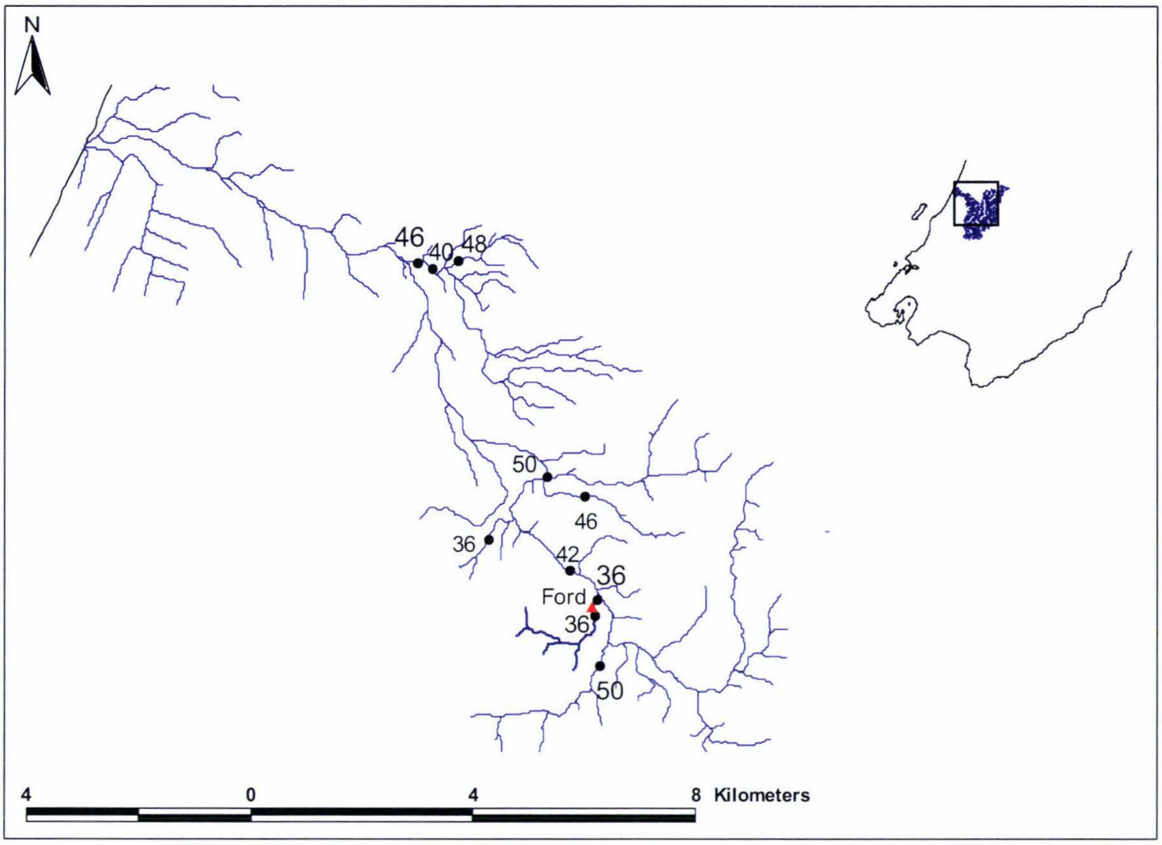

Fig. 8.1 Map of potential migration barrier on a tributary of Otaki River (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 8.2 Number of sites where each fish species was found in relation to the location of the weir with average IBI and O/E scores ± standard error.

Fish species present	Below ford (/3)	Downstream tributaries on Otaki River (/5)	Above ford (/1)	Total (/9)	Upstream tributary of Otaki River (/1)
Shortfin eel	2	3	-	5	-
Longfin eel	3	5	1	9	1
Torrentfish	2	1	-	3	-
Giant kokopu	-	1	-	1	-
Shortjaw kokopu	-	-	-	-	1
Banded kokopu	-	1	-	1	-
Redfin Bully	2	3	-	5	1
Common bully	1	1	-	2	-
Koaro	2	-	1	3	1
Total spp.	**6**	**7**	**2**	**8**	**4**
Mean IBI	**43** ± 4.1	**43** ±2.2	**36,** n=1	**42** ± 1.8	**50** n=1
Mean O/E	**1.73** ± 0.33	**0.99** ± 0.12	**0.98,** n=1	**1.11** ± 0.12	**1.27** n=1

- The potential for this ford to be a migration barrier is low largely due to its significant inland location.

- Five species that were found downstream of the ford were not found upstream of it despite being predicted to be there.
- O/E ratio may be limited in is ability to detect an impact due to the low number of species included in its analysis.
- More fish surveys upstream and downstream of dam are needed to strengthen conclusions

Table 8.3 Summary of results

Final structure score (/4)	1.33
Final impact score (/4)	3.00
Priority for remediation	**Moderate**
Priority score (/16)	**4**

9.0 Owhiro Stream

Table 9.0 **Owhiro Stream ford, structure 1, Owhiro bay parade**

Easting	2657203
Northing	5983324
Distance upstream	0.35km
Elevation	11.3masl
Structure	Ford
If perched - height	0.2m
Inlet water depth	Flat - 0.12m
Outlet water depth	Perched – 0.15
Alignment	Straight in, straight out
Barriers upstream	Yes
Barriers downstream	No
Likely severity as a barrier	None
Flow condition in which barrier will be most severe	most flows

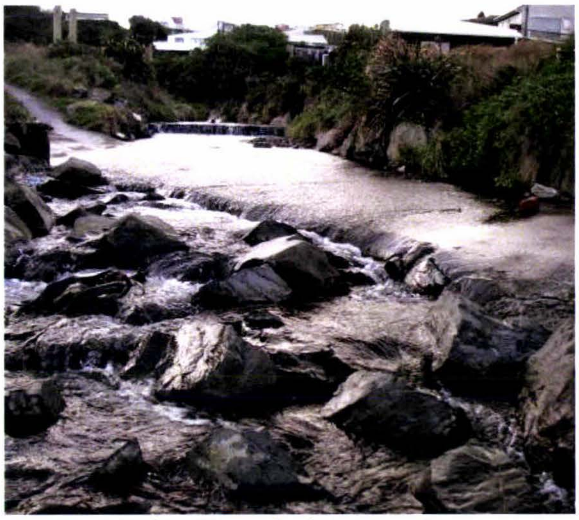

Fig. 9.0 Owhiro Stream ford, structure 1

Table 9.1 **Owhiro Stream weir, structure 2, Owhiro bay parade**

Easting	2657203
Northing	5983324
Distance upstream	0.40km
Elevation	11.7masl
Structure	weir
Height	0.5m
Inlet water depth	Flat - 0.15m
Outlet water depth	Pooled – 0.70
Alignment	Straight in, straight out
Barriers upstream	Yes
Barriers downstream	yes
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	most flows

Fig. 9.1 Owhiro Stream weir, structure 2

Table 9.2 **Owhiro Stream culvert, structure 3, Owhiro bay parade**

Easting	2657203
Northing	5983324
Distance upstream	0.40km
Elevation	11.7masl
Structure	weir
If perched height	0.80m
If perched undercut	0.25m
Diameter	1.2m
length	5m
Inlet water depth	Flat - 0.15m
Outlet water depth	Pooled – 0.60
Alignment	Straight in, straight out
Barriers upstream	Yes
Barriers downstream	yes
Likely severity as a barrier	Moderate
Flow condition in which barrier will be most severe	most flows

Fig. 9.2 Owhiro Stream culvert, structure 3

Table 9.3 Distance of suitable native fish habitat upstream of ford. Calculated for each native species found in the Owhiro Stream catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of structure 1**	**Proportion of catchment upstream of structure 1**	**Proportion of Wellington region upstream of structure 1**
Shortfin eel	0.94	50.81	0.015
Longfin eel	8.96	86.11	0.098
Inanga	2.84	82.17	0.102
Giant kokopu	1.73	89.55	0.231
Banded kokopu	4.46	93.84	0.279
Redfin Bully	3.39	92.24	0.117
Common bully	0.04	75.52	0.004
Koaro	2.86	71.78	0.143
Total	**25.23km**	**83.76%**	**0.096%**

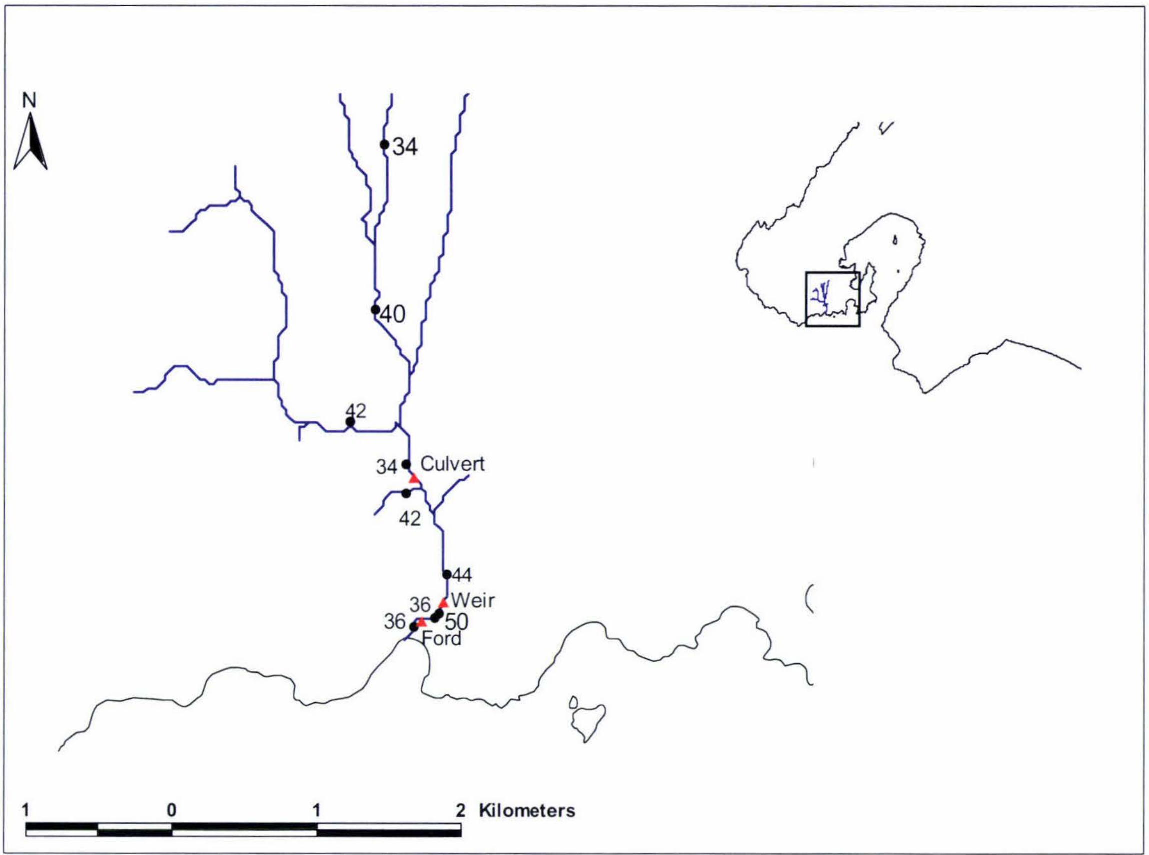

Fig. 9.3 Map of potential migration barrier on Owhiro Stream (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 9.4 Number of sites where each fish species was found in relation to the location of each structure with average IBI and O/E scores ± standard error.

Fish species present	Below (/1)	Between structure 1 & 2 (/2)	Between structure 2 & 3 (/2)	Above (/4)	Total (/10)
Shortfin eel	1	2	1	2	6
Longfin eel	-	1	1	1	4
Inanga	1	2	-	-	4
Giant kokopu	-	-	-	-	1
Banded kokopu	-	1	1	2	5
Redfin Bully	-	1	1	1	2
Common bully	1	1	-	-	4
Koaro	-	-	2	1	4
Total spp.	**3**	**6**	**5**	**5**	**9**
Mean IBI	**36,** n=1	**43** ± 7.0	**43** ± 1.0	**37.5** ± 1.8	**41.2** ± 1.2
Mean O/E	**0.72,** n=1	**0.91** ± 0.19	**0.89** ± 0.43	**0.75** ± 0.23	**0.93** ± 0.17

- Structure 1 on Owhiro Stream is unlikely to inhibit the migration of any native fish species. Structure 2 may inhibit the migration of species with weak climbing abilities. Structure 3 is a perched culvert that may stop the migration of most species.

- There are also numerous other culverts both upstream and downstream of structure 3 where Happy Valley Road and private drive ways cross Owhiro Stream.
- Due to the close proximity of these structures to the coast 84% of the fish habitat in Owhiro Stream catchment is upstream of structure 1.
- Three species that were found downstream of the structures were not found upstream of them despite being predicted to be there.
- Structure 2 may be inhibiting the migration of inanga and common bullies.
- More fish surveys upstream and downstream of each structure is needed to strengthen conclusions.

Table 9.5 Summary of results

Final structure score (/4)	2.33
Final impact score (/4)	1.33
Priority for remediation	**Low**
Priority score (/16)	**3.11**

10.0 Porirua stream

Table 10.0	Porirua Stream weir, structure 1, Keneperu Drive, Porirua
Easting	2664694
Northing	6005673
Distance upstream	1.4km
Elevation	14masl
Structure	Weir
Height	0.68m
Inlet water depth	Flat – 0.26m
Outlet water depth	Pooled – 0.42m
Alignment	Straight in, straight out
Barriers upstream	Yes
Barriers downstream	No
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	Low flows

Fig. 10.0 Porirua Stream weir, structure 1

Table 10.1	Porirua Stream weir, structure 2, Keneperu Drive, Porirua
Easting	2664734
Northing	6005263
Distance upstream	2.2km
Elevation	20masl
Structure	Weir
Height	0.75m
Inlet water depth	Flat – 0.23m
Outlet water depth	Pooled – 0.57m
Alignment	Straight in, straight out
Barriers upstream	Unknown
Barriers downstream	Yes
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	Low flows

Fig. 10.1 Porirua Stream weir, structure 2

Table 10.2 Distance of suitable native fish habitat upstream of structure 1. Calculated for each native species found in Porirua Stream catchment and as a percentage of the total catchment and wellington region using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of structure 1**	**Proportion of catchment upstream of structure 1**	**Proportion of Wellington region upstream of structure 1**
Shortfin eel	28.49	72.25	0.455
Longfin eel	48.39	72.64	0.530
Giant kokopu	13.88	72.14	1.850
Koaro	3.57	94.37	0.178
Inanga	9.76	55.46	0.350
Common Bully	2.08	66.35	0.207
Smelt	0.00	0.00	0.000
Total	**106.18km**	**70.87%**	**0.482%**

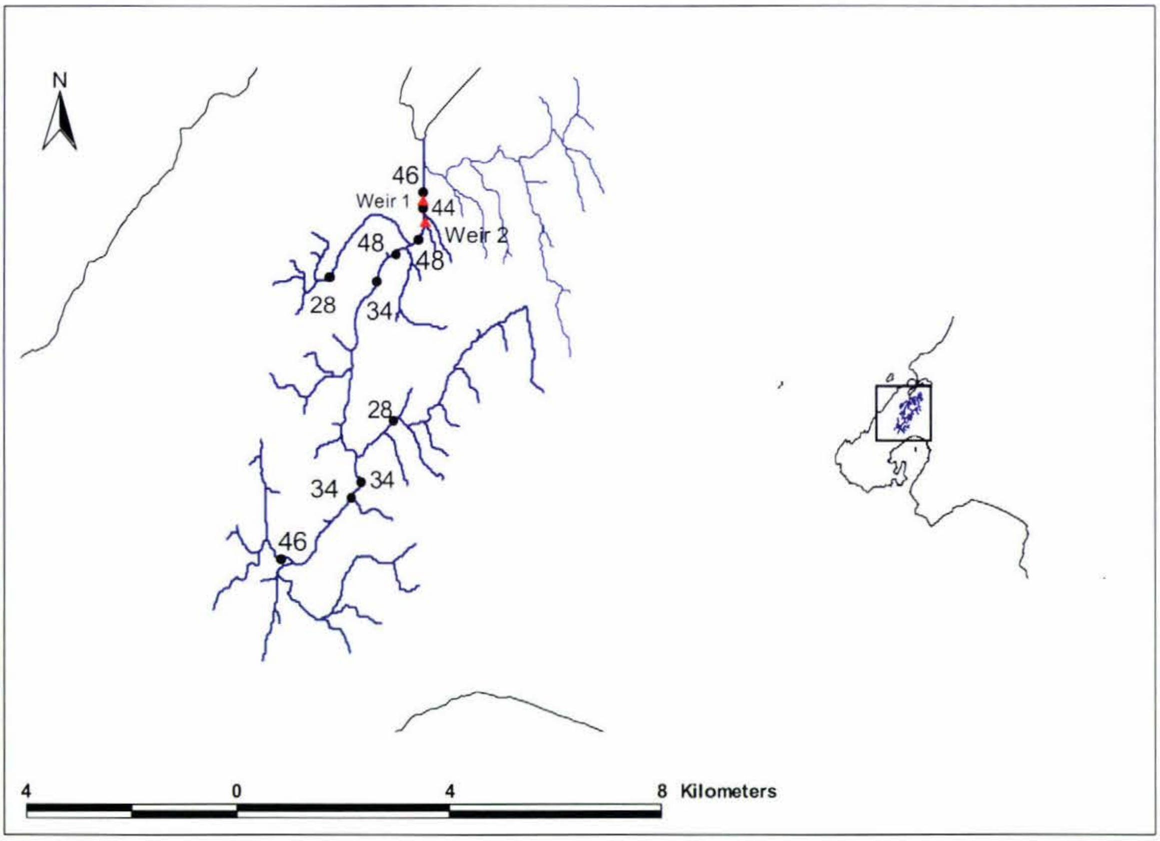

Fig. 10.2 Map of potential migration barrier on Orongorongo River (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 10.3 Number of sites where each fish species was found in relation to the location of each structures with average IBI and O/E scores ± standard error.

Fish species present	Below structure 1 (/1)	Between structures 1 & 2 (/1)	Above structure 2 (/8)	Total (/10)
Shortfin eel	1	1	5	7
Longfin eel	1	1	5	7
Giant kokopu	-	-	2	2
Koaro	-	-	1	1
Inanga	1	1	3	5
Common Bully	1	1	5	7
Smelt	1	-	1	2
Total spp.	**5**	**4**	**7**	**7**
Mean IBI	**46, n=1**	**44, n=1**	**37.5 ± 3.01**	**39 ± 2.59**
Mean O/E	**0.87, n=1**	**0.87, n=1**	**0.77 ± 0.18**	**0.79 ± 0.15**

- Both structures 1 and 2 may present small climbing barriers to species that have weak climbing abilities.
- A significant proportion (0.5%) of native fish habitat in the wellington region is upstream of structure 1.
- All species found below the structures on Porirua Stream are also found upstream of them. However, both the IBI and O/E ratio decreases upstream of both structures, suggesting they have an impact.
- More fish surveys upstream and downstream of each structure is needed to strengthen conclusions

Table 10.4 Summary of results

Final structure score (/4)	3.00
Final impact score (/4)	1.33
Priority for remediation	**Moderate**
Priority score (/16)	**4.00**

11.0 Wainui Stream

Table 11.0 Wainui Stream weir, structure 1, State Highway 1

Easting	2675575	Outlet water depth	Flat – 0.10m
Northing	6023107	Alignment	Straight in, straight out
Distance upstream	1.4km	Barriers upstream	Yes
Elevation	14masl	Barriers downstream	Unknown
Structure	Weir	Likely severity as a barrier	Moderate (previously high)
Height	0.6m	Flow condition in which barrier will be most severe	All flows
Inlet water depth	Flat – 0.07m		

Fig. 11.0 Wainui Stream weir, structure 1. Photo taken 13/06/2008

Fig. 11.1 Wainui Stream weir, structure 1. Photo taken 25/1/200

Fig. 11.2 Wainui Stream culvert, structure 2. Photo taken 13/06/2008

Fig. 11.3 Wainui Stream culvert, structure 2. Photo taken 25/01/2006

Table 11.1 **Wainui Stream culvert, structure 2, State Highway 1**

Easting	2675633	If perched - undercut	n/a
Northing	6023027	Inlet water depth	Flat -
Distance upstream	1.7km	Outlet water depth	Flat -
Elevation	16masl	Alignment	Straight in, straight out
Structure	Culvert - box	Barriers upstream	Yes
Diameter	1.5m	Barriers downstream	Yes
Length	13m	Likely severity as a barrier	None/minimal
If perched – height	n/a	Flow condition in which barrier will be most severe	High Flows

Table 11.2 **Wainui Stream weir, structure 3, State Highway 1**

Easting	2675633
Northing	6023027
Distance upstream	1.7km
Elevation	16masl
Structure	Weir
Height	0.40m
Inlet water depth	Flat – 0.04m
Outlet water depth	Flat 0.05m
Alignment	Curved in, straight out
Barriers upstream	Unknown
Barriers downstream	Yes
Likely severity as a barrier	Minimal
Flow condition in which barrier will be most severe	Low

Fig. 11.4 Wainui Stream weir, structure 3

Table 11.3 Distance of suitable native fish habitat upstream of structure 1. Calculated for each native fish species found in Wainui Stream catchment and as a percentage of the total catchment using predictive model and REC database

Fish Species	Kilometres of suitable fish habitat: Upstream of structure 1	Proportion of catchment upstream of structure 1	Proportion of Wellington region upstream of structure 1
Shortfin eel	0.24	6.05	0.004
Longfin eel	2.52	27.23	0.028
Giant kokopu	0.66	15.59	0.089
Redfin Bully	3.27	35.93	0.112
Common bully	0.09	5.65	0.009
Total	**6.79km**	**23.99%**	**0.034%**

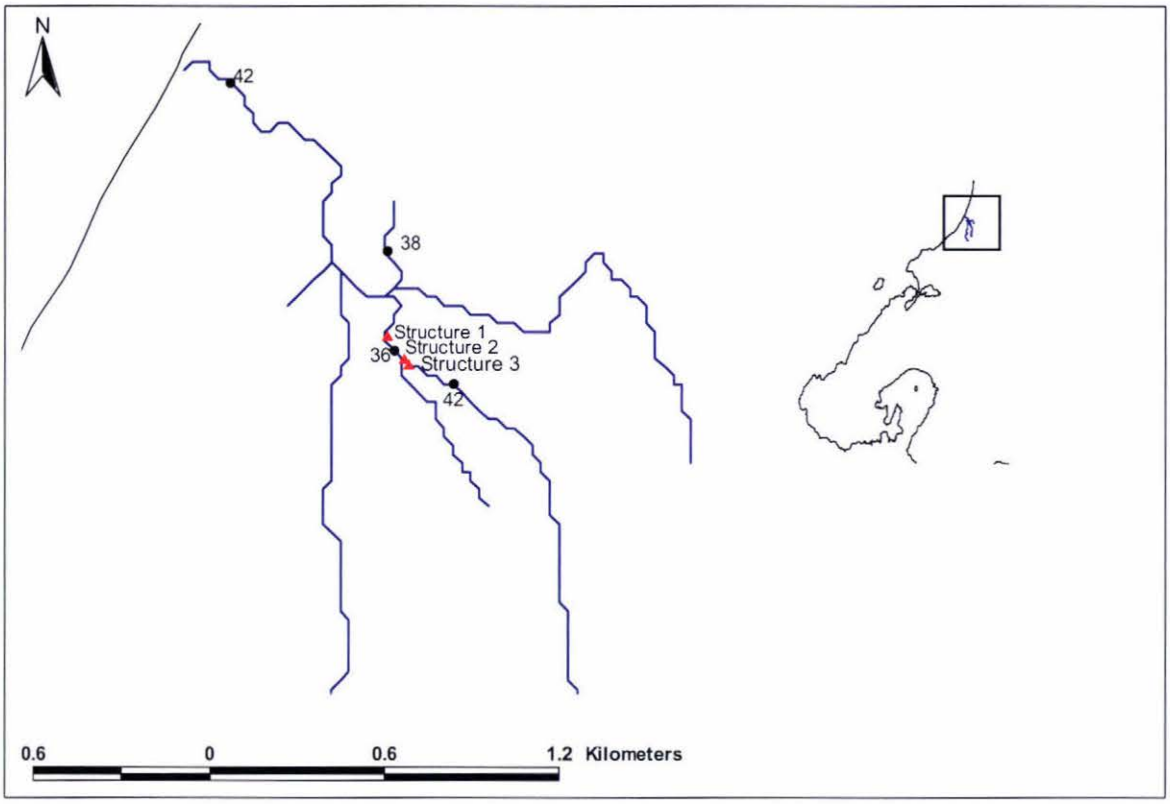

Fig. 11.5 Map of potential migration barrier on Wainui Stream (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 11.4 Number of sites where each fish species was found in relation to the location of the weir with average IBI and O/E scores ± standard error.

Fish species present	Below structure 1 (/2)	Between structure 1 & 2 (/1)	Above structure 3 (/1)	Total (/4)
Shortfin eel	1	-	-	1
Longfin eel	2	1	1	4
Giant kokopu	1	-	-	1
Redfin Bully	2	1	1	4
Common bully	1	-	-	1
Total spp.	**5**	**2**	**2**	**5**
Mean IBI	**40** ± 2.0	**36,** n=1	**42,** n=1	**39.5** ± 1.5
Mean O/E	**0.90** ± 0.17	**0.86,** n=1	**1.19,** n=1	**0.96** ± 0.10

- Structure 1 is likely to inhibit the migration of species with weak swimming and climbing abilities. Structure 2 is unlikely to be a barrier to any native fish species. Structure 3 may inhibit species with weak climbing abilities.

- Structure 1 was originally a series of 3 weirs that over a period of about 2 years has gradually been reduced to one weir through the infilling of gravel coming down from upstream. Similarly a drop at the outlet of structure 2 has also been in-filled with gravel.

- Three species that were found downstream of the weir were not found upstream of it despite being predicted to be there.

- More fish surveys upstream and downstream of each structure is needed to strengthen conclusions

Table 11.5 Summary of results

Final structure score (/4)	2.33
Final impact score (/4)	0.67
Priority for remediation	**Low**
Priority score (/16)	**1.56**

12.0 Wainuiomata River - Morton Dam

Table 12.0 Morton Dam, Wainuiomata River, Reservoir Road, Wainuiomata

Easting	2677200	Inlet water depth	Unknown
Northing	5991900	Outlet water depth	Unknown
Distance upstream	28km	Alignment	Straight in, straight out
Elevation	120masl	Barriers upstream	Yes
Structure	Dam	Barriers downstream	Unknown
Construction	Concrete	Likely severity as a barrier	Very High
Width relative to stream	narrower	Flow condition in which barrier will be most severe	All flows
Height of dam	12.5		

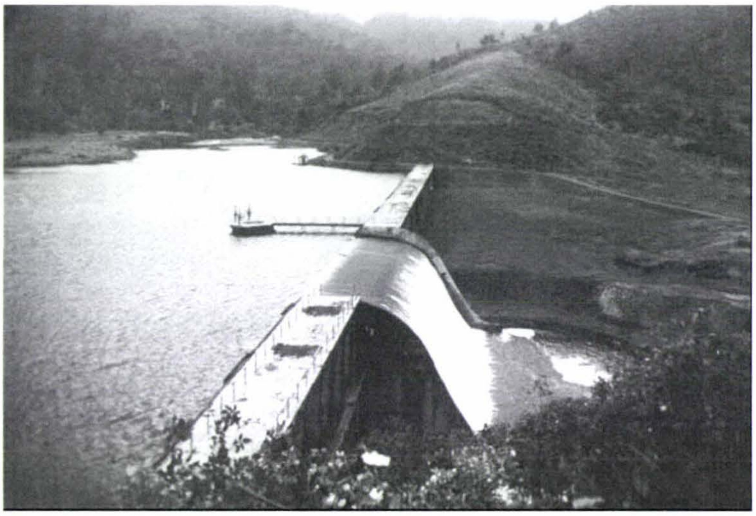

Fig. 12.0 Morton Dam, Wainuiomata River (photo from Greater Wellington website: http://www.gw.govt.nz)

Table 12.1 Distance of suitable native fish habitat upstream of dam. Calculated for each native species found in Wainuiomata River catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of dam**	**Proportion of catchment upstream of dam**	**Proportion of Wellington region upstream of dam**
Shortfin eel	0.64	2.74	0.010
Longfin eel	37.07	26.92	0.406
Inanga	0.31	1.09	0.011
Koaro	23.29	51.64	1.162
Redfin Bully	17.20	27.93	0.591
Bluegill bully	1.58	55.67	0.887
Common bully	1.74	7.73	0.174
Lamprey	0.00	0.00	0.000
Total	**81.84km**	**25.41%**	**0.334%**

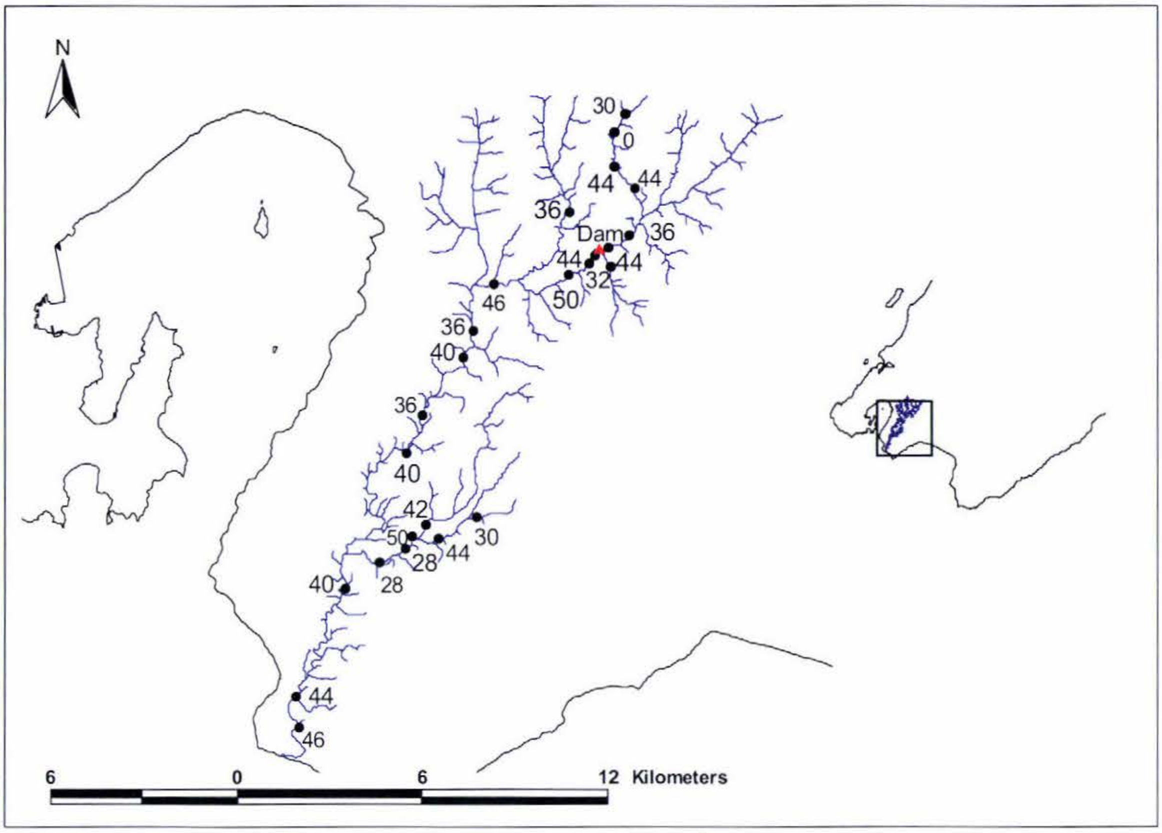

Fig. 12.1 Map of potential migration barrier on Wainuiomata River (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present

Table 12.2 Number of sites where each fish species was found in relation to the location of the dam with average IBI and O/E scores ± standard error.

Fish species present	Below (/11)	Below on tributaries (/7)	Above (/7)	Total (/25)
Shortfin eel	4	-	-	4
Longfin eel	10	6	4	20
Inanga	1	-	-	1
Koaro	1	1	-	2
Redfin Bully	5	3	-	8
Bluegill bully	-	1	-	1
Common bully	4	-	-	4
Lamprey	-	-	-	2
Total spp.	**7**	**4**	**1**	**8**
Mean IBI	**45** ± 1.3	**37** ± 3.3	**32** ± 5.9	**38** ± 2.0
Mean O/E	**1.20** ± 0.10	**0.91** ± 0.10	**0.37** ± 0.14	**0.89** ± 0.09

- Morton Dam is extremely likely to impede the passage of all native fish species.
- A significant proportion of native fish habitat (0.33%) in the Wellington region is upstream of Morton Dam.

- The quality of the habitat upstream of dam is extremely high, with most of the catchment being unlogged native bush.
- Six species that were found downstream of the dam were not found upstream of it despite being predicted to be there.
- Only large (>1m) longfin eels were found above the dam. Due to the longevity of longfin eels it may be possible that they migrated upstream of the dam before it was built.
- The downward migration of eels is likely to be inhibited.
- There is a significant population of non-diadromous dwarf galaxiid upstream of the dam (Atkinson & Joy unpubl. data). These fish are classified to be in gradual decline and may be threatened by the return of diadromous species.

Table 12.3 Summary of results

Final structure score (/4)	3.00
Final impact score (/4)	3.67
Priority for remediation	**High**
Priority score (/16)	**11.00**

13.0 Wharemauku Stream

Table 13.0 **Wharemauku Stream culvert, structure 1, State Highway 1, Paraparaumu**

Easting	2678800
Northing	6030200
Distance upstream	3.3km
Elevation	20masl
Structure	Grading weir
Height	1.8m (sloped)
Inlet water depth	Pooled
Outlet water depth	Pooled
Alignment	Straight in, straight out
Barriers upstream	Yes
Barriers downstream	Unknown
Likely severity as a barrier	Moderate
Flow condition in which barrier will be most severe	Low flows

Fig. 13.0 Wharemauku Stream weir, structure 1

Table 13.1 **Wharemauku Stream culvert, structure 2, State Highway 1, Paraparaumu**

Easting	2678900	If perched - undercut	n/a
Northing	6030100	Inlet water depth	Flat
Distance upstream	3.8km	Outlet water depth	Pooled
Elevation	21masl	Alignment	Straight in, straight out
Structure	Culvert - box	Barriers upstream	Yes
Diameter	2m	Barriers downstream	Yes
Length	13m	Likely severity as a barrier	Moderate
If perched – drop	0.9m	Flow condition in which barrier will be most severe	Low flows

Fig. 13.1 Wharemauku Stream culvert, structure 2. Note broken fish pass on right.

Fig. 13.2 Wharemauku Stream culvert, structure 2

Table 13.2 Distance of suitable native fish habitat upstream of structure 1. Calculated for each native species found in the Wharemauku Stream catchment and as a percentage of the total catchment using predictive model and REC database

	Kilometres of suitable fish habitat		
Fish Species	**Upstream of Structure 1**	**Proportion of catchment upstream of structure 1**	**Proportion of Wellington region upstream of structure 1**
Shortfin eel	3.51	28.13	0.056
Longfin eel	10.12	55.75	0.111
Inanga	0.03	0.68	0.001
Redfin bully	7.65	86.07	0.263
Common bully	1.39	44.63	0.138
Koaro	4.08	96.99	0.204
Banded kokopu	7.19	61.64	0.450
Shortjaw kokopu	3.31	100.00	0.406
Total	**37.29km**	**56.09%**	**0.141%**

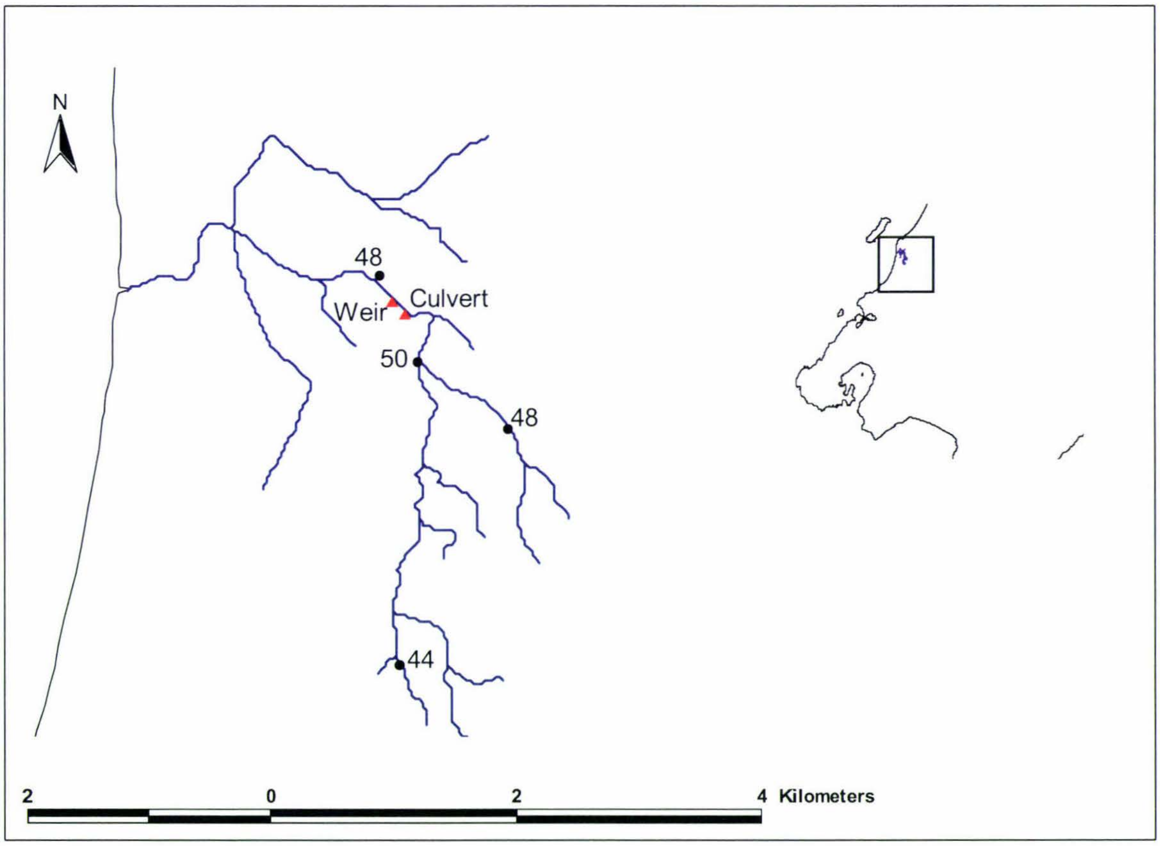

Fig. 13.3 Map of potential migration barriers on Wharemauku Stream (red triangle) and sites where fish surveys have been conducted (black dots). Each fish survey site is labelled with an IBI score generated from the species present.

Table 13.3 Number of sites where each fish species was found in relation to the location of each structure with average IBI and O/E scores ± standard error.

Fish species present	Below structure 1 (/1)	Above structure 2(/3)	Total (/4)
Shortfin eel	1	2	3
Longfin eel	1	2	3
Inanga	1	-	1
Redfin bully	1	2	3
Common bully	1	-	1
Koaro	-	2	2
Banded kokopu	-	2	2
Shortjaw kokopu	-	1	1
Total spp.	**5**	**6**	**8**
Mean IBI	**48,** n=1	**47** ± 1.76	**47.5** ±1.26
Mean O/E	**1.22,** n=1	**0.90** ± 0.11	**0.98** ± 0.11

- In most flow conditions structure 1 may restrict the migration of species with good climbing abilities. In low flow all species are likely to be inhibited. Structure 2 is likely to impede the passage of species with moderate climbing abilities.
- A concrete ramp fish pass is present on structure 2. However, this pass is broken and a large amount of weed growing at the top of the pass may inhibit fish from using it.
- Two species that were found downstream of the structures were not found upstream of them despite being predicted to be there.
- The IBI and O/E ratio are relatively high both upstream and downstream of the structures, reflecting the high quality of the fish communities present.
- More fish surveys upstream and downstream of each structure is needed to strengthen conclusions.

Table 13.4 Summary of results

Final structure score (/4)	2.67
Final impact score (/4)	2.00
Priority for remediation	**Moderate**
Priority score (/16)	**5.33**

Taylor MJ, Kelly RG 2003. Structures in rivers of the greater Wellington Region. Wellington, Greater Wellington Regional Council, report no. GW/RP-T-03/32.

Wild M, Snelder T, Leathwick JR, Shankar U, Hurren H 2005. Environmental variables for the Freshwater Environments of New Zealand River Classification, NIWA Client Report CHC2004.086