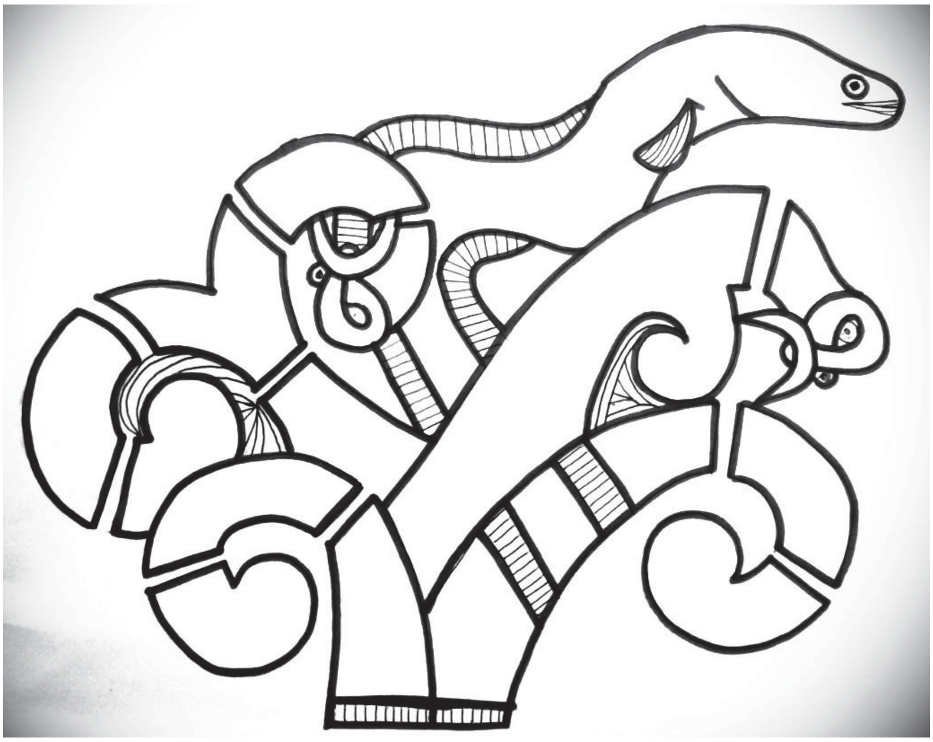
Restoring connectivity for migratory native fish:

investigating the efficacy of Fish Friendly Gates



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KEYWORDS : Fish Friendly Gate, tide gate, flap gate, migratory fish, connectivity, fragmentation, diadromous, inanga, whitebait, barrier.

ABSTRACT

Stream connectivity and habitat diversity are key components of healthy river ecosystems. Human modification of natural flow regimes disrupts natural connectivity, and results in physical, chemical, and biological changes that impair natural river function. Such changes can be detrimental to freshwater species, particularly those which have evolved to be reliant on a variety of different habitats throughout their life cycles. Consequently, restoring connectivity has become a major restoration goal in freshwater ecology.

Tide gates, a man-made coastal structure designed to protect low-land infrastructure from flooding, can negatively impact freshwater ecosystems. Through disrupting connectivity, tide gates impede the movement of aquatic biota and degrade upstream habitats. It is thought that the vast majority of tide gates in New Zealand and worldwide could be modified to enhance connectivity and fauna passage through the installation of Fish Friendly Gates (FFG's). This study is the first to investigate these claims.

FFG's increased both the duration and distance that tide gates were held open over a tide cycle. These operational changes reintroduced some tidal fluctuation to upstream habitats but water levels remained within safe levels for infrastructure. FFG influence enabled upstream passage for giant bully and adult inanga, for which tide gates were otherwise impassable. Furthermore, upstream passage of whitebait (migratory galaxiid juveniles) and common bully were significantly increased when aided by FFG's. Although rapid and sustained increases in migratory species richness of resident populations were observed following FFG installation, due to small sample sizes these changes could not be regarded as statistically significant. Additionally, evidence of rehabilitation of degraded sites was limited and suggests care should be taken when restoring connectivity to poor quality habitat.

Overall, this study demonstrated that FFG's can enhance upstream fish passage at tide gates while maintaining adequate flood protection. Whether FFG's can provide ecological benefits to degraded habitats requires supplementary research. Provided the limitations of FFG's are recognised and they are only installed where tide gate removal is not feasible, FFG's are an effective tool for facilitating fish passage through tide gates in New Zealand and worldwide.

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Introduction: connectivity, fish passage & retrofits

Damage to freshwater ecosystems

Degradation of freshwater environments reduces their ability to support biodiversity and provide vital ecosystem services. Freshwater environments cover less than 1% of the worlds surface but support 10% of the worlds species, including a third of all vertebrates (Strayer & Dudgeon, 2010). As well as supporting a rich diversity, they provide goods and services that are vital for the livelihood of millions of people worldwide; however, human population growth and economic development has put these important ecosystems at risk (Dudgeon et al., 2006). Traditionally conservation priorities have largely ignored freshwater environments, as a result some of the most speciose, threatened and valuable taxa have been neglected (Abell et al., 2011; Darwall et al., 2011). Additionally, because human activity on the land accumulates first in freshwater environments, biodiversity declines are greater than even the most affected terrestrial ecosystems (Ricciardi & Rasmussen, 1999; Sala et al., 2000). As a result of their lack of protection and vulnerability to human activities, freshwater ecosystems are likely the most degraded ecosystems in the world (Dudgeon et al., 2006).

Fragmentation of freshwater systems is occurring worldwide

One of the largest human disturbances on freshwater environments is hydrological alteration. Various human activities can disrupt natural flows, the most common being the placement of artificial structures such as: hydroelectric dams, weirs, culverts, and tide gates (Rosenberg, McCully, & Pringle, 2000). Freshwater environments are being altered at unprecedented rates

(Pringle, 2003; Rosenberg et al., 2000). Worldwide impoundment of water is so great that sea levels have been reduced (Chao, 1991). Humans use over half of the global freshwater runoff and this is predicted to increase to 70% by 2025 (Jackson et al., 2001; Postel, Daily, & Ehrlich, 1996). Control over water systems is so extensive that 98% of total river area in the US and 77% of the largest river systems in the northern third of the world are fragmented by dams, reservoirs and water diversion projects (Benke, 1990; Dynesius & Nilsson, 1994). With increasing demand for power generation, water supply and urban and agricultural development, there is greater need for flood management and irrigation, thus river systems are further fragmented.

Connectivity is critical to ecosystem function

Disruption of river connectivity has deleterious effects on the river system itself, as well as the biota contained within. Connectivity, a fundamental property of river systems, is important in maintaining both ecological and physical, structure and function (Rolls, et al., 2014). Altering in-stream flow directly modifies physical habitat, through changes to water depth and velocity (Bain, Finn, & Booke, 1988). Furthermore, these changes alter sediment transport, changing stream structure and habitat characteristics (Bain et al., 1988; Pringle, 2003). As well as effects on biota through altered stream habitat, in-stream structures can also limit upstream and downstream movement of freshwater organisms, restricting access to habitats required for foraging, feeding, predator avoidance, shelter and spawning (Pringle, 2003). In particular, barriers have a great effect on obligatory migratory species, for whom connectivity is critical for long-term persistence and success (Fullerton et al., 2010; Lake, Bond, & Reich, 2007). Consequently, habitat fragmentation is thought to be a key factor in aquatic biodiversity decline (Rolls et al., 2014), with reduced abundances, species richness and survival of biota upstream of structures widely observed and recorded (Allibone, 1999; Bain et al., 1988; Gibson, Haedrich, & Wernerheirn, 2005; Jellyman & Harding, 2012; Joy & Death, 2001; Nislow et al., 2011).

New Zealand species are particularly susceptible to fragmentation

Many of New Zealand's freshwater species are entirely dependent on river connectivity for survival. Although New Zealand's freshwater fish fauna is made up of a relatively small number of species, it is unique for its unusually high proportion of diadromous species (McDowall, 1998). Because diadromous species require access to and from the sea to complete their lifecycles, they are sensitive to in-stream migration barriers and consequently these barriers have a dramatic impacts on the ecology, flora and fauna of New Zealand waterways. For example, migration barriers have effectively closed off a third of the country's rivers and lakes to longfin eels (PCE, 2013). New Zealand has the highest proportion of threatened or at-risk species and some of these diadromous species continue to support valued fisheries despite these conservation concerns (Joy & Death, 2013). In 2009, 67% of native fish fauna were listed as threatened or at-risk and this has increased to 74% over four years (Allibone et al., 2010; Goodman et al., 2014). Although the endemic grayling is the only native fish thought to have become extinct since human settlement, many native fish have become locally extinct, or experienced declines in abundance and range restriction, which greatly increases their vulnerability to extinction in the future (Joy & Death, 2013).

Legal obligations for connectivity

As well as important biologically, fish passage is legally required in various locations across the world. Fish passage has been part of water resource policy in the USA for over a century and incorporated in to Australian legislation in the 1990's. All fisheries in New Zealand are governed by the Conservation Act 1987, which includes the Fisheries Act 1983 and the Freshwater Fisheries Regulations 1983. DOC (Department of Conservation) and regional councils have responsibilities to manage fish passage in New Zealand's waterways under the Freshwater Fisheries 1983:

"... no person shall construct any culvert or ford in any natural river, stream, or water in such a way that the passage of fish would be impeded, without the written approval of the Director-General incorporating such conditions as the Director-General thinks appropriate."

This applies to all structures built after the 1st January 1984 and although compliance so far has been poor, DOC and Regional Councils are working on better implementation of these rules in the future (Franklin, Bowie & Bocker, 2014).

There is hope: mitigating the connectivity problem

In light of the importance of connectivity for ecosystems and to meet legal requirements, reducing fragmentation has become a major restoration goal in freshwater ecology (Lake et al., 2007). Reducing fragmentation can however, be challenging, as complete removal of problem structures is often not an option. The impacts of large-scale barriers have been well documented and many large dams in New Zealand provide facilities such as fish ladders or trap and transfer programmes (Jellyman & Harding, 2012). However, small-scale structures (those less than 4m in height) form the majority of barriers and therefore a greater potential for influencing fish dynamics. Hence greater focus has been placed on remediating fish passage at small-scale structures, because it is seen as the most cost effective means of achieving significant environmental and biodiversity gain (Franklin, Bowie & Bocker, 2014).

Small-scale changes have positive results

Numerous innovative ideas for retrofitting small-scale problem structures, to restore or improve passage have been tested and have yielded promising results. Ramps of various surface type, gradient, and length, and baffles of different type and arrangement have allowed for greater passage (Baker & Boubee, 2006; Doehring, Young, & McIntosh, 2011; Doehring, Young, & McIntosh, 2012; Franklin & Bartels, 2012). Furthermore, mussel spat ropes can increase passage for a range of species, including those regarded as 'climbers': (David, Hamer, & Collier, 2009), (Tonkin, Wright, & David, 2012) ; as well as swimming species: adult inanga, juvenile trout and shrimp (David, Tonkin, Taipeti, & Hokianga, 2014; Tonkin et al., 2012). Additionally, successful remediation of weirs, without interfering with hydrological measurements has been investigated (Bowman & Rowe, 2002). These studies have provided a range of simple and cost effective tools that can be used to facilitate passage through in-stream barriers for a range of aquatic biota.

Common coastal barrier yet to be addressed

Although culverts and weirs have been addressed, tide gates have received little attention to date, despite their common use in coastal regions. Tide gates are used worldwide to limit tidal ingress to allow for greater human development of low lying coastal zones. Barriers at all altitudes are detrimental; however, lowland barriers in particular can obstruct a larger portion of habitat, and have greater impact on diadromous species (Cote, Kehler, Bourne, & Wiersma, 2009; Fullerton et al., 2010). As well as hindering fish passage, tide gates result in the accumulation of poor quality water upstream (acidification, nutrient enrichment) and the fragmentation of wetland habitat (Halls, Hoggarth, & Debnath, 1998). Furthermore, by eliminating tidal variability, tide gates result in the loss of potential inanga spawning habitat (Benzie, 1968). Nevertheless tide gates continue to be installed with little consideration of their environmental effect.

A retrofit design for tide gates

Although the detrimental impacts of tide gates have been observed, complete removal is often not an option because of competing land use and flood mitigation requirements. However, it has been suggested that a vast majority of tide gates in New Zealand and worldwide could be changed to enhance connectivity and fauna passage. Fish Friendly Gates (FFGs) were developed by ATS Environmental, with funding and assistance from Bay of Plenty Regional Council and National Institute of Water and Atmospheric research (N.I.W.A.). The FFG works by counter weights which keep the tide gate further open during low tide and as the water rises it delays the closing moment. In theory, FFG's allow for greater upstream passage of all fish species, and improved water quality through flushing; however, like many of the retrofit options it lacks infield testing. This was highlighted as a key research gap in the 2013 Fish Passage Workshop - which advocated the need robust testing and evaluation of fish passage solutions to ensure they are fit for purpose (Franklin et al., 2014).

Research objectives

This thesis aims to address this gap in knowledge, by investigating the efficacy of FFG's, and to provide information to aid in the installation and design of future retrofits.

The overall aim of this research was:

> *To carry out a comprehensive investigation of FFG's as a retrofit option for tide gates. Including assessing their ability to provide ecological benefits, while maintaining acceptable levels of flood mitigation.*

There were three main elements to this research aim:

1. *Examine how FFG's alter normal tide gate operation*
2. *Assess how altered tide gate operation affects fish passage*
3. *Investigate the longer term impacts of FFG's on upstream water quality (salinity & dissolved oxygen levels) and fish community structure.*

Thesis outline

To address the research aim and its three main elements, a series of field experiments of differing designs were carried out.

Firstly, how FFG's alter tide gate operation was examined across a range of tide gate designs (*Chapter Three*). Secondly, upstream fish passage with and without FFG influence was assessed in a manipulative study (*Chapter Four*). Finally, a wider evaluation of the impact of FFG installation, not only on fish passage, but water quality, and fish communities was investigated in a Before-After-Control-Impact (BACI) style design (*Chapter Five*). In *Chapter Six* the main findings of this research and areas for future research are summarised. The following chapter provides more background context and a review of available literature on tide gates and other fish friendly designs.

Summary

Fragmentation of river ecosystems is a well recognised, yet ongoing, worldwide problem; consequently increasing connectivity has become a key goal in freshwater ecology. Due to the high proportion of diadromous species, fragmentation is of particular concern in New Zealand.

Numerous studies have investigated various retrofit options which seek to increase connectivity at small-scale barriers. Such studies have resulted in significant advances in the knowledge of fish swimming and climbing abilities and provided promising results, including allowing fish passage at previously insurmountable structures. However, not all barriers and retrofit options have been studied adequately. To sustain New Zealand freshwater fish diversity and stable fish populations into the future, investigation of such barriers and how we can alleviate them will become increasingly important. As compounding effects result in an ever increasing reduction of available habitat, restoring connectivity to remaining habitat will be crucial in conservation of freshwater species. It is important that the effectiveness of these mitigation attempts are quantified, and not just whether individual fish can get past barriers but if natural fish communities are maintained above barriers.

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2

Literature review: barriers in the tidal zone

Tidal restriction in coastal areas

Coastal floodplains worldwide are under pressure from human settlement. Population growth drives greater urban and agricultural development of lowland areas, and in turn flood mitigation works are required to protect such developments. Wetland ecology in coastal areas is commonly altered using a combination of culverts, tide gates, causeways, and levees/embankments/dikes. These structures are designed to prevent storm surges and natural flooding at spring tides from damaging agricultural land and infrastructure on low-lying coastal zones. Flood mitigation schemes are widespread, for example, 23% of the total area of Bangladesh has extensive drainage and flood protection schemes (Sultana & Thompson, 1997). Unfortunately, these land drainage works are also connected with: declines in fish stocks (Halls et al., 1998; Pollard & Hannan, 1994; Sultana & Thompson, 1997; Swales, 1982), deleterious effects on fish migration and habitat availability (Gibson et al., 2005), and vegetation changes (Sun, Cai, & Tian, 2003).

The role of tide gates in flood prevention

Tide gates, alternatively known as flap gates or flood gates, are one of the vital structures for controlling the flow of tidal waters and have been used worldwide for several centuries. tide gates have a one-way opening system, allowing drainage, but limiting or excluding tidal flooding, in order to maintain low water levels upstream (Williams & Watford, 1997). Originally developed to protect coastal development from flooding storm surges, such structures have subsequently been used to drain wetlands to provide greater land for agriculture and urban development (Giannico & Souder, 2004). Once land is reclaimed through altering the wetland areas, it is the role of the tide gates to prevent saltwater intrusion into this reclaimed land (Pollard & Hannan, 1994).

Tide gates are common in tidal zones

Flood mitigation structures, especially tide gates, are widespread both globally and nationally. Tide gates are typically found at the interface between salt and freshwaters. In estuaries and coastal wetlands of New South Wales Australia, it has been estimated some 4200 structures, including more than 1000 tide gates, have been constructed that impact on hydrology (Williams & Watford, 1997). A survey conducted in the Bay of Plenty Region identified three different types of structures: pump stations and gated and non-gated culverts. By far the majority of structures were culverts (84%) and 83% of these culverts were gated (Hamill, Hughes & Ellery, 2013). Being low altitude structures, tide gates can have effects on large areas of upstream habitat (Cote et al., 2009). Approximately 1900km or 20% of rivers and streams of the lower catchment of the Waikato River are located upstream of tide gates (Franklin & Hodges, 2015). Because of their small size and lack of consent the extent of such of structures largely unknown (Williams & Watford, 1997; Franklin et al. 2014).

Tide gate operation

There are many different types and styles of tide gates, and since tide gate operation is an outcome of their design, installation, and stream characteristics, every tide gate is unique. The opening and closing of a tide gate is dependent on the water level differences either side of the gate. The amount of water level difference required to open a tide gate is unique for each gate and this is referred to as the "effective weight" of the gate (Giannico & Souder, 2004). When the water upstream of the tide gate is greater than that downstream, and large enough to overcome the effective weight of the gate, the tide gate will open and allow the water to drain out. In reverse, when the water downstream is greater than the water upstream the tide gate will close, stopping upstream flow as well as downstream drainage. This generally results in a tide gate that is closed at high tide and open at low tide; however, in a localised high rainfall event it is possible for a tide gate to be open at high tide (K. Hughes, personal communication, July 20, 2014).

The effect of tide gate installation

Despite the flood mitigation and land grabbing benefits of tide gates, their negative environmental effects have been recognised for over two decades (Pollard & Hannan, 1994). The primary reason that tide gates are installed, is to limit the upstream flow of tidal waters; however, although often over-looked, the tide gate also has another primary physical effect: changing the pattern of downstream flow. For the time period tide gates are closed they represent a complete barrier to both upstream and downstream flow and this has major environmental consequences. The main approach adopted in studies that have evaluated the effects of tide gates has been comparison studies between gated and non-gated catchments or streams (Greene et al., 2012; Gordon et al., 2015; Kroon & Ansell, 2006; Pollard & Hannan, 1994). Additionally, there have been comparisons above and below tide gates (Dick & Osunkoya, 2000; Franklin & Hodges, 2015), long-term monitoring (Roman, Niering, & Warren, 1984) and observations at tide gates (Doehring, Young, Hay, & Quarterman, 2011). As these studies have revealed, tide gate installation results in a myriad of secondary changes of a physical, chemical and biological nature (Figure 2.1).

Primary changes result in secondary changes

By limiting upstream flow and changing the pattern of downstream discharge, tide gates cause secondary alterations in: water levels, soil moisture, salinity, water temperatures, dissolved oxygen levels and channel morphology. By design, closing of the tide gate on the incoming tide limits the tidal inflow, and as a result the *water levels* upstream are reduced. This increases the area of usable land by reducing *soil moisture*, and through wetland drainage. As well as decreased water levels, tide gates limit the natural pulses of saline water to upstream environments, lowering upstream salinity. This creates dramatic differences in *salinity* on either side of tide gates, changing the position of the salt wedge, and lowering soil salinity. Constant downstream drainage is altered due to periods of stagnation and drainage. During periods of stagnation, water circulation is restricted not only by restricted downstream flow but tidal inflow as well. As a result water *temperatures* tend to increase upstream, while *dissolved oxygen levels* decrease (Franklin & Hodges, 2015). Higher velocities during periods of drainage result in downstream and upstream scour, changing the *channel morphology,* resulting in the formation of an upstream inlet and downstream outlet pool and altering stream substrate (Dick & Osunkoya, 2000).

Loss of wetland habitat and connectivity

Fisheries effects

Degradation of wetland habitat has negative effects on fisheries. Tide gates reduce the total area, as well as the connectivity, of coastal wetland habitats. Estuarine wetlands are well recognised as important nursery areas and living space for both freshwater and marine species (Boesch & Turner, 1984). The complexity of these habitats provides protection from predation and hence enhances the survival of juveniles. Wetlands are important areas to both fish and crustaceans alike, including those of fishery value. The abundance of these areas is linked with high fisheries production. Declines in fisheries production have been observed after implementation of flood schemes in Bangladesh (Sultana & Thompson, 1997). Loss of connectivity between wetlands and estuarine habitats compromises their ecological function and is detrimental to biodiversity and sustainability of species.

Loss of carbon burial potential

As well as being detrimental for fisheries, loss of coastal wetlands results in a significant loss of carbon burial potential. Coastal wetlands are more efficient at sequestering carbon than many terrestrial sinks. In particular, saline coastal wetlands are the most efficient natural system at the capture and retention of carbon (Alongi, 2012). As well as the increase of more variable weather patterns, climate change is projected to result in the rising of sea levels, by as much as 100 - 180 cm (Grinsted, Moore, & Jevrejeva, 2010; Horton et al., 2008). Using modelling, the effect of sea level rising on coastal wetlands was investigated under two scenarios: with tide gates closed and with tide gates open (Rogers, Saintilan, & Copeland, 2014). It was suggested that open tide gates allowed for wetland expansion and facilitated their capacity to build elevation such that tide gate remediation could play an important role in guarding against future coastal habitat loss (Rogers et al., 2014).

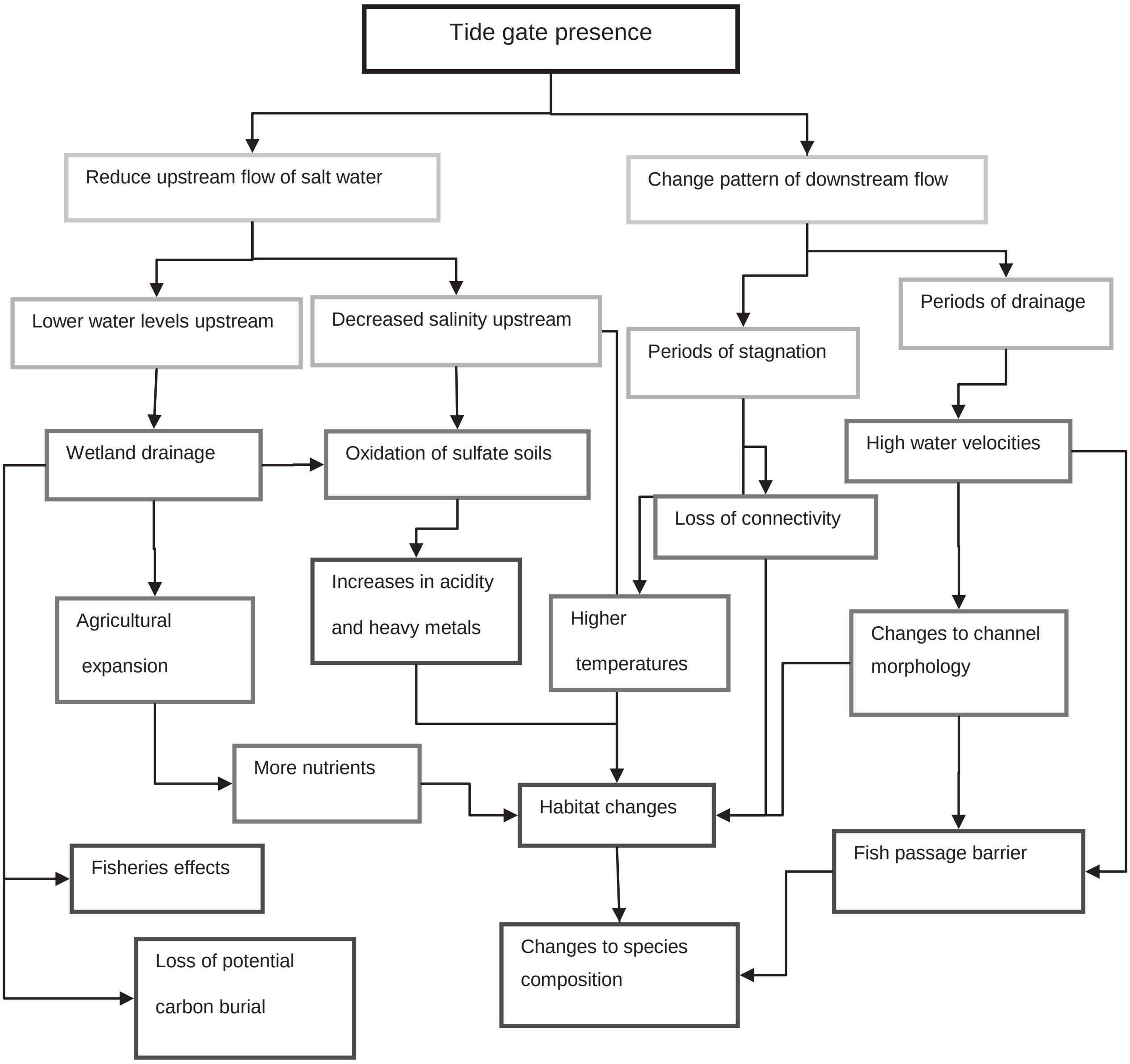

Figure 2.1: Flowchart demonstrating physical, chemical and biological consequences resulting from tide gate presence. Dark boxes at end of flowchart are discussed in text.

Increases in acidity and heavy metals

The combination of acidic soils and tide gates can have severe effects. Sulfidic sediments occur in coastal floodplains around the world. Tide gates increase the risk of oxidation of these sediments in two ways: lowering soil salinity and lowering water levels. Soils in estuarine marshes naturally lack oxygen; however, artificial drainage of coastal floodplains through the use of tide gates exposes sulphidic minerals to oxidation. The salinity in wetland soils determines their oxidation-reduction potential and in turn affects the liberation and sequestration of heavy metals (Golab & Indraratna, 2009). In addition to decreased pH, heavy metals can be released into the water in rainfall events and can result in extensive fish and invertebrate kills. Poor water quality and acidic conditions are more abundant at gated sites than non-gated sites (Kroon & Ansell, 2006).

Fish passage barrier

Tide gates restrict the movement of biota and contribute to declines in migratory species. For the majority of a tide cycle, fish passage is restricted by closed tide gates or by water velocities that exceed species swimming capabilities. Consequently, migratory fish, especially juveniles, are frequently found in lower abundance in gated systems (Franklin & Hodges, 2015; Greene et al., 2012; Kroon & Ansell, 2006). Based on the presence of migratory species upstream of tide gates and observations at tide gates, research suggests that fish are able to take advantage of certain conditions to move upstream past these barriers but that the abundance of fish passage is reduced significantly (Doehring, Young, Hay, et al., 2011; Franklin & Hodges, 2015). Doehring et al. (2012) observed that less than half as many fish were able to pass through a gated relative to a non-gated culvert. The degree that fish passage is impeded at any given site depends on the characteristic of the tide gates, stream environments, as well as the season and fish swimming capabilities (Franklin & Hodges, 2015). Nevertheless significantly reducing upstream recruitment is likely to have consequences on the abundance and diversity of fish communities, the viability of upstream populations, and the inflow of nutrients into the system. Additionally, restricting the time available for fish passage makes fish vulnerable to predation below tide gates (Doehring, Young, Hay, et al., 2011).

Habitat & species composition

Changes to the physical stream environment modify the suitability for different aquatic species. The structure of an ecological community is the outcome of environmental factors and species interactions. Tide gates not only significantly alter stream environments but they also restrict the available species pool. Consequently, significant differences in species community structure can be found in gated systems relative to reference streams including: lowered abundance of migratory species (Kroon & Ansell, 2006); lowered species richness and evenness (Pollard & Hannan, 1994); exclusion of estuarine-marine species (Boys & Williams, 2012); invasion of less salt-tolerant species (Roman et al., 1984); and accumulation of exotics, pest fish and plant species (Boys, Kroon, Glasby, & Wilkinson, 2012; Franklin & Hodges, 2015). There are also changes to habitat 'quality': vegetation changes to unsuitable or less preferred habitat and food (Roman et al., 1984), prevention of establishment of fringing mangrove vegetation (Pollard & Hannan, 1994), greater macrophyte cover (Franklin & Hodges, 2015); and changes to decomposition of litter and release of nutrients to foodwebs (Dick & Osunkoya, 2000).

Tide gates degrade the overall quality of habitat, but of particular concern for fish communities, is the poor water quality that accumulates above tide gates. Areas of high temperatures and low dissolved oxygen levels are common above tide gates (Franklin & Hodges, 2015). Depending on species tolerances low DO levels and high temperatures can limit species abundance and diversity by lowering survival where tolerable limits are exceeded. It is not uncommon for water immediately above tide gates to regularly exceed these tolerances. These conditions are unfavourable for native species such as *Galaxias maculatus* (inanga) and *Retropinna retropinna (*smelt) and can impede successful migration (Franklin & Hodges, 2015).

Tidal restoration/tide gate remediation

Tidal restoration

Restoration at sites that have been degraded due to tidal restriction, including above tide gates, is possible with the reintroduction of tidal flow. Tidal restoration, or allowing greater tidal exchange, has been found to provide ecological benefits in several studies: culvert removal (Boys & Williams, 2012), culvert enlargement (Eberhardt, Burdick, & Dionne, 2011) and dike breaching (Able et al., 2008). In the case of tide gates, the best solution ecologically is their complete removal; however, this is often not an option because reinstating full tidal flows and removing flood protection would put infrastructure at risk (Franklin et al 2014). Instead, a few studies have manually opened tide gates for periods of time, and have found improvements in dissolved oxygen and water temperatures (Franklin & Hodges, 2015), and increases in species richness over longer periods of time (Kokubu & Matsuda, 2013).

Tide gates retrofits/modifications

Recognising the benefits of opening tide gates, new ways of altering tide gates to allow greater tidal exchange while maintaining their flood mitigation services have emerged. The recommendation that the time tide gates are open needs to be increased to reduce their negative impacts was proposed 20 years ago (Pollard & Hannan, 1994); however, designs capable of achieving this without manual input are relatively new. Tide gate retrofits or 'fish friendly' designs structurally or operationally modify tide gates to improve fish passage and water quality, while maintaining their flood mitigation function. There are a considerable variety of tide gate retrofits and although they differ in design, they share a common approach of increasing the opening time and/or the opening width of tide gates (Giannico & Souder, 2004). Although these have gained popularity with conservationists and decision-making agencies, there is a need for adequate and independent testing of these designs, including an new Fish Friendly Gate currently used in New Zealand (Franklin et al. 2014).

How have tide gates retrofits been tested?

Although the negative impacts of tide gates have been well investigated by comparison studies, tide gate retrofits seem to have been given relatively little scientific testing. Only three tide gate retrofits have been scientifically tested for fish passage gains in the literature, these include: pet door designs (smaller tide gate built into a larger tide gate), manual winching (intermittent opening of gates) and a self regulating tide gate design (SRT) (Boys et al., 2012; Greene et al., 2012). These studies were carried out in the USA and Australia, both locations with long histories of coastal modification due to flood mitigation. An infield BACI design with the use of controls sites (with unmodified tide gates), and reference creeks (unimpeded flow, no hydrological modification), and test sites were adopted in both studies. These were sampled before and after installation of the design of interest with measurement of biotic communities as well as physical water measurements. Another study has been carried out with a particular focus on acidic soils, investigating the use of modified two-way tide gates (one that is winch operated and another an automated 'smart gate' design) (Golab & Indraratna, 2009).

Tide gate retrofits & fish passage

The results of the BACI studies testing the retrofit designs provided interesting results. They show that fast and sustained increases of species richness and abundance are possible. Within one month of installation, a double in the species richness observed, mostly made up of an increase in estuarine-marine species (Boys et al., 2012). Although both studies saw measurable changes in communities after tide gate retrofit, the interpretation of these changes differed significantly between papers. The Australian study stated that test sites *"Changed to quickly resemble reference creeks"*, while the American study stated test sites were *"Much less than natural channels and a little better than traditional flap gates".* This difference reflects the differing measures of success between the two studies. Although the tide gate modifications had largely positive results, there was also a case of fish decline; a 7 fold reduction in the number of salmon was observed when a side-hinged gate replaced with a SRT (Greene et al., 2012).

Fish Friendly Gates are untested

As mentioned above, a tide gate retrofit design called a "Fish Friendly Gate" (FFG) is currently being used in New Zealand. In theory, FFG's allow for greater upstream passage of all fish species and improved water quality through flushing; however, like many of the available retrofit options it lacks infield testing. This was highlighted as a key research gap in the 2013 Fish Passage Workshop - which advocated the need for improved understanding of how tide gates impact fish communities in New Zealand and how their effects can be mitigated (Franklin et al. 2014). The majority of overseas tide gate retrofit designs have been made to accommodate species with strong swimming abilities, such as adult salmonids, while to date few have been tested on species with weaker swimming abilities. This is particularly important in New Zealand where amphidromy is the prevalent form of diadromy, meaning fish migrate upstream as juveniles. Conservation biology is often referred to as a crisis science in which the prioritisation of limited resources is critical (Soulé, 1985; Meine, 2010). Installing and designing retrofit options takes time, money and energy away from other conservation actions therefore it is important to determine if they are fit for purpose.

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3

Active tide gate management using FFG's

In this chapter, modification of normal tide gate operation by the addition of Fish Friendly Gates (FFG's) was investigated. For a range of tide gates, measurements were taken of: opening and closing time, opening distance, and water levels above and below the gate. This information was collected both with and without FFG influence at each site, thus allowing comparison between tide gate operation under each condition. The results of this investigation are presented and interpreted below.

Introduction

As part of flood protection and land reclamation schemes, tide gates are used widely in coastal zones around the world. Coastal areas have been the focal point of human settlement and marine resource use throughout history (Anisfeld & Benoit, 1997). Flooding is a common and costly natural disturbance inherent in living in low-lying coastal zones; consequently, coastal settlements require various structural protection measures. A key part of coastal protection involves the use of tide gates, which are simple hinged doors with a one way opening system to allow drainage while limiting upstream water movement (Williams & Watford, 1997). This feature enables them to maintain low upstream water levels, protecting lowland areas and coastal developments from storm surges or natural flooding events. Additionally, through drainage of wetlands and floodplains, tide gates allow for expansion of infrastructure or agriculture into areas where the risk of seasonal or daily flooding would otherwise be too great (Giannico & Souder, 2004).

While tide gates provide protection to valuable infrastructure, unfortunately they also have numerous negative impacts on freshwater ecosystems. Installed with the objective of controlling upstream water movement, tide gates also alter the pattern of downstream flow. Rather than free draining, the water in the channel above tide gates experiences extended periods of stagnation. As a result, water levels, salinity, temperatures and dissolved oxygen levels, as well as channel morphology, above tide gates are altered. These physical changes have cascading effects, resulting in the reduction of water quality, fragmentation and degradation of freshwater habitats. Additionally, tide gates can impede fish movement: interrupting migrations, restricting access to preferred habitat, and reducing genetic flow (Cote et al., 2009). Although the environmental damage caused by tide gates has been recognised for over two decades (Pollard & Hannan, 1994), tide gates continue to be installed in coastal environments around the world.

Active gate management may provide a tool to mitigate the negative environmental impacts of tide gate presence. The best solution ecologically is complete removal of tide gates; however, this is often not an option because reinstating full tidal flows and removing flood protection would put infrastructure at risk (Franklin & Hodges, 2015). Additionally, saline intrusion into shallow groundwater could negatively impact lowland agriculture, particularly those with salt sensitive crops (Johnston, Slavich, & Hirst, 2005). Instead, a shift from passive to active gate management, where normal tide gate operation is altered, has gained popularity (Haskins & Slavich, 2000). Opening gates during non-flood periods has been promoted as a means of improving water quality (Haskins & Slavich, 2000; Indraratna, Glamore, & Tularam, 2002). Studies which have manually opened tide gates for periods of time have found improvements in dissolved oxygen levels and water temperatures (Franklin & Hodges, 2015), and increases in species richness over longer periods of time (Kokubu & Matsuda, 2013).

The normal operation of a tide gate under passive management is determined by the characteristics of the gate itself and the stream environment. The opening and closing of a tide gate is driven by water level differences between the downstream and upstream sides of the gate (hydraulic head differential). These water level differences are the result of: tidal cycles (and magnitudes), inflow into the channel above the gate, and the extent of drainage in the previous opening. The amount of hydraulic head differential required to open the gate is called the 'effective weight' of the gate and is determined by gate characteristics (eg. size and material) (Giannico & Souder, 2004). As a result, generally tide gates close on the incoming (flood) tide and open during outgoing tide (ebb); however, tide gates can differ from this depending on environmental conditions. For example, a tide gate can open during high tide if there is a substantial rainfall event. In this way, normal tide gate operation is determined by both its characteristics and environment, and since tides differ in their locations as well their size and materials, each tide gate is unique in its operation.

To achieve the ecological gains from active gate management but avoid the need for manual operation, a range of gate 'retrofits' or 'fish friendly' designs have emerged. These designs structurally or operationally modify gates to improve fish passage and water quality, while maintaining their flood mitigation function. Designs that have been tested overseas have shown fast and sustained increases of species richness and abundance are possible (Boys et al., 2012; Greene et al., 2012). A tide gate retrofit designed by ATS environmental, called a "Fish Friendly Gate" has emerged in New Zealand. This new design is effectively a large lever, that delays the closing moment of tide gates in order to allow greater tidal flushing. The degree the FFG delays opening can be altered by the length of cable and weights applied to the lever. This FFG offers major advantages over other designs in its adjustability and that it is able to be attached to an existing tide gate, reducing installation costs.

Recently, this design has been installed in several locations throughout New Zealand; however, the use of FFG's as an active management tool is yet to be effectively investigated. FFG's must balance mitigating ecological impacts of tide gates while maintaining their flood protection function. The ecological gains of FFG's installation are investigated in the following two chapters, while here the aim was to examine (1) normal tide gate operation in a range of environments and (2) how tide gate operation is altered by the use of FFG's.

Methods

Study site details

The present study was carried out at four locations, in the Bay of Plenty Region, New Zealand (Figure 3.1). While tide gates were present at all four sites, there were differences in the number of gates, gate material/shape, as well as site characteristics (Table 3.1). This allowed FFG use to be investigated under a range of conditions.

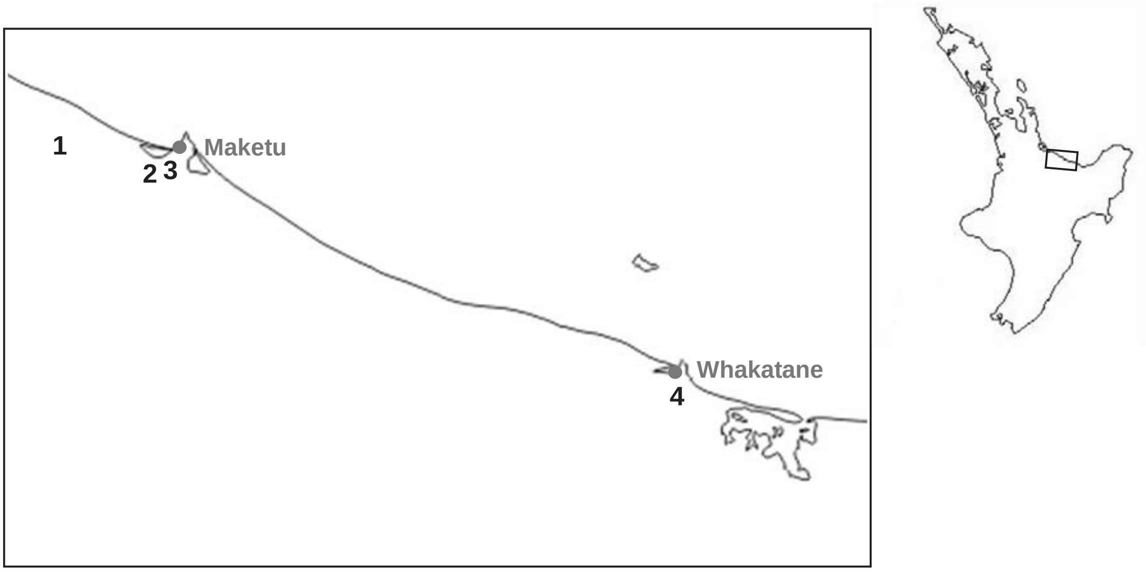


Figure 3.1: Numbers indicate the approximate location of four study sites used to investigate FFG use in the Bay of Plenty, New Zealand (1 - Bell Road, 2 - Maketū, 3 - Otumakoro, 4 - Awatapu). Locations of Maketū and Whakatane are indicated by grey dots.

Two of the sites, Maketū (Structure ID: 999069)[1] and Otumakoro (Structure ID: 999070), were located at the Southern edge of the Maketū Township. Both of these sites had a single, tide gated, culvert running under Maketū Road, through which they drained into the Maketū Estuary. The tide gate at Maketū was made of a light cast alloy, mainly performing wetland drainage. In contrast, Otumakoro was made of cast iron and drained a larger upstream catchment of both farm and urban land.

[1] Structure ID numbers given here are from Lower Kaituna Survey (Hamill et al. 2013).

The remaining two sites, Bell Road (Structure ID: 999061) and Awatapu Lagoon, were similar in that they were both remnant stretches of old river paths. At Bell Road, two large culverts, with wooden tide gates connect upstream farm drains to the Kaituna River below. This site performs mostly farmland drainage but may have some underground spring contributions. The most Eastern site, Awatapu Lagoon in Whakatane, also had two side-by-side culverts. These run under Awatapu Drive and drain into the Whakatane River through two circular tide gates. This site had significant freshwater contribution from the Wainui Te Whara.

Table 3.1: Basic tide gate details of four test sites used to investigate FFG use in the Bay of Plenty, New Zealand

Site name	No. of tide gates present	No. of tide gates modified	Culvert diameter (m)	Tide gate shape	Tide gate material
Bell Road	2	1	2	Square	Wood
Otumakoro	1	1	0.9	Circular	Cast Iron
Maketū	1	1	0.9	Circular	Cast Alloy
Awatapu	2	2	1.5	Circular	Cast Iron

Study design

Across the four study sites, a total of six tide gates (five with FFG's) were investigated. In order to investigate how FFG's impact tide gate operation, a series of measurements were taken at each site with and without FFG influence. Opening and closing times of the tide gates were recorded with the assistance of a Trail-Cam (Buck Watch, Browning Trail Camera Inc.) which was set up on time-lapse to take a photo per minute. Water depths, immediately upstream (<1 m of culvert mouth) and downstream (<1 m of tide gate), and tide gate opening width (distance from wall to back of tide gate flap) were measured manually. These measurements were taken every 15 minutes for 6.5 hours, on two separate days, which were subsequently overlapped in order to capture tide gate operation over a full tide cycle (12.5 hrs). The same data collection process was repeated with all FFG's functioning and with all FFG's disengaged at each site. When altering FFG operation, no measurements of tide gate operation were taken for 24 hours, to allow the system to settle. Additionally, measurements were taken only on days with similar tidal coefficients and not for several days after rainfall events.

Results

Pre-FFG tide gate operation

Tide gates located at the same study site did not differ significantly in their operation (total time closed: ±5 minutes; max opening distance: ±10 cm), while variation in tide gate operation between sites was large (total time closed: ±5.5 hrs; max opening distance: ±38.5 cm). Two of the sites observed (Awatapu & Otumakoro) remained closed for just under half of a tide cycle (~43%), whereas the other sites (Maketū & Bell Road) were closed for the majority of a tide cycle (>50%). Out of the four sites Maketū was closed for the greatest percentage of a tide cycle (86%), and Awatapu closed for the least (42%). There were also differences in opening widths between sites, with the largest opening distance at Bell Road (45 cm), while the opening distances at Otumakoro, Maketū and Awatapu were similar at around 10 cm.

Post-FFG tide gate operation

Use of FFG increased opening time

At all four sites FFG's increased the length of time the gates were open (Table 3.2). For three of the sites this increase was between 45mins-1hour (+6 - +8%), while at Maketū the increase was much greater 7 hrs 45 minutes - 10 hrs 45 minutes (depending on the amount of weight on the FFG). The increase in time gates were open was a result of delayed closing moment but also earlier opening times, at each site the tide gates opened 15 - 30 minutes earlier with the FFG than without. As well as increasing the total time open the FFG's increased the opening distance of all of the tide gates. At three of these sites there was a twofold - threefold increase in opening width, with the exception of Bell Road, where this effect was far smaller (+10 cm).

Table 3.2: Opening and closing of tide gates with and without FFG influence across four test sites in Bay of Plenty, New Zealand.

Site	Pre-FFG					Post-FFG					% change
	Closed		Open		Width (cm)	Closed		Open		Width (cm)	Open
	Hour	%	Hour	%		Hour	%	Hour	%		
Bell Road	7.75	62	4.75	38	45	7	56	5.5	44	55	+6%
Otumakoro	5.25	42	7.25	58	6.5	4.25	34	8.25	66	12.5	+8%
Maketū	10.75	86	1.75	14	7	3	24	9.5	76	11.5	+62%
Awatapu	5.5	44	7	56	8	4.75	38	7.75	62	26	+8%

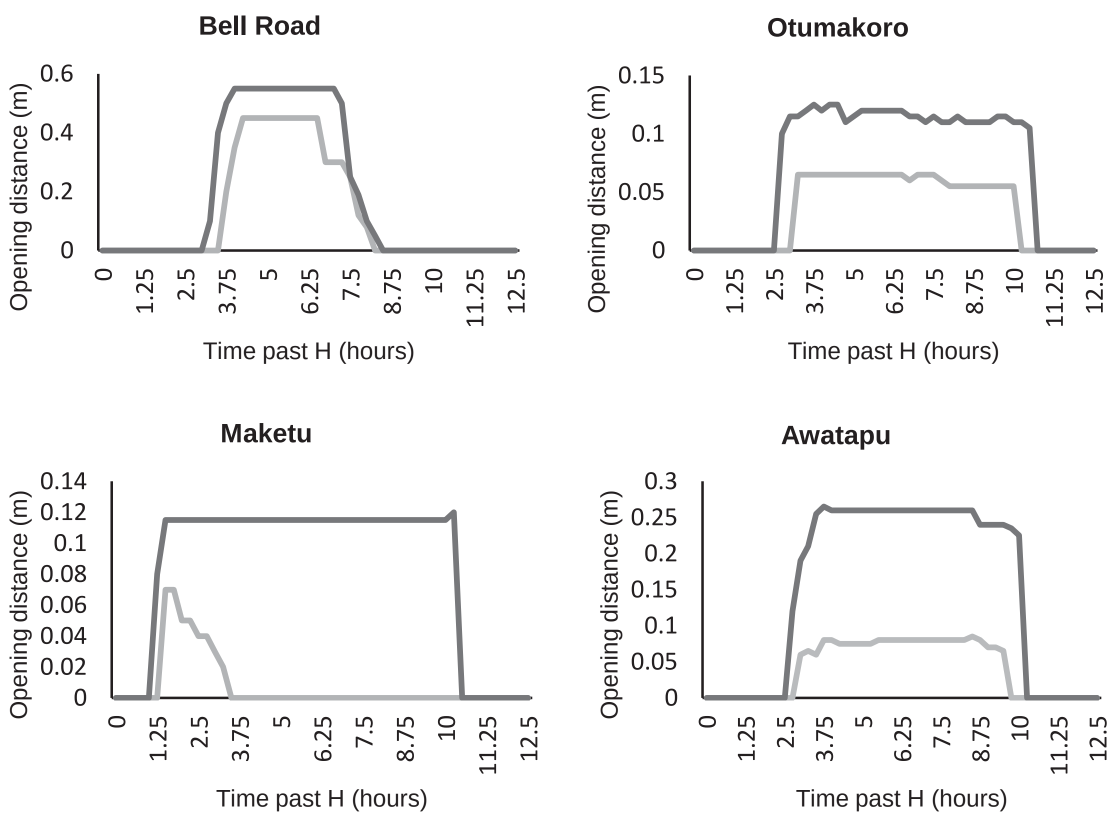
Water Levels

At all sites there were large differences in downstream water levels across the tide cycle. Water level fluctuations were similar at Maketū (±45 cm) and Otumakoro (±47 cm), while greater fluctuations were observed at Bell Road (±89 cm) and Awatapu (±153 cm). While tidal influence downstream of tide gates was clear, changes in water upstream levels over the tide cycle were less than 20 cm at all sites. Highest upstream water levels were recorded just before tide gate opening, at lowest levels at low tide. Following tide gate modification, some tidal variation was reintroduced to upstream habitats; however, increases in recorded maximum water levels were very small <15 cm. There were no obvious differences to downstream water levels following tide gate modification.

Discussion

Passive tide gate operation

Tide gates in various environments differ hugely in their passive operation. Giannico and Souder (2004) suggest that top-hinged gates can be expected to be closed for at least half a tide cycle (50%) and possibly longer depending on gate characteristics and environmental inputs. This was supported by the findings in this investigation: two of the sites investigated were closed close to half of a tide cycle (42%, 44%), while the tide gates at the other two sites were closed for a much greater percentage of time (62%, 86%). There were also large variations in the distances that the



Figures 3.2-3.5: Tide gate operation over a full tide cycle (0=High tide) at each of the four test sites. Light grey represents passive tide gate operation while dark grey indicates tide gate operation under FFG influence.

tide gates were held open. The differences in tide operation observed here can largely be put down to site differences. For example, Maketū North, had very little freshwater contribution relative to the other sites, as it was largely a wetland drain, resulting in a smaller opening window. Furthermore, tide gates that were side-by-side had practically identical opening and closing times, reflecting their identical environment and design. With sea level rise and increasing demand for abstraction, tide gate operation will be altered in the future, likely increasing the total time they remain closed.

Although the large variation in tide gate operation identified in this study, has been observed elsewhere, it seems to have been given very little attention in biological studies. From the data collected in this study, under passive operation the time tide gates are open per tide cycle can fall anywhere between 14% - 58%. Other studies that have recorded tide gate operation also mainly fall within this range: 42% (Wright, Wright, & Kemp, 2014), 25% (Giannico & Souder, 2004), 28% (Greene et al., 2012), with the one notable exception of 71.7% (Greene et al., 2012). Additionally, tide gates differ widely in their opening distance. Clearly with such large variation in tide gate operation, tide gates need to be considered on an individual basis or at least the wide variation in their operation acknowledged in studies. Of the few biological studies that have investigated tide gates from a biological view point, many have based their findings upon a single tide gate (Doehring, Young, Hay, et al., 2011; Franklin & Hodges, 2015). These studies have provided new biological insights; however, it is important to recognise the limitations of such studies when applying the results of these studies elsewhere, especially when the operation of the specific tide gate studied is not documented.

Active tide gate operation

Active tide gate operation aimed to mitigate negative environmental effects through altered tide gate operation. Following modification with FFG's, despite their individual differences, all of the tide gates exhibited increased opening duration. Again this was site dependent, with three of the sites showing around an hour increase in opening per tide cycle, while one site showed almost 8 hours increased opening. This altered total opening percentage of three of the sites to greater than 50%, but one remained a bit lower at 44%. Similar gains in opening times (1.5 - 2.5 hrs) have been achieved in other studies through installation of a self-regulating tide gate (SRT) (Greene et al., 2012). The large variance between sites again highlights the importance of site location/environment in tide gate operation. Maketū showed the greatest improvement in opening time, likely because of its small size and the lightweight gate material (cast alloy).

The increase in duration of time open observed in the study as a result of FFG's, was distributed between later closing as predicted, but also earlier opening. The opening and closing of a tide gate is driven by water level differences between the downstream and upstream sides of the gate (hydraulic head differential). These water level differences are the result of: tidal cycles (and magnitudes), inflow into the channel above the gate, and the extent of drainage in the previous opening. Through closing later in the tide cycle as a result of the FFG's, more water was able to move upstream. This increased the water in the channel above the gate for the next cycle and explains the earlier opening times observed in this study. An interesting example was Bell Road and Awatapu, both had side-by-side gates, but both gates were modified at Awatapu and only one of the two were modified at Bell Road. By altering the operation of the one gate, the unmodified gate operation was also altered, resulting in earlier opening but the same closing time. This shows how increased tidal influx in to the upstream channel can affect both the modified and unmodified gate.

As well as the duration open, the width of the opening was also increased with FFG installation. The increase in opening distance also differed between sites, with Bell Road showing the lowest increase, likely due to the material of this gate (wood). With wider opening distances, the same volume of water was pushed through a greater aperture resulting in less pressure. Although not measured, this visually decreased the water velocities flowing in and out of the culvert during incoming and outgoing tides. This decrease in water velocity may be particularly important for swimming species, who only have a limited duration of burst swimming to deal with high velocities. It would be beneficial to measure the velocity in further studies.

A key factor for the FFG to be a successful active management tool is that the tide gate maintains its original function. Tide gates often protect valuable infrastructure on low lying land. While upstream water levels did rise as a result of the delayed closing time, at no point during recording were these levels concerning for the upstream infrastructure. Upstream water penetration can also be kept at an acceptable level through changes to the weights and cable length of the FFG. At one of the study sites, survey equipment was used to plot spring high tide water levels and demonstrated that even these levels would be insufficient to overtop the banks. Furthermore, even when a large amount of weight was put on FFG causing it to remain fully open for several full tide cycles, the tidal influx was not sufficient to cause any back flooding. From this it was concluded that FFG was very unlikely to cause flooding on its own. On the contrary, it is possible that in the event of a flood they would help to evacuate flood water faster by reducing the head loss at the tide gate.

However, a simultaneous high rainfall event and malfunctioning FFG is a potential risk and an area that would merit further study and consideration on a case by case basis.

Following installation of the FFG's land owners and community members raised concerns about the levels of upstream water penetration. While most concerns could be appeased by further explanation of the FFG's and their aims and operation, others became increasingly negative towards the FFG's over time. This mainly occurred at one test site, where lack of communication with landowners at the point of FFG installation and a history of flooding in the catchment were the main driving factors. Adding fuel to the fire was a underlying misconception about 'floodgates' and their function. The term 'floodgate' invokes images of large gates, holding back huge volumes of water which would otherwise be on path of death and destruction (Haskins & Slavich, 2000). In reality, the majority of 'tide gates' are small features which are designed to exclude tidal waters, minor backflood events, and reduce post flood event drainage times (Haskins & Slavich, 2000). It is preferable to use the term tide gate, as it more accurately describes the function of the gates and holds less negative connotations. These interactions highlight the need for good catchment selection and effective education and communication with landowners pre and post FFG installation.

Environmental interpretations

The length of time a tide gate is open and the width that it is held open are important values ecologically. Specifically to fish passage, fish cannot move past a closed tide gate. Therefore, increasing the length of time a gate is open intuitively gives greater opportunity for fish passage; however, gate opening times do not give the full picture, as fish passage can also be limited by other factors including high water velocities and poor water quality. Even open gates can delay fish passage, showing that there is more to fish passage than just a physical blockage, there is also a behavioural component (Wright et al., 2014). Therefore, although some of the tide gates are closed for less than half a tide cycle, it is likely that they represent a barrier for fish passage for a much greater period of time than this, due to combination of small opening distance, high velocities and poor water quality. As well as increasing the length of time in the open position, it was recognised that all FFG's also increased the opening width. The opening width of gates determines the water velocity. Although a small increase in the total time open may seem underwhelming, this is likely to under represent fish passage gains, due to the contribution of increased opening width, subsequent decrease in water velocities, and potential improvements in water quality.

Furthermore, individual site characteristics greatly affect fish passage. At three of the sites fish passage is not possible/restricted at low tide (due to overhanging culverts, or lack of connectivity - empty estuary). This greatly restricts the opportunity for fish passage and makes increases in fish passage outside of these times more valuable. For example, fish passage is restricted at Awatapu for the time period gates are closed, as well as 5.5 hours around low tide, where there is a overhang at the culvert mouth. This means that a 8% increase in the total time the gate is open, actually equates to a 50% increase in fish passage opportunities.

A potential limitation of this study, was the lack of velocity measurements. Measuring velocity across the tide cycle with and without FFG influence would have been a good addition to this study. The velocity measures would have given more information about fish passage than the opening and closing times of tide gates could. Additionally, upstream water levels were measured manually and could be investigated more rigorously and accurately in further studies with the use of depth loggers. In saying this the adjustability of the FFG allows for an agreement to be made on acceptable levels of influx and for this to be modified over time, allowing an adaptive management strategy to be employed. A key observation made in this study was the large variation in passive tide gate operation and to highlight that this requires more consideration in future biological studies. Whether there is a correlation between the time a gate is open and how much it represents a barrier to fish passage is an interesting area for future research.

In conclusion, FFG's were able to successfully increase connectivity for a range of tide gate designs. Both the distance and duration tide gates were held open over a tide cycle were increased with FFG influence. Despite increases in upstream water levels, tide gate function was not compromised. Large variations in tide gate operation were identified in this study and justify need for tide gates to be considered on an individual basis. Future studies could investigate changes to upstream water levels more rigorously using depth loggers and incorporate velocity measurements. The operational changes through active tide gate management may provide ecological benefits, such as increased opportunity for fish passage. Whether fish will actually take advantage of these increased opportunities is investigated in the following chapter.

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4

FFG's facilitate upstream fish passage at tide gates

In the previous chapter, it was established that the duration, as well as the distance, tide gates are held open can be increased by the use of Fish Friendly Gates (FFG's). It was postulated that this observed increase in connectivity would allow for greater fish passage past modified tide gates. This chapter investigates whether this increased opportunity for fish passage actually translates into real fish passage gains. For this part of the study, fish moving upstream were trapped above two side-by-side tide gates in a series of trials, allowing comparison between fish passage with and without FFG influence.

Introduction

Stream connectivity and habitat diversity are critical to maintain healthy rivers and sustainable fish populations. Connectivity is a fundamental property of river ecosystems and is crucial for maintaining physical river structure and function (Rolls et al., 2014), as well as long-term persistence and success of fish populations (Fullerton et al., 2010; Lake et al., 2007). Many aquatic species have evolved to be reliant on a variety of habitats throughout their lifecycles and need access between these habitats. In particular, connectivity is critical to diadromous species, who migrate between the sea and freshwater to complete their lifecycles (McDowall, 1998). Diadromous species are particularly prevalent in New Zealand, making up almost half of the indigenous freshwater fish.

Anthropogenic in-stream barriers, such as: dams, culverts, tide gates, and weirs, disrupt connectivity resulting in habitat loss and degradation. There has been a proliferation of anthropogenic barriers in the last 50 years. These structures provide a range of uses to humans; however, can result in habitat degradation and impede freshwater fish movement. The 2014 National Fish Passage Symposium defined any structure that impedes or prevents upstream or downstream movement of fish as a migration barrier (Franklin, Bowie & Bocker, 2014). These structures are a significant factor in the decline of freshwater species, with the presence of impassable structures ultimately leading to declines in adult stocks, reduced biodiversity and localised extinctions. As of 2013, 74% of New Zealand's native fish fauna were listed as threatened or at-risk (Goodman et al., 2014).

The degree to which a barrier impacts upstream fish communities is dependent on the barrier characteristics as well the swimming abilities and behaviour of the fish. Not only the differences between barrier types, but also the location of a barrier within the freshwater system, can determine its impacts. For example, low altitude barriers can have a greater affect on fish with diadromous life histories due to greater upstream habitat loss (Cote et al., 2009). Fish size and species also plays an important role in fish passage success. Different fish species vary in size and swimming ability. Most New Zealand native fish do not pass barriers by jumping as salmonids do (Naughton et al. 2007; Kemp & Williams 2008), instead some possess the remarkable ability to climb the wetted margins of in-stream obstacles (i.e. kokopu and koaro). Species lacking climbing abilities, may 'burst-swim' to get through high velocity areas (e.g. inanga and bullies); however, 'burst' swimming has a limited duration (Baker, 2003; Nikora et al., 2003). Despite these adaptations, barriers which exceed the swimming abilities of a fish species obstruct their distribution.

Remediation of migration barriers to reinstate physical connectivity is now an integral part of river restoration. Research has focused the development of tools to facilitate fish passage, with the aim of restoring habitat connectivity and re-establishing fish populations. A range of designs referred to as 'retrofits' have been tested in the lab (Baker & Boubee, 2006; David et al., 2009; David et al., 2014; Doehring et al., 2012) and have resulted in rapid and measurable ecological gains when installed and monitored in the field (David & Hamer, 2012; Franklin & Bartels, 2012). While multiple designs have been tested and adapted for facilitating fish passage at culverts and weirs, tide gates, despite their wide use in coastal zones, have received substantially less consideration.

Fish passage can be impeded at tide gates through a combination of physical blockage, hydrological barrier, and by artificial conditions that act as a behavioural barrier. On incoming tides, tide gates shut, physically preventing fish passage for the duration they are closed (Giannico & Souder, 2004). This delay can significantly increase predation risk and energy expenditure (Wright et al., 2014). When the gates re-open on the ebb tide, high velocities from the stored water can exceed fish swimming capabilities. Furthermore, low dissolved oxygen levels, high water temperatures and disruption of salinity gradients caused by the presence of tide gates (Franklin & Hodges, 2015), can limit fish passage further through avoidance behaviour (Richardson, Williams, & Hickey, 2001), reducing swimming performance (Bannon & Ling, 2004; Bannon, 2006) and the masking of migratory cues (Russell et al., 1998). Consequently, the abundance of migratory fish (Franklin & Hodges, 2015; Greene et al., 2012; Kroon & Ansell, 2006) as well as fish movement (Doehring, Young, Hay, & Quarterman, 2011a) is limited by the presence of tide gates.

A Fish Friendly Gate (FFG) which seeks to facilitate fish passage at tide gates has been designed in New Zealand. FFG's keep tide gates open longer and wider, potentially providing greater opportunities for fish passage through reduction of physical and hydrological barriers; however, their efficiency is yet to be comprehensively tested. It is important to test the design on New Zealand native species, which are unable to sustain the high swimming velocities of larger fish species. Inanga were chosen as the main target species as they are a small swimming fish that do not possess any climbing ability and are easily hindered by in-stream obstacles (Baker & Hicks, 2003). In this study tide gates are manipulated to compare fish passage with and without FFG influence, to investigate (1) upstream fish passage past unmodified tide gates and (2) how fish passage is altered under FFG influence.

Methods

Study site

This study was conducted at the Western end of Whakatane's Awatapu Lagoon, New Zealand (Figure 4.1). The Awatapu Lagoon was originally part of the Whakatane River but was isolated in 1970 to prevent flooding of Whakatane. Today, it remains isolated from the main river flow but drains into the river through two tide-gated culverts which run under Awatapu Drive. In 2012, FFG's were installed to both tide gates with the objective of facilitating fish passage and assisting with weed management in the lagoon.

The lagoon has an approximate area of 7.7 ha and maximum depth of 2.5 m. Macrophyte species in the lagoon include hornwort, parrots feather and the emergent species raupo. Brown trout (2), shortfin eels (88) and goldfish (170) were present when the lagoon was electrofished by boat in 2005 (Waikato University). Additionally, numerous smelt, inanga and gambusia were sighted, but not recovered.

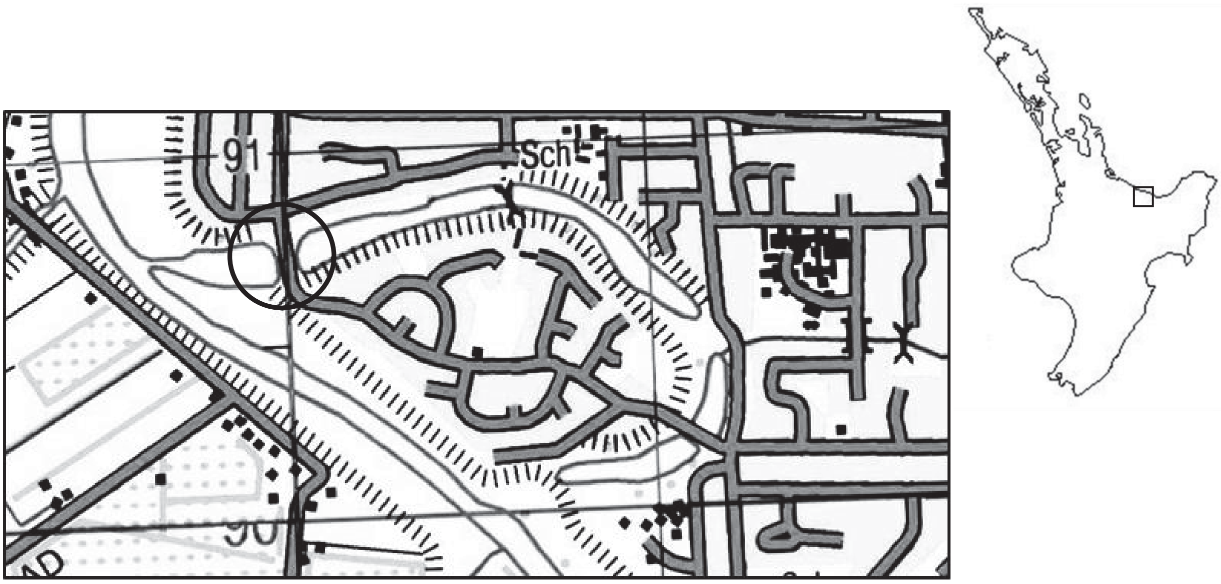

Figure 4.1: Areal view of Awatapu lagoon and part of the Whakatane River. Location of the two tide-gated culverts which run under Awatapu Drive are circled.

A freshwater contribution called the Wainui Te Whara enters the eastern side of the lagoon coming from the Mokorua Bush Scenic Reserve. The Wainui Te Whara was electric fished by NIWA in 1998, where banded kokopu and shortfin eels were found (New Zealand Freshwater Fish Database).

Experimental set-up

For the following experimental trials, two 'Southland Sock' nets (rectangular mouth: 100 cm, 130 cm, trap: 1, length: 3 m) were attached to the upstream end (lagoon side) of both culverts, in order to capture any fish moving upstream (Figure 4.2) [2]. Shade netting was used to cover the full culvert mouth (150 cm) to limit the potential for any upstream moving fish to by-pass the net and for any downstream moving fish to enter the nets from the lagoon side.

Figure 4.2: Experimental set up at Awatapu Lagoon in Whakatane, New Zealand. Two Southland Sock nets attached upstream at culvert mouths.

Full tide trapping:

From the 6th to the 8th of September 2014, fish passage upstream was assessed for five consecutive tide cycles using fish traps, with the FFG activated at Awatapu. Every three hours the fish that were trapped in the nets over that period were identified, measured, recorded and then

[2] Note: A dispensation was approved by DoC to allow whitebaiting outside of the standard Whitebait Fishing Regulations.

released into the lagoon. The nets were then reset in the same arrangement for the next trial. To investigate how tidal conditions affect fish passage, the three-hour trials were arranged to occur at four different tidal stages: HIGH (1.5 hrs either side), LOW (1.5 hrs either side), EBB (1.5 hrs after high tide), FLOOD (1.5 hrs after low tide). Resulting in a total of five HIGH, five EBB, five LOW and five FLOOD trials trapped over the three day period.

Part tide trapping:

Following full tide trapping, more intensive trapping trials were carried out from the 11th of September to the 6th of October 2014. These trials used the same upstream net arrangement, but were limited to flood and ebb tides and reduced to two hours in length. The timing of trials were adjusted to occur: EBB (2.15 hrs after high tide), FLOOD (1.75 hrs after low tide).

As before, the fish that were trapped in the nets over that period were identified, measured, and recorded before being released into the lagoon. Field notes of interest, along with spot water quality measurements, weather conditions (rainfall) and moon were recorded for each trial. The nets were then reset for the next trial. The main difference with this set of trials was that they were conducted under two different tide gate conditions: FFG (both FFG's operating) & TG (both FFG's disengaged). A total 48 trapping trials (FFG: 24, TG: 24) were carried out at the Awatapu Lagoon - 12 EBB and 12 FLOOD trials trapped under each tide gate condition. To reduce the possible impact of seasonal effects, tide gate conditions were rotated over the study period. When switching between FFG & TG, no trials were conducted for 12 hours to allow the system to settle before sampling continued.

Data analysis

Full tide trapping and part tide trapping data were analysed separately. Non-parametric statistical tests were used throughout to avoid assumptions about data distribution that may not be met. The statistical programme R 3.1.0 was used throughout (R Development Core Team, 2014). Tidal influence on the three most abundant species in full tide trapping trials was investigated using non-parametric Kruskal-Wallis rank sum tests and pair-wise differences were assessed using *post-hoc*

Tukey and Kramer (Nemenyi) tests. Wilcoxon rank sum tests were used to investigate potential bias between nets. Wilcoxon rank sum tests were also used on part tide trapping data to investigate tide, FFG, and diurnal effects on the three most abundant species in the part tide trapping trials.

Results

Full tide trapping:

Trapping for five tide cycles with FFG active, more than seven species were caught: common bully (*Gobiomorphus cotidianus)*, giant bully (*Gobiomorphus gobiodes)*, shrimp (*Paratya curvirostris)*, grey mullet (*Mugil cephalus)*, eels (both longfin & shortfin as well as unidentified elvers), and whitebait sp. (adults identified as inanga and unidentified whitebait). The three most commonly caught/abundant species were common bully (N=473), shrimp (N=292), whitebait (N=171). All other species present were much lower in abundance (N<20 total).

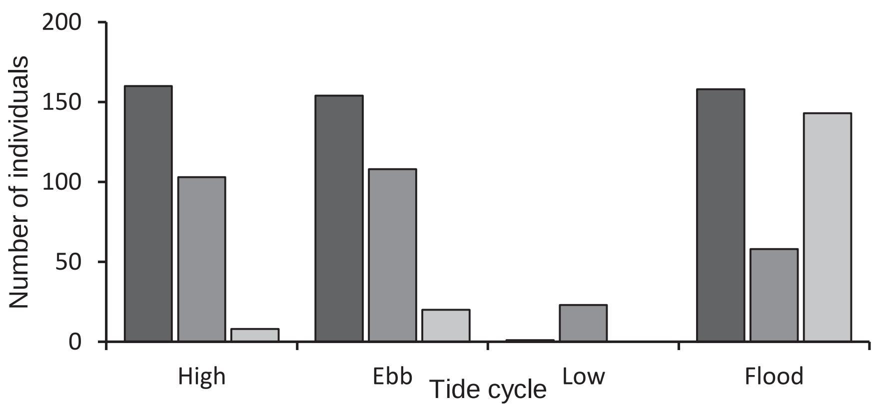

Figure 4.3: Number of individuals of common bully (dark grey), freshwater shrimp (medium grey), whitebait (light grey) caught on full tide trapping trials across tidal stages at Awatapu Lagoon, Whakatane.

Common bully, shrimp and whitebait exhibited different tidal patterns in their catch rate. There were significant differences in catch between tidal stages for whitebait (K_{3df}=11.70, P=0.008), and common bully (K_{3df}=22.41, P=0.0005), but not for shrimp (K_{3df}=1.32, P=0.7236). *Post hoc* tests showed the majority of whitebait came through on the flood tides, with high, low, ebb not significantly different from one another. Whereas common bully numbers on low tide were significantly lower, ebb (N=154), flood (N=158), and high tide (N=160) didn't differ significantly from one another. There was no significant difference in whitebait catch between the two nets (W=232, P=0.2309).

Part tide trapping:

A greater range of fish species were caught over the selected tide trapping trials. These included all of the species caught in full tide trapping with the addition of flounder (N=2) and goldfish (N=1). Again, the three most abundant species were common bully (N=880), whitebait (N=498), and shrimp (N=354), making up 94% of the total catch (T=1834).

Significantly more whitebait were caught upstream of the tide gates with FFG influence (N=475) than without (N=24) (W=1491.5, P=0.0027). As 24 trials were carried out for each trial type, this equates to an average of 20 whitebait per FFG trial and 1 per TG trial. There were also significantly greater common bully caught on FFG trials (N=716) relative to TG trials (N=164) (W=1795.5, P=0.0001). Although twice as many shrimp were caught on FFG trials (N=238) relative to TG trials (N=116), this difference was not statistically significant (W=1298, P=0.2116). Giant bully, adult inanga, grey mullet and flounder were absent from TG trials and only caught in FFG trials.

In both the FFG and TG trials whitebait moved during the day and night. For FFG trials, day and night whitebait movement was significantly different (W=114.5, p-value=0.0001), with substantially greater whitebait movement during the day (89%) than during the night (11%). Although TG trials also showed greater whitebait movement in the day (87%) relative to night (13%) the difference was not statistically significant (W=262.5, P=0.4664) due to the low total catch for TG trials. While greater numbers of common bully were caught on day trials (N= 624) relative to night trials (N=256) this difference was not statistically significant (W=252, P=0.1555). In contrast, significantly more shrimp were caught at night (N=296) than in the day (N=58) (W=503.5, P=0.0015). Giant bully were the only species to be caught exclusively in night trials.

Ebb and flood trials were found to be significantly different for all of the three most common species, with flood trials yielding greater catches for all three species (whitebait W=749, P=0.0038; common bully W=713, P=0.0012; shrimp W=918.5, P=0.0455). This difference between ebb and flood trials was greatest for whitebait (30 vs. 468), common bully (212 vs. 668) and roughly double for shrimp (132 vs. 222). Elvers (<150mm) were only caught on flood trials.

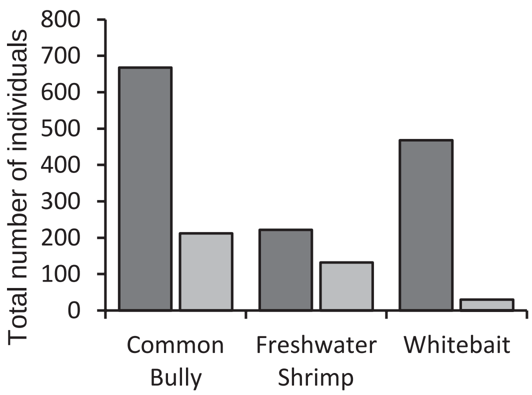

Fig. 4.4: Total number of individuals of common bully, freshwater shrimp and whitebait caught upstream of tide gates, with (dark grey) and without (light grey) FFG influence during trapping at Awatapu Lagoon, Whakatane.

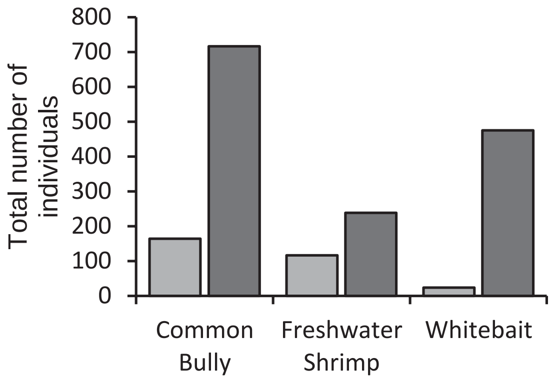

Fig. 4.5: Total number of individuals of common bully, freshwater shrimp and whitebait caught upstream of tide gates, during flood (dark grey) and ebb trials (light grey) at Awatapu Lagoon, Whakatane.

Additional fish trapping

Through trapping carried out in 2014 in accordance with the New Zealand Freshwater Fish Sampling Protocol for Wadeable Rivers and Streams numerous inanga (204) and common Bully (173) were caught in the Wainui Te Whara, as well as: redfin bully (13), longfin eels (3), and shrimp (3). Additionally a single giant kokopu was recorded in 2015 through electric fishing using standard protocols.

Discussion

Through a 45 minute increase in opening duration and doubling of opening distance (Chapter 3), FFG's were found to enhance upstream fish passage. The total number of species, as well as the abundance of weak-swimming species that were able to successfully negotiate the barrier was significantly greater under FFG influence. This study also provided greater insight into the extent that tide gates can impede fish passage, and suggests that tide gates should be classified as temporal migratory barriers. While the findings of this study have application to tide gates at other sites, the magnitude of the results observed will vary on an individual basis dependent on stream environment, tide gate characteristics, as well as the season and fish swimming capabilities.

As well as tidal influence, the characteristics of individual tide gates can alter opportunities for fish passage. Tide gates generally open on outgoing tides and close during incoming tides, therefore upstream fish passage was predicted to be concentrated at low tide and limited at high tide. Contrary to expectations, during full tide trapping, a number of species were caught across high tide (despite both tide gates being closed), and almost no upstream fish movement occurred during low tide trials. This disparity with Doehring et al. (2011a), who observed the greatest whitebait passage around low tide, can be explained by the significant overhang at the culvert mouth at this site (for ~5 hours across low tide). Perched culverts are a well-known barrier to fish passage (Doehring, Young, & McIntosh, 2011b; Franklin & Bartels, 2012). While this explains the lack of upstream movement at low tide, the reason for fish movement despite tide gates being closed is less clear. Two possible explanations exist: when closed the tide gates did not form a full seal, therefore upstream passage through small leaks in the gates was possible; alternatively, fish moved past the tide gate prior to closing, but their upstream passage was delayed. The length and slope of the culvert pipes potentially posed a barrier of its own and upstream fish passage may have been aided by rising water levels as water built up behind the closed tide gates. These results call attention to the importance of individual site characteristics in fish passage.

In part tide trapping, four fish species were caught exclusively on trials where the FFG was active. Two of these species were migratory freshwater species (giant bully and adult inanga), and the other two could be considered marine wanderers (grey mullet and flounder). Unlike other whitebait species, inanga do not possess any climbing ability and are easily hindered by in-stream obstacles (Baker & Hicks, 2003). Although surprisingly little study has been conducted on giant bully, they are often also generally considered poor swimmers due to their lowland distribution (Jellyman, Sagar, Glova, & Sykes, 2000). Therefore, reduced water velocities may have been a significant factor in the increased fish passage success of these species, as observed in other remediation studies (David et al., 2014; MacDonald & Davies, 2007). Additionally, salt water was able to penetrate further inland under FFG influence and this may have had behavioural effects on the upstream movement (Russell et al., 1998). Increased inland movement of marine species had been observed elsewhere following tide gate modification (Boys et al., 2012). While it is unclear whether this result reflects the swimming ability of those species or a behavioural response, the absence of these species in TG trials supports enhanced fish passage through FFG use. It also indicates that unmodified tide gates may limit access to preferred or biologically important habitats, such as inanga spawning sites upstream of the saltwater wedge (Mitchell, 1990), and upper reaches of estuaries preferred by giant bully (Jellyman et al., 2000).

As well as a greater number of species, increases in abundance of fish passage were observed under FFG influence, which may have significant effects on upstream populations. Four times as many common bully were able to negotiate their way upstream under FFG influence. This effect was even greater for whitebait, with a 20 fold increase in upstream passage. These results indicate that whilst the tide gates did not present a total blockage to upstream migration for these species, their presence limited fish passage. Passage limitation of whitebait was also observed by Doehring, et al. (2011a) where three times fewer whitebait passed a gated site relative to an un-gated site. Furthermore, large pools of whitebait and elvers were observed below the tide gates in TG trials, in this study and elsewhere (Doehring et al., 2011b). Limiting the upstream movement of individuals can have important ramifications on upstream populations, as their long-term sustainability is dependent on juvenile recruitment. Lowered abundances and absences of migratory species have been observed in gated systems (Franklin & Hodges, 2015; Kroon & Ansell, 2006). The 'biological meaningful success rate', i.e. how many individuals need to pass a barrier to sustain viable upstream populations, remains unclear (Doehring et at., 2012); however, where recruitment is insufficient it would be expected to result in the extirpation of upstream populations (McDowall, 1993). In this study, dense populations of adult inanga were present upstream suggesting that recruitment under FFG influence is sufficient for sustaining inanga at this site.

Whitebait movement occurred during both day and night in the study, however, daytime movement was substantially greater. This is consistent with the majority of the literature, which suggests that most whitebait movement occurs during daytime (Baker & Boubee, 2006; McDowall & Eldon, 1980; Stancliff, Boubee, Palmer, & Mitchell, 1988). In contrast, Doehring et al. (2011a) observed greater night-time migration at a tide-gated site and suggested that the shift to night-time movement may reflect an adaptive strategy to avoid increased predation as a result of tide gate presence. As well as increased protection, the speed of migration can be greater at night (Wright et al., 2014). This result was not supported in this study, with greater daytime passage of whitebait on both TG and FFG trials; however, freshwater shrimp showed a preference for night time movement. Giant bully were the only species to be caught exclusively at night.

During part tide trapping, significantly more whitebait, common bully, and freshwater shrimp were caught on flood trials relative to ebb trials. This result suggests that increased fish passage on FFG trials was primarily driven by delaying the closing moment rather than the earlier opening times. The inconsistency with full tide trapping trials, where there was no significant difference between ebb and flood tides for common bully or freshwater shrimp, is unclear. Reduced trial length of part tide trials, therefore less opportunity for fish passage, may provide some explanation. While this study didn't quantify how long fish were delayed before achieving upstream passage, it is likely delays were significant. Through tagging juvenile sea trout, Wright et al. (2014) found that although passage success was high (90%), the delay before fish were able to achieve passage was extensive, with some fish waiting longer than a full tide cycle. Furthermore, Doehring et al. (2011a), observed that whitebait movement was greatest just before high tide, therefore at the study site whitebait may have been waiting from high tide to flood tide (when passage was greatest) a period of ~9hours. Delayed migration and congregation of fish below structures can increase potential for predation, not just from predatory fish but birds and humans as well (Schilt, 2007). Dual-frequency Identification Sonar (DIDSON) recorded mullet attacking shoals of whitebait that were pooled below a closed tide gate (Doehring, Young, Hay, et al., 2011a).

Defining the impacts of tide gates is more complicated than other in-stream barriers because opportunities for fish to pass tide gates are intermittent. The most significant in-stream barriers could be considered to be those which prevent fish passage at all flows, resulting in the absence of migratory fish communities upstream of the barrier (Franklin & Hodges, 2015). However, fish species have evolved to take advantage of even small opportunities for fish passage and consequently even above a severely perched culvert migratory fish have been caught (David & Hamer, 2012). This is also true of tide gates with migratory fish (whitebait, eels, banded kokopu, mullet and shrimp) found upstream of tide gates (Doehring, et al., 2011a; Franklin & Hodges, 2015). At tide gates delays before fish passage is achieved can be extensive and pose real challenges for fish species through increased predation risk and energy expenditure. Consequently the impacts of tide gate presence on fish communities are only fully appreciated when the full tide cycle is considered. Therefore tide gates should be considered as temporal barriers.

Due to resource constraints, only a single test site was used in this study. It is important to acknowledge the limitations of this approach and the potential impacts on the results. There is substantial variation in operation of individual tide gates depending on tide gate characteristics and stream environment. For example, the length of time a tide gate is open per tide cycle can vary from 14% - 72%, not to mention differences in opening width (Chapter 3). Therefore the tide gates investigated here may over or under represent the extent to which other tide gates impede fish passage. Furthermore, the weights and cable length of each FFG can be adjusted. Consequently, although the underlying findings of this study are applicable elsewhere, the magnitude of fish passage gains will vary between individual sites, dependent on stream environment, tide gate characteristics, as well as the season and fish swimming capabilities.

Similar testing in further locations, running an open trial, and quantifying delay with and without FFG influence are potential areas for future research. Originally, an open trial was included in this study, where upstream fish passage would be monitored with the tide gate open throughout the tide cycle; however, this was removed due to time and resource constraints. An open trial could be used alongside FFG and TG trials in future studies to quantify fish passage in the absence of a tide gate and to assess how this compares with FFG trials. Additionally, neither passage efficiency nor delay at tide gates were investigated in this study. There has only been one study to date that has investigated passage efficiency and delay at tide gates (Wright et al., 2014). To do so in future studies would require identification of individual fish. Elastomer tags have been successfully used to evaluate upstream passage of inanga at culverts (Franklin & Bartels, 2012).

This study documented enhanced upstream fish passage at tide gates through FFG influence. Significantly more whitebait (20x) and common bully (4x) were able to negotiate their way upstream when aided by FFG's. Additionally, the tide gates were impassable for some species (giant bully and adult inanga) unless FFG's were engaged. In contrast, other species (elvers, eels) achieved successful passage regardless of whether FFG's were active or not. Data collection for this study was carried out at a single site therefore fish passage gains through FFG installation will vary on a case by case basis. Future studies could conduct similar testing and include an open trial to quantify fish passage in the absence of a tide gate. While this study supports that operational modification of tide gates can enhance upstream fish passage, it does not address whether increased passage will support the maintenance of natural fish communities upstream. Long-term sustainability of fish populations depends on more than fish passage alone, but also the maintenance of suitable conditions for resident species. This important area is investigated in the following chapter.

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5

Using FFG's to passively rehabilitate degraded sites

In the two previous chapters, it was found that Fish Friendly Gates (FFG's) increase connectivity by augmenting tide gate opening duration and distance, and that upstream fish passage, particularly of fish considered to be weak swimmers, was substantially increased by these modifications. How increased connectivity impacts upstream water quality and the maintenance of viable native fish communities upstream is yet to be addressed. In this chapter, the longer term impacts of FFG installation, on water quality and fish community structure were investigated through a year-long Before-After-Control-Impact (BACI) study to enhance our understanding of these important areas.

Introduction

An underlying principle of rehabilitation ecology is that the removal of stressors reinstate ecological processes which can move a degraded site towards a more natural state (Simenstad, Reed, & Ford, 2006). Worldwide, the placement of anthropogenic in-stream barriers has resulted in extensive habitat loss and degradation of freshwater environments (Poff & Hart, 2002). In particular, coastal floodplains have been subject to extensive anthropogenic developments as a result of concentrated human settlement (Vitousek, Mooney, Lubchenco, & Melillo, 1997). The restriction of tidal flushing in these areas has significantly compromised ecosystem function and negatively impacted wetland productivity, species assemblages (Brazner & Beals, 1997). There has been increasing effort in recent decades to 'passively rehabilitate' coastal areas by removing tidally restrictive structures (Boys & Williams, 2012).

Tide gates are a key component of flood protection and land reclamation schemes in coastal areas; however, they have several negative environmental consequences. As well as being physically restrictive to fish movement, tide gates significantly degrade upstream habitat. Of particular concern for fish communities, are the areas of high temperature and low dissolved oxygen (DO) that commonly occur above tide gates (Franklin & Hodges, 2015). Depending on individual species tolerances, these areas can reduce fish survival, and consequently limit species abundance and diversity. Additionally, a number of other changes to habitat 'quality' have been observed: vegetation shift to unsuitable or less preferred habitat and food (Roman et al., 1984), prevention of establishment of fringing mangrove vegetation (Pollard & Hannan, 1994), greater macrophyte cover (Franklin & Hodges, 2015); and changes to decomposition of litter and release of nutrients to foodwebs (Dick & Osunkoya, 2000).

As a result of the habitat degradation caused by tide gates, there are changes to the fish communities that these habitats can support. Changes to the physical stream environment modify the suitability for different aquatic species (Chapter 4). For example, low dissolved oxygen (DO) and high temperatures are adverse for native species such as inanga and smelt, and can impede successful migration (Franklin & Hodges, 2015). Consequently, significant differences in species community structure can be found in gated systems relative to reference streams: lowered abundance of migratory species (Kroon & Ansell, 2006); lowered species richness and evenness (Pollard & Hannan, 1994); exclusion of estuarine-marine species (Boys & Williams, 2012); invasion of less salt-tolerant species (Roman et al., 1984); and accumulation of exotics, pest fish and plant species (Boys et al., 2012; Franklin & Hodges, 2015).

Re-instating tidal flows may provide an opportunity to mitigate some of these negative environmental changes. The rationale being that by removing the key stressor - tidal restriction, rehabilitation of the site will occur due to reinstating the natural tidal flushing (Simenstad et al., 2006). Rapid and sustained recovery of salt marsh assemblages has been observed following dyke breaching (Able et al., 2008) and culvert removal (Boys & Williams, 2012). In the case of tide gates, although removal would be the most effective solution ecologically, it is often not feasible due to flooding concerns. Alternatively, modification of tide gates has been explored as a way to increase fish passage and improve habitat quality.

A variety of gate modifications have been proposed, which vary greatly in design and operation. Simply opening tide gates, even for short periods of time, has resulted in improvements in upstream dissolved oxygen levels (Franklin & Hodges, 2015). Changes in fish and decapod assemblages with increases in estuarine-marine dependent species has been achieved with manual opening and cat door designs (Boys et al., 2012). However, the results of self-regulating tide gates (SRT's) were mixed (Greene et al., 2012). Improved habitat use and density increases were achieved at some but not all sites. To date the effectiveness of Fish Friendly Gates in improving and maintaining water quality and fish communities above tide gates has yet to be tested.

This study aimed to assess the response of 1) aquatic assemblages and 2) water quality, to FFG installation. To do so, a Before-After-Control-Impact (BACI) design study was conducted. In this study, half of the selected tide gated sites were modified with FFGs, allowing a before and after comparison between modified and unmodified sites over a one year period and thus an evaluation of the FFG. Conducting both before and after sampling provides an opportunity to assess both the need for remediation prior to installation as well as an evaluation of the success of remediation post installation.

Methods

Study area background

The Kaituna River flows from Okere Falls at Lake Rotoiti and out to sea at Te Tumu. Historically, the full flow of the Kaituna River passed through the Papahikahawai Channel into the Ōngātoro/Maketū Estuary. Since the 1950s there have been significant changes to the flow regime of the estuary, including creation of the Te Tumu cut, which have affected the saltmarsh, sedimentation and erosion rates. The Kaituna River and Ongatoro/Maketū Estuary Strategy seeks to restore a greater amount of flow back into the estuary with the intended outcome of ‘restoring healthy ecosystems’. Associated with this strategy there are a number of additional initiatives aimed at linking and expanding wetland habitats, improving the habitat of freshwater fish (and other wildlife), and restoring ecosystem function. Over time large areas of historical wetland have been lost from the lower Kaituna River, including large areas of inanga rearing habitat. This has in part resulted because of flood protection works that reclaim water bodies and drain wetlands, thus affecting water levels, flooding and the shape of the river and estuary as well as damaging habitats for aquatic and bird life. Ensuring fish passage through structures in the waterways is an important consideration when trying to achieve these outcomes.

ATS-Environmental and River Lake Ltd were commissioned by Bay of Plenty Regional Council (BOPRC) to assess structures in the lower Kaituna River and Ongatoro/Maketū Estuary for potential or actual limitations to fish passage. From the structure assessments, 41 structures were identified as barriers for most flows and three of these sites were selected to be modified with FFG's in 2014.

Study sites

For the present study, these three selected sites were used as test sites in a mBACI style design (Figure 5.1). Each of the test sites was paired with a control site which was as close a match as possible in terms of location and stream conditions (Table 5.1). These study sites were located in two main areas:

Maketū Estuary sites

Four of the six sites in the study (Otumakoro, Maketū, Waitipuia and Burgess) were located around the edge of the Maketū Estuary. All of these sites drained into the Maketū Estuary through a top-hinged tide gate, although each tide gate varied in material and size. There was a mixture of farmland and urban settlement in the upstream catchment of these four low-land streams.

Otumakoro and Maketū were modified with FFG's on the 6th of March 2014, while Waitipuia and Burgess acted as control sites and were not modified over the study period.

Figure 5.1: Location of study sites used in a BACI study to investigate FFG installation in Bay of Plenty, New Zealand. Map on left side shows location of Maketu Estuary sites and on right Kaituna River sites are shown. Dots on both maps indicate approximate locations of test (striped) and control sites (black).

Kaituna River sites

The other two study sites (Bell Main and Bell Farm) were located further North and inland. The control site paired to this test site differed from the other control sites used as a pump station rather than a tide gate connects it to the lower river. Despite this difference its close proximity to the test site made it the best control available for this site. Upstream catchments of these sites contain a mixture of horticulture and farming. Bell Main was modified with a FFG on the 13th of August 2014, while Bell Farm was used as a control site and remained unmodified for the duration of the study.

Experimental design

Pre-installation sampling

Prior to any tide gate modifications, fish community and water quality measures, were collected for all control (3) and treatment sites (3) during late January and early February 2014. Fish communities were sampled using the New Zealand Freshwater Fish Sampling Protocol for Wadeable Rivers and Streams. In line with the protocol, 6 fykes and 12 gee-minnows were set over 150 m of the stream. Sampling was conducted immediately upstream of the tide gates at all sites and downstream the tide gates at four of the six sites. Each site (upstream and downstream) was sampled on three separate occasions (two overnight trials and one day trial), with the order of sampling determined randomly. All fish caught in trapping trials were identified, measured, recorded and returned to the stream. Additional notes were made concerning in-stream and bank vegetation, water clarity, weather conditions and water levels at each site. Water salinity, dissolved oxygen levels and water temperature were measured using Onset HOBO dissolved oxygen loggers and Onset HOBO conductivity loggers during early February 2014. These were deployed 10 - 25 m upstream of the tide gates at each location (both control and test sites) with measurements taken every 15 minutes for 72 hour period.

Post-installation sampling

Following FFG installation, two rounds of post-treatment sampling were carried out: short term and long-term. Short-term post-treatment sampling was carried out a month after FFG installation (Maketū: April, Bell Road: September). Upstream and downstream re-sampled using standardised trapping methods. Long term post-treatment sampling was carried out a full year after pre-treatment sampling, in January-February 2015 (10 months post FFG installation for Maketū Sites or 5 months for Bell Road). Again this was carried out using the same procedures as used in the pre-sampling. In addition, water quality measures: conductivity and dissolved oxygen, were retaken using data loggers in the same location.

Table 5.1: Location and details of paired control and test sites U/S = upstream, D/S= downstream

Parameter	Test 1	Control 1	Test 2	Control 2	Test 3	Control 3
Site name	Otumakoro	Burgess	Maketū	Waitipuia	Bell Main	Bell Farm
Structure ID	999070	999006	999069	999028	999060/1	999059
Structure Type	Tide gate	Tide gate	Tide gate	Tide gate	Tide gate (x2)	Pump station
Latitude	-37.76027	-37.762534	-37.76167	-37.767546	-37.74303	-37.4295
Longitude	176.447943	176.43638	176.44682	176.443631	176.359574	176.35971
D/S water body	Maketū Estuary	Maketū Estuary	Maketū Estuary	Maketū Estuary	Kaituna River	Kaituna River
U/S water body	Farmland drain	Farmland drain	Wetland Drain	Waitipuia Stream	Old oxbow	Farm Drain
Substrate type	Soft sediment	Soft sediment	Soft sediment	Soft sediment	Soft sediment	Soft sediment
Within salt wedge ?	Yes	Yes	Yes	Yes	No	No
Potential fish habitat U/S	Moderate	Moderate	Large	Large	Minor	Large
D/S sampling possible	Yes	Yes	No	Yes	Yes	Shared with Bell Main

Statistical analysis

To test the primary hypothesis that diadromous fish abundance and water quality would increase at the treatment sites relative to the control sites following FFG installation, data was analysed using the statistical programme R 3.1.0 (R Development Core Team, 2014). Prior to running the analyses, Shapiro-Wilk tests were used to evaluate the normality of each data set and non-parametric tests were used where assumptions of normality could not be met. Friedmans rank sum test was applied to the difference in species abundance prior to modification and one month and one year. As well as investigating each species independently, four species groups were considered: 'pest' (gambusia + goldfish), 'marine' (marine wanderers), 'diadromous fish' (common bully, giant bully, inanga, shortfin and longfin eels), 'diadromous species' (diadromous fish + freshwater shrimp). For the water quality data, a representative 72 hour period was selected for each site and the daily mean, minimum, and maximum of temperature, conductivity and dissolved oxygen were calculated. The change in temperature and conductivity values were investigated using analysis of variance testing, while dissolved oxygen levels were analysed using Kruskal-Wallis rank sum tests.

Results

Catch summary

A total of 90 standard protocol net samples (30 pre-installation, 30 one month, 30 full year, total of 9 trials per site) were collected across the six sites over the year-long study. These samples revealed the presence of 13 different species, from 10 different families. The majority were native freshwater species: shortfin eel, *Anguilla australis* (Richardson); longfin eel, *Anguilla dieffenbachii* (Gray); common bully, *Gobiomorphus cotidianus* (McDowall); giant bully, *Gobiomorphus gobiodes* (Valenciennes); redfin bully, *Gobiomorphus huttoni* (Ogliby); and inanga, *Galaxias maculatus* (Jenyns). A number of estuarine-marine species were also present: cockabullies, *Forsterygion nigripenne* (Valenciennes); kahawai, *Arripis trutta* (Forster); yellowbelly flounder, *Rhombosolea leporina* (Gunther); grey mullet, *Mugil cephalus* (Linnaeus) and yelloweyed mullet, *Aldrichetta forsteri* (Valenciennes). Two pest species were present in high abundance: goldfish, *Carassius auratus* (Linnaeus) and gambusia, *Gambusia affinis* (Baird and Girard). Finally, freshwater shrimp (Atyidae: paratya) were also present.

Pre-installation sampling

Prior to any tide gate modification, there was site specific variation in species richness upstream and downstream of tide gates at each site. Upstream of tide gates, variation in species richness between sites was large, ranging from 9 species (control site 2) to 3 species (control site 3). Downstream species richness was less variable, with 11 species at the richest site (control site 2) and 7 species at the most depauperate site (test site 2). Upstream and downstream species richness was significantly different (F_{1df}=4, P=0.04) with a greater number of species present downstream relative to upstream at all sites. Pest species were widespread upstream, with gambusia present at all six sites and goldfish at four of the six sites. Estuarine-marine species were present in greater richness and abundance downstream at the Maketū Estuary Sites but absent from the Kaituna River sites. The same was true of freshwater shrimp, who were present at all Maketū Estuary sites but absent from Kaituna River sites. At some sites there were noticeable absences of migratory species. Only at one site were five diadromous species present (common bully, giant bully, inanga, longfin and shortfin eel) with other sites having as few as one of these species present (control site 3).

One month post-installation sampling

One month following tide gate modification, differences in species richness between upstream and downstream were reduced and were no longer statistically significant (F_{1df}=2, P=0.18). Diadromous species richness increased at all three test sites (upstream), with giant bully present at test site 1 (Otumakoro) and inanga at test site 2 and 3 (Maketū & Main) where they had previously been absent. In contrast, there were no increases in diadromous species richness at any of the control sites. Despite these differences, change in diadromous species richness at test sites relative to control sites was not quite sufficient to meet the threshold for statistical significance (F_{1df}=3, P=0.08).

Common bully abundance decreased in all locations (both upstream and downstream) except for upstream of the tide gate at test site 2, where there was a four-fold increase in abundance (4 - 18). However, since there was limited support for this result at the other test sites, the difference in common bully abundance between test and control sites was not significant (F_{1df}=0.3, P=0.56). Additionally, there was no significant difference between control and test sites for the abundance of any species tested (F_{1df}=0.3, P=0.56). When control and test sites were considered together there were significant decreases in gambusia abundance from pre to post testing (F_{2df}=7, P=0.03).

There were no statistically significant differences in treatment and control site responses to FFG installation, for pest (F_{1df}=0.3, P=0.56) or marine groupings (F_{1df}= 1, P=0.32). Although the abundance of diadromous fish and species showed measurable increases at each test site relative to paired control sites (Figures 5.3-5.4) these changes were not quite statistically significant (diadromous species (F_{1df}=3, P=0.08); diadromous fish (F_{1df}=3, P=0.08).

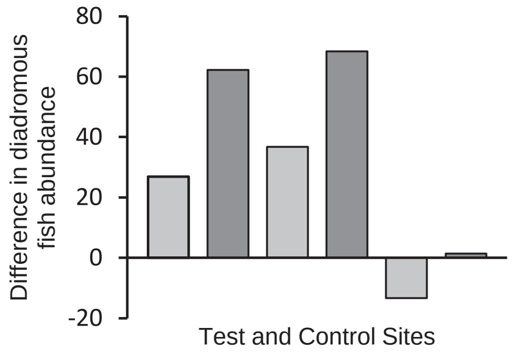

Fig. 5.2. Pre-installation and one month post-installation difference in diadromous fish abundance recorded using standardised trapping methods. Control (light grey bars) and test sites (dark grey bars).

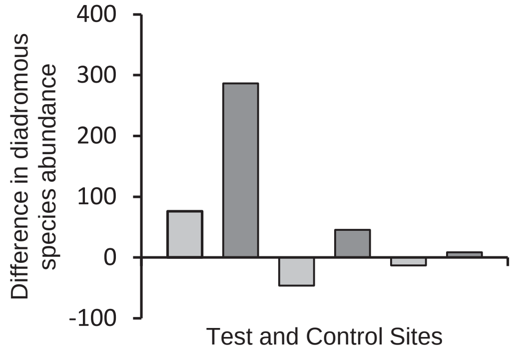

Fig. 5.3 Pre-installation and one month post-installation difference in diadromous species abundance recorded using standardised trapping methods. Control (light grey bars) and test sites (dark grey bars).

One year sampling

One year following the pre-installation sampling, the gains in species richness observed one month post-modification, remained. Differences in richness upstream and downstream of the tide gate had diminished to a point where they were no longer significant (F_{1df}=0.3, P=0.57), with all test sites showing equal species richness upstream and downstream.

Inanga abundance increased at all three test sites from 2014 to 2015, with a particularly remarkable increase observed at test site 1 (N=0.3-54.7). Although there were increases at test sites, since one control site also showed an increase in inanga abundance, overall inanga response was not considered statistically significant (F_{1df}=2, P=0.16). There were further increases in common bully abundance at test site 2, however because there were also increases at control site 2, overall there was no significant difference between test and control site responses (F_{1df}=0.3, P=0.57). Giant bully abundance declined at all sites except for test site 1, however this did not meet thresholds for statistical significance (F_{1df}=1, P=0.32). When control and test sites were considered together there was a significant increase in shortfin eel abundance between pre and post testing (F_{2df}=10.3, P=0.005).

There were no statistically significant differences in treatment and control site responses to FFG installation, for any of the species groups: pest (F_{1df}=0.3, P=0.56); marine (F_{1df}= 1, P=0.32); diadromous species (F_{1df}=0.3, P=0.56). The increase in abundance of diadromous fish though at test sites relative to paired control sites was close to the margins for statistical significance (F_{1df}=3, P=0.08).

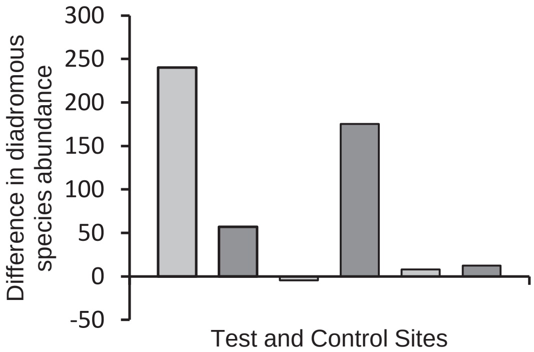

Fig 5.4. Pre-installation and post-installation difference in diadromous fish abundance recorded standardised trapping methods. Control (light grey bars) and test sites (dark grey bars).

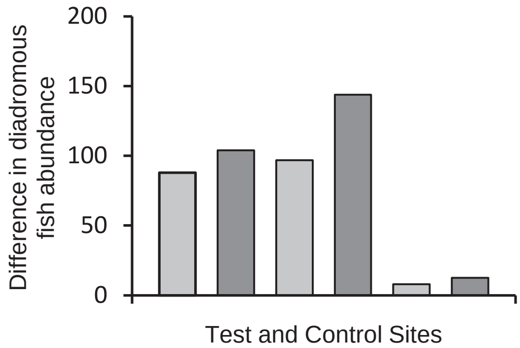

Fig 5.5. Pre-installation and post-installation difference in diadromous species abundance recorded standardised trapping methods. Control (light grey bars) and test sites (dark grey bars).

Water quality results

Water temperatures

All sites exhibited a clear daily pattern in water temperature, with lowest temperatures recorded in the early morning (5:30-8:30am) and highest temperatures in the evening (5:30-8:30pm). Average (22-23˚C), maximum (24-28˚C), and minimum (17-19˚C) daily temperatures were similar at all four of the Maketū Estuary sites and, with the exception of test site 1, were not significantly different when sampled at the same sites and times one year later. Site one showed significant increases in mean and maximum daily temperatures in 2015 relative to 2014. Although both Kaituna River sites also showed significant differences in daily temperature values, before and after values were taken at different times of year so comparison value is limited.

Table 5.2: Statistical comparison of water temperature prior to and following tide gate modification. Analysis of Variance (ANOVA). NS = Not significant (P>0.05); * = P<0.05; ** = P<0.01 *** = P<0.0001.

Site	Mean daily temperature	Daily maximum temperature	Daily minimum temperature
Test Site 1	**	**	NS
Control Site 1	NS	NS	NS
Test Site 2	NS	NS	NS
Control Site 2	NS	NS	NS
Test Site 3	***	***	***
Control Site 3	***	***	***

Dissolved oxygen

There were large fluctuations in daily dissolved oxygen levels at all sites. To a degree, the DO fluctuations followed temperature patterns with lowest concentrations recorded in the early morning and highest concentrations in the evening. Average daily DO levels were low at all sites (3-8mg/L) due to extended periods of low DO (<3mg/L). There were occasional periods of localised anoxic conditions where sediment had build up around probes which were removed from the data analysis. When re-sampled at the same sites a year later, there were significant increases in mean daily DO at test site 2 and 3 but not at any of the control sites. A significant decrease in DO minimum occurred at test site 1.

Table 5.3: Statistical comparison of dissolved oxygen concentrations prior to and following tide gate modification. Non-parametric Kruskal-Wallace rank sum test. NS = Not significant (P>0.05); * = P<0.05; ** = P<0.01 *** = P<0.0001.

Site	Mean daily DO	Daily DO maximum	Daily DO minimum
Test Site 1	NS	NS	*
Control Site 1	NS	NS	NS
Test Site 2	*	NS	NS
Control Site 2	NS	NS	NS
Test Site 3	*	*	NS
Control Site 3	NS	NS	NS

Conductivity

Daily conductivity showed very little fluctuation at the Kaituna River Sites (test site 3 and control site 3) and average daily conductivities (2000-2500μS/cm) were lower than the Maketū test sites (Test site 1 and 2) (6000-7000μS/cm). Due to resource limitations, conductivity measures were only collected at Maketū test sites and not control sites. When sampled one year later, there were significant increases in conductivity at all three test sites but no change at the control site. As well as higher conductivity readings, the penetration of salt was greater with the salt wedge moved further in land at test site 1.

Table 5.4: Statistical comparison of water conductivity prior to and following tide gate modification. Analysis of Variance (ANOVA). NS = Not significant (P>0.05); * = P<0.05; ** = P<0.01 *** = P<0.0001.

Site	Mean daily conductivity	Daily maximum conductivity	Daily minimum conductivity
Test Site 1	***	***	***
Test Site 2	***	***	***
Test Site 3	**	**	**
Control Site 3	NS	NS	NS

Discussion

Need for remediation

Prior to FFG installation, water directly upstream of tide gates was highly degraded. Upstream habitats were characterized by high water temperatures (24-28˚C) and frequent low dissolved oxygen events (<3mg/L). Large daily swings in dissolved oxygen concentrations, like those observed above the tide gates, are typical of streams with excess nutrients (Joy, 2015). Tide gates, through limiting tidal exchange, encourage the accumulation of nutrients and prevent mixing and periodic renewal of oxygen (Gordon et al., 2015; Kroon & Ansell, 2006). This drives the creation of 'dead zones' or hypoxic zones, which can extend over 100m upstream of tide gates (Gordon et al., 2015). Although there were no reference sites in this study to compare these findings with, these observations are typical of the degradation caused by tide gate presence (Franklin & Hodges, 2015; Pollard & Hannan, 1994).

Fish species richness was greater downstream relative to upstream at all sites, with noticeable absences of migratory species at some sites. Dissolved oxygen levels are considered a key factor in habitat quality and a measure of stream health. Dissolved oxygen frequently dropped to levels generally considered lethal to most New Zealand native fish species (Dean & Richardson, 1999). Similarly, maximum temperatures exceeded species preferred water temps (Boubee, Schicker, & Stancliff, 1991; Richardson, Boubée, & West, 1994). Species such as inanga and giant bully, appeared to be more susceptible to the combined effects of the physical barrier and poor water quality and were absent from several sites. Lowland streams and estuaries are important habitats for a range of fish species. Not only are they the location of spawning of inanga and smelt, they are pathways to upstream habitat for other fish species. Consequently, due to the proliferation of tide gates, cumulatively they may present large losses of habitat for native fish (Gordon et al., 2015).

Shortfin eels were the only migratory species to be present above all tide gates sampled. Poor quality habitats are more likely to be lethal for sensitive species and favor tolerant pest species, which were abundant at the sites (gambusia and goldfish). While inanga are poorly adapted to survive periods of hypoxia (Urbina & Glover, 2012), shortfin eels are known to have a greater tolerance of high water temperatures and low DO concentrations (Franklin, 2013; Dean & Richardson, 1999). Even so, hypoxia presents a significant challenge to fish and it is likely the species present above tide gates were forced to adopt strategies in order to survive. Aquatic surface respiration is a common response to hypoxia (Urbina & Glover, 2012). The use of nets to catch fish would have restricted the use of this strategy and it is likely that this explains the two large fish kill events that were encountered during the study.

Success of remediation

Tide gate modification was predicted to reduce the severity of negative upstream impacts through increased water circulation. While average daily DO significantly improved at two out of three test sites, there was no evidence of increased DO minima. Additionally, there were no significant decreases to water temperatures, rather water temperature increased at one site. Mixed changes following increased tide gate flushing are not unusual, Franklin & Hodges, (2015) observed reduced water temperatures and increased DO in some locations, whilst deterioration of DO concentrations occurred further upstream. These decreases in DO were thought to be the result of elevated oxygen demand as increased flushing remobilised deposited nutrients. Additionally it was suggested that reductions in water quality may only be a temporary, and may settle as sediments are flushed from the system over time.

Increased conductivity following FFG installation may have both positive and negative consequences. Increases in conductivity were recorded at all three test sites following tide gate modification. Greater tidal influx of salt water was attributed to the delayed closing of tide gates. At one site where the salt wedge position had been recorded, tide gate modification resulted in the salt wedge moving further inland. These changes could have ecological benefits by restoring a gradual transition zone between marine and freshwaters, that may restore migratory cues (Russell et al., 1998). It could also influence the location of inanga breeding, which typically spawn close to the fresh and salt water interface as fertilisation success can be reduced by high salinities (Hicks, Barbee, Swearer, & Downes, 2010). Changing the penetration of salt may have other ramifications, for example, negative impacts on human infrastructure, such as low-land agriculture (Johnston et al., 2005) and risk of compromising water abstrations. These risks would need to be assessed and managed appropriately on a individual basis.

Following FFG installation, rapid and sustained increases in migratory species richness occurred at all three test sites. Only one month following FFG installation, inanga and giant bullly were caught upstream at sites where they were previously absent. It is reasonable to attribute these changes to FFG installation as such changes were not observed at any of the control sites. Rapid recolonisation following tide gate modification was also documented in Boys et al. (2012). Fish are extremely mobile and can move quickly into defaunated habitats as they become available (Peterson & Bayley, 1993; Sheldon & Meffe, 1995), particularly diadromous species which can repopulate areas through marine dispersal. As inanga and giant bully are generally considered to be weak swimmers, it is likely their upstream passage was restricted by the tide gates until FFG installation provided an opportunity for these species to overcome this barrier. Furthermore, the same two species were only able to negotiate their way upstream under FFG influence at another site (Chapter 4), providing further evidence to the assertion that FFG's can enhance upstream fish passage.

As well as increased species richness post modification, there were measurable shifts in species abundances across the study period. Increases in the abundance of diadromous species at test sites were particularly remarkable. For example, inanga and shrimp numbers increased over 50 fold after FFG installation at one test site. However, species responses varied between sites and some increases occurred at both test and control sites. Varied responses to coastal rehabilitation are common (Simenstad et al., 2006). Natural variability in annual recruitment is well recognised and can be influenced by environmental factors in both marine and freshwater environments. It appears 2015 was a better year for recruitment for a range of diadromous species than 2014. Shortfin eels showed increases at all sites, including those which there had been substantial fish kills in the previous year. Although the magnitude of responses at control sites was lower than that observed in the test sites, this could not be derived from the seasonal 'noise'. Consequently, despite evidence of greater increases in diadromous fish at each test site relative to its paired control, this was insufficient to show statistically significant differences in response between test and control sites following tide gate modification.

In this study, a passive approach to rehabilitation was taken. As a result, upstream fish populations were enhanced following restored connectivity; however, improvements in habitat quality were limited. Such poor quality habitat is unlikely to support self-sustaining fish populations over the long-term, especially considering modified and degraded catchments are unlikely to provide suitable spawning habitat for species like inanga (Benzie, 1968; Hickford & Schiel, 2011). Therefore by restoring connectivity to poor quality habitat the creation of population 'sinks' has the potential to be a significant issue (Pelicice & Agostinho, 2008; Rolls et al., 2014). Populations sinks, a concept developed by Dunning et al. (1992), describe unproductive habitats that are dependent on recruitment from productive habitats to sustain populations. Where sink populations can no longer be supported by source populations, they can compromise long-term species survival. While this may be less of an issue for species which migrate upstream of the degraded habitat, it is certainly an area that would merit further consideration and research in future studies. Ideally, FFG installation would be part of larger restoration project with ongoing monitoring and additional actions to restore habitat.

The time frame of this study was a considerable limitation. Although the study was conducted over a full year, the FFG's were only operating for 5 or 10 months (depending on installation date). Additionally, disturbance of test sites compromised FFG function for periods of time further limiting the total time they were active. Short-term studies (less than two years) are not long enough for ecosystems to reach maturity and longer term studies of 5-10 years are recommended (Boys & Williams, 2012). Over time successional changes could take place that cannot be observed over such a short time frame. Furthermore, fish communities were sampled for a small amount of time prior to FFG installation. While more intensive sampling would have allowed a more accurate and closer monitoring of species composition changes, this would not have feasible in this study due to resource limitations. Additionally, due to the degraded nature of the sites, the probability of fish kills was high, therefore further sampling would likely have damaged fish communities. Alternatively, future studies could monitor fish communities using Dual-frequency Identification Sonar (DIDSON); however, use of this equipment was beyond the funding available for this research.

Long-term sustainability of fish populations depends not only on successful fish passage but also the maintenance of suitable conditions for resident species. Despite the short time frame and significant interferences to FFG operation, positive trajectories of species richness and abundance were observed following FFG installation. Rapid and sustained increases in migratory species richness as well as increases in species abundances were observed at test sites; however, due to small sample sizes and seasonal variability these changes could not be regarded as statistically significant. Water quality responses to FFG installation were mixed and highlight the potential limitations and pitfalls of a passive rehabilitation approach. FFG's would benefit from supplementary research over longer time periods to comprehensively investigate their effects on habitat quality.

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6

Synthesis: main findings & future research

Introduction: research topic and objectives

This thesis provides the first documented investigation of the efficacy of Fish Friendly Gates (FFG's). FFG's were designed by ATS Environmental as a means of mitigating the negative ecological impacts caused by tide gate presence. Management of fish passage obstructions is a key challenge for freshwater conservation and evaluation of fish passage solutions has been identified as a key research need (Franklin, Bowie & Bocker, 2014). While significant research has been carried out on retrofit options for some in-stream barriers, tide gates, despite their common use in coastal zones, have received little attention to date. The central aim of this thesis was to address this gap in knowledge, to inform water resource managers and to aid in the installation and design of future retrofits.

Central research aim:

To carry out a comprehensive investigation of FFG's as a retrofit option for tide gates. Including assessing their ability to provide ecological benefits, while maintaining acceptable levels of flood mitigation.

Within this central research aim, three fundamental areas of research were identified. Firstly, tide gates provide flood protection to valuable infrastructure, therefore it is important that any modification to their operation must not undermine this function. This was addressed in Chapter Three, where *tide gate operation was examined with and without FFG influence.* Secondly, altering tide gate operation aimed to mitigate ecological impacts of tide gate presence. In Chapter Four, *how altered tide gate operation affects fish passage was assessed.* Finally, long-term sustainability of fish populations depends on more than successful fish passage but the maintenance of suitable habitat for resident species. Thus in Chapter 5, *the longer term impacts of FFG's on upstream water quality (salinity & dissolved oxygen levels) and fish community structure were investigated.*

Main findings

While all tide gates may be barriers, their impacts as barriers are not equal

Throughout this research there were clear differences between individual tide gates investigated. This was evident in their operation, with up to 5.5 hours difference observed in total time closed between gates. Additionally, there were substantial differences in fish communities present upstream of tide gates. At several tide gates upstream communities were depauperate while at others a range of native migratory species were present upstream. These results correlate with other observations in the literature (Franklin & Hodges, 2015), and show that the impacts of an individual tide gate on upstream communities will vary on a case by case basis, dependent on stream environment, tide gate characteristics, season, and fish swimming capabilities.

FFG's enhance connectivity at tide gates

FFG installation successfully increased the duration, and width, that tide gates were held open for a range of tide gate designs. Opening duration was increased in part through later closing, but also through opening earlier in the tide cycle. As well as being held open longer, the opening distance of tide gates was greater under FFG influence. Increased opening may decrease water velocities and help evacuate flood water through reduced head-loss. Together these changes in tide gate operation restored some tidal fluctuations to upstream habitat; however, all sites maintained safe upstream water levels. Due to the adjustable nature of the FFG, operation can be altered on a site specific basis and an adaptive management strategy can be employed.

Facilitation of upstream fish passage with FFG influence

Increases in upstream fish passage past tide gates were observed under FFG influence. Some species (giant bully and inanga) were only able to successfully negotiate the barrier under FFG influence. Other species (whitebait and common bully) were able to ascend without FFG influence but significantly more individuals moved upstream when aided by FFG's. Increased upstream fish passage could play important roles in increased survival and recruitment to upstream populations. Additionally, following FFG installation, positive trajectories of species richness and abundance of resident species at test sites were observed, but due to small sample sizes these were not regarded as statistically significant.

Limited evidence of passive rehabilitation through FFG installation

Reinstating natural tidal flushing through FFG installation was predicted to rehabilitate degraded areas upstream of tide gates. Water quality is a key factor in the long-term success of resident species. Poor water quality - high water temperatures, low average dissolved oxygen levels and frequent anoxic events - was evident at test sites prior to FFG installation. There were no significant improvements in water temperature over the study period, but significant increases in average daily dissolved oxygen levels occurred at test sites. While this shows some benefit of saline flushing, there were no increases in DO minima post modification, so it is unclear how much ecological benefit these increases would provide. This highlights the need for care when re-establishing connectivity at particularly degraded sites for there is a potential risk of creating population sinks. Significant increases in salinity occurred at test sites and increased inland penetration of salt was observed, which could have important biological implications. Water quality results may have been limited by the short time frame and disturbance of FFG's and would benefit from further study.

Recommendations for practice

Recommendation one: remove redundant tide gates

While this study may have provided evidence of FFG's benefits relative to unmodified tide gates, in reality no retrofit option is truly "fish friendly". Even when modified, tide gates remain closed for a significant length of the tide cycle and in doing so disrupt natural connectivity, impede fish passage and degrade upstream habitat to some degree. Consequently, the best ecological outcome is tide gate removal. Admittedly, tide gate removal is not always a feasible option but it is important to demonstrate that removal is not possible before considering FFG installation.

Recommendation two: think logically about prioritisation

There are many in-stream barriers in New Zealand and due to lack of regulation, the location and extent of these barriers is often unknown. Due to limited conservation resources, it is not feasible to fix all barriers, therefore decisions must be made about what are the most important barriers to fix. An important consideration is the location of other in-stream barriers. Efforts to develop inventories of river infrastructure are becoming more common and where available this information should be utilised in decision making. For example, remediation of one barrier may provide little ecological benefit if another barrier is present further upstream or downstream. Tide gates, like other river infrastructure, have a limited lifespan before they need replacing to maintain functionality. Tide gate replacement is a prime opportunity for FFG installation as full replacements (tide gate with FFG) are available.

Recommendation three: effective site selection and communication with landowners pre and post FFG installation

When installing FFG's in urban areas effective communication with landowners pre and post FFG installation is critical. In this study, lack of notification and misconceptions of tide gate function resulted in vandalism of one of the FFG's. Therefore, communication and education with the community and landowners can be an important factor in the success of FFG installation. Site selection is also an important consideration for FFG installation. A catchment with existing flooding problems is not a good choice for remediation, unless flooding concerns are dealt with prior. Although tide gate modification may not exacerbate flood risk, FFG installation is unlikely to gain support from communities under these conditions.

Recommendation four: getting the most out of FFG installation

With FFG's, the number of weights and cable length applied determines how much tide gate operation is modified. The greater the weight applied, and the shorter the cable, the longer and wider tide gates will be held open. Therefore to mitigate the negative impacts of tide gates one could aim to have tide gates open as long as is possible (by applying a large amount of weight to the FFG's). Clearly this would need to be balanced against the protection of low-land infrastructure and risks assessed and managed on a individual basis. Additionally, management of FFG's can be altered across the seasons to optimise their function. Most diadromous freshwater species exhibit a seasonal peak in migration, therefore maximising the time tide gates are open during these periods may be beneficial. This could be achieved by adding more weights to the FFG or even using the FFG to fix the tide gate open for periods of time. Furthermore, management of FFG's could be altered between periods of low and high flood risk.

Recommendation five: consider additional site rehabilitation and monitoring

Evidence of passive rehabilitation though FFG installation alone is limited at best and care should be taken when reconnecting particularly degraded habitat. Long-term persistence of fish populations relies on suitable habitat for resident species as well as successful fish passage. Reinstating fish passage to poor quality habitat could potentially create population sinks. For example, low DO may have adverse effects on fish or habitat may not be suitable for species to breed. Therefore, ideally site and species specific rehabilitation actions should be considered alongside FFG installation, for example, the creation of off-stream pool habitat and planting of vegetation suitable for inanga breeding (Ellery & Hicks, 2009).

Future research

The objective of this research was to investigate the efficacy of FFG's as a retrofit option for tide gates. While this research aim was largely achieved, due to resource constraints and limitations some areas would benefit from supplementary research. Additionally, new questions and areas for investigation in future studies have arisen through this research.

Using tide gate differences in prioritisation

Clear differences in the impacts of individual tide gates as barriers were observed in this study. Not only did their operation differ widely, but also the fish populations upstream, with some gates proving more restrictive to fish passage than others. There was some evidence to link their impacts as barriers to the total time open per tide cycle. Future experiments could investigate this potential link by sampling upstream fish communities and tide gate operation across a range of tide gates. Due to limited conservation resources, not all tide gates can be retrofitted, therefore there is a need for prioritisation. It is logical that tide gates with more severe impacts would be more of a priority for remediation than those which pose less of a barrier. To sample above every tide gate to examine its impacts would be time and energy consuming while recording tide gate operation could provide a quick way to prioritise remediation.

Fish passage efficiency and delay

Subsequent studies could utilise technology such as Dual-frequency Identification Sonar (DIDSON) or elastomer tags which were outside the resources available for this study. Such technology would allow investigation of fish passage efficiency and delay that were not addressed by this research. Observations of pooled whitebait and elvers below tide gates suggest that even with the aid of FFG's not all fish were able to negotiate the barrier. Therefore it would be interesting to quantify passage efficiency (what percentage of fish achieve passage) and delay (how long it takes to achieve passage) with and without FFG influence. Fish have been observed making repeated attempts to pass a barrier (Franklin & Bartels, 2012), which raises another interesting area for investigation: how long will fish attempt to pass a barrier before moving on?

More rigorous study of water parameters

Future studies could measure upstream water levels more rigorously with the use of depth loggers. In this study, water level changes were monitored immediately above the culvert mouth, but with the use of several data loggers water level changes could be monitored at several upstream locations. Additionally, changes to salinity profiles were observed post FFG installation, to investigate the long-term ecological impacts of these changes would be an interesting area for further study.

Conclusions

Overall, this research suggests FFG's are an effective tool for facilitating upstream fish passage through tide gates. By increasing connectivity, FFG's can enhance upstream fish passage, particularly of fish considered to be weak swimmers. Whether FFG's can provide ecological benefits to degraded habitats is an area that needs supplementary research, therefore care should be taken when restoring connectivity to poor quality habitat. Furthermore, FFG's are not the perfect fix to the myriad of issues impacting freshwater ecosystems today but rather are one more item in the 'toolbox' of water resource managers. It is thought that even minor alterations that result in improvements in the distribution of freshwater fish species can help to maintain and enhance the health of stream ecosystems. Therefore FFG's certainly could have a role to play in freshwater conservation.

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