Stimulating Fish Migration: Adapting Fish Passage Design to Weaker Swimming Fish Species

Focussing on increasing the effectiveness of migratory aids for native fish species in New Zealand.

Final Thesis

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Abstract

The native fish populations in New Zealand have proven to be declining. There are various reasons for this change in population size, one of the biggest being structures that form barriers to migration. This shows the need for fish passage options that are better adjusted to these 'weaker' swimmers and their lifecycles (since most of these species migrate in their juvenile stage). Acquiring information about the swimming abilities of these species is critical in order to create fitting solutions.
In this paper the swimming endurance of inanga (*Galaxias maculatus*) is measured. This was done in the form of an endurance test in a swim tunnel.

The purpose of this research is to fill a gap in knowledge about the swimming capabilities of native fish species in New Zealand, in particular inanga. Filling this gap will help with the design of more appropriate fish passage options. The central question in this report is: *'What is the maximum water velocity in a culvert with a maximum length of 50 meters that will allow 90% of the inanga population to migrate through the structure*?'

The gathered results show the importance of not only decreasing fall height, but also adding baffles or other structures inside the culvert itself. These structures reduce water velocities and will create a place where inanga can rest when tired and thus provide a better chance of migration.
In addition to this, the results show that without any changes to the current culverts, on most velocities, 90% of the inanga population would not be able to overcome a 50-meter-long culvert.

The highest water velocity within a culvert that will still let 90% of the population pass is 0.16 m s^{-1} when the inanga itself swims at a speed of 0.2 m s^{-1}.

Acknowledgements

With completing this final thesis project my time as student Aquatic Ecotechnology will come to an end. I thoroughly enjoyed working on the subject of fish passage in New Zealand and being able to add new information to a not commonly published on field. I am also thankful for being able to experience this country and its warm and welcoming inhabitants.

I want to thank Dr. Paul Franklin and Dr. Eleanor Gee for sharing their knowledge and advise with me. I have learned a lot about fish passage options and the (native) fish population in New Zealand. Without their support I could not have completed this research project. In addition, I would like to express my gratitude to Peter Williams for setting up the swim tunnel as well as helping when problems would come up with the material. Moreover, I would like to thank NIWA and especially the members of the fish team for making me feel welcome during my stay in Hamilton and always being willing to help me out (or take me out in the field) when necessary.

Lastly, I would like to thank my in-school supervisor Anne Oele for offering me the support I needed in order to fulfil the expectations the HZ has set for its students.

Dana Nolte
24rd of May, 2019
Hamilton, New Zealand

List of definitions

Amphidromous	Migration between the two water types due to food availability.
Anadromous	Migration from sea to fresh waters to spawn.
One-way ANOVA	Analystical method to compare the means of two or more groups.
Burst swimming	Anaerobic movement at a high intensity with a short duration, <20 seconds.
Catadromous	Migration from fresh water to salt water to spawn.
Critical swimming speed	Measures the prolonged swimming mode. The experiment exposes fish to water velocities that proceed to increase over time until they reach a fatigued stage.
Diadromous	Fish that switch between salt and fresh water to complete their lifecycle.
Dispersion	The exchange between individuals of different sub populations.
Fall heights	Sudden change in water surface or bed level.
Fish migrations	Large distance coverage and often seasonal movements (often for reproduction).
Fish movements	Shorter distance movements. The distance travelled to find food or movements between day and night habitats.
ggplot	A data visualization package which is available for the statistical programming language R.
Potamodromous	Entire life cycle in fresh water and may migrate large distances inland.
Prolonged swimming	Lasts between 20 seconds and 200 minutes and ends in exhaustion depending on the swimming speeds.
RStudio	open-source integrated development environment (IDE) computer program for R. Which is a programming language for statistical analysis and graphics.
Sustained swimming	Aerobic movement at which a speed can be maintained for extended periods of time, >200 minutes.
Swim tunnel	Also known as flume. System that recirculates water in order to recreate water velocities in streams and rivers.
Unpaired two-sample T-Test	Analystical method to compare the means of two groups.
Whitebait	Juvenile fish. Consists of five native species, namely inanga (*Galaxias maculalus*), koaro (*Galaxias brevipinnis*), banded kokopu (*Galaxias fasciatus*), giant kokopu (*Galaxias argenteus*), and shortjawed kokopu (*Galaxias postvectis*)

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1. Introduction

The Waikato river is longest river in New Zealand, reaching a length of 425 kilometres. Sourcing from the central North Island volcanic zone, flowing to the sea whilst passing eight hydroelectric dams, Lake Taupō and merging with the Waipā River. The river passes rural as well as urban areas (Waikato Regional Council, 2008).

Along with the settlement of European colonies on the island, came many ecological changes within the catchment area. One of the first measured impacts was the introduction of the rainbow trout and later the brown trout into the Waikato waters. However, changes are not only made in previous centuries, also activities in more recent years drastically altered the water basin. One of these changes is the Tongario Power Development (TPD). This project required diversion of some of the water from the Rangitikei River catchment into the upper portion of the Tongariro River, so it could be used in the Rangipo Power Station, which discards the water into Lake Rotoaira. The natural outlet of the Rangitikei, the Poutu Stream, now carries very little water (Chapman, 1996).

There are eight different hydro electrical dams present in the Waikato river, however these are not the only obstructions migrating fish encounter in this river (Chapman, 1996). At this moment the river is known for its diverse waterbodies, for example rivers, lakes, mountain streams and ground water. These different types of water bodies are used for different (human) purposes, including irrigation, drainage, water supplies and recreational purposes (Waikato Regional Council, 2012).

1.1 Problem Statement

Many fish species, for example inanga (*Galaxias maculatus)*, have a significant migration in their life cycle. In order to maintain a healthy and diverse fish stock the various migrating species should be able to reach the right habitats at the desired time period. However, due to manmade structures like dams this process is disturbed. Inadequate or non-existent measures to provide fish passage slow down or even prevent migration of species towards salt or fresh waters. This can lead to a reduction in fish population numbers (Franklin, Gee, Baker & Bowie, 2018).

The current instream structures (culverts), but also certain fish passages in New-Zealand are not adapted and well suited for all the fish species that can be commonly found in the water body. This effect is magnified when looking at juvenile fish or whitebait (juvenile forms of five species of the fish family Galaxiidae which are native to New Zealand). These life stages often have lower swimming capabilities. This creates the need for a location specific solution, instead of a standardized design for every location in New Zealand. To increase the spawning rate and survival rate, the passage must be redesigned (Franklin, Gee, Baker & Bowie, 2018).

The problem statement therefore is the decline of the native fish populations due to limited migration options in New Zealand currently. In the time from 2009 to 2013, five species of native fish have been added to the at risk or even threatened column (Allibone et al. 2010; Goodman et al. 2014), making this an urgent situation. This shows a drastic decline in population size. In order to maintain the current ecosystem functions and a diverse fish stock, the survival rate of the juvenile fish must go up. This could be partially achieved by creating better fitting fish passage.

One way to adapt fish passage strategies to the native fish species is by looking at their swimming abilities, for example how long a fish can swim against a certain water velocity. In this report the swimming endurance of the New Zealand native inanga will be measured.

1.2 Research objective

The aim of this research is to fill a gap in knowledge about the swimming capabilities of native fish species in New Zealand, in particular inanga. By filling this gap, more options will become available for fish passage design. This is important for improving migration opportunities and overall population survival rates. In addition, the methodology can be improved by testing and developing sufficient knowledge on the effects of holding fish before conducting endurance trials.

1.3 Research questions

To make current structures a better fit to migratory native fish, the swimming abilities of the native species must be determined. One of the common native species found in New Zealand is the inanga. Unfortunately, not a lot of research has been done into the swimming abilities of this native species. This brings forth the following research: *'What is the maximum water velocity in a culvert with a maximum length of 50 meters that will allow 90% of the inanga* (Galaxias maculatus) population to migrate through the structure*?*'

To be able to answer this question correctly the following sub questions have been created:

- Does the holding time influence the swimming capabilities of the inanga?
- What is the difference in swimming capabilities between individuals?
- At what velocities would at least 90% of inanga be able to pass a 50-meter-long culvert?

The hypothesis set for the main research question is that a velocity above 0.6 m s^{-1} will cause significant problems for the majority of wild inanga (assuming the tested population has similar abilities to the wild population) trying to migrate.

1.4 Research method

The research presented in this paper has a combination of methods. However, the focus lies on collecting data through experiments in a controlled environment. In order to do so, a method has to be developed for measuring endurance within such an environment. This portion will consist of a literature review. After creating the method based upon the results of the literary research the experiments will take place. Results gathered from these experiments combined with a literature study into fish passage designs will form the base of the recommendations for future applications.

1.5 Contents of this paper

This research paper will specifically focus on inanga. Besides this, the focus is on culverts within New Zealand, however, the results of this research can be applied throughout New Zealand. The endurance measurements taken in this research can additionally be used for various other physical migration barriers that involve prolonged swimming against high water velocities. The results are also applicable to other native species with similar migration needs.

In the next chapter the background and baseline of the research project will be defined. In this chapter the steps that have already been taken to improve fish migration in New Zealand will be highlighted. This chapter is followed by an explanation of the method that will be used to obtain the necessary data on endurance. In the fourth chapter of this report the results will be displayed and explained in the chapter that follows. That chapter will also include recommendations on application of the results as well as recommendations for future research. The final chapter will show the conclusions of this research.

2. Theoretical Framework

2.1 Fish migration

Fish migration is a well-known phenomenon (Ministerie van de Vlaamse Gemeenschap, 2005). Fish reproduce, forage, and spend the winter in different areas, which can be far apart from each other (Coenen, Antheunisse, Beekman & Beers, 2013).

The distance that fish travel to reach these different areas can show a large variation between species or even between individuals from the same species. Migration itself can be categorized in three distinct sections: fish migrations, fish movements and dispersion. During a migration the distance is often very large and seasonal. Migration to spawning areas would therefore belong to this category.

Shorter distances belong to the fish movement section. The distance travelled to find food or movements between day and night habitats will be a part of this type of migration. The exchange between individuals of different sub populations is the main reason for dispersion (Ministerie van de Vlaamse Gemeenschap, 2005).

Based on the migrating behaviour fish species can be divided into several groups of which potamodromous and diadromous are the most common. Potamodromous species will spend their entire life cycle in fresh water and may migrate large distances inland. Diadromous species can be divided into three subcategories, namely anadromous (migration from sea to fresh waters to spawn), catadromous (migration from fresh water to salt water to spawn) and amphidromous (migration between the two water types due to food availability) (Ministerie van de Vlaamse Gemeenschap, 2005).

Stimuli that initiate fish migration can be external (food availability, predation, water temperatures, etc.) or internal (hormones, hunger, etc.). However, only a combination of external as well as internal factors will start the migration process. Due to this reason the time of migration will vary each year. Before spawning is the moment where the number of fish migrating is highest (Ministerie van de Vlaamse Gemeenschap, 2005).

In order to maintain a healthy and diverse fish stock the various migrating species should be able to reach the right habitats at the desired time period. Currently, fish are often prohibited from migration by barriers like weirs, culverts and pumping stations. The most natural solution to this problem would be to remove the barrier. Unfortunately, this is often not possible due to water management issues or due to a lack of space and finance. In cases like these, fish passages will enable the fish to cross these barriers (Coenen, Antheunisse, Beekman & Beers, 2013).

2.1.1 Fish migration in New Zealand

There is a large variety of freshwater sources within New Zealand, creating a large array of ecosystems and habitats. These habitats are used by over 50 different native freshwater species and around 10 different fish species used for sport fishing. However, there is an increasing amount of fish species at risk of decline in population numbers or even extinction present in New Zealand. In table 1 the increase of threatened species between 2009 and 2013 is visible (Goodman et al. 2014).

Table 1: Statistics of the status of the Freshwater fish species of New Zealand assessed in 2009 (Allibone et al., 2010) and 2013 (Goodman et al., 2014).

CATEGORY	TOTAL 2009	TOTAL 2013
Extinct	1	1
Data Deficient	0	1
Threatened—Nationally Critical	4	5
Threatened—Nationally Endangered	3	6
Threatened—Nationally Vulnerable	7	10
At Risk—Declining	13	14
At Risk—Recovering	0	0
At Risk—Relict	1	0
At Risk—Naturally Uncommon	6	5
Non-resident native—Migrant	0	0
Non-resident native—Vagrant	0	0
Non-resident native—Coloniser	3	3
Not Threatened	17	12
Introduced and Naturalised	20	20
Total	**75**	**77**

One of the explanations for this decline are the barriers to fish migration in the freshwater (and before saltwater) systems. These barriers can have a negative impact on the current fish populations in number and diversity. In New Zealand many of the native fish species migrate between freshwater and marine environments to complete a portion of their lifecycle. The majority of these fish species have their larval stage in marine environments and migrate into fresh waters as juveniles. The population numbers are therefore dependent on the success of this generation's migration (Franklin et al., 2018).

2.1.2 Inanga (Galaxias maculatus)

One of the species that is at risk due to a decline in population number is the inanga (*Galaxias maculatus*). Inanga is a freshwater species for most of its lifecycle. As can be seen in Figure 1, this species can be found in the southern hemisphere, and is commonly present in Argentina, Australia, Chile and New Zealand (IUCN, 2014).

Figure 1: Distribution of Inanga across the southern Hemisphere (IUCN, 2013).

The lifecycle of this diadromous species was a topic of controversy for quite some time. Captain Hutton, a scientist that studied the theory of natural selection to explain the natural history of New Zealand, believed that the adults would migrate towards the sea and spawn in that location. However, this was not believed to be true by several scientist in New Zealand, which were convinced of the inanga spawning in the estuaries or lagoons, after which the larvae then entered the sea. This controversy was not resolved until Philips published a paper in 1924 in which the observation of Galaxias maculatus spawning in the estuarine waters of New Zealand (Pollard, 1971).

This leads to the following lifecycle: Adults, who live in freshwater systems upstream, migrate towards tidal areas downstream in late summer and Autumn (from February till May). Amongst the vegetation after the peak of a spring-tide the spawning takes place. The eggs strand due to the decreasing water level and develop without any water present. The eggs hatch after the water has reached them once again. This means that hatching can be delayed for at least six weeks after fertilization. After this process the larvae are transported into the sea by the outgoing tide where they develop further over the winter period. The following spring, the juvenile inanga migrate upstream toward fresh water where they can be caught as whitebait. Once the inland streams and rivers have been reached the juveniles will grow to adulthood after which they migrate downstream again to spawn the following autumn (Pollard, 1971).

In New Zealand, inanga is one of the species that is commercially fished by the whitebait industry. Whitebait consists of juvenile fish that are captured and eaten in big numbers. One of the more popular whitebait dishes in New Zealand is the Whitebait Fritter, which consists of an omelette in which the juvenile fish have been mixed (Figure 2) (McDowall, 1990).

The total whitebait catch consists of five native species, namely inanga (*Galaxias maculalus*), koaro (*Galaxias brevipinnis*), banded kokopu (*Galaxias fasciatus*), giant kokopu (*Galaxias argenteus*), and

shortjaw kokopu (*Galaxias postvectis*). The species are listed in order of which species contributes the most to the whitebait fisheries (inanga) to the least (shortjaw kokopu). The migratory patterns of these fish were known to the Maori before the European colonisation and their ways of preparing and preserving this food has been discussed in some early reports (McDowall, 1990).
To prevent overexploitation, there have been many regulations and management strategies developed for whitebaiting (McDowall, 1991). However, even with these precautions set in place the population numbers are still declining (DOC, N.D.).

Figure 2: Whitebait fritters, a popular dish in New Zealand (Smith, 2012).

Whitebaiting is not the only reason for the decline in population size of the inanga, barriers that are found on the route to freshwater systems additionally form a threat to the *Galaxias maculatus*. Barriers to fish migration can be natural as well as artificial. Artificial structures are manmade barriers such as tide gates, culverts, weirs and dams, which are commonly found in streams and rivers countrywide (Franklin et al., 2014). To improve the situation for weaker swimmers like the juvenile inanga new mitigation methods for these barriers should be created.

2.2 Current strategies and passages

Barriers, physical as well as natural (oxygen levels, pH etc.), can prevent fish from reaching critical habitats that are necessary to complete their lifecycle. Building structures like culverts, weirs and tidal gates can negatively impact the water life in streams by, for example, altering habitats, disrupting stream processes and blocking organism movements between streams or habitats. When looking from a migratory perspective, tide gates are often the first barrier that is reached. These barriers close when the high tide comes in, coinciding with the time that fish migrate towards streams and rivers. If the fish have overcome the tidal gate barriers, there are more barriers to come (Franklin et al., 2018).

Weirs, dams and culverts change water velocities. A correlation between changes in habitats due to physical structures and an increase in exotic fish species (followed by a decline in native fish species) has been found (MacDonald & Davies, 2007; Jellyman & Harding, 2012).

Key features in obstruction of fish movements and other aquatic organisms are vertical drops, high water velocities, sharp corners, overhanging edges, a lack of shallow wetted margins and a total blockage of passage (for example a hydroelectric dam). For manmade structures with these features fish passage solutions are necessary to ensure passage of aquatic organisms to other habitats. In the case of natural features like waterfalls, cascades or naturally dry reaches mitigation strategies will not be applied (Franklin et al., 2018).

The challenge that is faced when creating fish passage design guidelines is accommodating for a range of different fish species that can be found in New Zealand by making sure weaker swimmers are included in the new designs. Up until now fish passage design was based on knowledge gained during research on large, strong swimming fish that often belong to the Salmonid species. This decision was made due to their economic importance (Mallen-Cooper & Brand, 2007; Williams, Armstrong, Katopodis, Larinier & Travade, 2012).
However, it is becoming more apparent that the designs created in the past do not provide passage to the variety of species that are normally present in streams and rivers. The current designs exclude small, weak swimming fish that are typical in New Zealand (Mallen-Cooper & Brand, 2007; Williams, Armstrong, Katopodis, Larinier & Travade, 2012).

2.3 Opportunity for improvements

To ensure a steady population size of native fish species within New Zealand new fish passage designs are needed. One of the factors that is critical in creating new solutions is the determination of fish swimming abilities. These abilities will be the guideline for which barriers fish are able to overcome (Franklin & Gee, 2019). The duration of swimming at a certain velocity (endurance) and the intensity (speed) at which fish swim are often used to describe the swimming abilities (Beamish, 1978).
There are three different, dominant swimming modes that are used by most researchers:

1.) Sustained swimming (aerobic movement at which a speed can be maintained for extended periods of time, >200 minutes).

2.) Prolonged swimming (lasts between 20 seconds and 200 minutes and ends in exhaustion depending on the swimming speeds)

3.) Burst swimming (anaerobic movement at a high intensity with a short duration, <20 seconds) (Beamish, 1978).

The critical swimming speed (Brett, 1964) is the most frequently used method to determine swimming performance (Plaut, 2001). It measures the prolonged swimming mode. The experiment exposes fish to water velocities that proceed to increase over time until they reach a fatigued stage. This measurement has often been used for water velocity design criteria. Another commonly used method of measuring swimming abilities is endurance. This provides information on how long a fish can swim at a certain velocity (Katopodis and Gervais, 2012).

The majority of the New Zealand species migrate upstream at a small size. This means that a more conservative design is needed (for example lower water velocities, more resting areas etc.) in order to ensure passage to these species when compared to salmonids, which migrate upstream as adults.

However, there is very limited data available on the swimming abilities of native New Zealand fish species. Inanga and shortfin eel are the only species for which information on swimming performance (either critical speed or endurance) is available (Nikora, Aberle, Biggs, Jowett & Sykes, 2003; Langdon & Collins, 2000). While there is limited information available on swimming speeds of native species, it is known that some of the species have developed climbing skills. The banded kokopu and koaro are both skilled climbers and can pass significant falls (MacDowall, 2000). This ability makes it more likely for these species to be able to pass barriers and eventually migrate upstream.

Certain aspects of physical barriers need to change or be removed to provide passage to the native fish. The features that form barriers in culverts are the following:

1.) Fall height (a sudden change in water surface or bed level), which is found to be a problem with passing through culverts. The energy it requires for a fish to negotiate fall heights and the ability to pass these sorts of obstacles depend on the individual abilities of the fish and their life stage (Franklin et al., 2018).

    Baker (2003) found that in the case of inanga, with an increased fall height the number of juveniles passing drastically lowered. Only 30% could pass a fall height of 50 mm and none were able to pass a 100 mm fall height. For adult inanga 75% could pass the fall height of 50 mm, however, none could pass a 200 mm fall height. Most climbing species can overcome certain fall heights, if there is enough wetted surface along the obstacle. However, where there is an undercut present even climbers are unsuccessful in passing the structure (Franklin et al., 2018).
2.) High water velocities. To make progress during upstream traveling, fish swimming speeds must exceed the water velocity (Laborde et al., 2016). In addition to this, when the water velocity increases, and thus higher swimming speeds are required, the duration at which the fish can swim at this speed decreases. This shows a trade-off between swimming speeds and distance that can be travelled (Franklin et al. 2018). This makes the relation between velocities in or over a barrier and the length of the barrier an important factor for fish migration.
3.) Water depth. Shallow pools at the outlets of culverts or weirs are areas where the water depth is often insufficient. This reduces the swimming capabilities of the passing fish due to the gills not being fully submerged. This leads to a reduced oxygen uptake which in turn affects the aerobic swimming capabilities (Webb, Sims & Schultz, 1991).

Factors that might influence passage over other structures are:

1.) Turbulence. When turbulence creates avoidant behaviour or velocities that exceeds swimming performance it can prohibit fish passage (Williams et al., 2012).
2.) Physical blockage. For example, tidal gates block entry to upstream rivers and streams completely when closed.
3.) Crest shape. More rectangular or sharp edges leave little low velocity margins (Baker, 2003).
4.) Attraction flows. Instream structures alter flow patterns and thus altering the cues that keeps fish orientated in the flow (Bunt, Castro-Santos & Haro, 2012).

3. Method

The method to determine endurance of inanga using a swim tunnel has been used to examine the swimming abilities of various fish species. Although this will not be the first time that this method has been used, there are various factors that differ per research paper and the influences that certain environmental aspects have on the outcome of the experiments. For example, little research has been done on the impact of different holding times, water temperature, feeding (and fasting) patterns and acclimation time. In order to start filling this gap in knowledge, the difference between fish that have been held for several weeks and fish that have been recently caught is examined.

To minimize the impact of other environmental aspects, such as the water temperature and feeding pattern, such parameters will be kept stable during holding as well as during the experiments. Furthermore, all experiments will be performed in the same manner and by the same person to ensure the results are reliable.

The experiments will take place from February until the end of April. At the end of March, the *Galaxias maculatus* will start migrating toward the tidal areas to reproduce. This aspect will make catching new individuals difficult. At the end of the experimental phase the results will be displayed in a graph showing the relation between water velocity and endurance as well as the differences or similarities between the two test groups.

3.1 Materials

The experiments are done in a swim tunnel (Loligo System SW10050, Figure 3). The discharge is controlled by a variable frequency drive and the water temperature is kept constant during the experiment using a chiller. Besides this, a pump to quickly change the water level in the tunnel itself and a camera is present at the test location. The final system present is a filtration system that consists of a filter as well as a UV light. The entire process is controlled via a computer in a nearby office (or the control room).

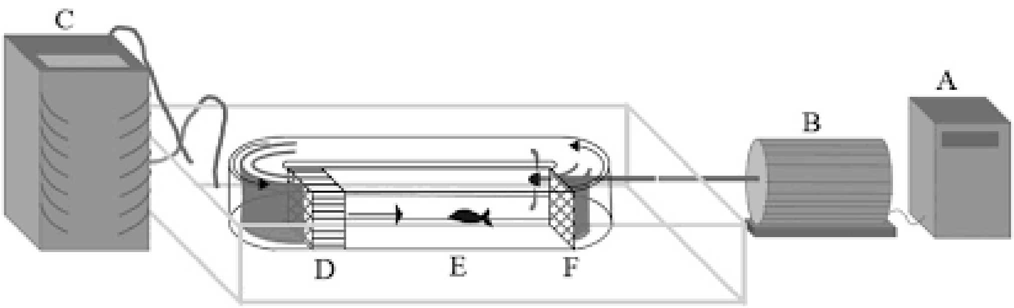

Figure 3: Swim tunnel with (A) = Variable frequency drive, (B) = pump, (C) = chiller, (D) = honeycomb matrix for flow alignment, (E) = swim chamber, and (F) = net (Laborde, González, Sanhueza, Arriagada, Wilkes, Habit & Link, 2016).

For catching test subjects, Gee Minnow traps (figure 4) are used. These traps are filled with fish food to attract targeted species.

Figure 4: Gee Minnow traps (Craig, Mifsud, Briggs, Boase & Kennedy 2015).

3.2 Procedure

3.2.1 Catching

To catch inanga the Gee Minnow traps are set out horizontally in various cross-sections of the river. Within these traps fish food is placed to attract individuals to the object. The traps are set out for 2 hours before removal from the stream. Fish are then transported to the holding facility and acclimated for at least 24 hours.

3.2.2 Holding

The fish are held in tanks with a water temperature of 18°C and are placed in a cold room with an air temperature of 16°C. Each tank houses around 40 fish. The feed used is frozen bloodworms, which will be fed to the fishes every two days. The fish experience a 12-hour light and 12-hour dark routine.

3.2.3 Individual variation & Effects of holding time

To create an effective fish passage structure, around 90% of fish should be able to pass the blockage (Lucas & Baras, 2001). This is done by looking at the variation in endurance between individuals of the same length class. If there is a large variety between individuals the water velocity within structures should be adjusted to a velocity at which even the weaker swimmers within the population can overcome the obstacle.

Since the experiments are done in a laboratory, the fish will need to be held in an unnatural environment for a certain amount of time. To determine the effect that holding times have on the endurance performance several tests in the swim tunnel are performed. The fish that are tested will

be held for over 12 weeks, six weeks and under one week. There will be 20 fish tested for each holding time.
The individuals that will be used for the testing were fasted for 24 hours after which they are placed in the swim tunnel where the water temperature is set on around 18°C. The acclimation period of half an hour without any velocity is initiated at this point. The tests are done in a dark room and monitored from the control room using a camera with an infrared light. The water velocities used for these experiments are 0.6 m s^{-1} and 0.8 m s^{-1}. This will remain stable throughout the entire experiment. The fatigue stage is reached when the fish is unable to remove itself from the back panel for three seconds. The tested individual is weighed and measured before it is placed back in a holding tank. The same process was repeated to test the difference in endurance measurements between individuals.

3.2.4 Endurance measurements

To reach the threshold of 90% mentioned in paragraph 3.2.3, the impact of a higher water velocity should be determined. This will be done by testing the endurance of several individuals at various velocities. The maximum velocity in structures that can form a barrier will be sought out by these tests. Once the endurance over several velocities is known the highest velocity at which 90% of the population can still migrate will be made apparent.
The individuals that will be used for the testing are fasted for 24 hours after which they are placed in the swim tunnel where the water temperature is set on around 18°C. The acclimation period of half an hour without any velocity is initiated at this point. The tests itself are done in a dark room and monitored from the control room using a camera with an infrared light. Seven different velocities are chosen for the experiments, namely 0.2, 0.4, 0.5, 0.6, 0.7, 0.8 and 1.0 m s^{-1}. These velocities will be randomly appointed to the test subjects and will remain stable throughout the experiments. The fatigue stage is reached when the fish is unable to remove itself from the back panel for three seconds. If the fish is not fatigue after one and a half hour the trial ends. The tested individual is weighed and measured before it is placed back in holding tank. For each chosen velocity at least 20 experiments with 20 different individuals will be performed.

3.2.5 Analyses

The raw data is collected and organized in excel and then transported to RStudio (an open sourced computer program used for statistical analysis and visualization) for the analysis. These analyses are visualized by using the ggplot package provided in RStudio. The codes used for these analyses can be found in appendix 4.
The maximal water velocity for a 90% passage rate is calculated with the following equations:

$$Stream\ velocity = swimming\ velocity - water\ velocity$$

$$Time\ needed = \frac{swimming\ velocity}{culvert\ length}$$

With these two calculations a lookup table (appendix 3) will be create in order to calculate the maximum water velocity.

3.3 Justification

The acclimation time and velocity are chosen based on research published in the past. Fangue, Cocherell, La Luz, Cech and Thompson (2015) experienced no advantage by letting fish acclimate overnight and experienced similar or even better test results after an acclimation time of one to two hours. For the acclimation velocity (or the lack thereof) the protocol of Fangue et al. (2015) is again used. This choice was made in combination with a test run of the swim tunnel which showed better acclimation results with no velocity than a low velocity. Furthermore, the chosen velocity levels are based on the results of Nikora et al. (2003).

In the literature various methods are used for determining when the fish is fatigue, for example when at least 50% of the body of the fish was against the back wall of the swimming chamber (Fangue et al., 2015), resting for over 20 seconds on the back wall (Lee, Farrell, Lotto, MacNutt, Hinch & Healey, 2003) or resting for over 30 seconds on the back wall (Nikora et al., 2003). The chosen strategy however, is to label the fish as fatigued if the fish is on the back panel for over 3 seconds. Test rounds performed before starting this research have shown that this is enough time to conclude that the fish is not able to remove itself from the back wall without causing unnecessary stress or harm to the tested individual.

The time limitation given in this experiment is 1.5 hours. If the fish is not fatigued by the end of the hour it will be measured, weighed and placed back in the holding facility. This choice was made based on endurance results of Nikora et al. (2003) which shows that with the minimal velocity used in this experiment, the fish should fatigue within one hour. Besides this, most of the culverts in New Zealand do not exceed 50 meters in length.
During an assessment of the barriers in the Waikato region only 14 of the 3365 culverts measured exceeded 50 meters. Additionally, the average of all culverts is 14 meters long. When the water velocity would be 0.1 m s^{-1}, it would take the fish only around 140 seconds, or a bit more than 2 minutes to swim through a culvert of this length. Which means that even with the lowest chosen velocity wild fish should be able to cross the culvert within one hour. The same time limitation was used by Kern, Cramp, Gordos, Watson, & Franklin in endurance experiments published in 2018.

The amount of fish that will be tested on the same velocity is chosen to create a reliable outcome, while taking experiment time into account. This is partially determined by the outcome of the swimming tests that show the individual variation. The larger the variation between individuals of the same length class, the more fish will be used for the experiments.

4. Results

4.1 Effects of holding time

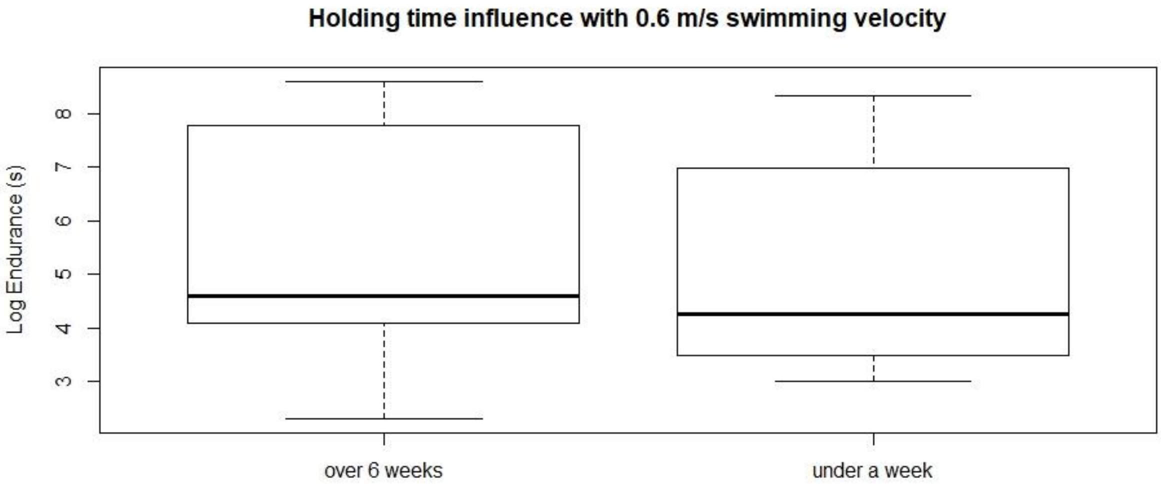

Figure 5: Boxplot showing the different holding time groups at a velocity of 0.6 m s^{-1}. The box itself represents the bulk of the fish, namely 50% of the results. The black line within the box shows the median, or the mid-point of the results. The dotted lines above and beneath the box represent 25% of the data each.

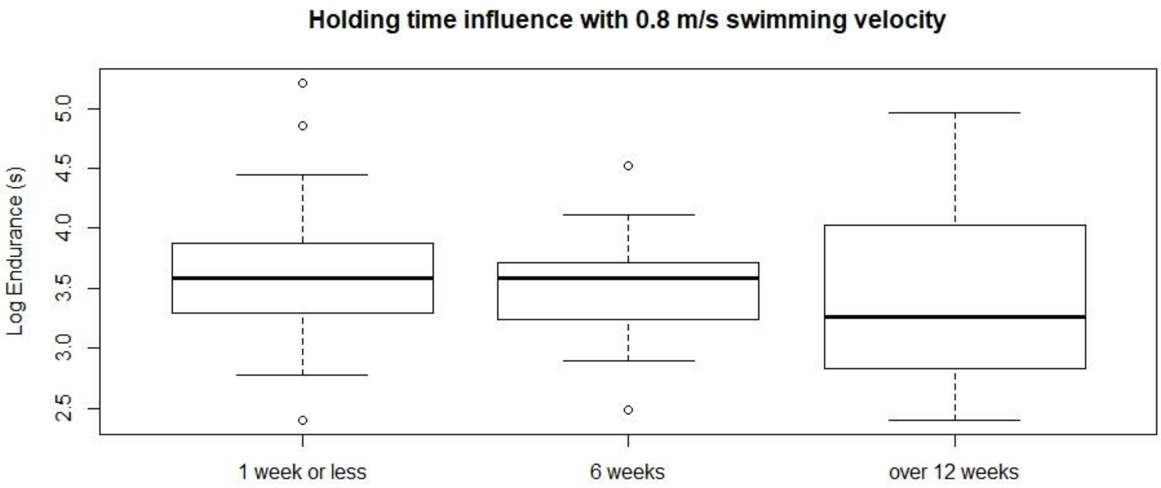

Figure 6: Boxplot showing the different holding time groups at a velocity of 0.8 m s^{-1}. The box itself represents the bulk of the fish, namely 50% of the results. The black line within the box shows the median, or the mid-point of the results. The dotted lines above and beneath the box represent 25% of the data each. The points displayed outside these lines are outliers, results that do not comply with the bulk of the data.

Figure 5 and 6 show the results of the holding time measurements in a boxplot. On the left the data collected from the individuals held for less than a week is represented, in the middle the data of fish held for six weeks and on the right the results for fish held for over 12 weeks is shown. The lines in the middle of the boxes show the average endurance, which is located at almost the same height for all groups. This shows that there is no significant impact of holding fish for a longer time period.

Measurements done at 0.6 m s^{-1} show a higher variability than individuals tested on 0.8 m s^{-1}. One of the reasons for this difference could be a change in choice of swimming mode. Individuals might choose burst or sustained swimming at 0.6 m s^{-1}, whereas on a higher velocity almost all individuals will use the same swimming mode. This is the main reason for using 0.8 m s^{-1} for the individual difference analysis.

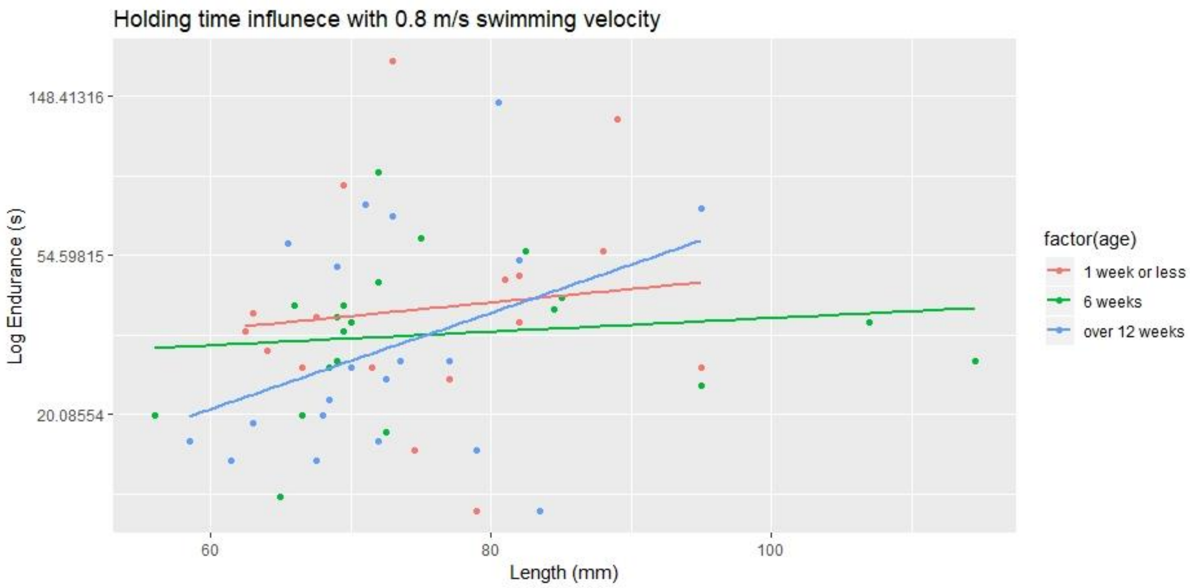

Figure 7: graph showing the influence of the different holding times at a velocity of 0.8 m s^{-1}.

Figure 7 above shows a scatter graph of the holding time measurements with a regression line for the two holding time groups (red is held for less than a week, green is held for six weeks and blue shows the individuals held for over 12 weeks). Although the regression lines show a slight difference, the individual points show a large variety between individuals. This variance makes it difficult to examine the true extent of the effects of holding test subjects.

This graph can also be used for the individual differences. Although most individuals seem to cluster around 40-50 seconds, there are a few individuals that swim shorter or longer. This shows that there is a large array of swimming abilities based on endurance measurements within one population.

The effect of length at this velocity seems to have little effect of endurance. The longer fish do not seem to have a better endurance rate than shorter individuals. The average length of around 70 mm shows the largest individual differences.

Table 2: Table showing a performed one-way ANOVA test, showing no significant difference between the tested holding times.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)
age	2	1878	939	0.882	0.42
Residuals	54	57494	1065		

The table above shows a one-way ANOVA test conducted in Rstudio. The F value represents the P value. A P value lower than the significance level of 0.05 shows that there is a significance difference between two tested groups. In Table 2 this value is above 0.05, meaning that an increased holding time does not have a significant influence on the endurance results. This shows that there is no significant difference in endurance between all tested holding times.

Table 3: Table showing a T-Test, showing no significant difference between the tested holding times of under a week and six weeks.

```
        Two Sample t-test

data:  Endurance by age
t = -1.2558, df = 35, p-value = 0.2175
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -35.462653   8.356771
sample estimates:
     mean in group 6 weeks mean in group under a week
                  36.80000                   50.35294
```

Table 3 shows the results of an unpaired two-samples t-test. The table above are the results retrieved from Rstudio. The P-value shows the significance level of the t-test, where a value lower than 0.05 means there is a significant difference between groups of under 1 week and six weeks in holding. This number in the table above is higher than the set significance level, showing there is no significant difference between holding times and confirming the results of the one-way ANOVA test.

Table 4: Table showing a T-Test, showing no significant difference between the tested holding times of under a week and 12 weeks.

```
        Two Sample t-test

data:  Endurance by age
t = 1.6204, df = 38, p-value = 0.1134
alternative hypothesis: true difference in means is not equal to 0
95 percent confidence interval:
 -117.3615 1058.9615
sample estimates:
mean in group 1 week or less  mean in group over 12 weeks
                       510.0                         39.2
```

The table above shows the results of an unpaired two-samples t-test. The table above are the results retrieved from Rstudio. The P-value shows the significance level of the t-test, where a value lower than 0.05 means there is a significant difference between groups of under 1 week and 12 weeks in holding. This number in the table above is higher than the set significance level, showing there is no significant difference between holding times and confirming the results of the one-way ANOVA test.

4.2 Endurance trials

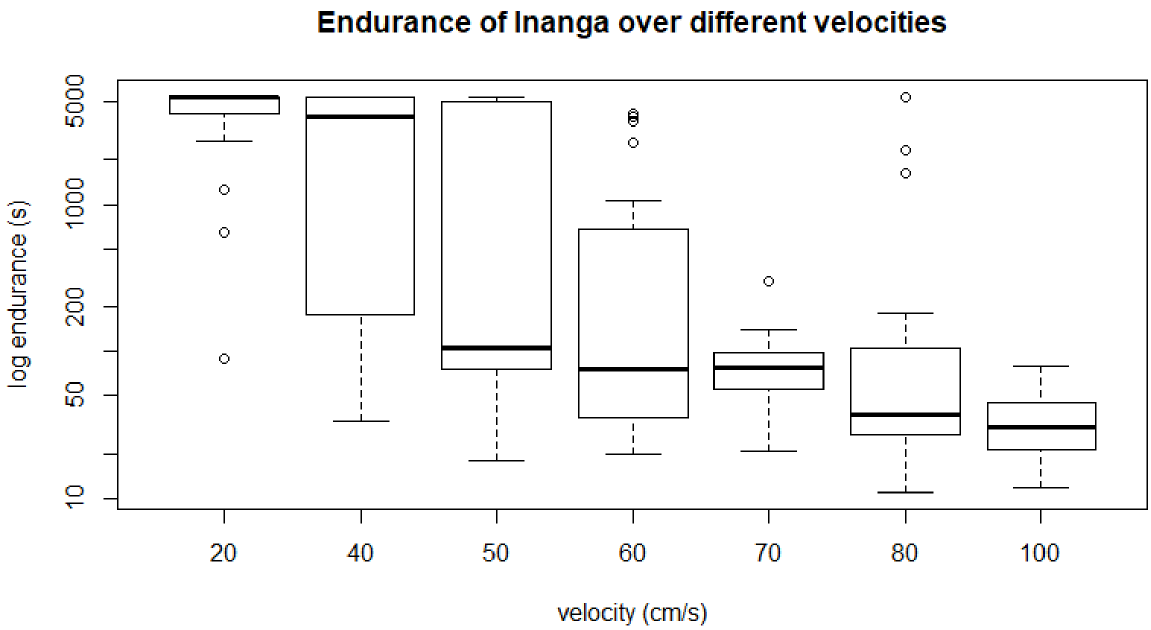

Figure 8: Boxplot showing the endurance of inanga based upon different velocities. The endurance is placed on a log scale. The box itself represents the bulk of the fish, namely 50% of the results. The black line within the box shows the median, or the mid-point of the results. The dotted lines above and beneath the box represent 25% of the data each. The points displayed outside these lines are outliers, results that do not comply with the bulk of the data.

The figure above shows the endurance on a log scale over the different velocities tested. In the boxplot a large drop in average endurance between 0.4 m s^{-1} and 0.5 m s^{-1} becomes visible. After this point the median shows a slight decrease over the remaining velocities.

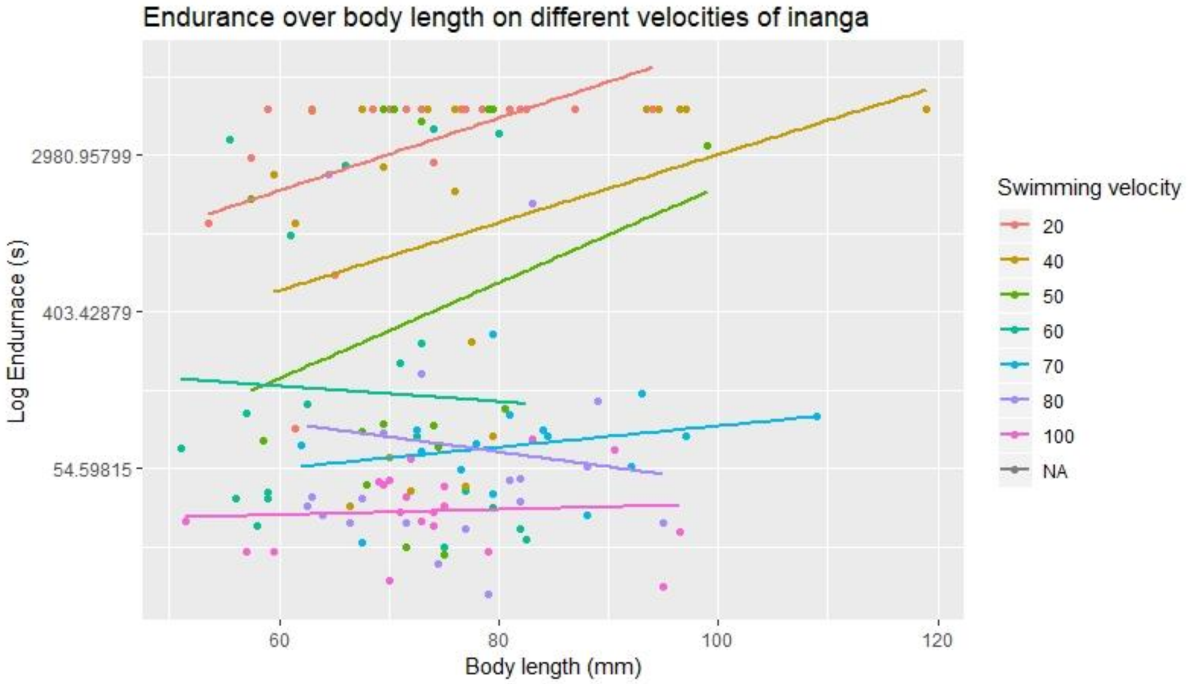

Figure 9: Graph showing the influence of length on endurance over different velocities.

Figure 9 shows the endurance over length with the different velocities shown in the different colours. There is a clear division between the lower velocities and higher velocities visible, as you can also see in figure 8, making velocities below 0.4 m s^{-1} the lower velocities and high endurance output and everything higher than 0.6 m s^{-1} the higher velocities with low endurance rates. The line that represents 0.5 m s^{-1} sits right in between those two groups.

The body length of the fish seems to influence endurance rates at the lower velocities. This effect however decreases when swimming velocities increase. In order to test the significance of this difference an unpaired one-way ANOVA test was conducted. The results in the table below (table 5) show a P value (shown as F value in the table) that is located above the significance level of 0.05. This shows when including all velocities, body length does not have a significant influence on swimming abilities.

Table 5: Table showing the results of the unpaired one-way ANOVA test based on the influence of body length.

	Df	Sum Sq	Mean Sq	F value	Pr(>F)	
Length	1	16064143	16064143	3.214	0.0753	.
Residuals	130	649778759	4998298			

Table 6: Table showing the maximal culvert length based on the average swim time of the weakest 10%.

swimming velocity (m/s)	average swim time weakest 10% (s)	max culvert length (m)
0.2	369	176.2
0.4	37.5	8.1
0.5	19	4.3
0.6	23.5	6.9
0.7	25.5	8.9
0.8	13.5	5.1
1	12.5	5.4

Table 6 shows the maximal length of a culvert based on the endurance of the 10% which displayed the weakest swimming abilities. The average endurance of this 10% is multiplied with the set swimming velocity, creating the maximal length.

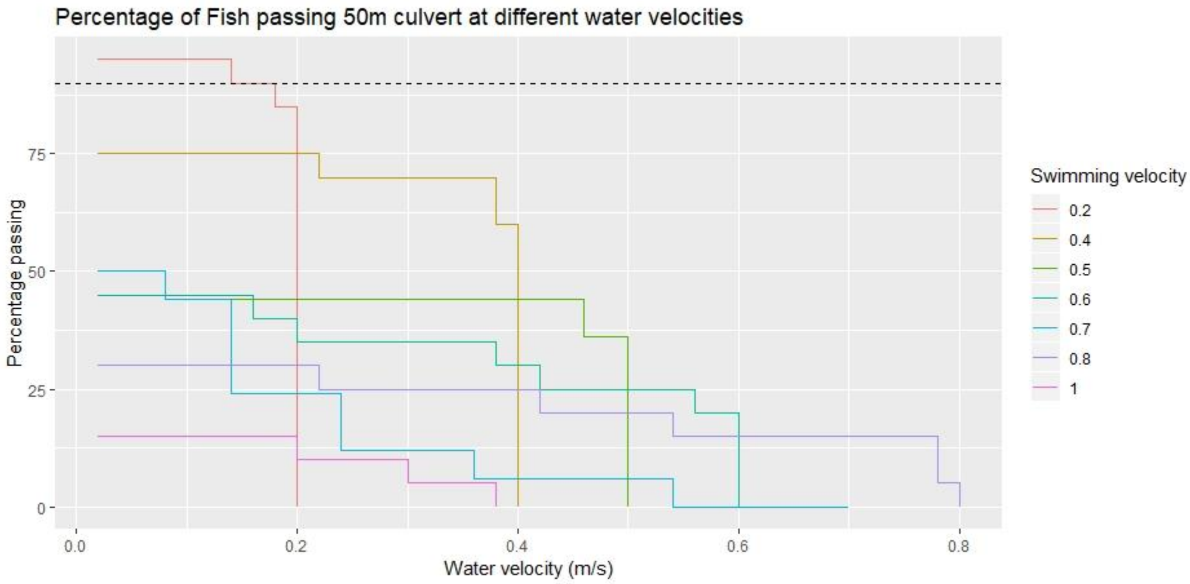

Figure 10: Graph showing the percentage of fish that would be able to pass a 50-meter culvert on different combinations of water and swimming velocities.

The figure above shows passing success at different water velocities of a 50-meter culvert. Almost all culverts within the Waikato region are smaller than 50 meters, meaning that the results shown in the figure above are applicable to most culverts in the region. The different colours represent the different swimming velocities tested. The graph displays steps rather than fluent lines as it shows the decrease each time an individual (from the 20 fish tested at each velocity) is not able to surpass a certain water velocity.

The dashed line shows the 90% passing mark. Only at 0.2 m s^{-1} swimming velocity this line is surpassed. This line drops below 90% after reaching a water velocity of 0.16 m s^{-1}.

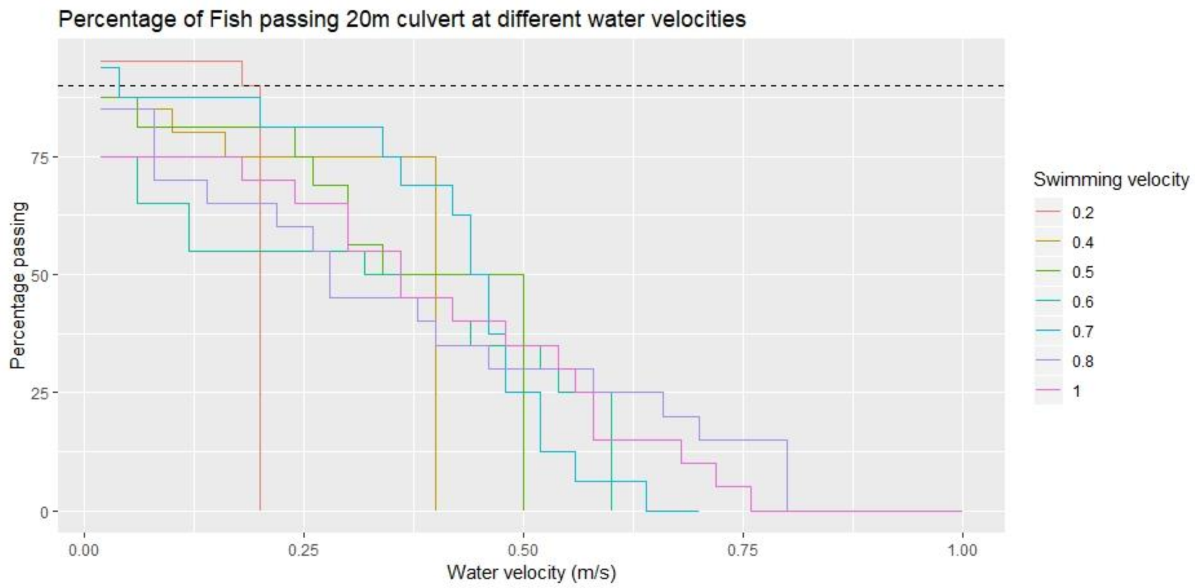

Figure 11: Graph showing the percentage of fish that would be able to pass a 20-meter culvert on different combinations of water and swimming velocities.

The same principles and calculations done for the 50-meter-long culvert were repeated for a 20-meter-long culvert. This is the average width of motorways in New Zealand and thus most culverts will have this length. The dashed line shows the 90% passing mark.

In figure 11 there is a small amount of water velocities at which 90% of the fish can pass with a swimming velocity of 0.7 m s^{-1}. This means that on a swimming velocity of 0.2 m s^{-1} fish will be able to pass through the culvert until a water velocity of 0.18 m s^{-1} and with a swimming velocity of 0.7 m s^{-1} until 0.02 m s^{-1}.

5. Discussion

From analysing the first portion of results, retrieved from the holding time experiments, there is no significant difference presented between the fish held for under one week, for six weeks and individuals held for over 12 weeks. The difference visible in figure 7 can be traced back to individual differences in endurance. This means that fish can be held for over 12 weeks before completing the experiments. This finding will make performing experiments near migration dates easier, since more fish can be brought back to the holding facility to test in the experimental setting.
As can be derived from the same figure, the individual differences are quite large. This would suggest that choosing a bigger sample size for endurance experiments would give a more reliable outcome.

Now focussing on the main portion of the project, the endurance measurements. Figures 8 and 9 show a large difference between the mean endurance of 0.4 and 0.5 m s^{-1} swimming velocities, giving the impression that there is a turning point between those two velocities. Besides this, these velocities also give the largest variation in swimming time. This result could point to fish choosing different swimming modes (burst or sustained swimming) around these velocities, however, to prove this hypothesis, more research into this topic is necessary.
Figure 10 shows that with an increase in velocity, there is a decrease in the influence of fish size on swimming capabilities. The length of the fish does play a significant part in the endurance on lower swimming velocities like 0.2 and 0.4 m s^{-1}. In addition, the lower and higher velocities (except for 0.5 m s^{-1}) are divided into two separate sections when looking at endurance times. This may be related to the before mentioned choice of swimming mode.

Based upon the numbers gathered during the trial (appendix 9.1) the only water velocity at which 90% of the inanga population can pass a 50-meter culvert, is up to 0.16 ms^{-1}. These results are consistent with the results retrieved by Nikora et al. (2003). This means the velocity must be very low in order to hit the 90% mark, which would be unrealistic in terms of design for these types of structures. This points toward This result suggests that baffling the interior of culverts to ensure a continuous, low velocity as well as sufficient resting areas would improve current structures.

However, when looking at the results a couple of limitations should be considered. The first limitation is the difference between results collected in an experimental setting, where the entire environment is controlled and what can be observed in the wild. Behaviour might change when the tested individuals are placed into this controlled environment due to for example stress. In addition to this, the physical environment also changes. In nature there will always be lower velocity areas. For example, in culverts the sides will act as one of these lower velocity areas. Inanga will seek out these areas which might make them able to overcome this structure, even though the velocity of the cross-section of the culvert might be too high.
The most obvious way to decrease the effects of this limitation would be to perform field surveys as well. The things to keep in mind when testing in the field would be temperature and velocity fluctuations as well as changing substrates.

Moreover, the choice of materials used can influence outcomes. As shown by Kern et al. (2018) the types of swim tunnels can cause differences in variability of flow conditions inside the flume. Larger flumes often give a higher endurance result than the smaller versions. This can be due to the higher variability in water velocities within smaller tunnels as well as different swimming techniques applied by the fish in different sized flumes (in larger flumes fish often use a swimming technique that saves energy by bursting to the front of the flume and drifting to the back with the currents). This means that when applying these results to nature, the effect of using an experimental setting should be taken into account. Smaller flumes will give more conservative results, compared to larger ones.

Changing material can also help create more accurate results. Free-surface flumes tend to resemble flow conditions within some structures, for example boxed culverts, more closely than a swim tunnel with no free-surface. Longer tunnels tend to show more of the natural behaviours. To take the influence of material on results into account it is important to know the extent of the influence, the differences it causes and compare results with results from different research projects and field measurements.

Additionally, chosen methods might influence the results. There has been little to no research done on the effects of different methods on the results. As shown in chapter 3.3 different authors have applied different methods to measure endurance. The first differences are already noticeable in acclimation time. While some researchers let fish acclimate overnight, others will only let this period go on for the duration of a couple of minutes. Other than the observation that acclimation overnight does not have a (positive) impact of Fangue et al. (2015), there is no information on effects on longer or shorter acclimation periods. To know the extent of these impacts more research into the topic is necessary.
In addition to this, the time the fish spends on the back panel before concluding the experiment also differs between methods. While one chooses to lower the velocity after a couple second, another method shows this only been done after half a minute. Some fish might use the back wall as an opportunity to rest, while they have not reached exhaustion. Yet, to find a balance between fish reaching exhaustion before stopping the experiment and creating a method that harms the test subjects as less as possible is difficult. More research into this aspect of the method would be beneficial.

Besides this, stopping experiments at the one-and-a-half-hour mark has an impact on the range displayed in the results in this paper. The slopes of the endurance graphs are influences by the limitations set. When looking at the work of Nikora et al. (2003), inanga can swim up to a couple of hours on lower velocities. This means that the endurance results would be more spread out and the slopes of the lower velocities would change. A way to overcome this is either remove the time limitations or apply more statistical analysis, like the survival-statistics, to the gathered data.

Another factor is group behaviour in fish. This behaviour might also have an impact on the endurance of an individual or strategy used in the case of encountering a barrier. Inanga are known to swim in group formations, which mean they might experience benefits in the form of lower velocity areas when swimming behind each other.

The last aspect of the method that will be discussed is running individual fish one time. The impacts of using one fish for multiple experiments are unknown. Testing the impact of running multiple trials with one fish could give insight into the training abilities of inanga. If there are no changes in results one fish could be tested for multiple times, decreasing the amount of wild fish needed for experiments.

It has been proven that water temperature can have significant effects on swimming abilities of fish. In nature the water temperature will change with the seasons or even from day to day. To get more accurate results of how many fish will be able to pass the boundary throughout the year, tests with different water temperatures should be conducted.
When looking at natural conditions, also the change between day and night plays a role. A conclusive research on the effects of light or dark on swimming capabilities has not yet been conducted. If tests conclude a lower level of capabilities with a certain amount of light, conditions in a culvert (or other types of obstructions) should take these disadvantages into account when designing a structure. The

design should be fitted to the conditions that generate the highest disadvantages to ensure a good passage at each moment.

Lastly, to be able to fully adjust each barrier to all the fish species that are native in New Zealand and show a decline in population numbers more research into various aspects of this topic is needed. One of the most important areas that require more in-depth research is the swimming capabilities of different native species which might have a different swimming pattern or strength. For example, bullies (*Gobiomorphus sp.*) often remain on the bottom of the water column and hold onto substrate when a resting period is needed. This means this species would have different requirements in terms of passage design. Accordingly, further research comparing a variety of native species is required to build a comprehensive knowledge of their associated swimming capabilities and therefore structure requirements to be able to accommodate all species.

5.1 Recommendations for application

As mentioned above, the results of the trials show that on the highest velocities the weaker swimming inanga can only overcome a culvert of 13 meters long. This shows that when solely based on the endurance measurements of inanga, various culverts will have to be adjusted to improve the migration options for this native fish species. As mentioned in the theoretical framework chapter, the aspects that can inhibit a fish movement are vertical drops, high water velocities, sharp corners, overhanging edges, a lack of shallow wetted margins and a total blockage of passage (for example a hydroelectric dam) (Franklin et al., 2018).

Because removing barriers like culverts or replacing them with a good-practice designs not always possible, small adjustments can also bring an improvement in fish migration numbers without it being a large project. The aspect of culverts that forms a barrier to fish migration, which is linked to the results in this report, is the velocity inside the structure. The water velocities often exceed the swimming capabilities of fish, in the case of a 50-meter-long culvert 0.16 m s^{-1} and the 20-meter-long culvert 0.18 m s^{-1}. Placing baffles inside culverts is often used as a way to modify the high, uniform velocities and improve fish passage (MacDonald and Davies, 2007). Baffles are typically blocks or sills that are placed at the base and/or wall of a culvert in a regular pattern. This reduces the water velocity, creates low velocity resting zones and develops flow patterns to guide fish through the obstacle. Different options for baffling patterns are available (figure 12), although spoiler baffling is recommended (Farnklin et al., 2018).

When looking at other types of baffles, for example weir baffles, they also show a decrease in flow velocity as well as provision of resting areas. However, these type of structures also create a higer flow velocity at the top, still forcing fish to use burst swimming modes to progress upstream. The aim is to avoid this type of swimming when creating fish passage solutions due to the (by definition) short time period individuals can swim in this mode. When fish are repeatedly presented with the use of burst swimming, they might fatigue quite fast and drift downstream again. Spoiler baffles do not have this aspect and create an evenly distributed flow pattern. This is the reason why a spoiler baffle is recommended (Stevenson, Kopeinig, Feurich & Boubée, 2008).

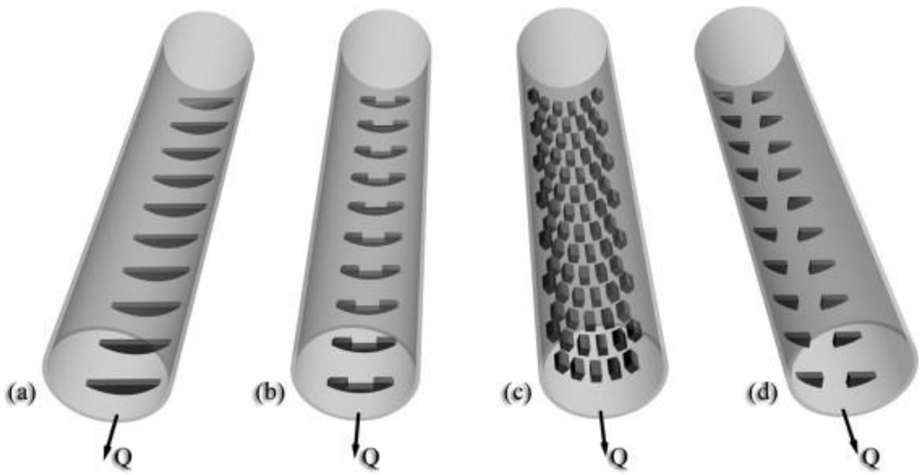

Figure 12: Examples of possible baffling patterns that have been proposed to facilitate fish passage (a) weir baffle; (b) Alberta fish weir; (c) spoiler baffle (recommended); (d) slotted weir baffle (Feurich & Olsen, 2012).

Adjustments to overcome a large drop are also necessary. The lowered water velocity is unnecessary if fish cannot reach the inside of the culvert. This can be done by installing various types of ramps. Recommended is to place a more natural ramp way. This ramp is created by the placement of various rocks to create a smaller drop, in addition to creating resting areas as well as imitate natural stream conditions and creating new habitats. This technique divides the drop over a greater distance (Franklin et al., 2018). General design principles can be found in appendix 2.

If it is not possible to install a natural rock ramp due to location or space restrictions, concrete and artificial substrate ramps will form a solution. There are two types of concrete structures, namely formal structural designs (a concrete ramp into which ricks are embedded), grouted rock-ramps (takes a more natural form, where concrete is used to create a fish ramp) and artificial substrate ramps (figure 13). Note that for the best results a good medium between ramp length, slope, wetted margins and substrate that accommodates all native species should be found.

Figure 13: Examples of an artificial substrate ramp (top left), a grouted rock-ramp (top right) and a formal structural design (bottom) (Franklin et al., 2018).

For obstacles where the previously mentioned structures do not form a solution a bypass could be the only effective solution to enhance fish migration success in that case. There are two main types of bypasses, nature-like (mimics the natural stream conditions) or technical (structural bypass like the 'De Wit' passage) fishways. The nature-like fishway will generally take up more space but are generally more suitable for multiple fish species and life stages. While the technical solutions often need less space, however, it might not form a solution to fish that are too big or small and display different swimming patterns (for example, staying mostly on the surface) (Franklin et al., 2018; Ministerie van de Vlaamse Gemeenschap, 2005).

6. Conclusion

In order to ensure stability or even an increase in native fish population numbers an increase in migratory success is needed. To do this, sufficient migration routes and thus passable structures are key for inanga. Changes to current culverts in New Zealand must be made to provide this aspect.

As seen in the results, the velocity would have to be lower than 0.16 m s^{-1} for 90% of the inanga population to overcome a 50-meter-long culvert. However, this would be impossible to implement in many cases. To increase migratory success while still respecting financial and technical aspect of culvert management, the best option would be to baffle the interior of culverts in order to ensure continuous low velocity zones as well as sufficient resting areas. Besides this, decreasing fall height at culvert outlets will additionally improve migration success.

Coming back to the research questions mentioned in the beginning of this research paper and beginning with the main question: 'What is the maximum water velocity in a culvert with a maximum length of 50 meters to allow 90% of the inanga *(Galaxias maculatus)* population to migrate through the structure?' The answer to this question is only at water velocities up to 0.16 ms^{-1} the 90% mark is surpassed and thus this will be considered the maximum water velocity within a culvert. The other velocities have a much lower passing rate.

Now looking at the sub questions, starting with individual differences within one population. It can be concluded that there is large variability between individuals. Consequently, this makes it difficult to truly determine if there is an impact of holding fish. However, based on the data collected through this project, it is safe to assume there is no real impact on the swimming abilities when holding fish for up till 12 weeks.

It can also be concluded that the hypothesis of velocities above 0.6 m s^{-1} causing a migration barrier set at the beginning of the report can be accepted. However, it is worth to point out that the velocity at which problems start to form lies below 0.6 m s^{-1}.

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8. Appendices

8.1 Appendix 1: Excel sheets with raw data

Table 7: Raw data directly retrieved from experiments.

Fish	Endurance	Weight	Length	Oxygen_s	Temp_Sta	Oxygen_e	Temp_end	Velocity
1	30	1.11	64	88.3	17.8	88.2	17.8	80
2	5400	3.96	93.5	88.9	17.8	89.1	18	40
3	34	2.14	75	89.1	18	89.1	18	100
4	648	1.2	65	89	18	89.2	18.1	20
5	19	0.89	57	89.1	18	89.1	18.1	100
6	1260	1.09	53.5	89.1	18	89.3	18.1	20
7	2328	0.82	59.5	89.5	18.2	89.5	18.1	40
8	37	1.5	67.5	89.5	18.2	89.4	18.2	80
9	38	1.52	71.5	97.6	18.1	97.5	18	100
10	85	1.51	69.5	97.7	18.4	97.7	18.1	80
11	276	2.23	77.5	97.6	18.15	97.5	18.15	40
12	5400	1.91	73	97.5	18.17	97.7	18.2	20
13	48	3.14	82	97.5	18.25	97.5	18.25	80
14	28	0.73	51.5	97.5	18.22	97.5	18.2	100
15	34	1.14	62.5	97.4	18.2	97.2	18.1	80
16	5400	2.11	78.5	88.3	18.02	89.4	18.2	20
17	5400	2.13	82	89.3	18.2	89.5	18.2	20
18	5235	0.85	63	89.3	18.2	89.5	18.2	40
19	128	3.46	89	89.3	18.2	89.1	18.2	80
20	34	1.07	66.5	88.9	18.2	89	18.2	40
21	5400	1.73	71.5	89	18.2	89.2	18.2	20
22	36	2.53	82	89.1	18.2	89	18.2	80
23	46	1.35	69	88.9	18.1	89.2	18.2	100
24	5400	3.32	87	89.7	18.2	89.5	18.3	20
25	31	1.5	71	89.3	18.2	89.4	18.3	100
26	16	1.95	74.5	89.4	18.2	89.3	18.2	80
27	13	1.78	70	89.4	18.2	89.4	18.2	100
28	5400	4.74	96.5	89	18.7	89.4	18.8	40
29	12	5.34	95	89.3	18.8	89.4	18.8	100
30	5400	2.34	76.5	89.4	18.8	89.6	18.8	20
31	47	2.7	81	89.2	18.5	89.2	18.5	80
32	5400	2.62	82.5	89.5	18.1	89.6	18.5	20
33	5400	5.17	97	90	18.4	90.2	18.4	40
34	28	1.96	73	89.9	18.6	89.9	18.6	100
35	1870	2.27	76	89.3	18.7	89.2	18.7	40
36	5400	1.3	67.5	89	18.8	89.1	18.9	40
37	2877	0.67	57.5	88.9	18.9	88.9	18.9	20
38	41	1.88	72	88.5	18.8	88.2	18.9	40
39	47	1.42	70	88.4	18.8	88.3	18.9	100
40	56	3.26	88	88.1	18.8	88.3	18.9	80

41	123	0.84	62.5	89.9	17.8	90.7	17.95	60
42	270	1.88	75	89.9	17.45	89.9	17.87	60
43	26	0.52	59	90.1	17.88	90.2	17.91	60
44	4144	1.43	73	89.8	18.02	89.7	18.16	60
45	110	2.36	82	90.25	17.91	90.33	17.91	60
46	20	0.58	58	89.7	18.04	89.5	18.04	60
47	40	2	77	90.2	17.93	90.2	17.93	60
48	25	0.6	59	90.1	17.93	90.1	17.93	60
49	41	1.7	74	89.3	17.98	89.4	17.95	60
50	37	0.55	57	89.4	17.95	89.3	17.95	60
51	22	0.48	51	89.7	17.9	89.3	17.97	60
52	33	0.72	55.5	89.3	17.9	89.3	17.9	60
53	82	0.69	56	89.2	17.9	89.08	17.91	60
54	71	0.78	61	89.2	17.8	89.2	17.9	60
55	210	1.09	66	89.5	17.9	89.5	17.9	60
56	37	1.48	71	89.4	17.88	89.2	17.94	60
57	2593	1.48	72.5	89.7	17.99	89.7	17.9	60
58	3920	2.08	79.5	89.9	17.92	89.7	17.99	60
59	3630	2.27	80	89.3	17.9	89.3	17.9	60
60	1070	2.24	82.5	90.1	17.93	89.9	17.94	60
61	11	2.09	79	87.9	18.3	88	18.3	80
62	27	2.05	71.5	88.5	18.5	88.6	18.5	80
63	184	1.51	73	88.7	18.5	88.8	18.6	80
64	1621	3.04	83	88.8	18.6	89.3	18.8	80
65	38	1.07	63	89	18.7	89.1	18.8	80
66	2323	1.17	64.5	88.1	18	88.8	18	80
67	27	4.45	95	88.8	17.9	88.9	17.9	80
68	5400	1.59	68.5	89	18	89.9	18	80
69	27	1.29	66.5	89.5	18	89.6	18.1	80
70	25	2.19	77	89.3	18	89.5	18	80
71	5400	1.96	77	89.1	17.9	89.1	18.1	40
72	61	1.89	72	89.1	18	89.1	18	100
73	2700	1.99	74	89	18	88.9	18	20
74	5400	1.88	77	88.7	17.9	89	18.1	20
75	5400	4.27	94	88.9	19	88.9	19.5	20
76	5400	1.97	76	88.6	19.4	89	19.5	40
77	43	1.88	75	88.9	19.5	88.8	19.6	100
78	43	2.04	77	88.6	19.5	88.4	19.5	40
79	5400	3.08	82.5	88.4	19.6	88.5	19.7	20
80	24	5.41	96.5	88.3	19.6	88.4	19.6	100
81	44	1.64	69.5	89.3	19.1	89.3	19.2	100
82	5400	0.85	63	88.9	19	89.3	19	20
83	5400	1.71	70	88.9	18.9	89.1	19	20
84	5400	0.82	59	88.8	19	88.9	19.1	20
85	5400	4.18	94.5	88.6	19	88.8	19	40
86	19	0.76	59.5	88.8	19	88.7	19	100
87	5400	1.75	68.5	88.6	18	88.8	17.8	20
88	80	2.98	83	87	17.6	88.5	17.7	100
89	5400	1.35	73.5	86.6	17.5	88.8	17.5	40
90	90	1.15	61.5	86.6	17.4	88.1	17.5	20

91	19	2.5	79	85.8	17.4	87.2	17.4	100
92	31	1.86	74	85	17.4	87	17.4	100
93	5400	8.78	119	85.8	17.6	87.6	17.5	40
94	26	1.84	74	84.5	17.2	85.1	17.3	100
95	69	4.32	90.5	85.1	17.2	86.3	17.2	100
96	2568	1.53	69.5	85.2	17.2	87.1	17.2	40
97	83	2.54	79.5	84.7	17.2	86.3	17.2	40
98	5400	2.45	81	85	17.1	87	17.2	20
99	63	1.77	70	84.6	17.2	86.1	17.1	40
100	1260	0.8	61.5	84.2	17.1	86.1	17.2	40
101	30	3.47	88	84.5	17.2	85.6	17.2	70
102	304	2.31	79.5	84.4	17.2	86.6	17.2	70
103	20	1.97	71.5	84.8	17.1	80.8	17.1	50
104	94	1.93	74	85.5	17.2	82.8	17	50
105	142	4.52	93	85.5	17.3	85.6	17.3	70
106	5400	2.96	79.5	85.2	17.5	87.4	17.8	50
107	87	1.32	67.5	85.5	17.8	86.9	17.8	50
108	83	5.23	97	85.7	17.8	86.5	17.8	70
109	3379	4.94	99	85	17.7	87.3	17.8	50
110	89	1.57	72.5	85	17.7	86.7	17.8	70
111	117	2.73	80.5	87.22	18.7	87.2	18.6	50
112	96	1.63	69.5	87.3	18	87.3	18	50
113	54	2.14	76.5	87.4	17.8	87.6	17.8	70
114	18	2.16	75	87.7	17.4	87.8	17.7	50
115	5400	1.43	69.5	88	17.8	88.9	18	50
116	4601	1.72	73	88.5	18	88.8	18	50
117	44	1.52	68	88.4	18	88.3	18	50
118	89	2.89	84	88.2	18	88.1	18	70
119	39	2.32	79.5	88	18	87.9	18	70
120	21	1.47	67.5	88	17.9	88	18	70
121	75	2.46	78	88	17.3	88	18	70
122	5400	2.5	79	87.6	17.7	89.3	18	50
123	56	4.49	92	88	17.8	88.1	17.8	70
124	73	1.06	62	88.1	17.7	88.2	17.8	70
125	1707	0.68	57.5	88.4	17.8	89.1	17.9	50
126	82	3.03	84.5	89.2	17.9	89.1	17.9	70
127	78	0.78	58.5	89	17.8	89	17.9	50
128	5400	1.58	70.5	89.2	17.9	89.6	18	50
129	72	1.96	74.5	89.1	18	89.4	18	50
130	108	2.65	81	89	17.9	89	18	70
131	106	6.77	109	89	17.9	89.1	18	70
132	68	1.66	73	89	17.9	89	18	70

8.2 Appendix 2: General design principles

These design specifications and principles are a part of the fish passage guidelines (Franklin et al., 2018) which were adapted from international guidelines (DVWK 2002; O'Connor, Mallen-Cooper & Stuart, 2015).

8.2.1 Design specifications and principles for nature-like rock ramps

Table 8: Summary of design specifications for rock-ramp fishways, adapted from O'Connor et al. (2015) (Franklin et al., 2018).

Design aspect	Specification
Longitudinal gradient	The overall longitudinal slope of the structure should be 1:30 for small-bodied (<200 mm) fish.
Functional range	Maintaining a v-shaped cross-section or sloped lateral (bank-to-bank) channel profile will allow the fishway to operate over a greater range of flows than a fishway with a flat lateral profile.
Pool to pool head loss	A head loss of <75 mm is suitable for small-bodied fish.
Minimum slot width	The width of the gap between lateral ridge rocks should be 100-150 mm.
Pool size	The recommended pool size for a ridge-style rock fishway is 2 m long to allow dissipation of flow and maintain acceptable turbulence levels.
Minimum depth	The minimum recommended water depth is 0.3 m in at least 50% of the pool area in a continuous path ascending through the rock ramp.
Maximum slot water velocity	Maximum water velocity as calculated from the head loss in a vertical slot[6] should be <1.2 m s^{-1}.
Energy dissipation	Turbulence should be minimised, with little 'white' water in the fishway pools. Stream power should be <25 W m^{-3} (calculated as per vertical slot[7]).

General design principles suggest:

- Large diameter rocks embedded a minimum of 50-60% of their diameter in to the fill rock are recommended for the ridge rocks.
- Ridge rocks should generally protrude 0.3 m above the water surface under normal flows and remain protruding from the water surface within the full design operational range.
- The ridge rocks should extend across the total width of the stream and into the banks, and be keyed in.
- Geo-fabric material may be used on the rock ramp foundation and upstream face of the ridge rocks to trap fine material and decrease permeability.
- It is recommended that several layers of graded rock infill are utilised within the structure.

- Larger infill boulders can be placed to support the protruding ridge rocks.
- Mixed media fill should be augmented with fines to infill interstitial spaces and help ensure the minimum water depth over the ramp is maintained.
- The toe of the ramp should always be secured with rows of large rocks, buried to 1m below bed level and into the banks.

8.2.2 Design specifications and principles for Culvert baffles.

Stevenson et al. (2018) indicated that for culverts with slopes up to 2% rectangular baffles (0.25 m long, 0.12 m wide and 0.12 m high) with 0.2 m spacing between rows and 0.12 m spacing between individual block created continuous low velocity zones along the base of the culvert as well as provided resting zones behind the baffles (figure 14). The spacing will allow the fish to be able to use the resting areas as well as ensure that fish up to 200 mm (which includes most of New Zealand's native fish species) to fit between rows.

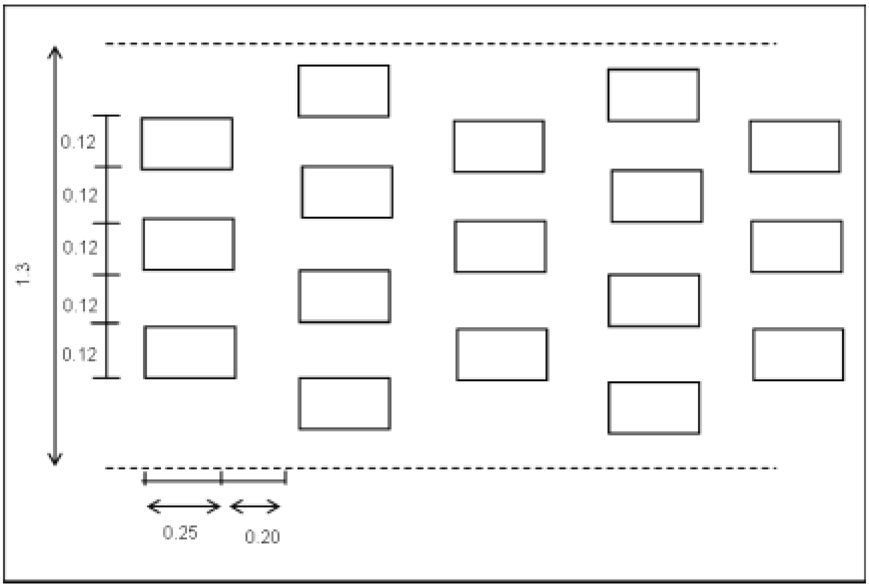

Figure 14: Spacing plan of spoiler baffles within a culvert with a 1.3 m diameter. Rectangles represent the baffles (0.25 m length, 0.12 m width and 0.12 m height), dotted lines show culvert edges. Rows of baffles are staggered and alternate in rows of three and four baffles. All dimensions are in Meters (Franklin et al., 2018).

Table 9: Guide to the number of baffles required for different culvert diameters (Franklin et al., 2018).

Culvert diameter (m)	Number of baffles in alternating rows
1.2	5 and 6
1.5	6 and 7
1.8	7 and 8
2.1	9 and 10
2.4	10 and 11

8.3 Appendix 3: Lookup tables passing success

These tables show how the raw data is converted into a passing percentage per swimming velocity tested. Besides this, also the average passing length is calculated for the 50-meter-long culvert.

8.3.1 50-meter-long culvert

Tables 10 & 11: Tables showing the passing rate and average fish length when passing for 0.2 m s^{-1} and 0.4 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish av	av.succes	percentage	average length succes	average length failure
50	0.02	0.2	0.18	277.7778	4429	yes	95%	73	61.5
50	0.04	0.2	0.16	312.5	4429	yes	95%	73	61.5
50	0.06	0.2	0.14	357.1429	4429	yes	95%	73	61.5
50	0.08	0.2	0.12	416.6667	4429	yes	95%	73	61.5
50	0.1	0.2	0.1	500	4429	yes	95%	73	61.5
50	0.12	0.2	0.08	625	4429	yes	95%	73	61.5
50	0.14	0.2	0.06	833.3333	4429	yes	90%	74	63
50	0.16	0.2	0.04	1250	4429	yes	90%	74	63
50	0.18	0.2	0.02	2500	4429	yes	85%	75	60
50	0.2	0.2	0	0	4429	no	0%	NA	NA

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentage	average length succes	average length failure
50	0.02	0.4	0.38	131.5789	3120	yes	75%	80.1	73
50	0.04	0.4	0.36	138.8889	3120	yes	75%	80.1	73
50	0.06	0.4	0.34	147.0588	3120	yes	75%	80.1	73
50	0.08	0.4	0.32	156.25	3120	yes	75%	80.1	73
50	0.1	0.4	0.3	166.6667	3120	yes	75%	80.1	73
50	0.12	0.4	0.28	178.5714	3120	yes	75%	80.1	73
50	0.14	0.4	0.26	192.3077	3120	yes	75%	80.1	73
50	0.16	0.4	0.24	208.3333	3120	yes	75%	80.1	73
50	0.18	0.4	0.22	227.2727	3120	yes	75%	80.1	73
50	0.2	0.4	0.2	250	3120	yes	75%	80.1	73
50	0.22	0.4	0.18	277.7778	3120	yes	70%	80.3	73.8
50	0.24	0.4	0.16	312.5	3120	yes	70%	80.3	73.8
50	0.26	0.4	0.14	357.1429	3120	yes	70%	80.3	73.8
50	0.28	0.4	0.12	416.6667	3120	yes	70%	80.3	73.8
50	0.3	0.4	0.1	500	3120	yes	70%	80.3	73.8
50	0.32	0.4	0.08	625	3120	yes	70%	80.3	73.8
50	0.34	0.4	0.06	833.3333	3120	yes	70%	80.3	73.8
50	0.36	0.4	0.04	1250	3120	yes	70%	80.3	73.8
50	0.38	0.4	0.02	2500	3120	yes	60%	82.2	72.5
50	0.4	0.4	0	0	3120	no	0%	NA	NA

Table 12: Table showing the passing rate and average fish length when passing for 0.5 m s^{-1} and 0.4 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentage	average length succes	average length failure
50	0.02	0.5	0.48	104.1667	1995	yes	50%	76.1	69.8
50	0.04	0.5	0.46	108.6957	1995	yes	50%	76.1	69.8
50	0.06	0.5	0.44	113.6364	1995	yes	50%	76.1	69.8
50	0.08	0.5	0.42	119.0476	1995	yes	44%	75.4	71
50	0.1	0.5	0.4	125	1995	yes	44%	75.4	71
50	0.12	0.5	0.38	131.5789	1995	yes	44%	75.4	71
50	0.14	0.5	0.36	138.8889	1995	yes	44%	75.4	71
50	0.16	0.5	0.34	147.0588	1995	yes	44%	75.4	71
50	0.18	0.5	0.32	156.25	1995	yes	44%	75.4	71
50	0.2	0.5	0.3	166.6667	1995	yes	44%	75.4	71
50	0.22	0.5	0.28	178.5714	1995	yes	44%	75.4	71
50	0.24	0.5	0.26	192.3077	1995	yes	44%	75.4	71
50	0.26	0.5	0.24	208.3333	1995	yes	44%	75.4	71
50	0.28	0.5	0.22	227.2727	1995	yes	44%	75.4	71
50	0.3	0.5	0.2	250	1995	yes	44%	75.4	71
50	0.32	0.5	0.18	277.7778	1995	yes	44%	75.4	71
50	0.34	0.5	0.16	312.5	1995	yes	44%	75.4	71
50	0.36	0.5	0.14	357.1429	1995	yes	44%	75.4	71
50	0.38	0.5	0.12	416.6667	1995	yes	44%	75.4	71
50	0.4	0.5	0.1	500	1995	yes	44%	75.4	71
50	0.42	0.5	0.08	625	1995	yes	44%	75.4	71
50	0.44	0.5	0.06	833.3333	1995	yes	44%	75.4	71
50	0.46	0.5	0.04	1250	1995	yes	36%	78.4	69.5
50	0.48	0.5	0.02	2500	1995	no	36%	78.4	69.5
50	0.5	0.5	0	0	1995	no	0%	NA	NA

Table 13: Table showing the passing rate and average fish length when passing for 0.6 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentage	average length succes	average length failure
50	0.02	0.6	0.58	86.2069	825.2	yes	45%	66.7	68.3
50	0.04	0.6	0.56	89.28571	825.2	yes	45%	66.7	68.3
50	0.06	0.6	0.54	92.59259	825.2	yes	45%	66.7	68.3
50	0.08	0.6	0.52	96.15385	825.2	yes	45%	66.7	68.3
50	0.1	0.6	0.5	100	825.2	yes	45%	66.7	68.3
50	0.12	0.6	0.48	104.1667	825.2	yes	45%	66.7	68.3
50	0.14	0.6	0.46	108.6957	825.2	yes	45%	66.7	68.3
50	0.16	0.6	0.44	113.6364	825.2	yes	40%	67.9	67.4
50	0.18	0.6	0.42	119.0476	825.2	yes	40%	67.9	67.4
50	0.2	0.6	0.4	125	825.2	yes	35%	68.6	67
50	0.22	0.6	0.38	131.5789	825.2	yes	35%	68.6	67
50	0.24	0.6	0.36	138.8889	825.2	yes	35%	68.6	67
50	0.26	0.6	0.34	147.0588	825.2	yes	35%	68.6	67
50	0.28	0.6	0.32	156.25	825.2	yes	35%	68.6	67
50	0.3	0.6	0.3	166.6667	825.2	yes	35%	68.6	67
50	0.32	0.6	0.28	178.5714	825.2	yes	35%	68.6	67
50	0.34	0.6	0.26	192.3077	825.2	yes	35%	68.6	67
50	0.36	0.6	0.24	208.3333	825.2	yes	35%	68.6	67
50	0.38	0.6	0.22	227.2727	825.2	yes	30%	68.2	67.3
50	0.4	0.6	0.2	250	825.2	yes	30%	68.2	67.3
50	0.42	0.6	0.18	277.7778	825.2	yes	25%	67.3	67.7
50	0.44	0.6	0.16	312.5	825.2	yes	25%	67.3	67.7
50	0.46	0.6	0.14	357.1429	825.2	yes	25%	67.3	67.7
50	0.48	0.6	0.12	416.6667	825.2	yes	25%	67.3	67.7
50	0.5	0.6	0.1	500	825.2	yes	25%	67.3	67.7
50	0.52	0.6	0.08	625	825.2	yes	25%	67.3	67.7
50	0.54	0.6	0.06	833.3333	825.2	no	25%	67.3	67.7
50	0.56	0.6	0.04	1250	825.2	no	20%	68.9	67.3
50	0.58	0.6	0.02	2500	825.2	no	20%	68.9	67.3
50	0.6	0.6	0	0	825.2	no	0%	NA	NA

Table 14: Table showing the passing rate and average fish length when passing for 0.6 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentage	average length succes	average length failure
50	0.02	0.7	0.68	73.52941	89	yes	50%	87.6	77.1
50	0.04	0.7	0.66	75.75758	89	yes	50%	87.6	77.1
50	0.06	0.7	0.64	78.125	89	yes	50%	87.6	77.1
50	0.08	0.7	0.62	80.64516	89	yes	44%	86.5	79.8
50	0.1	0.7	0.6	83.33333	89	yes	44%	86.5	79.8
50	0.12	0.7	0.58	86.2069	89	yes	44%	86.5	79.8
50	0.14	0.7	0.56	89.28571	89	no	24%	90.6	79.5
50	0.16	0.7	0.54	92.59259	89	no	24%	90.6	79.5
50	0.18	0.7	0.52	96.15385	89	no	24%	90.6	79.5
50	0.2	0.7	0.5	100	89	no	24%	90.6	79.5
50	0.22	0.7	0.48	104.1667	89	no	24%	90.6	79.5
50	0.24	0.7	0.46	108.6957	89	no	12%	86.3	81.8
50	0.26	0.7	0.44	113.6364	89	no	12%	86.3	81.8
50	0.28	0.7	0.42	119.0476	89	no	12%	86.3	81.8
50	0.3	0.7	0.4	125	89	no	12%	86.3	81.8
50	0.32	0.7	0.38	131.5789	89	no	12%	86.3	81.8
50	0.34	0.7	0.36	138.8889	89	no	12%	86.3	81.8
50	0.36	0.7	0.34	147.0588	89	no	6%	79.5	82.5
50	0.38	0.7	0.32	156.25	89	no	6%	79.5	82.5
50	0.4	0.7	0.3	166.6667	89	no	6%	79.5	82.5
50	0.42	0.7	0.28	178.5714	89	no	6%	79.5	82.5
50	0.44	0.7	0.26	192.3077	89	no	6%	79.5	82.5
50	0.46	0.7	0.24	208.3333	89	no	6%	79.5	82.5
50	0.48	0.7	0.22	227.2727	89	no	6%	79.5	82.5
50	0.5	0.7	0.2	250	89	no	6%	79.5	82.5
50	0.52	0.7	0.18	277.7778	89	no	6%	79.5	82.5
50	0.54	0.7	0.16	312.5	89	no	0%	NA	NA
50	0.56	0.7	0.14	357.1429	89	no	0%	NA	NA
50	0.58	0.7	0.12	416.6667	89	no	0%	NA	NA
50	0.6	0.7	0.1	500	89	no	0%	NA	NA
50	0.62	0.7	0.08	625	89	no	0%	NA	NA
50	0.64	0.7	0.06	833.3333	89	no	0%	NA	NA
50	0.66	0.7	0.04	1250	89	no	0%	NA	NA
50	0.68	0.7	0.02	2500	89	no	0%	NA	NA
50	0.7	0.7	0	0	89	no	0%	NA	NA

Table 15: Table showing the passing rate and average fish length when passing for 0.8 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentage	average length succes	average length failure
50	0.02	0.8	0.78	64.10256	510	yes	30%	74.6	75.3
50	0.04	0.8	0.76	65.78947	510	yes	30%	74.6	75.3
50	0.06	0.8	0.74	67.56757	510	yes	30%	74.6	75.3
50	0.08	0.8	0.72	69.44444	510	yes	30%	74.6	75.3
50	0.1	0.8	0.7	71.42857	510	yes	30%	74.6	75.3
50	0.12	0.8	0.68	73.52941	510	yes	30%	74.6	75.3
50	0.14	0.8	0.66	75.75758	510	yes	30%	74.6	75.3
50	0.16	0.8	0.64	78.125	510	yes	30%	74.6	75.3
50	0.18	0.8	0.62	80.64516	510	yes	30%	74.6	75.3
50	0.2	0.8	0.6	83.33333	510	yes	30%	74.6	75.3
50	0.22	0.8	0.58	86.2069	510	yes	25%	75.6	74.9
50	0.24	0.8	0.56	89.28571	510	yes	25%	75.6	74.9
50	0.26	0.8	0.54	92.59259	510	yes	25%	75.6	74.9
50	0.28	0.8	0.52	96.15385	510	yes	25%	75.6	74.9
50	0.3	0.8	0.5	100	510	yes	25%	75.6	74.9
50	0.32	0.8	0.48	104.1667	510	yes	25%	75.6	74.9
50	0.34	0.8	0.46	108.6957	510	yes	25%	75.6	74.9
50	0.36	0.8	0.44	113.6364	510	yes	25%	75.6	74.9
50	0.38	0.8	0.42	119.0476	510	yes	25%	75.6	74.9
50	0.4	0.8	0.4	125	510	yes	25%	75.6	74.9
50	0.42	0.8	0.38	131.5789	510	yes	20%	72.3	75.8
50	0.44	0.8	0.36	138.8889	510	yes	20%	72.3	75.8
50	0.46	0.8	0.34	147.0588	510	yes	20%	72.3	75.8
50	0.48	0.8	0.32	156.25	510	yes	20%	72.3	75.8
50	0.5	0.8	0.3	166.6667	510	yes	20%	72.3	75.8
50	0.52	0.8	0.28	178.5714	510	yes	20%	72.3	75.8
50	0.54	0.8	0.26	192.3077	510	yes	15%	72	75.6
50	0.56	0.8	0.24	208.3333	510	yes	15%	72	75.6
50	0.58	0.8	0.22	227.2727	510	yes	15%	72	75.6
50	0.6	0.8	0.2	250	510	yes	15%	72	75.6
50	0.62	0.8	0.18	277.7778	510	yes	15%	72	75.6
50	0.64	0.8	0.16	312.5	510	yes	15%	72	75.6
50	0.66	0.8	0.14	357.1429	510	yes	15%	72	75.6
50	0.68	0.8	0.12	416.6667	510	yes	15%	72	75.6
50	0.7	0.8	0.1	500	510	yes	15%	72	75.6
50	0.72	0.8	0.08	625	510	no	15%	72	75.6
50	0.74	0.8	0.06	833.3333	510	no	15%	72	75.6
50	0.76	0.8	0.04	1250	510	no	15%	72	75.6
50	0.78	0.8	0.02	2500	510	no	5%	68.5	75.4
50	0.8	0.8	0	0	510	no	0%	NA	NA

Table 16: Table showing the passing rate and average fish length when passing for 1.0 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentage		
50	0.02	1	0.98	51.02041	35.6	no	15%	81.8	72.4
50	0.04	1	0.96	52.08333	35.6	no	15%	81.8	72.4
50	0.06	1	0.94	53.19149	35.6	no	15%	81.8	72.4
50	0.08	1	0.92	54.34783	35.6	no	15%	81.8	72.4
50	0.1	1	0.9	55.55556	35.6	no	15%	81.8	72.4
50	0.12	1	0.88	56.81818	35.6	no	15%	81.8	72.4
50	0.14	1	0.86	58.13953	35.6	no	15%	81.8	72.4
50	0.16	1	0.84	59.52381	35.6	no	15%	81.8	72.4
50	0.18	1	0.82	60.97561	35.6	no	15%	81.8	72.4
50	0.2	1	0.8	62.5	35.6	no	10%	86.8	72.4
50	0.22	1	0.78	64.10256	35.6	no	10%	86.8	72.4
50	0.24	1	0.76	65.78947	35.6	no	10%	86.8	72.4
50	0.26	1	0.74	67.56757	35.6	no	10%	86.8	72.4
50	0.28	1	0.72	69.44444	35.6	no	10%	86.8	72.4
50	0.3	1	0.7	71.42857	35.6	no	5%	83	73.3
50	0.32	1	0.68	73.52941	35.6	no	5%	83	73.3
50	0.34	1	0.66	75.75758	35.6	no	5%	83	73.3
50	0.36	1	0.64	78.125	35.6	no	5%	83	73.3
50	0.38	1	0.62	80.64516	35.6	no	0%	NA	NA
50	0.4	1	0.6	83.33333	35.6	no	0%	NA	NA
50	0.42	1	0.58	86.2069	35.6	no	0%	NA	NA
50	0.44	1	0.56	89.28571	35.6	no	0%	NA	NA
50	0.46	1	0.54	92.59259	35.6	no	0%	NA	NA
50	0.48	1	0.52	96.15385	35.6	no	0%	NA	NA
50	0.5	1	0.5	100	35.6	no	0%	NA	NA
50	0.52	1	0.48	104.1667	35.6	no	0%	NA	NA
50	0.54	1	0.46	108.6957	35.6	no	0%	NA	NA
50	0.56	1	0.44	113.6364	35.6	no	0%	NA	NA
50	0.58	1	0.42	119.0476	35.6	no	0%	NA	NA
50	0.6	1	0.4	125	35.6	no	0%	NA	NA
50	0.62	1	0.38	131.5789	35.6	no	0%	NA	NA
50	0.64	1	0.36	138.8889	35.6	no	0%	NA	NA
50	0.66	1	0.34	147.0588	35.6	no	0%	NA	NA
50	0.68	1	0.32	156.25	35.6	no	0%	NA	NA
50	0.7	1	0.3	166.6667	35.6	no	0%	NA	NA
50	0.72	1	0.28	178.5714	35.6	no	0%	NA	NA
50	0.74	1	0.26	192.3077	35.6	no	0%	NA	NA
50	0.76	1	0.24	208.3333	35.6	no	0%	NA	NA
50	0.78	1	0.22	227.2727	35.6	no	0%	NA	NA
50	0.8	1	0.2	250	35.6	no	0%	NA	NA
50	0.82	1	0.18	277.7778	35.6	no	0%	NA	NA
50	0.84	1	0.16	312.5	35.6	no	0%	NA	NA
50	0.86	1	0.14	357.1429	35.6	no	0%	NA	NA
50	0.88	1	0.12	416.6667	35.6	no	0%	NA	NA
50	0.9	1	0.1	500	35.6	no	0%	NA	NA
50	0.92	1	0.08	625	35.6	no	0%	NA	NA
50	0.94	1	0.06	833.3333	35.6	no	0%	NA	NA
50	0.96	1	0.04	1250	35.6	no	0%	NA	NA
50	0.98	1	0.02	2500	35.6	no	0%	NA	NA
50	1	1	0	0	35.6	no	0%	NA	NA

8.3.2 20-meter-long culvert

Tables 17 & 18: Tables showing the passing rate for 0.2 m s^{-1} and 0.4 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish av	av.succes	percentag
20	0.02	0.2	0.18	111.1	4429	yes	95
20	0.04	0.2	0.16	125.0	4429	yes	95
20	0.06	0.2	0.14	142.9	4429	yes	95
20	0.08	0.2	0.12	166.7	4429	yes	95
20	0.1	0.2	0.1	200.0	4429	yes	95
20	0.12	0.2	0.08	250.0	4429	yes	95
20	0.14	0.2	0.06	333.3	4429	yes	95
20	0.16	0.2	0.04	500.0	4429	yes	95
20	0.18	0.2	0.02	1000.0	4429	yes	90
20	0.2	0.2	0	0.0	4429	no	0

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentag
20	0.02	0.4	0.38	52.6	3120	yes	85
20	0.04	0.4	0.36	55.6	3120	yes	85
20	0.06	0.4	0.34	58.8	3120	yes	85
20	0.08	0.4	0.32	62.5	3120	yes	85
20	0.1	0.4	0.3	66.7	3120	yes	80
20	0.12	0.4	0.28	71.4	3120	yes	80
20	0.14	0.4	0.26	76.9	3120	yes	80
20	0.16	0.4	0.24	83.3	3120	yes	75
20	0.18	0.4	0.22	90.9	3120	yes	75
20	0.2	0.4	0.2	100.0	3120	yes	75
20	0.22	0.4	0.18	111.1	3120	yes	75
20	0.24	0.4	0.16	125.0	3120	yes	75
20	0.26	0.4	0.14	142.9	3120	yes	75
20	0.28	0.4	0.12	166.7	3120	yes	75
20	0.3	0.4	0.1	200.0	3120	yes	75
20	0.32	0.4	0.08	250.0	3120	yes	75
20	0.34	0.4	0.06	333.3	3120	yes	75
20	0.36	0.4	0.04	500.0	3120	yes	75
20	0.38	0.4	0.02	1000.0	3120	yes	75
20	0.4	0.4	0	0.0	3120	no	0

Table 19: Table showing the passing rate and average fish length when passing for 0.5 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentag
20	0.02	0.5	0.48	41.7	1995	yes	87.5
20	0.04	0.5	0.46	43.5	1995	yes	87.5
20	0.06	0.5	0.44	45.5	1995	yes	81.3
20	0.08	0.5	0.42	47.6	1995	yes	81.3
20	0.1	0.5	0.4	50.0	1995	yes	81.3
20	0.12	0.5	0.38	52.6	1995	yes	81.3
20	0.14	0.5	0.36	55.6	1995	yes	81.3
20	0.16	0.5	0.34	58.8	1995	yes	81.3
20	0.18	0.5	0.32	62.5	1995	yes	81.3
20	0.2	0.5	0.3	66.7	1995	yes	81.3
20	0.22	0.5	0.28	71.4	1995	yes	81.3
20	0.24	0.5	0.26	76.9	1995	yes	75
20	0.26	0.5	0.24	83.3	1995	yes	68.8
20	0.28	0.5	0.22	90.9	1995	yes	68.8
20	0.3	0.5	0.2	100.0	1995	yes	56.3
20	0.32	0.5	0.18	111.1	1995	yes	56.3
20	0.34	0.5	0.16	125.0	1995	yes	50
20	0.36	0.5	0.14	142.9	1995	yes	50
20	0.38	0.5	0.12	166.7	1995	yes	50
20	0.4	0.5	0.1	200.0	1995	yes	50
20	0.42	0.5	0.08	250.0	1995	yes	50
20	0.44	0.5	0.06	333.3	1995	yes	50
20	0.46	0.5	0.04	500.0	1995	yes	50
20	0.48	0.5	0.02	1000.0	1995	no	50
20	0.5	0.5	0	0.0	1995	no	0

Table 20: Table showing the passing rate and average fish length when passing for 0.6 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentag
20	0.02	0.6	0.58	34.5	825.2	yes	75
20	0.04	0.6	0.56	35.7	825.2	yes	75
20	0.06	0.6	0.54	37.0	825.2	yes	65
20	0.08	0.6	0.52	38.5	825.2	yes	65
20	0.1	0.6	0.5	40.0	825.2	yes	65
20	0.12	0.6	0.48	41.7	825.2	yes	55
20	0.14	0.6	0.46	43.5	825.2	yes	55
20	0.16	0.6	0.44	45.5	825.2	yes	55
20	0.18	0.6	0.42	47.6	825.2	yes	55
20	0.2	0.6	0.4	50.0	825.2	yes	55
20	0.22	0.6	0.38	52.6	825.2	yes	55
20	0.24	0.6	0.36	55.6	825.2	yes	55
20	0.26	0.6	0.34	58.8	825.2	yes	55
20	0.28	0.6	0.32	62.5	825.2	yes	55
20	0.3	0.6	0.3	66.7	825.2	yes	55
20	0.32	0.6	0.28	71.4	825.2	yes	50
20	0.34	0.6	0.26	76.9	825.2	yes	50
20	0.36	0.6	0.24	83.3	825.2	yes	45
20	0.38	0.6	0.22	90.9	825.2	yes	45
20	0.4	0.6	0.2	100.0	825.2	yes	45
20	0.42	0.6	0.18	111.1	825.2	yes	40
20	0.44	0.6	0.16	125.0	825.2	yes	35
20	0.46	0.6	0.14	142.9	825.2	yes	35
20	0.48	0.6	0.12	166.7	825.2	yes	35
20	0.5	0.6	0.1	200.0	825.2	yes	35
20	0.52	0.6	0.08	250.0	825.2	yes	30
20	0.54	0.6	0.06	333.3	825.2	no	25
20	0.56	0.6	0.04	500.0	825.2	no	25
20	0.58	0.6	0.02	1000.0	825.2	no	25
20	0.6	0.6	0	0.0	825.2	no	0

Table 21: Table showing the passing rate and average fish length when passing for 0.7 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentag
20	0.02	0.7	0.68	29.4	89	yes	93.8
20	0.04	0.7	0.66	30.3	89	yes	87.5
20	0.06	0.7	0.64	31.3	89	yes	87.5
20	0.08	0.7	0.62	32.3	89	yes	87.5
20	0.1	0.7	0.6	33.3	89	yes	87.5
20	0.12	0.7	0.58	34.5	89	yes	87.5
20	0.14	0.7	0.56	35.7	89	no	87.5
20	0.16	0.7	0.54	37.0	89	no	87.5
20	0.18	0.7	0.52	38.5	89	no	87.5
20	0.2	0.7	0.5	40.0	89	no	81.3
20	0.22	0.7	0.48	41.7	89	no	81.3
20	0.24	0.7	0.46	43.5	89	no	81.3
20	0.26	0.7	0.44	45.5	89	no	81.3
20	0.28	0.7	0.42	47.6	89	no	81.3
20	0.3	0.7	0.4	50.0	89	no	81.3
20	0.32	0.7	0.38	52.6	89	no	81.3
20	0.34	0.7	0.36	55.6	89	no	75
20	0.36	0.7	0.34	58.8	89	no	68.8
20	0.38	0.7	0.32	62.5	89	no	68.8
20	0.4	0.7	0.3	66.7	89	no	68.8
20	0.42	0.7	0.28	71.4	89	no	62.5
20	0.44	0.7	0.26	76.9	89	no	50
20	0.46	0.7	0.24	83.3	89	no	37.5
20	0.48	0.7	0.22	90.9	89	no	25
20	0.5	0.7	0.2	100.0	89	no	25
20	0.52	0.7	0.18	111.1	89	no	12.5
20	0.54	0.7	0.16	125.0	89	no	12.5
20	0.56	0.7	0.14	142.9	89	no	6.3
20	0.58	0.7	0.12	166.7	89	no	6.3
20	0.6	0.7	0.1	200.0	89	no	6.3
20	0.62	0.7	0.08	250.0	89	no	6.3
20	0.64	0.7	0.06	333.3	89	no	0
20	0.66	0.7	0.04	500.0	89	no	0
20	0.68	0.7	0.02	1000.0	89	no	0
20	0.7	0.7	0	0.0	89	no	0

Table 22: Table showing the passing rate and average fish length when passing for 0.8 m s^{-1}.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentag
20	0.02	0.8	0.78	25.6	510	yes	85
20	0.04	0.8	0.76	26.3	510	yes	85
20	0.06	0.8	0.74	27.0	510	yes	85
20	0.08	0.8	0.72	27.8	510	yes	70
20	0.1	0.8	0.7	28.6	510	yes	70
20	0.12	0.8	0.68	29.4	510	yes	70
20	0.14	0.8	0.66	30.3	510	yes	65
20	0.16	0.8	0.64	31.3	510	yes	65
20	0.18	0.8	0.62	32.3	510	yes	65
20	0.2	0.8	0.6	33.3	510	yes	65
20	0.22	0.8	0.58	34.5	510	yes	60
20	0.24	0.8	0.56	35.7	510	yes	60
20	0.26	0.8	0.54	37.0	510	yes	55
20	0.28	0.8	0.52	38.5	510	yes	45
20	0.3	0.8	0.5	40.0	510	yes	45
20	0.32	0.8	0.48	41.7	510	yes	45
20	0.34	0.8	0.46	43.5	510	yes	45
20	0.36	0.8	0.44	45.5	510	yes	45
20	0.38	0.8	0.42	47.6	510	yes	40
20	0.4	0.8	0.4	50.0	510	yes	35
20	0.42	0.8	0.38	52.6	510	yes	35
20	0.44	0.8	0.36	55.6	510	yes	35
20	0.46	0.8	0.34	58.8	510	yes	30
20	0.48	0.8	0.32	62.5	510	yes	30
20	0.5	0.8	0.3	66.7	510	yes	30
20	0.52	0.8	0.28	71.4	510	yes	30
20	0.54	0.8	0.26	76.9	510	yes	30
20	0.56	0.8	0.24	83.3	510	yes	30
20	0.58	0.8	0.22	90.9	510	yes	25
20	0.6	0.8	0.2	100.0	510	yes	25
20	0.62	0.8	0.18	111.1	510	yes	25
20	0.64	0.8	0.16	125.0	510	yes	25
20	0.66	0.8	0.14	142.9	510	yes	20
20	0.68	0.8	0.12	166.7	510	yes	20
20	0.7	0.8	0.1	200.0	510	yes	15
20	0.72	0.8	0.08	250.0	510	no	15
20	0.74	0.8	0.06	333.3	510	no	15
20	0.76	0.8	0.04	500.0	510	no	15
20	0.78	0.8	0.02	1000.0	510	no	15
20	0.8	0.8	0	0.0	510	no	0

Table 23: Table showing the passing rate and average fish length when passing for 1.0 m s⁻¹.

L culvert	Vwater	Vfish	Vstream	Tl	Tfish	av.succes	percentag
20	0.02	1	0.98	20.4	35.6	no	75
20	0.04	1	0.96	20.8	35.6	no	75
20	0.06	1	0.94	21.3	35.6	no	75
20	0.08	1	0.92	21.7	35.6	no	75
20	0.1	1	0.9	22.2	35.6	no	75
20	0.12	1	0.88	22.7	35.6	no	75
20	0.14	1	0.86	23.3	35.6	no	75
20	0.16	1	0.84	23.8	35.6	no	75
20	0.18	1	0.82	24.4	35.6	no	70
20	0.2	1	0.8	25.0	35.6	no	70
20	0.22	1	0.78	25.6	35.6	no	70
20	0.24	1	0.76	26.3	35.6	no	65
20	0.26	1	0.74	27.0	35.6	no	65
20	0.28	1	0.72	27.8	35.6	no	65
20	0.3	1	0.7	28.6	35.6	no	55
20	0.32	1	0.68	29.4	35.6	no	55
20	0.34	1	0.66	30.3	35.6	no	55
20	0.36	1	0.64	31.3	35.6	no	45
20	0.38	1	0.62	32.3	35.6	no	45
20	0.4	1	0.6	33.3	35.6	no	45
20	0.42	1	0.58	34.5	35.6	no	40
20	0.44	1	0.56	35.7	35.6	no	40
20	0.46	1	0.54	37.0	35.6	no	40
20	0.48	1	0.52	38.5	35.6	no	35
20	0.5	1	0.5	40.0	35.6	no	35
20	0.52	1	0.48	41.7	35.6	no	35
20	0.54	1	0.46	43.5	35.6	no	30
20	0.56	1	0.44	45.5	35.6	no	25
20	0.58	1	0.42	47.6	35.6	no	15
20	0.6	1	0.4	50.0	35.6	no	15
20	0.62	1	0.38	52.6	35.6	no	15
20	0.64	1	0.36	55.6	35.6	no	15
20	0.66	1	0.34	58.8	35.6	no	15
20	0.68	1	0.32	62.5	35.6	no	10
20	0.7	1	0.3	66.7	35.6	no	10
20	0.72	1	0.28	71.4	35.6	no	5
20	0.74	1	0.26	76.9	35.6	no	5
20	0.76	1	0.24	83.3	35.6	no	0

20	0.78	1	0.22	90.9	35.6	no	0
20	0.8	1	0.2	100.0	35.6	no	0
20	0.82	1	0.18	111.1	35.6	no	0
20	0.84	1	0.16	125.0	35.6	no	0
20	0.86	1	0.14	142.9	35.6	no	0
20	0.88	1	0.12	166.7	35.6	no	0
20	0.9	1	0.1	200.0	35.6	no	0
20	0.92	1	0.08	250.0	35.6	no	0
20	0.94	1	0.06	333.3	35.6	no	0
20	0.96	1	0.04	500.0	35.6	no	0
20	0.98	1	0.02	1000.0	35.6	no	0
20	1	1	0	0.0	35.6	no	0

8.4 Appendix 4: R codes used

8.4.1 Codes most used

The following codes were used to retrieve results and graphs from Rstudio.

Read and Create data set:

setwd("C:\\Users\\nolted\\Documents\\")

HoldingData <- read.csv("Holdingdata.csv")

ANOVA and T-Test:

ANOVA:

sighold <- aov(Endurance ~ age, data = HoldingData)

T-Test:

thold <- t.test(Endurance ~ age, data = HoldingData, var.equal = TRUE)

Create Boxplots:

boxplot(Length~Age, data=HoldingData)

Create linear graphs:

Normal:

plot(log(Endurance)~Length, data=HoldingData, col=c(1,2)[Age])

GGplot:

ggplot(HoldingData, aes(x=Length, y=Endurance, color=factor(age))) + geom_point() +labs(title = "The effects of holding time on endurance")+labs(colour = "Age")+labs(x = "Length (mm)")+labs(y = "Log Endurance (s)")+scale_y_continuous(trans = 'log')+geom_smooth(method=lm, se=FALSE)

Stepped GGplot:

ggplot(passing, aes(y=percentage,x=Vwater,color=factor(Vfish)))+geom_step()+labs(x = "Water velocity (m/s)")+labs(y = "Percentage passing")+labs(title = "Percentage of Fish passing 50m culvert at different water velocities")+labs(colour = "Swimming velocity")

8.4.2 Coding screens

```
#################  Code for analysing fish swimming trial data  ############################

## Set the working directory ##
setwd("C:\\Users\\nolted\\Documents\\")
HoldingData <- read.csv("Holdingdata.csv")

## Read in the data ##
fishData <- read.csv("resultatenind.csv")
colnames(fishData)
FinalEndurance <- read.csv("final_endurance.csv")
colnames(FinalEndurance)
bodylength <- read.csv("body.csv")
passing <- read.csv("passing.csv")

## Make some boxplots ##

# Look at the difference in fish lengths between the two groups
boxplot(Length~Age, data=fishData)

# Look at the difference in endurance between the two groups
boxplot(Endurance~Age, data=fishData)
boxplot(Endurance~age, data=Holdingsubset)

ggplot(fishData,aes(y=Endurance,x=Length,color=factor(Age)))+geom_point()+stat_smooth(method="lm",se=FALSE)+scale_y_continuous(trans = 'log')
ggplot(Holdingsubset,aes(y=Endurance,x=Length,color=factor(age)))+geom_point()+stat_smooth(method="lm",se=FALSE)+scale_y_continuous(trans = 'log')

Holdingsubset <- subset(HoldingData, HoldingData$Endurance < 200)

## ANCOVA test ##
endurance.model1 <- lm(Endurance~Age*Length, data=fishData)
anova(endurance.model1)
summary(endurance.model1)
endurance.model2 <- lm(Endurance~Age+Length, data=fishData)
anova(endurance.model2)
summary(endurance.model2)
endurance.model3 <- lm(Endurance~Age, data=fishData)
anova(endurance.model3)
summary(endurance.model3)


## Create Plots ##
plot(log(Endurance)~Length, data=fishData, col=c(1,2)[Age])
plot(log(Endurance)~Length, data=Holdingsubset, col=c(1,2)[age])


## Subset data##

fishSubset <- subset(fishData, fishData$Endurance < 200)
plot(Endurance~Length, data=fishSubset, col=c(1,2)[Age])
test<- lm(Endurance~Age*Length, data=fishSubset)
anova(test)


##Endurancetrials##
setwd("C:\\Users\\nolted\\Documents\\")
enduranceData <- read.csv("endurance_trials.csv")
colnames(enduranceData)
```

```
boxplot(Endurance~Velocity, log="y", data=enduranceData, main="Endurance of Inanga over different velocities", xlab="velocity (cm/s)", ylab="log endurance (s)")

endurance.model4 <- lm(Endurance~Velocity*Length, data=enduranceData)
anova(endurance.model4)
summary(endurance.model4)
endurance.model5 <- lm(Endurance~Velocity+Length, data=enduranceData)
anova(endurance.model5)
summary(endurance.model5)
endurance.model6 <- lm(Endurance~Velocity, data=enduranceData)
anova(endurance.model6)
summary(endurance.model6)

boxplot(Length~Velocity, data=enduranceData)

plot(Velocity~Endurance, data=enduranceData, log="x")

plot(Endurance~Length, data=enduranceData, col=c(1:5)[as.factor(Velocity)])

##multiple regression lines GGplot##
#normal
ggplot(enduranceData,aes(y=Endurance,x=Length,color=factor(Velocity)))+geom_point()+stat_smooth(method="lm",se=FALSE)
#log
ggplot(enduranceData,aes(y=Endurance,x=Length,color=factor(Velocity)))+geom_point()+stat_smooth(method="lm",se=FALSE)+scale_y_continuous(trans = 'log')

##installed packages##
library(ggplot2)

##final endurance graphs##

boxplot(Endurance~Velocity, log="y", data=FinalEndurance,main="Endurance of Inanga over different velocities", xlab="velocity (cm/s)", ylab="log endurance (s)"

boxplot(Endurance~Velocity, data=FinalEndurance,main="Endurance of Inanga over different velocities", xlab="Velocity (cm/s)", ylab="Endurance (s)")

boxplot(Endurance~Velocity, data=FinalEndurance,main="Endurance of Inanga over different velocities", xlab="Velocity (cm/s)", ylab="Endurance (s)")

abline(h=c(2500), lty=2, col=c(2:4))
abline(h=c(3.4), lty=2, col=c(2:4))

plot(Endurance~Velocity, data=FinalEndurance)
plot(log(Endurance)~Velocity, data=FinalEndurance)

ggplot(FinalEndurance,aes(y=Endurance,x=Length,color=factor(Velocity)))+geom_point()+stat_smooth(method="lm",se=FALSE)+scale_y_continuous(trans = 'log')+labs(x = "Body length (mm)")+labs(y = "Log Endurnace (s)")+labs(title = 
"Endurance over body length on different velocities of inanga")+labs(colour = "Swimming velocity")

ggplot(FinalEndurance,aes(y=Endurance,x=Weight,color=factor(Velocity)))+geom_point()+stat_smooth(method="lm",se=FALSE)+scale_y_continuous(trans = 'log')+labs(x = "Water velocity (m/s)")+labs(y = "Percentage passing")+labs
(title = "Percentage of Fish passing 50m culvert at different water velocities")+labs(colour = "Swimming velocity")

#bodylength
ggplot(bodylength,aes(y=Endurance,x=bls,color=factor(Velocity)))+geom_point()+stat_smooth(method="lm",se=FALSE)+scale_y_continuous(trans = 'log')

plot(log(Endurance)~bls, data=bodylength)
plot(log(Endurance)~bls, data=bodylength, col=c(1:7)[as.factor(Velocity)])
```

```
##passing##

plot(percentage~Vwater, data=)
ggplot(passing,aes(y=percentage*100,x=Vwater,color=factor(Vfish)))+geom_point()+stat_smooth(method="lm",se=FALSE)

ggplot(passing, aes(y=percentage,x=Vwater,color=factor(Vfish)))+geom_step()+labs(x = "Water velocity (m/s)")+labs(y = "Percentage passing")+labs(title = "Percentage of Fish passing 50m culvert at different water velocities"
)+labs(colour = "Swimming velocity")

##ggplots##
#holding#
ggplot(Holdingsubset, aes(x=Length, y=Endurance, color=factor(age))) +
  geom_point() +labs(title = "The effects of holding time on endurance")+labs(colour = "Age")+labs(x = "Length (mm)")+labs(y = "Log Endurance (s)")+scale_y_continuous(trans = 'log')+
  geom_smooth(method=lm, se=FALSE)

#individual#

ggplot(Holdingsubset, aes(x=Length, y=Endurance) + geom_point() +labs(title = "Individual swimming capacity")+labs(x = "Length (mm)")+labs(y = "Log Endurance (s)")
```

Figure 15: Coding screens used for analysis and graph creation in Rstudio.