Wedge-wire fish screen refinement experiments

Reporting of Year 2 results

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Cover image: A consented screen used to exclude fish at the Levels Plains Irrigation Scheme intake [photo credit: NIWA].

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Executive summary

Irrigation is the largest water use sector, currently accounting for about 70% of global water withdrawals. Globally, surface waters are abstracted to varying degrees to meet human needs such as agriculture, drinking water, urban water supply, industry and electricity generation, and New Zealand is no exception. When surface water diversions are not properly screened, they can result in the physical removal of fish from rivers. In New Zealand, regional councils issue the consents for the taking of surface waters in consultation with agencies that have statutory responsibilities for managing native and sports fish populations. A recent review of council plans, as part of a Ministry for Primary Industries-funded project focussed on fish screening, highlighted that regulations pertaining to fish screening are highly variable across New Zealand and that the greatest source of variation in plans was related to the aperture size of suitable screening materials. Experimental work was undertaken by NIWA to examine the effectiveness of different types of fish screens being consented and then started to address inconsistencies relating to aperture size of screens (Year 1 report). This Year 2 report was focussed on refining previous experimental work to enable fish screening recommendations to be produced.

The Year 2 experiments were conducted in an outdoor 'stream simulator' and were focussed solely on testing wedge-wire screens. The differences compared to Year 1 experiments were changing the approach direction of fish to reflect how diadromous species would interact with a screen, altering some of the species tested, altering the life stage/size of shortfin eels (i.e., testing smaller fish), as well as decreasing the slot size encountered by fish (i.e., 2 mm and 1.5 mm). Experiments tested five fish species: bluegill bully (32–56 mm), common bully (38–61 mm), īnanga whitebait (39–51 mm), shortfin 'glass' eel (54–66 mm) and Chinook salmon (43–71 mm). Each experiment had five replicates (five fish per replicate) and a duration of 30 minutes, all of which was recorded on video. The video footage was reviewed for evidence of screen contacts, impingements, penetrations and to explain any recorded fish mortality events. Experiments examining fish responses for the 1.5 mm wedge wire screen were only conducted if a species had penetrated the 2 mm screen.

Five fish species were tested during 2 mm wedge-wire screen experiments with most species exhibiting a strong motivation to move upstream against the flow, the exception being Chinook salmon where fish in the majority of replicates did not move the short distance upstream to interact with the screen. For the size range tested, bluegill bully, common bully and Chinook salmon were excluded by the 2 mm screen but 64% of shortfin glass eels and 16% īnanga whitebait penetrated the 2 mm screen. No īnanga penetrated the 1.5 mm screen but 68% of shortfin glass eels were able to get through the screen. For glass eels there was no marked difference in the mean size of glass eels penetrating the screens compared to those that did not get through. All species tested contacted the screen and all native species tested showed some level of impingement (i.e., immobilised on the screen for 10 seconds or more). For the native species, bluegill bully had the most impingements and shortfin glass eels the least; no impingements were recorded for Chinook salmon. There were 12 mortalities recorded during the experiments all were associated with the 2 mm experiments. Four īnanga mortalities occurred as a result of impingement on the screens during the trials whereas common bullies typically got their tails through the screen and were then unable to swim back out; these two species accounted for 75% of the mortalities.

As identified in the recent review of council plans, the requirements for a water user to screen to exclude fish and the approach for doing so can vary markedly depending on where the water is consumed in the country. The purpose of the experimental fish screening work undertaken has been to provide some of the fundamental science data needed to assist decision makers to determine whether

or not an existing fish screen or future screen design is likely to meet its intended objective of protecting fish. Recommendations to assist screen designers, water users and decision makers are outlined below:

- Rock bunds are ineffective as a fish screening method for native fish and the use of a rock bund as a fish screen is not recommended;
- When first installed, woven wire is an effective material for screening fish, however, over time the aperture size can change as the material may deform (bend or break). For decision makers, a more rigid screening material, such as wedge wire, provides greater confidence that the original screen design will persist through time and continue to perform as intended;
- Wedge wire is highly effective at screening both native fish and salmonids and the leading fish screen manufacturers globally are preferentially using this screening material in their designs;
- A screening aperture size of 1.5 mm is recommended in areas of the lower catchment where īnanga whitebait ≤50 mm are captured;
- Upstream of the 1.5 mm īnanga whitebait screening zone, it is recommended that a requirement for 2 mm screening is required to protect both elvers and the juvenile life stages of other species;
- It is recommended that 3 mm is the largest approved aperture size that is consented across New Zealand. Where in the catchment it is appropriate to transition to a 3 mm screening requirement is harder to prescribe but planning provisions should be allow for more restrictive screening requirements in specific sub-catchments or waterways where high fishery values (e.g., threatened non-diadromous galaxiids, Chinook salmon fry) exist;
- Screens with a 5 mm aperture size are considered inadequate to protect juvenile native and salmonid fish.

It is acknowledged that several of these recommendations are catchment-specific potentially making implementation more difficult. However, many regional councils are making sub-regional plans at the catchment-scale or creating Freshwater Management Units (FMUs) for larger catchments so providing screening recommendations at this scale is considered appropriate.

1 Introduction

Water for irrigation is the largest water use sector, currently accounting for about 70% of global water withdrawals and nearly 90% of consumptive water use worldwide (Shiklomanov and Rodda 2003). In regions of the world, including New Zealand, economic activities can be constrained by water availability, leading to competition both among sectors and between human uses and the needs of the environment. Surface waters are abstracted to varying degrees to meet human needs such as agriculture, drinking water, urban water supply, industry and electricity generation and New Zealand is no exception (Figure 1). Increasing water abstraction has resulted in increased food security, a higher standard of living and greater economic gains for individuals and the country but there are environmental costs. The abstraction of these surface waters, typically to increase dryland production, results in altered river flows and habitats and has the potential to impact aquatic biota.

When surface water diversions are not properly screened, they can result in the physical removal of fish from rivers (Unwin et al. 2005; Boys et al. 2013; Bonnett et al. 2014). Screens are used to physically block fish from entering water intakes because fish loss through entrainment at irrigation diversions is a worldwide problem linked to global declines in freshwater fish species (Moyle and Williams 1990; Musick et al. 2000). In New Zealand, fish screens on water intakes (e.g., inclined flat screens and rotary screens) started to be required in the 1980's. Under the Freshwater Fisheries Regulations (1983), a screen was a requirement to consider for new dam/diversion structures. However, the quality of these early screens was highly variable and often had design and/or installation issues (Jamieson et al. 2007). A lack of screens and/or their ineffectiveness led to fish populating water distribution networks and whilst some species have formed viable populations in these systems, there has seldom been return passage to the river for these fish so they are lost from natural river populations. This is particularly detrimental to those species that need to move within and between fresh water and the sea to complete their lifecycles.

There are many complex freshwater management issues (e.g., water quality, over-allocation of water) but reducing fish losses at water intakes is more straight-forward because the source of the problem is easily identifiable as is assigning responsibility to a person or party. Other countries (e.g., USA) have for many years required significant fish screens at water diversions and been successful in reducing the number of fish entrained[1] whilst still meeting the requirements of out-of-river water users (Moyle and Israel 2005). In New Zealand, fish screening has in the past primarily been considered for east coast regions like Canterbury and Otago but the distribution of surface water takes shown in Figure 1 highlights that the issue is of national relevance. Moreover, climate change predictions of longer and hotter summers in the drought-prone regions of New Zealand[2] suggests water demand will increase at the same foothill and lowland waterways have reduced flows. All these factors indicate the pressure to abstract surface waters will increase in the future with the potential for more water takes across the country and an associated increase in the number of fish interacting with these takes.

In New Zealand, regional councils issue the consents for the taking of surface waters and consult iwi partners and with agencies such as the Department of Conservation and Fish and Game New Zealand about proposals for water infrastructure because all have responsibilities for managing fish passage and protecting native and sports fish populations. As it is the councils that write the consents, a review of the council plans was conducted as part of a Ministry for Primary Industries (MPI) funded Sustainable Food and Fibre Futures (SFFF) project titled the "Adoption of Good Practice Fish Screening". The review

[1] Fish entrainment is defined in this report as fish being transported along with the flow of water and out of their normal stream, river or lake/reservoir habitat into unnatural environments (e.g., constructed canals).
[2] https://www.mfe.govt.nz/climate-change/likely-impacts-of-climate-change/likely-climate-change-impacts-nz

of Jellyman (2020a) concluded that “regulations pertaining to fish screening are highly variable across New Zealand ranging from nearly absent to highly prescriptive”. It was apparent that whilst some guidelines have been developed for Canterbury that are broadly applicable to regions across New Zealand (see Section 1.1; Jamieson et al. 2007), there has never been a request for national adoption/implementation and this has resulted in variable plan requirements (see Jellyman 2020a). The greatest source of variation identified in the plans was around screen aperture guidance related to the appropriate ‘gap size’ for screening materials and filling knowledge gaps on this issue has been the focus of experimental work conducted by NIWA.

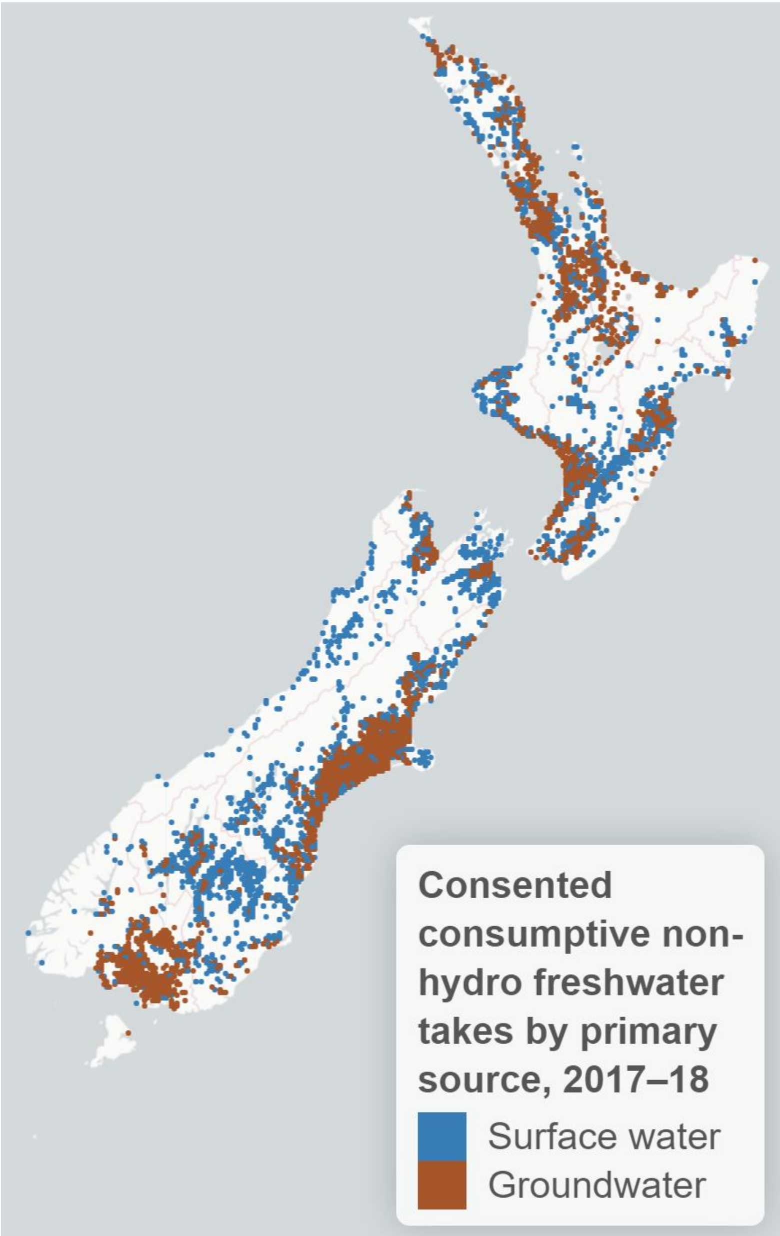

Figure 1: The distribution of groundwater and surface takes across New Zealand. Data source: Stats NZ (https://www.stats.govt.nz/indicators/consented-freshwater-takes); Booker and Henderson (2019).

1.1 Current best practice guidance for fish screening

The following guidelines are taken from Jamieson et al. (2007) in which a fish screen would only be considered effective[3] when all seven criteria below are met:

- **Site location**: The site is located to minimize exposure of fish to fish screen structure, and minimizes the length of stream channel affected while providing the best possible conditions for the other criteria;
- **Screen apertures**: Screening material (mesh, profile bars or other) on the screen needs to have openings small enough to exclude fish, and a surface smooth enough to prevent any damage to fish. Jamieson et al. (2007) recommended a bar gap of 2 mm or mesh/plate aperture size of 3 mm;
- **Approach velocity**: Water velocity is slow enough to allow fish to escape entrainment (being sucked through or washed over the screen) or impingement (being squashed or rubbed against the screen). Jamieson et al. (2007) recommended an approach velocity of no more than 0.12 m/sec;
- **Sweep velocity**: Water velocity across (or past) the screen is sufficient to sweep the fish past the intake promptly. Jamieson et al. (2007) recommended a sweep velocity greater than the approach velocity;
- **Bypass provision**: A suitable fish bypass is provided so that fish are taken away from the intake and back into the source channel;
- **Bypass connectivity**: There needs to be "connectivity" between the fish bypass and somewhere safe, usually an actively flowing (i.e., not still) main stem of the waterway;
- **Operation and maintenance**: The intake needs be kept operating to a consistent, appropriate standard with appropriate operation and maintenance. This should be checked or monitored.

1.2 Report objectives

This report continues the work reported in Jellyman (2020b) and for background context it is necessary to briefly detail the work undertaken in that report. The effectiveness of different types of fish screens at excluding fish of various species and sizes were investigated in indoor flume experiments and Jellyman (2020b) also conducted outdoor refinement experiments in a 'stream simulator'. The outdoor experiments altered screen aperture and approach velocity and examined fish behavioural responses to screen penetration, bypass use and screen contacts by fish as they approached the screen from an upstream to downstream direction. The Jellyman (2020b) report acknowledged that several of the species tested in the experiments were diadromous (i.e., move between the ocean and freshwater habitats) and would most commonly approach fish screens when moving in an upstream direction (i.e., from downstream to upstream which was not the direction tested). Thus, Year 2 experiments contained in this report, where species would be tested in a downstream to upstream direction, were also required before making conclusions and fish screening recommendations.

Therefore, the current report was focussed on refining Year 1 experimental work related to the stream simulator. The Year 2 refinement experiments were focussed solely on wedge-wire screens and the

[3] Fish screen effectiveness is considered to be maximised at a site by Jamieson et al. (2007) when all the seven criteria have been satisfied.

refinements were: changing the approach direction for diadromous species, altering some of the species tested (to expand the understanding of a range of species and life stages), altering the life stage/size of shortfin eels for testing compared to what had been tested in Year 1 (i.e., testing smaller fish), as well as decreasing the slot size encountered by fish. The experimental design was discussed by a Technical Advisory Group that had been formed to advise on technical aspects of the MPI SFFF project.

Before outline the methodology for the experimental work it is relevant to note an important caveat. The objectives of this report were focussed on examining how fish interact with a fish screen and the purpose was *not* to try and determine what proportion of fish might interact with a screen when moving upstream. This is an important distinction to clarify because the stream simulator was very intentionally configured to increase the likelihood of interactions between fish and the screening material. Thus, it is important to be cognisant of this bias when interpreting the results of this report. For example, if this report found that 50% of shortfin glass eels penetrated a particular screen type this result should not be extrapolated to infer that for an actual river intake (with the same screen type), half of all shortfin glass eels would be lost to the river.

2 Methods

2.1 Fish collection and maintenance

Five fish species were tested during the Year 2 experiments (Table 1). Four native species were captured from the lower reaches of four rivers[4] during a series of collection trips from November 2019–March 2020 (i.e., during months when irrigation typically occurs). It is relevant to note that due to increased flooding compared to the previous year, smaller bullies were less available at collection sites during certain trips. Introduced Chinook salmon were obtained from Montrose fish hatchery operated by North Canterbury Fish and Game; note, the mean size of salmon tested was slightly larger than the size of greatest concern (i.e., c. 40 mm). To collect native fish, a Kainga EFM 300 (200–300 V pulsed DC) backpack electrofishing machine (NIWA Instrument Systems, Christchurch, New Zealand) was used to momentarily stun fish for capture. The smallest fish caught were preferentially selected for use in the trials, as smaller fish were more likely to penetrate screens, and thus most likely at risk from impingement and entrainment. Following capture, fish were transported in aerated containers back to the laboratory at NIWA Christchurch where they were transferred into 40 L aquaria (i.e., holding tanks) containing untreated artesian bore water. These aquaria were in a temperature-controlled room (17°C), with a 12 h light: 12 h dark photoperiod, and fish were acclimated in aquaria tanks for a minimum of 36 h prior to commencing the experiment. Aquaria were aerated and on a recirculating water supply with approximately 20% of the water replaced daily. Fish were fed each evening on live *Daphnia* spp. (water fleas) or fish flakes, depending on the dietary preference of each species. All fish were given at least 36 hours to recover from electrofishing and acclimate before trials commenced.

Table 1: Summary of fish species and lengths used in the Year 2 experiments. For comparative purposes, length data for species tested in stream simulator experiments in Year 1 are also provided. Note, for shortfin eel, Year 2 examined the glass eel stage (i.e., the stage at immediate entry from the sea) whereas Year 1 examined the elver stage, when they have likely been resident in freshwater for ≥1 year, which is why there is a larger length difference.

Species name	Common name	Year 2: Mean length and range (mm)	Year 1: Mean length and range (mm)
Anguilla australis	Shortfin eel	59 (54–66)	83 (70–95)
Gobiomorphus cotidianus	Common bully	47 (38–61)	40 (30–47)
Gobiomorphus hubbsi	Bluegill bully	44 (32–56)	40 (35–45)
Galaxias maculatus	Īnanga	45 (39–51)	Not tested
Oncorhynchus tshawytscha	Chinook salmon	63 (43–71)	Not tested

2.2 Experimental apparatus

The outdoor stream simulator, described in Jellyman (2020b), was an experimental apparatus that consisted of a header tank which released water into a fiberglass channel mounted above ground level (Figure 2). Originally, the fibreglass channel was lined with polyethylene followed by a layer of 6-mm pea gravel to simulate a more stream-like environment, however, the native fish species — particularly shortfin eels — would often attempt to find refuge rather than swim upstream. Therefore, it became necessary to remove the substrate to motivate species to move upstream and interact with the fish

[4] Co-ordinates for site locations were: Cust River (43°22´S, 172°38´E), Ashley River (43°27’S, 172°68’E), Heathcote River (43°55'S, 172°70'E), Grey River (42°44'S, 171°19'E) and Montrose Hatchery (43°29’S, 171°36’E).

screen. Substrate refuge was provided approximately two metres upstream of the fish screen (in the form of a cluster of larger stones; principal axis 155–180 mm) to reduce the likelihood of fish swimming back downstream and interacting with the screen in the same direction as Year 1 experiments; based on both video analysis and the location of native fish at the end of the trials, this technique proved to be effective at stopping native fish moving back downstream past the screen.

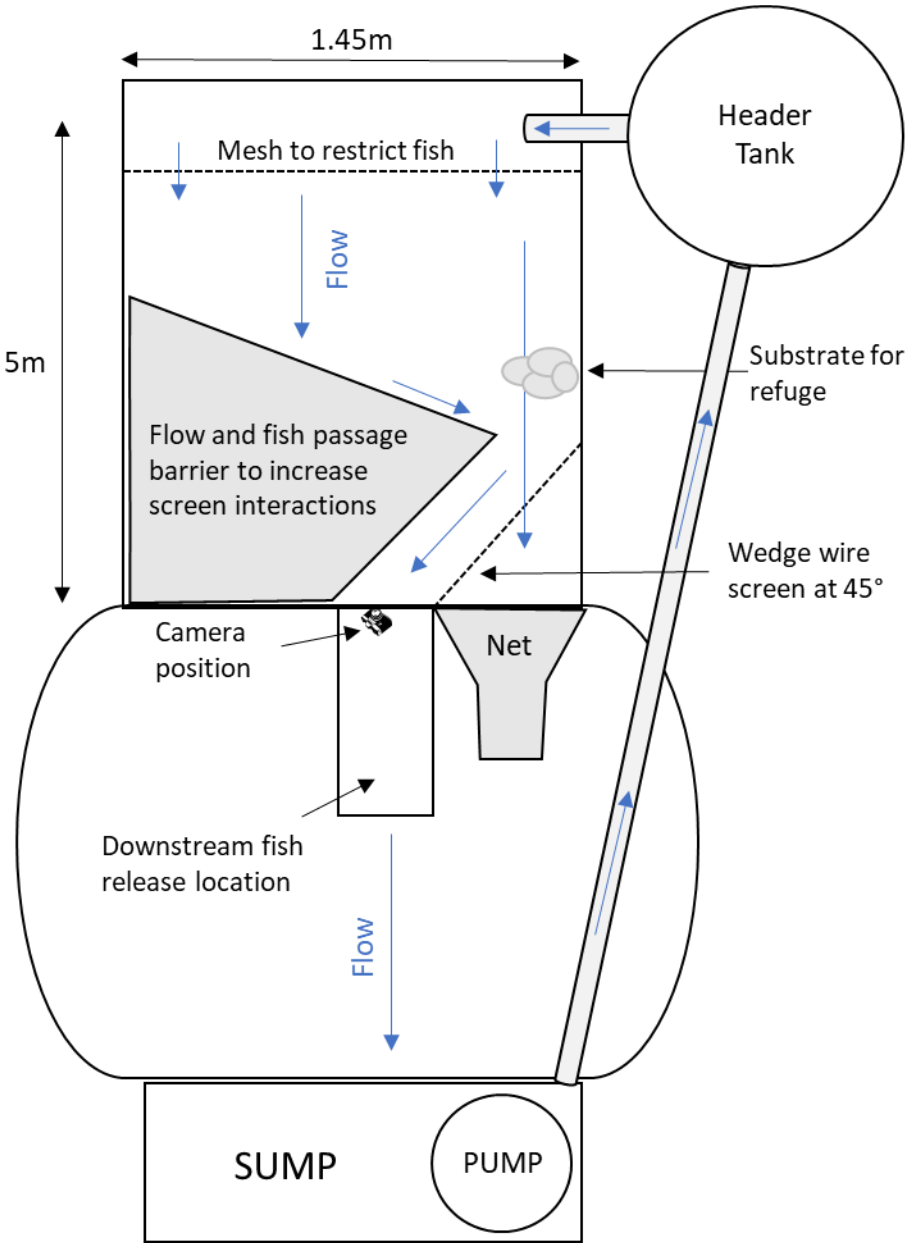

Figure 2: Bird's eye view schematic diagram of the outdoor stream simulator. The blue arrows indicate the direction of flow through the recirculating system.

For these Year 2 experiments, sections of vertical bar wedge-wire screen (100 cm L x 30 cm H) were vertically inserted into the channel at 45° to the flow direction; the maximum screen angle specified in New Zealand fish screening guidelines (Jamieson et al. 2007). There were two different wedge-wire screen treatments tested, either 1.5 or 2-mm spacing between bars (3 mm wedge-wire was trialled in Year 1). A channel (180-mm width × 900-mm length) was constructed parallel to the screen to generate a sweep velocity vector (Figure 2). Restricting the width of the upstream passage pathway was a very intentional bias that was introduced into the experimental design to increase the likelihood that fish would interact with the screen. For those fish that penetrated the screen, there was a short section of flume that led to a holding net. A camera (GoPro™ Hero4 Silver) in a waterproof housing was setup underwater to record footage of fish behaviour when interacting with the screen; the camera was positioned before the screen and in the middle to upper part of the water column (Figure 2). The position of the camera was considered to have no impact on the hydraulic conditions near the screen; this was tested and confirmed using a red vegetable-based dye prior to starting any experiments.

2.3 Experimental procedure

Previously, experiments conducted in the outdoor artificial stream evaluated the effectiveness of 3-mm and 2-mm wedge-wire screens at excluding bluegill bullies, common bullies, shortfin eels, and Canterbury galaxiids (Jellyman 2020b). During those experiments, fish were released upstream of the exclusion screen with counts of screen interactions and bypass usage recorded. In Year 2 experiments, bluegill bullies, common bullies, shortfin glass eels, īnanga whitebait and Chinook salmon were released downstream of the fish screen to simulate how they would encounter a screen during an upstream migration. The non-diadromous Canterbury galaxiids from Year 1 experiments were substituted for diadromous īnanga whitebait which migrate upstream as juveniles (McDowall 1990). No introduced salmonids were included in Year 1 stream simulator experiments (although rainbow trout were used in flume trials) but juvenile salmon were included in Year 2 experiments following a discussion about the experimental design with the MPI project's Technical Advisory Group. Whilst wild juvenile salmon would likely interact with screens in an upstream to downstream direction, the Chinook salmon available for the experiment were hatchery-reared so their tendency is to swim against the current. Therefore, they were expected to move in an upstream direction against the flow.

Prior to each experiment, approach velocity measurements were taken approximately 8 cm in front of the centre of the screen, as per North American fish screening guidelines (National Marine Fisheries Service 1997)[5]. These measurements were taken at the top of the screen around the point where the channel widened (Figure 2). Velocity measurements were taken with a SonTek FlowTracker before each trial; three measurements were taken and averaged to ensure water velocity was within ± 0.02 ms^{-1} of 0.12 ms^{-1}; the intended treatment velocity. The same water source was used as in the flume experiments and the setup of the simulator meant it was continuously being oxygenated and was regularly measured at close to 100% saturation (always >9 mg mL^{-1}). Water temperature was measured using a WP-81 Waterproof Conductivity/TDS-pH/mV-Temperature Meter (TPS PTY Ltd, Queensland, Australia) and was subject to natural ambient air temperature fluctuations. Therefore, to maintain a consistent water temperature range for the experiments, temperature was monitored and kept within 2.5°C of the 18°C water temperature of the indoor holding tanks. To maintain this water temperature standard, experiments were either ceased for that day if the water temperature exceeded 19.5°C (and allowed to cool again overnight) or more typically, replacement water from Christchurch's artesian supply, which was always below 18°C, was introduced into the header tank and then flowed through the experimental system until the water temperature reduced to below 19°C. Experiments were not started unless the water temperature was less than 19°C.

For each trial replicate, five fish of a given species were released downstream of the wedge-wire screen and a camera was used to record any interactions with the screen; fish were never re-used between replicates or screen-size treatments. Each trial lasted 30 minutes to give fish time to acclimatise to their

[5] It is relevant to note that the more recent National Marine Fisheries Service (2011) guidelines state that "Approach velocity should be measured as close as physically possible to the boundary layer turbulence generated by the screen face".

surroundings and ensure a normal behavioural response when approaching the screen. Every 5 minutes, the net installed behind the screen was checked for entrained fish and the position of individual fish was recorded (if visible from a viewing location that did not disturb fish). This process was repeated until the end of the trial. After each trial concluded, the fish were collected from either the stream simulator or the net behind the fish screen and their location, length (mm) and any visible injuries were recorded. Following a series of experiments, the video footage was reviewed for evidence of screen contacts, impingements and screen penetrations which were defined using the same criteria as Jellyman (2020b). Screen contacts included fish touching the screen, resting against the screen, swimming alongside it, and attempting to force themselves through the gaps between the bars. An impingement was defined as any fish that was immobilised on the screen for 10 seconds or more and this differed from a contact as it was not an active choice (some impingements eventually resulted in mortality). Two counts were recorded if a fish escaped the screen and was then 'impinged' for a second time. There were five replicates for each species tested with the 2-mm wedge-wire screen. If any species penetrated this screen, they were then tested against the 1.5-mm wedge-wire screen following the same protocol outlined above but using new, untested fish. All fish were monitored for 24 hours after the experiment to determine mortality, but were not assessed for further signs of damage after the experiments were completed.

2.4 Statistical analysis

For statistical analyses, response variables (screen penetrations, impingements, and contacts) from each trial were calculated as proportions by dividing count data by the number of fish within each replicate (i.e., five fish). As noted in Section 2.3, fish species were only tested against the 1.5 mm wedge-wire screen if individuals had penetrated the 2 mm wedge-wire screen trials. Because not all species penetrated the 2 mm screen the final dataset was unbalanced so two datasets were produced (one each for the 2 mm and 1.5 mm wedge-wire treatments) and analysed separately.

One-way analysis of variance (ANOVA) was performed to determine whether there was a significant effect of species on the proportion of fish that penetrated the 2-mm and 1.5-mm wedge-wire screens. A two-way ANOVA was performed to determine whether species and either mesh size or length effects were influencing the response variable. All analyses were completed using the software package R v4.0 (R Development Core Team 2020) and data figures were made using SigmaPlot 14.0 (Systat Software, San Jose, CA).

3 Results

3.1 Fish exclusion: 2 mm vs 1.5 mm wedge-wire

Five fish species were tested during 2 mm wedge-wire screen experiments with most species exhibiting a strong motivation to move upstream against the flow. The exception to this were Chinook salmon and in four of the five replicates, no salmon moved the short distance upstream to interact with the downstream end of the screen. In the fifth replicate, three salmon interacted with the screen during the 30-minute experiment; two salmon were upstream of the screen at the end of the experiment and one had returned downstream to its starting location.

Analyses showed a significant species effect on the proportion of screen penetrations for the 2 mm wedge-wire screen experiments ($F_{4,20}$ = 16.55, P < 0.003; Table 3). For the size range tested (see Table 1), bluegill bully, common bully and Chinook salmon were excluded by the 2 mm screen (Figure 3). This statement for Chinook salmon should be interpreted in combination with the extent of screen interactions noted in the previous paragraph. Only two species — shortfin eel and īnanga — penetrated the 2-mm screen and the screen was more effective at excluding īnanga than shortfin glass eels (Figure 3). The 2 mm screen did not exclude 16% of īnanga (length range: 42–46 mm) and 64% of shortfin glass eels (length range: 55–62 mm).

Only species that penetrated the 2 mm wedge-wire were tested in 1.5 mm wedge-wire screen experiments (see Section 2.3). There was a significant difference in the ability of shortfin glass eels and īnanga to penetrate the 1.5 mm screen with all sizes of īnanga whitebait tested (39–51 mm) excluded (Table 3, Figure 3). In contrast to īnanga, 68% of shortfin glass eels penetrated the 1.5 mm wedge-wire which was similar to the percentage of screen penetrations observed for the 2 mm wedge-wire screen experiments (Figure 3).

Table 2: The effect of different fish species on the proportion of screen penetrations. Results are shown for one-way ANOVA on 2-mm and 1.5-mm fish screens (significant P-values are shown in bold).

Screen aperture size (mm)	Predictor	d.f.	*F*	*P*-value
2	Species	4	16.55	**<0.003**
	Residuals	20		
1.5	Species	1	192.67	**<0.007**
	Residuals	8		

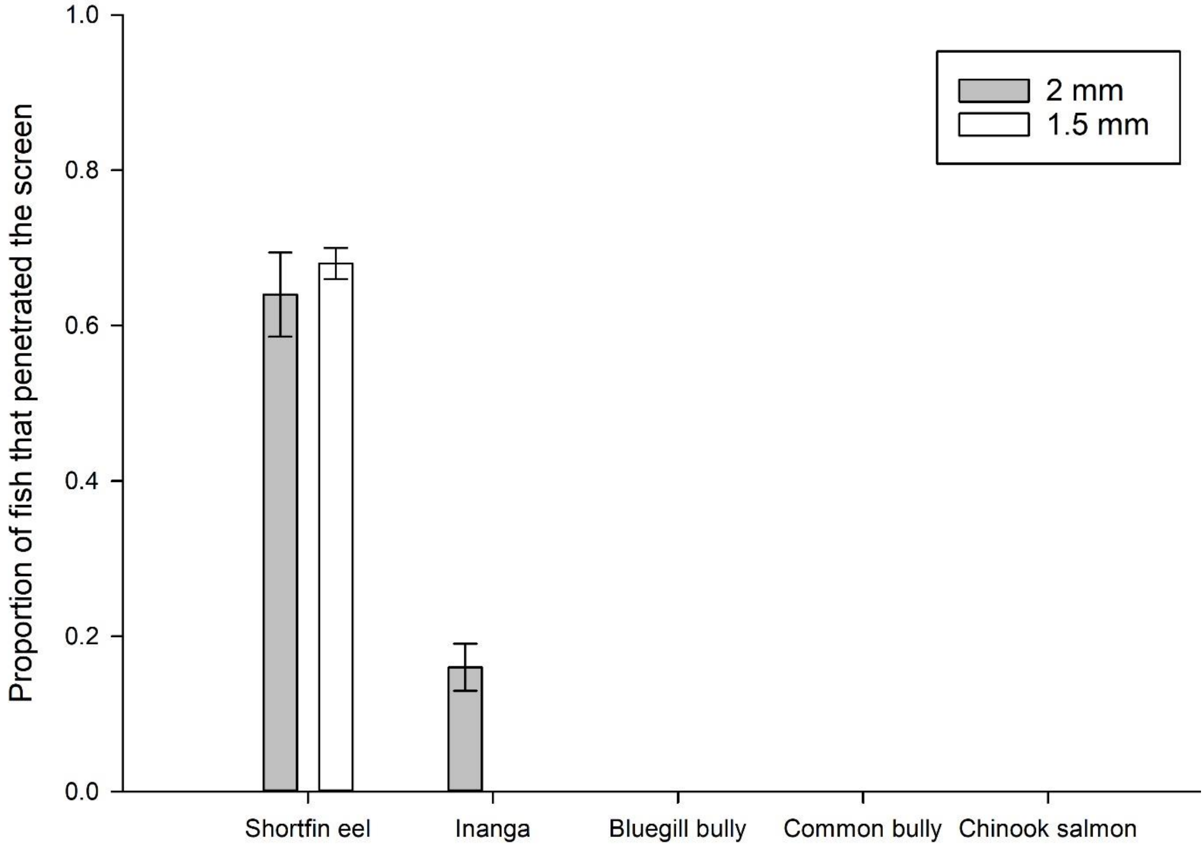

Figure 3: Mean proportion (±SE) of fish species that penetrated the two different-sized wedge-wire screens.

3.2 Screen penetration: the effect of fish length

Fish length analyses indicated that whilst screen penetration differed significantly between species, variation in mean fish length did not have a significant effect on the proportion of screen penetrations ($F_{1,15}$ = 0.03, P = 0.86; Table 3). Additionally, there was no significant interaction between the effects of species and mean fish length on the proportion of screen penetrations for the length range of species tested ($F_{4,15}$ = 0.17, P = 0.95; Table 4).

Analysis of the shortfin glass eel data showed that there was no significant difference in the length of glass eels penetrating the screen, compared to those that did not penetrate, for the 2 mm and 1.5 mm screen sizes (Figure 4). The 1.5 mm experiments were done once the 2 mm testing was completed for all replicates.

There was no significant difference in the length of īnanga that penetrated 2 mm screens compared to individual īnanga whitebait that did not penetrate (Figure 5). However, it is evident in Figure 5 that no fish larger than 46 mm penetrated the 2 mm screen despite approximately one-quarter of the fish from the trial being larger than this size. For the 1.5 mm screen, īnanga as small as 39 mm were tested but no fish were able to penetrate this screen size (Figure 5).

Table 3: **Effect of species and mean fish length on the proportion of screen penetrations.** Significant *P*-values are shown in bold.

Screen aperture size (mm)	Predictor	d.f.	*F*	*P*-value
2	Species	4	13.02	**<0.009**
	Length	1	0.03	0.86
	Species x Length	4	0.17	0.95
	Residuals	15		
1.5	Species	1	154.48	**<0.002**
	Length	1	0.14	0.72
	Species x Length	1	0.27	0.62
	Residuals	6		

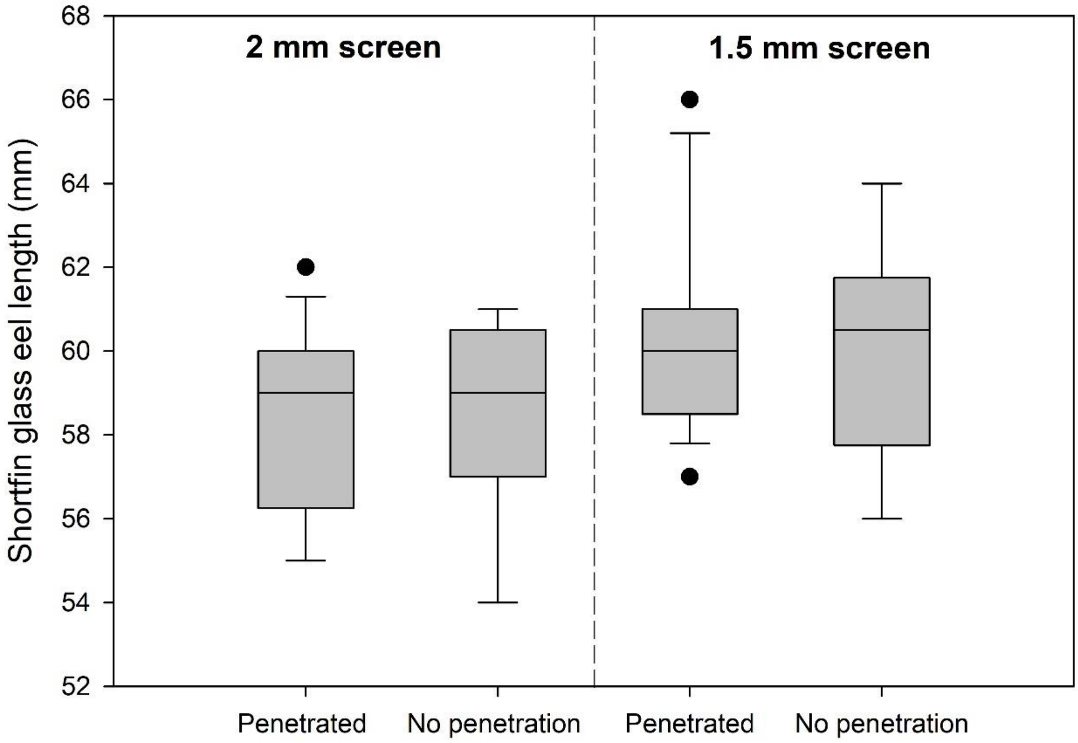

Figure 4: **The lengths of shortfin glass eel that penetrated (or did not penetrate) the 2 mm and 1.5 mm wedge-wire screens.** Boxplots present a picture of the entire length distribution for glass eel penetration between treatments. The upper and lower edges (hinges) of each box denote the 75th and 25th percentiles of the length estimates, respectively (also known as the 3rd and 1st quartiles). The horizontal line through each box denotes the median length. Upper whiskers extend to the smallest value within 1.5 x the interquartile range (IQR; difference between the 3rd and 1st quartiles) above the upper hinge. Lower whiskers extend to the largest value within 1.5 x the IQR below the lower hinge. Outliers, indicated by black dots, are individual estimates beyond the whiskers.

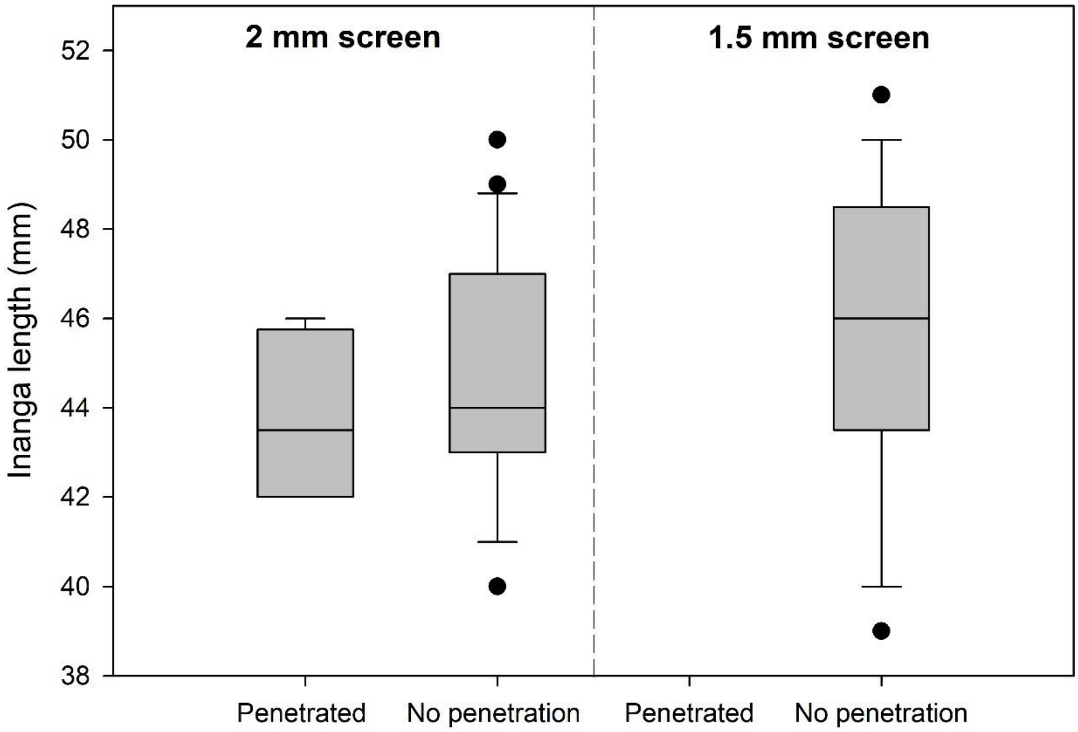

Figure 5: The lengths of inanga that penetrated (or did not penetrate) the 2 mm and 1.5 mm wedge-wire screens. An explanation of how to interpret boxplots is provided in the previous figure.

3.3 Screen contacts, impingements and mortalities

Video analysis showed that all species tested contacted the screen (i.e., fish touching the screen, resting against the screen or attempting to force themselves through). There was no significant difference between the numbers of contacts for different species ($F_{4,20}$ = 0.51, P = 0.73), although shortfin eels and īnanga that were able to penetrate the screen had slightly higher contact rates than either bully species (Figure 6). Chinook salmon had markedly higher screen contact rates than the native species but this was based on only one replicate where a proportion of the salmon had swum upstream.

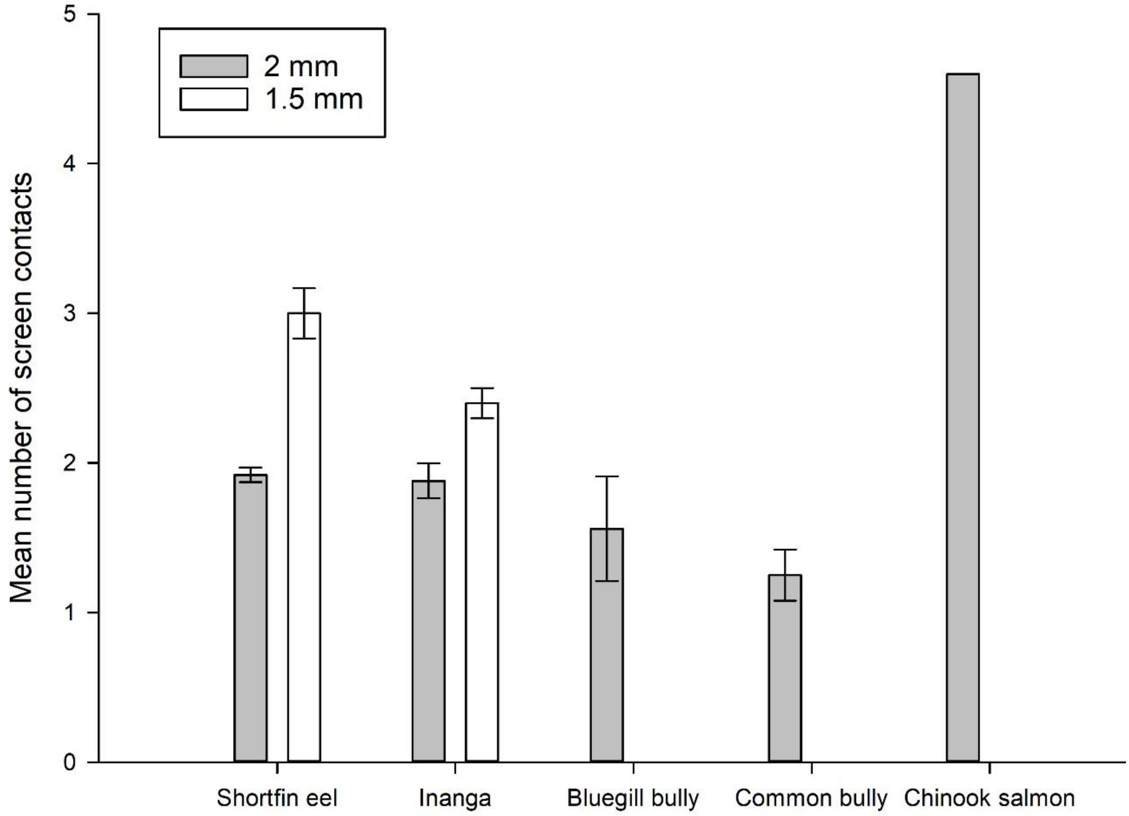

Figure 6: Mean number (±SE) of screen contacts for each species for the 2 mm and 1.5 mm wedge-wire screens. Screen contacts included fish touching the screen, resting against the screen (for less than 10 seconds) and attempting to force themselves through. Results for Chinook salmon should be viewed with caution as fish only interacted with the screen in one of the five replicates (which is why there is no error bar).

Video analysis showed some impingement of shortfin eels, īnanga, common bullies and bluegill bullies on the 2 mm wedge-wire screen (Figure 7). Impingements were highest for bluegill bully and the number of impingements recorded for this species was approximately half the number of screen contacts observed. In contrast, shortfin glass eels had the lowest number of impingements recorded for a native species on the 2 mm screen; the number of impingements was only 4% of the number of screen contacts (Figure 7). When examining impingements, and how common they are relative to screen contacts, it is relevant to note that shortfin eels could penetrate the 2 mm screen whereas bluegill bully could not (Figure 3). The two species that did penetrate the screen had a similar number of screen contacts but the number of impingements were more than five times higher for īnanga compared to shortfin eels for the 2 mm screen (Figure 7). No impingements were recorded for Chinook salmon but as noted earlier in this section, there were limited data available.

The number of impingements for īnanga on the 1.5 mm screen was approximately one-quarter of what was recorded for the 2 mm screen. In contrast, the number of shortfin glass eel impingements was six-fold higher on the 1.5 mm, however, this was in large part due to how glass eels behaved. Glass eels would often be recorded as impinged because they lay on the screen for more than 10 seconds and then in a subsequent movement would move along the screen, put their head through a slot and then penetrate the screen. This behaviour was observed far less with the larger 2 mm screen where the glass eels would often swim up to and then straight through the screen.

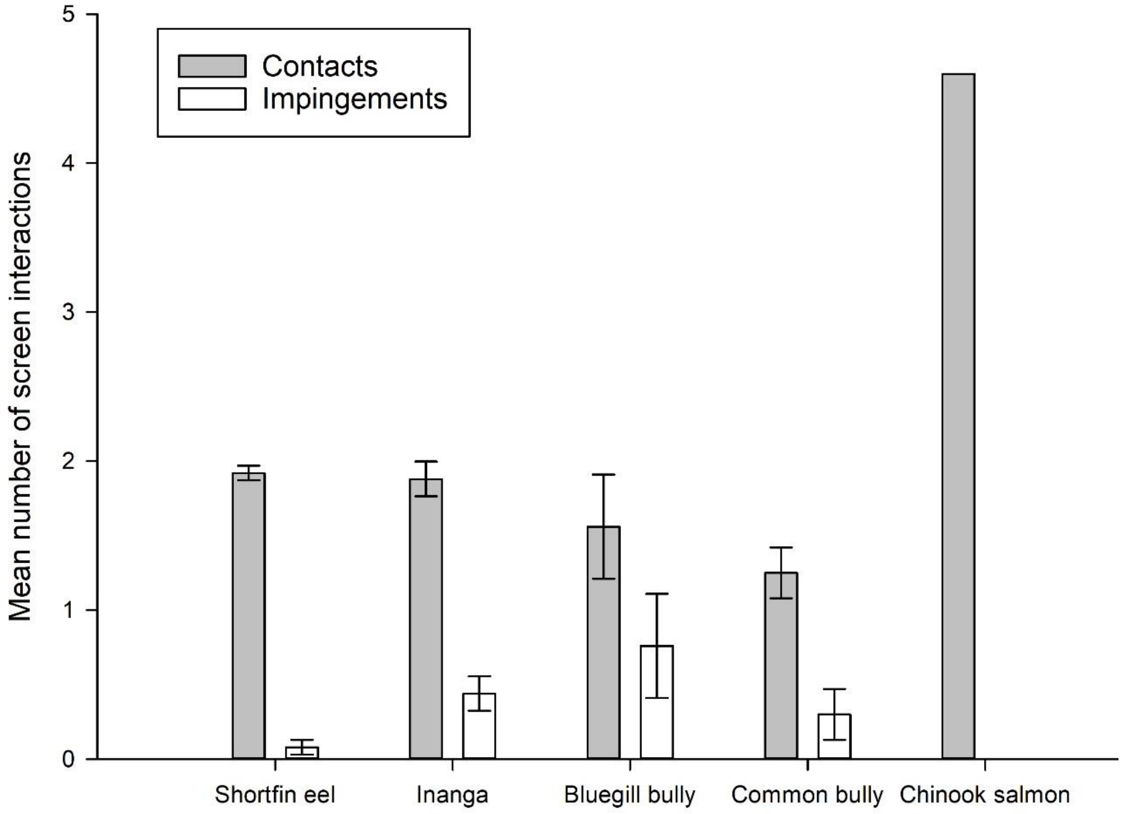

Figure 7: Mean number (±SE) of screen contacts and impingements for each species tested in 2-mm wedge-wire screen experiments. Note, separate counts were recorded if an individual fish was impinged more than once. Results for Chinook salmon should be viewed with caution as fish only interacted with the screen in one of the five replicates (which is why there is no error bar).

Of the 175 individual fish used in the Year 2 experiments, 163 fish were alive 24 hours after the experiment; all mortalities occurred during the 2 mm experiments. For the 12 mortalities recorded (two shortfin eels, four īnanga, five common bullies and one bluegill bully), all four īnanga mortalities occurred as a result of impingement on the screens during the trials (Figure 8) whereas common bullies typically got their tails through the screen and were then unable to swim back out. In contrast, the two shortfin glass eels died during the post-experiment monitoring period. One glass eel had gone through the screen and the other finished the experiment downstream of the screen and neither was observed as having any obvious injuries after the experiment so their deaths were less explainable.

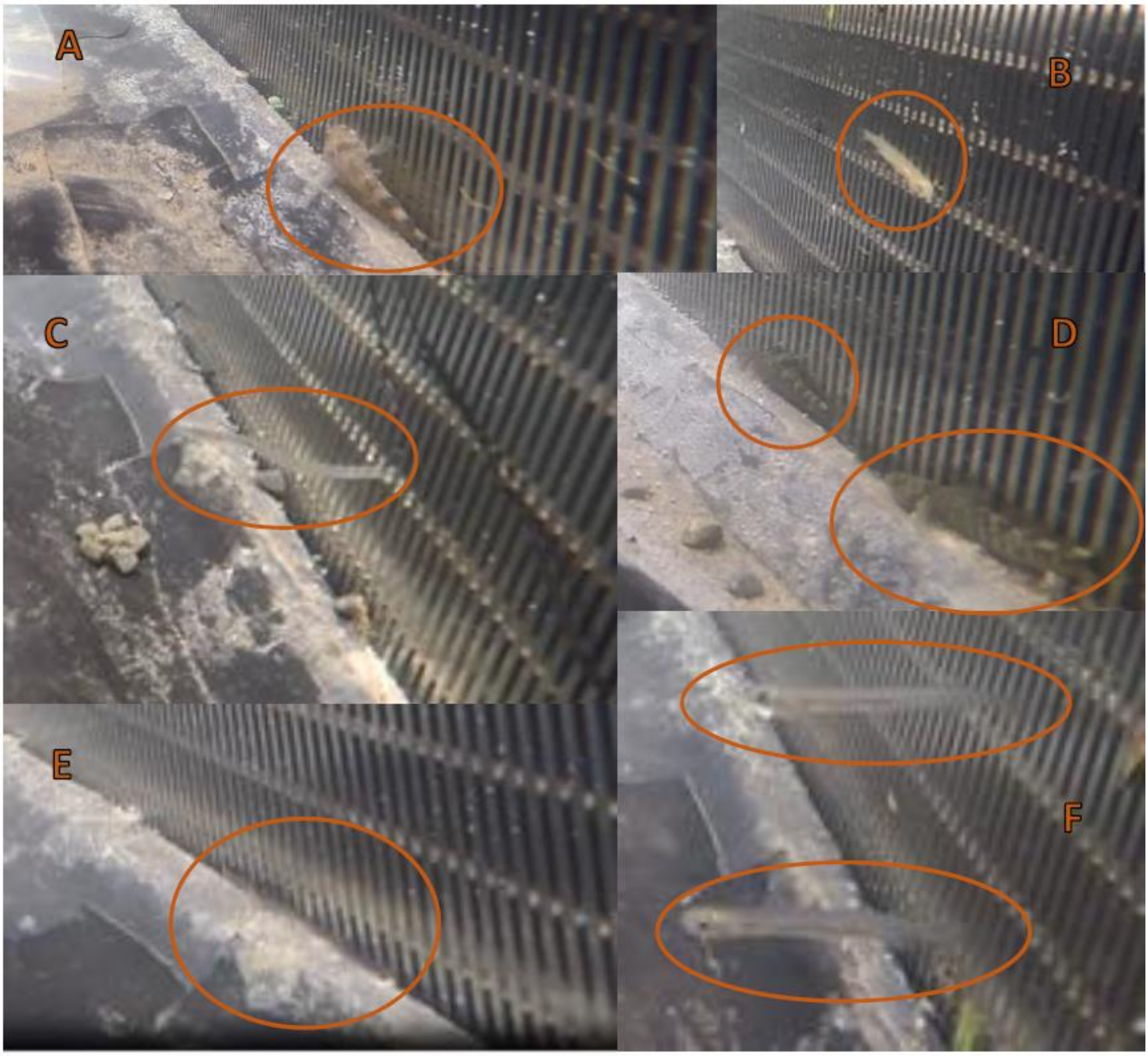

Figure 8: Examples of screen contacts, impingements and penetrations viewed on the video footage. Fish are circled in orange for clarity and the images show: A) common bully resting against the screen, B) īnanga impinged on the screen, C) shortfin eel attempting to penetrate the screen, D) two bluegill bullies resting against the screen, E) shortfin eel sitting next to the screen and F) two īnanga attempting to avoid the screen.

4 Discussion

4.1 Screen penetration

The two bully species tested were unable to penetrate either the 3 mm or 2 mm screens during the wedge-wire experiments of Jellyman (2020b) when fish were released upstream of the screens. Results from the present trials gave similar results when the same bully species were released downstream of the screens and interacted with a wedge-wire screen when swimming in an upstream direction. Common bully and bluegill bully as small as 30 and 32 mm, respectively were tested during the experiments indicating that juvenile bully species were being prevented from entering a hypothetical intake for the screen sizes tested. Charteris (2006) reviewed the limited information available at the time and concluded common bully would need a 2 mm mesh size to exclude these fish although the results of this experimental work indicate 3 mm will be sufficient for juvenile common bully (although larval life stages would be expected to penetrate a 3 mm screen).

Īnanga were able to penetrate the 2 mm screens but only fish 46 mm or smaller were able to get through. Charteris (2006) had concluded that a 2 mm screen could exclude whitebait, and whilst our results indicate that the majority of whitebait would be excluded at this mesh size, smaller individuals would make it through 2 mm screens. This is a particularly important point to note for North Island councils because īnanga migrate into river mouths at smaller and younger ages relative to South Island regions (Egan 2017). The widest part of the body preventing penetration is the head so in the absence of video analysis it would be assumed head width limited screen penetration. However, this assumption would be based on īnanga approaching the screen in a head-first direction. Mueller et al. (1995) discovered that Chinook salmon could penetrate 3.18 mm bar spacings if they encountered the screen tail-first. The video footage confirmed all the īnanga that penetrated the 2 mm wedge-wire did so in a tail-first orientation. It appeared that the swimming ability of this pelagic species had not sufficiently developed in these smaller individuals to overcome the approach velocities they encountered over a prolonged period.

The only species not excluded in the Year 1 stream simulator experiments that tested wedge-wire effectiveness was shortfin elvers. Effectiveness was influenced by elver length with individuals <85 mm penetrating the 3 mm screen and elvers ≤80 mm the 2 mm screen. Video analysis of elver interactions with the screens suggested that the direction of approach did not have a marked influence on screen penetration rates because elvers exhibited a searching behaviour moving along the screen in both directions regardless of flow direction. In the Year 1 experiments, 4% of elvers penetrated the 2 mm screen (length range: 77–80 mm), compared to 64% of shortfin glass eels (length range: 55–62 mm) in the Year 2 experiments. The notable size difference between elvers and glass eels explains the higher penetration result and highlights the obvious importance of fish size for screening effectiveness. The lack of a difference between 2 and 1.5 mm wedge-wire experiments for screening glass eels indicates just how difficult it is to screen all life stages, and how important it is to not just consider screen aperture size in isolation to the other key design criteria when trying to prevent impingement and entrainment of glass eels.

4.2 Screen contacts, impingements and mortality

When fish are swimming upstream against the flow, the potential time they are likely to be interacting with a screen would be expected to be higher compared to fish moving with the direction of flow downstream. Whilst total 'time on screen' was not calculated across stream simulator experiments, the number of screen contacts is a suitable surrogate measure to examine this. Results for the 2 mm wedge wire screen experiments in this report, where fish were moving in an upstream direction, showed that shortfin eels, bluegill bully and common bully all had between a three and seven-fold increase in the number of screen contacts when compared to fish approaching the 2 mm screen in a downstream direction (Jellyman 2020b). For shortfin eel, a three-fold increase in screen contacts was associated with a three-fold increase in penetration rate but it is acknowledged there were significant differences in the lengths of shortfin eels tested between these experiments.

Screen contacts were recorded during both Year 1 and 2 stream simulator experiments but Jellyman (2020b) reported no impingements during the upstream to downstream experiments. In contrast, all four native species had some extent of impingement recorded when approaching from a downstream direction. As noted above, the extent of screen contacts was markedly higher during Year 2 experiments although examination of video recordings suggested that a proportion of the bully impingements may have been resting behaviour on the surface of the screen (which was recorded as impingement because of the duration criterion used). This interpretation in partly corroborated by bluegill bully having the highest number of impingements but the lowest mortality across the native species. As noted in Section 3.3, most of the mortality recorded was related to impingements of īnanga and common bully. Mortality in īnanga was the result of impingement on the screen which appeared to be either from inadequate swimming ability or exhaustion. Based on video recordings, common bully typically got their tails through the screen and were then unable to swim back out.

4.3 Global fish screening trends

Screening water intakes to protect fish has been a requirement in many countries (e.g., USA) for longer than in New Zealand. For example, the United Kingdom enacted the Salmon and Freshwater Fisheries Act 1975 that mandated safe passage be provided for migratory Atlantic salmon (*Salmo salar*) and brown trout (*Salmo trutta*) and restricted intake screens to 12.5 mm. As fish life cycles, population losses through non-natural processes, and anthropogenic impacts on fish stocks have been better understood, requirements for fish screening have become more restrictive. Since 2010, England and Wales have legislated for the protection of all eel life stages with the smallest mesh size for glass eel/elver required to be 1–2 mm (Figure 9). A similar trend of requiring increasingly smaller aperture sizes on intake screens, albeit with a time lag relative to many European countries, is starting to be prescribed in New Zealand as the value of our indigenous fish fauna gains increasing recognition in national policy.

With increasing global concerns regarding the status of many freshwater fish species there is a general trend towards smaller bar spacings/finer mesh aperture at water intakes to increase fish protection. It is important to recognise that improved fish outcomes, typically driven by more stringent screening requirements (which comes with a financial cost to water users) is only part of an appropriate fish screening solution (i.e., only one of the seven criteria noted in Section 1.1). Aperture size is often a focus because it is straight-forward to legislate but the fish screening guidance for most developed countries recognises the need to take a 'whole of intake design' approach. This involves coupling both an understanding of key biological design criteria and site considerations *before* identifying the screen location, type and design. This framework, paired with appropriate operation and maintenance after installation, is seen as the most effective approach for achieving desirable outcomes for fish and efficient water screening.

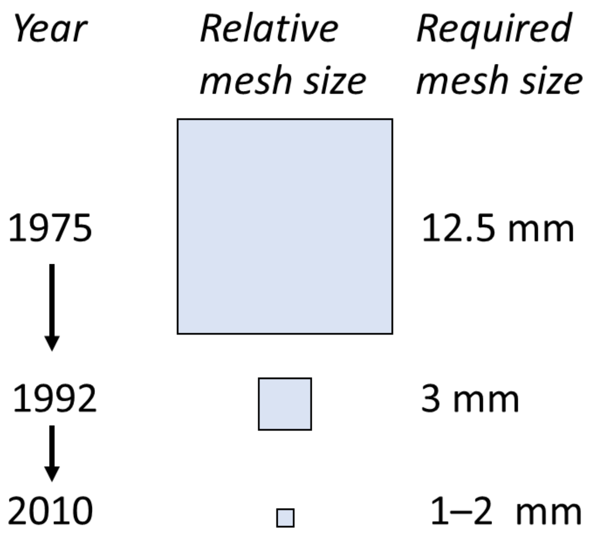

Figure 9: Changes in the mesh size requirements over time in England and Wales. The dates are associated with legislation requiring screening for migratory salmonids which specified 12.5 mm (1975), lamprey and juvenile shad as part of the *Habitats Directive* at 3 mm and *The Eels (England and Wales) Regulations 2009* covering all life stages including glass eels at 1–2 mm.

5 Conclusions and recommendations

The purpose of all fish screens is to prevent or significantly reduce the loss of fish from waterways where fish and intake infrastructure interact. Across New Zealand, surface waters are abstracted for out-of-stream purposes and the vast majority of these intakes will be from rivers where fish are present. However, as identified in the review of Jellyman (2020a), the requirements for a water user to consider fish when abstracting this water can vary markedly depending on the location of the abstraction (i.e., the region but also the location within a catchment or waterway). There is regional variability in approaches to screening fish and there is also notable variability in the types of screens being used to achieve this objective. The purpose of the work presented in Jellyman (2020b), and in this report, has been to provide some of the fundamental science data needed to assist decision makers to determine whether or not an existing fish screen or future screen design is likely to meet its intended objective. The implications for screen designers, water users and decision makers of the experimental results in this report and Jellyman (2020b) are discussed below alongside recommendations that will improve outcomes for fish communities.

5.1 Rock-bund screens

Rock-bund screens were tested by Jellyman (2020b) because they are a novel screen design that has been consented at large water intakes, particularly on the South Island's east coast, but for which almost no quantitative information is available (but see Webb and MacKenzie 2018 for a trial testing 120–180 mm Chinook salmon). Bund screens have a number of advantages and disadvantages based on experimental evidence and the author's experience examining and field testing these screens.

Advantages

- Relatively low capital cost to construct and repair;
- Screening material is readily available;
- Avoids mechanical screens;
- Conceptually and mechanically simple to design and operate;
- Effective at screening large fish;
- Relatively effective at screening salmonid species.

Disadvantages

- Can become a habitat, rather than a screen, for native fish;
- Experimental work has shown native fish move into and through rock-bund substrate. They are therefore concluded to be an ineffective screening method for several native fish species tested (e.g., bluegill bully, shortfin eel and Canterbury galaxias);
- Rock bunds will typically become clogged with debris and sediment over time;
- Requires a larger screen area than a mechanical screen;
- Can develop preferential flow paths over time;
- Difficult to inspect the screen for issues;

- Some examples are vulnerable to over-topping during floods;
- Screen may need to be rebuilt during irrigation season resulting in no screen at some time (whether this is legal/permissible within the consent is a contentious issue);
- When the screen is re-constructed after desilting it may perform differently (i.e., lack of consistent pore spaces over time) — this issue exists because unlike in other countries a backwashing/self-cleaning system has not been required;
- Screen deconstruction and rebuilding can result in further sediment mobilisation/disturbance in the waterway and further entrainment of fish into water intakes/lost to fishery.

Conclusion and recommendation

Rock bunds are ineffective as a fish screening method for native fish. For consent applications where decision makers need to consider the protection of native fish values, the use of a rock bund as a fish screen is not recommended. Under the National Policy Statement for Freshwater Management (2020), a decision maker is likely to be considering how diversity of life, as part of a compulsory value of ecosystem health, would be impacted by a fish screen. Therefore, whilst a rock bund screen should be effective at excluding salmonids, provided preferential flow paths through screens are not available, it is difficult to envisage a scenario where their ineffectiveness at excluding native fish is not considered.

The conclusions for rock bunds noted above should not automatically be assumed to apply to infiltration galleries (sometimes considered to be analogous to benthic rock bunds). Whilst there are similarities in design concepts for rock bunds and infiltration galleries, the extent and depth to which most of our native species will move into sub-surface riverine substrate is still poorly understood. The hydraulic conditions where infiltration galleries have been installed varies markedly, ranging from still ponds to swift braided rivers, and to what extent fish behaviour/movements might vary under these different contrasting flow conditions is unknown. However, testing of an infiltration gallery in a Canterbury pond by Bonnett (2013) found that 1.3% of the hatchery-reared juvenile Chinook salmon passed through the gallery screen.

5.2 Woven wire screens

Woven wire as a screening material has a far more consistent aperture size when compared to a rock-bund screen. Woven wire is synonymous in New Zealand with rotary drum screens and the advantages and disadvantages of drum screens have been documented in Jamieson et al. (2007); a fundamental design issue with these screens is often a very limited sweep velocity resulting in fish impingement (see Figure 10). A new woven wire screen is a relatively effective material for screening fish, and performed similarly to wedge-wire screens during the laboratory trials in Jellyman (2020b). Common bully ≥20 mm, bluegill bully ≥32 mm, Canterbury galaxias ≥47 mm and rainbow trout ≥40 mm were all excluded by a 3 mm woven wire screen. The issues associated with woven wire tend to occur over time as aperture size can change. Bent, or even broken wires can injure fish and make the water intake ineffective in the long-term at preventing entrainment and impingement. The woven wire material also has disadvantages for manufacturers as it has lower flow efficiency than wedge wire and can be harder to clean but it is markedly cheaper than wedge wire.

Figure 10: Chinook salmon trapped on the upstream side of a woven wire rotary drum screen. Photo credit: NIWA.

Conclusion and recommendation

When first installed, woven wire is an effective material for screening fish. However, with time effectiveness may decrease as aperture size has the potential to become more variable. For a given aperture width, the square configuration can result in woven wire being more effective for screening particular species (e.g., eels) when compared with the longer slots of wedge wire. As noted above, some of the issues with woven wire are associated with the screen designs they are linked with, as much as the material itself. For decision makers, a rigid screening material, such as wedge wire, provides greater confidence that different sized fish/life stages will not be entrained into the intake over time but an effective fish screen could still use woven wire as a material provided other criteria were met (e.g., regular inspection, maintenance and/or replacement schedule).

5.3 Wedge wire screens

Wedge-wire was as effective or more effective than other screening materials for four of the five species tested in Jellyman (2020b). Shortfin elvers were the fifth species and their ability to compress their body through bar spacings that are smaller than their body diameter potentially allowed them to exploit the longer vertical slot of wedge wire that other fish species could not. As previously noted, it is acknowledged that wedge wire is more expensive per square metre than woven-wire mesh and is likely to last much longer, but the focus of this experimental work has been on determining what is most effective for fish. Its effectiveness, alongside other desirable screen design properties, meant it was tested in the refinement experiments in this report which showed it is possible to use wedge-wire screens to exclude juvenile bully, whitebait and Chinook salmon smolt but preventing glass eel (and elver) entry in coastal intakes would be problematic, without optimising and strengthening other design criteria.

Conclusion and recommendation

Wedge wire is highly effective at screening fish, both natives and salmonids. Decision makers should be aware that leading fish screen manufacturers globally are preferentially using this screening material in their designs for a number of reasons including strength, longevity, ease of cleaning, etc. Whilst the use of wedge wire is industry-leading, it will not be suitable for all screen types and no screening material can overcome a poor fish screen (overall water intake) design. An appropriate fish screen design will always have taken a "whole of intake" approach and considered the seven criteria outlined in Section 1.1.

5.4 Aperture size

Based on the data from this report and Jellyman (2020b), a screening aperture size of 1.5 mm is recommended in areas of the lower catchment where īnanga whitebait ≤50 mm are captured. The size that īnanga whitebait enter rivers around the country varies with region and they are significantly younger and smaller at inward migration in the northern regions of New Zealand and older and larger in the southern regions (Egan 2017). Thus, the distance from the coast that a 1.5 mm screen may be required to protect whitebait, before it is appropriate to permit a 2 mm screen, will vary between regions. Waikato Regional Council (WRC) were the first council to require a mesh aperture size ≤1.5 mm to protect significant indigenous fisheries and fish habitat; this requirement has now been adopted by several councils. WRC specified an elevation limit (i.e., <100 m.a.s.l.) where this requirement needed to be met but in other regions it may be appropriate to set a distance inland depending on the type of rivers within a region. More generally, the approach taken in the revised 2021 whitebait regulations (i.e., whitebait fishing is only allowed where water levels are affected by the tide) is probably an appropriate guideline to adapt regionally to delineate 1.5 and 2 mm screening requirements[6]. Because other *Galaxias* species can comprise part of the whitebait catch, form landlocked populations and also penetrate far further inland than īnanga, from a practical implementation perspective this recommendation is made intentionally for īnanga whitebait.

The high level of penetration of 1.5 mm wedge wire by glass eels is highly problematic from a practical screening perspective[7]. That noted, after the initial migration into fresh water from the sea, upstream migration of the glass eels is delayed in tidal or estuarine areas while the eels undergo physical and behavioural transitions into pigmented elvers (Jellyman 1977, 1979). Shortfin elvers >80 mm did not penetrate 2 mm wedge wire screens so it is recommended that once upstream of the 1.5 mm īnanga whitebait screening zone, that a requirement for 2 mm screening is imposed to protect both elvers and the juvenile life stages of other species. Information on elver sizes at different distances inland around New Zealand is provided in Appendix A.

A 3 mm wedge wire screen was not penetrated by Canterbury galaxias (≥42 mm), bluegill bully (≥35 mm), common bully (≥34 mm) in either flume or stream simulator experiments. Based on various salmonid tests conducted, 3 mm wedge wire should also exclude individuals >40 mm although based on trapping in the Rangitata Diversion Race in the late 1990s, 30% of downstream salmon migrants were

[6] A publicly available Environment Canterbury report (Greer et al. 2015) provides an example of how to implement a GIS modelling approach to define a whitebait habitat boundary that could be used to delineate screen size requirements.
[7] Decreasing aperture size to screen glass eels is unlikely to be viable for water users so it is recommended that additional experimental work be undertaken that aims to quantify how different fish screen design options (e.g., smooth concrete footings, intakes raised a set distance off the river bed, etc.) could be used to protect glass eels though reducing the likelihood of glass eel entrainment into water intakes.

<40 mm (M. Webb, pers. comm.) so may require a smaller mesh size. Shortfin elvers c. 95 mm penetrated 3 mm screens, both wedge wire and woven wire screens, so further work could refine the size at which elvers are excluded by 3 mm screens, or could investigate what other key criteria should be optimised to prevent entrainment and impingement of elvers. In the absence of New Zealand-specific information, the United Kingdom's Environment Agency states that a 3 mm screen should protect eels ≥140 mm and given similarities in eel body shape, this information should be comparable to shortfin and longfin eels.

With increasing distance inland, other catchment-specific fisheries values may become more important (e.g., threatened non-diadromous galaxiids, salmonid fry) to consider and where there are waterways or sub-catchments with threatened species present it may be necessary to apply more restrictive aperture requirements to protect smaller life stages of these species. Thus, where in the catchment it is appropriate to transition to a 3 mm screening requirement is harder to prescribe. It is recommended that 3 mm is the largest approved aperture size that is consented across New Zealand. Jellyman (2020a) highlighted that screens with a 5 mm aperture size are currently permitted by several councils around the country but this is considered inadequate to protect juvenile fish from being entrained into water intakes.

It is acknowledged that these recommendations are catchment-specific and some may be problematic for some decision makers to implement. However, many regional councils are making sub-regional plans at the catchment-scale or creating Freshwater Management Units (FMUs) for larger catchments so providing screening recommendations at this scale is considered appropriate. It is important that fish screening recommendations that could be applied nationally have a defensible scientific basis and it is recognised that the practicalities of implementing those within a planning framework may require regional adaptation.

6 Acknowledgements

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Appendix A Elver lengths around New Zealand

Table A-1: Summary of elver lengths and estimated median ages at dam sites around New Zealand. Data are from Martin et al. (2015) as part of the MPI-funded National elver recruitment programme. Individual lengths of 100 shortfin (SFE) and 100 longfin (LFE) if available were measured monthly during 2013–14 season. Main sites (*) are listed above supplementary sites for the North Island and South Island. NA = Not available; an accurate age distribution could not be determined because an insufficient number of elvers were measured.

Site	No. Days	Species	Number	Length (mm)			Median age
			N	Mean	Median	Range	Y
North Island							
Wairua	214	LFE	7	60	59	55-66	NA
		SFE	1 318	63	61	48-130	0
Karapiro*	139	LFE	140	106	104	75-157	1
		SFE	295	93	91	74-153	1
Matahina*	135	LFE	272	111	110	86-152	1
		SFE	750	97	96	75-133	1
Patea*	178	LFE	124	80	79	59-124	1
		SFE	1 247	74	73	57-121	0
Piripaua	130	LFE	166	115	112	90-188	2
		SFE	497	101	100	85-142	1
South Island							
Arnold*	103	LFE	400	130	126	101-202	2
		SFE	418	111	108	90-175	1
Waitaki*	174	LFE	53	196	200	118-260	4
		SFE	103	132	130	102-203	2
Roxburgh	61	LFE	16	159	163	120-210	NA
Mararoa	119	LFE	1 591	152	137	92-240	2
		SFE	15	108	104	92-150	NA