Effectiveness trials for different fish screen materials

Reporting of Year 1 trial results

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Cover image: A consented rock-based screen used to 'exclude' fish at the Rangitata South Irrigation Scheme [photo credit: NIWA].

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Executive summary

Water for irrigation is the largest water use sector, currently accounting for about 70% of global water withdrawals. 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 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. Thus, this report designed research to address inconsistencies relating to both the aperture size of screens and also the type of fish screens being consented.

This research conducted two types of experiments: indoor flume experiments to examine the effectiveness of different types of fish screens and outdoor experiments in a 'stream simulator' to refine how altering screen aperture and approach velocity influenced screen penetration, bypass use and screen contacts by fish. Flume experiments tested five fish species (bluegill bully, common bully, Canterbury galaxias, shortfin eel, rainbow trout) against two rock screens (50–100 mm and 100–200 mm), 3 mm woven-wire mesh, 3 mm wedge-wire and a no screen 'control'. Rock screens were tested 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. Each experiment had five replicates (five fish per replicate) and a duration of 30 minutes with the location/zone each fish was present in noted at six-minute intervals (zones were: upstream of the screen, within the screen, downstream of the screen or on the back of the exclusion screen). Stream simulator experiments examined the effectiveness of two mesh sizes, for the leading screen type, under two 'approach' velocity treatments (0.12 and 0.24 m/s). These experiments examined the same species, except rainbow trout, as in the flume experiments and lasted 15 minutes.

In flume experiments, the presence of a screen significantly reduced the proportion of fish present in the upstream zone. Rock-bund screens had a high proportion of bluegill bullies that had penetrated through both sizes of rock screen, with 60% penetration of the 50–100 mm rock screen. Screen penetration (i.e., entering the upstream zone) was low for shortfin eel and Canterbury galaxias, however, this was because both species were instead spending the majority of time in the rock-bunds. For example, screen penetration of 100–200 mm and 50–100 mm rock screens by shortfin eels was 4% and 0%, respectively but shortfins spent 63% of their time in the larger rock screens and 71% of their time in the 50–100 mm screens where no penetration was recorded. The 3 mm woven wire mesh screen had no penetration by Canterbury galaxias, common bully or rainbow trout but there was reasonable penetration (40%) by shortfin eels and a single bluegill bully made it through the screen. With the exception of shortfin eels, there was no penetration of the 3 mm wedge-wire screen. The more flexible body shape of shortfins meant the slot shape was easier to penetrate than the square grid of the 3 mm woven-wire screen and shortfins were able to weave their bodies through the wedge-wire and use the screen as refuge habitat.

Based on the results of the flume experiments, wedge-wire screens were selected for refinement experiments in the outdoor stream simulator. Both the 2 mm and 3 mm wedge-wire excluded all bluegill bullies, common bullies and Canterbury galaxias when tested in the stream simulator, however a proportion of shortfin eels penetrated both screens. Eleven elvers (22%) penetrated the 3 mm screen ranging in size from 75–85 mm, whereas only two elvers (4%) that were 77 and 80 mm

penetrated the 2 mm screen. More shortfin eels penetrated the wedge-wire screens in the higher velocity (0.24 m/s) treatment, although this difference was not statistically significant due to high variability between replicates. No impingements were noted for any species in either velocity treatment although video analysis also suggested that the setup had an appropriate sweep velocity that minimised the risk of impingement as individuals of all species were observed being swept along the screen, rather than being impinged onto it. Shortfin eels and Canterbury galaxias were more active than the bully species in the stream simulator experiments and as a consequence had the most contacts with the screens and the highest bypass use.

Based on the results of the flume experiments it was concluded that:

- rock-bund screens should be effective at excluding salmonids, provided preferential flow paths through screens are not available;
- rock-bund screens are an ineffective fish screen for several native fish species tested, particularly bluegill bully, shortfin eel and Canterbury galaxias. Note, the species tested were anticipated to be representative of wider groups of fish, for example, results for shortfin eels should be highly applicable to longfin eels. Canterbury galaxias results should be applicable to other flathead and roundhead *Galaxias* species. It is acknowledged that rock-bund screens could become a screen for larger adult eels above a certain body length although the length at which a rock-bund becomes a screen will be relative to the size of rock used;
- woven-wire screens, when new, are likely to be a relatively effective screening material but because aperture size can change over time (i.e., within an irrigation season), there is concern about the potential for variable effectiveness with this screening material;
- with the potential exception of shortfin eels, wedge-wire was the most effective screening material and it had a number of advantages over woven-wire mesh as a screening material.

This summary is limited to the flume experiments. The Year 1 refinement experiments are not summarised because further testing in the stream simulator during Year 2 will result in a ‘package’ of recommendations from these experiments. Thus, all recommendations relating to the refinement experiments will be included in the Year 2 report scheduled for release in July 2021.

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 (Boys et al. 2013). 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 as a requirement to gain a water permit/consent under the Freshwater Fisheries Regulations (1983). 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.

Unlike many freshwater management issues (e.g., water quality, over-allocation of water, etc.), fish losses at water intakes is a very achievable problem to solve. 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 potentially been considered a key issue for several regions to grapple with (e.g., Canterbury, Otago) but the distribution of surface water takes shown in Figure 1 highlights that the issue is of nationally relevance. Moreover, climate change predictions for New Zealand suggest water demand will increase with longer and hotter summers causing reduced river flows coupled with more intense droughts[2]. 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 increasing number of fish interacting with these takes.

In New Zealand, regional councils issue the consents for the taking of surface waters and consult with agencies such as the Department of Conservation and Fish and Game New Zealand about proposals for water infrastructure because both those agencies have statutory responsibilities for managing fish passage and protecting native and sports fish populations. As it is the councils that write the consents, Jellyman (2020) conducted a review of the council plans and 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 (i.e., Jamieson et al. 2007), there has never been a request for national adoption/implementation and this has resulted in variable plan

[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

requirements (see Appendix A). The greatest source of variation in plans is around screen aperture guidance related to the appropriate 'gap size' for screening materials. Thus, this report has designed research to address inconsistencies relating to both the aperture size of screens and also the type of fish screens being consented.

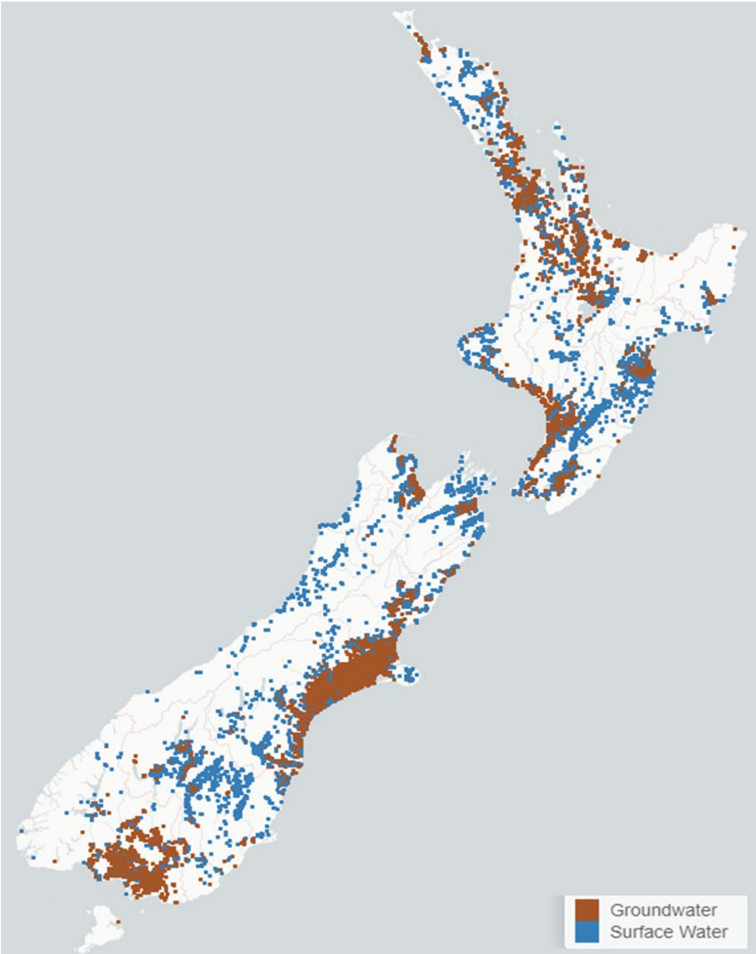

Figure 1: The distribution of groundwater and surface takes across New Zealand. Data source: Ministry for the Environment website.

1.1 Report objectives

This report is split into two types of experiments: testing and refinement. The objective of the **testing** research was to determine the effectiveness of different types fish screens at excluding fish of various species and sizes. Screen types/materials currently used in fish screens in New Zealand were tested in indoor flume trials. The top screen type from the flume testing was then used in **refinement** research. This research was conducted in an outdoor 'stream simulator' to replicate more 'real world' conditions. The objective of refinement testing was to examine whether screen effectiveness was altered in these more realistic conditions and how altering screen aperture and approach velocity[3] influenced screen penetration, bypass use or fish contact with the screens.

[3] Approach velocity was the water velocity vector perpendicular to the test screen and was measured 8 cm in front of the screen.

1.2 Workflow sequence

This report contains results nominally assigned as 'Year 1' findings but includes research conducted over two years funded primarily by NIWA's Strategic Science Investment Funding (Year 0 and 1) but with co-funding from the Ministry for Primary Industries Sustainable Food and Fibre Futures (Year 1). The workflow for this research is sequential so 'Year 0' results must be presented in this report as these results provide the rationale for the 'Year 1' work programme which followed. Note, Year 1 results will lead to refinement experiments in Year 2 which will be the basis of a different report next year (July 2021).

The authors acknowledge that several of the species tested in this report are diadromous species (i.e., move between the ocean and freshwater habitats) and will most commonly approach fish screens when moving in an upstream direction. Therefore, this Year 1 report which has conducted refinement experiments in an upstream to downstream direction will not conclude with fish screening recommendations because Year 2 experiments will test species in a downstream to upstream direction and all recommendations will be included in the Year 2 report scheduled for release in July 2021.

2 Methods

2.1 Fish collection and maintenance

Five fish species were tested during the screening trials (Table 1). Four native species were captured from the lower reaches of five rivers[4] during a number of collection trips from 2017–2019 whereas introduced rainbow trout were obtained from Montrose fish hatchery operated by North Canterbury Fish and Game. To collect native fish, a Kainga EFM 300 (200–300 V pulsed DC) backpack electrofishing machine (NIWA Instrument Systems, Christchurch, New Zealand) was used. All fish were collected during months, November to March, when irrigation typically occurs. The smallest fish caught were preferentially selected for use in the trials, as smaller fish were more likely to penetrate screens; trials in 2019 occurred over a shorter duration which is why the size range of the fish used in the experiments is smaller (Table 1). 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 frozen *Glycera* spp. (bloodworms) with any uneaten bloodworms cleaned from the tank the following morning; some species would not eat *Glycera* so in these instances other commercially available fish foods were used.

Table 1: Collection dates and sites of all fish species used in each experimental apparatus. Note, shortfin eel collection sites had markedly higher densities present in 2019 allowing us to be more size-selective for this species.

Apparatus	Trial period	Species	Mean length (mm) (length range)
Indoor flume	November 2017–April 2018	Shortfin eel	82 (56–111)
		Common bully	33 (15–45)
		Bluegill bully	35 (29–54)
		Canterbury galaxias	61 (47–75)
		Rainbow trout	51 (40–64)
Indoor flume	January–February 2019	Shortfin eel	70 (65–75)
		Common bully	38 (34–44)
		Bluegill bully	40 (36–45)
		Canterbury galaxias	50 (42–56)
Outdoor Stream simulator	March–April 2019	Shortfin eel	83 (70–95)
		Common bully	40 (30–47)
		Bluegill bully	40 (35–45)
		Canterbury galaxias	58 (53–60)

[4] Co-ordinates for site locations were: Cust River (43°22´S, 172°38´E), Waipara River (43°8´S, 172°47´E), Selwyn River (43° 30’S, 171°58’E), Ashley River (43°27’S, 172°68’E), Hinds River (44°06’S, 171°63’E) and Montrose Hatchery (43°29’S, 171°36’E).

2.2 Experimental apparatus and procedure

As shown in Table 1, experiments were conducted on two different types of apparatus: an indoor flume and an outdoor stream simulator. The two experiments were markedly different in their objectives, setup and testing so are written about separately below.

2.2.1 Indoor flume

Indoor flume experiments were undertaken in Year 0 and Year 1 of the research (2017–2019, Figure 2); flume experiments were split across two years because of difficulties sourcing wedge-wire mesh in Year 0. Therefore in Year 0, indoor flume experiments tested the effectiveness of 3 mm woven-wire mesh, two rock screens (50–100 mm and 100–200 mm) and a no screen 'control' with shortfin eel, common bully, bluegill bully, Canterbury galaxias and rainbow trout (Figure 3). With the exception of rainbow trout, the same species were tested the following year with 3 mm wedge-wire (Figure 3) to allow comparisons of screening effectiveness to be made between wedge-wire, rock screens and woven-wire mesh. For the rock screens, the two size ranges tested were selected based on conditions that had been written in recent regional council consents. As detailed in Section 3, rainbow trout had not penetrated any of the previous three screen types and as the mean size of rainbow trout available for testing in January 2019 was going to be larger than the fish tested in November/December 2017 (that failed to penetrate any screen at this smaller size) the trials could not be justified based on NIWA's animal ethics obligations.

The experiments were undertaken in a clear acrylic, six metre recirculating hydraulic flume (0.6 m width x 0.4 m height) that was filled to a depth of 0.15 m (Figure 2). There was no substrate lining the flume and water was sourced from the Christchurch City supply, which is artesian and untreated. There were 1 mm exclusion screens installed at either end of the flume to prevent fish from entering the pump. Different screen types (Figure 3) were inserted midway along the flume channel at 90° to the direction of flow. The woven and wedge-wire mesh were set within a thin frame for securing within the flume whereas rock screens were contained within a basket that measured 0.59 m W x 0.3 m H x 0.5 m L. Each screen created slightly different turbulence patterns on the 'downstream' side of the screen so a consistent velocity for each experiment was set based on velocity measurements taken 1 m from the screen. Mean water column velocity was set to 0.12 m/s using a SonTek FlowTracker (SonTek/YSI Inc., San Diego, USA) with alterations to flume velocity made using an inbuilt Teco 7300CV speed controller (TECO-Westinghouse Motor Co., USA) (see Larned et al. 2011).

For each experiment, five fish were released into the downstream flume section halfway between the exclusion screen and the test screen (Figure 2). Each experiment had a duration of 30 minutes and was undertaken between 0900–1700 h. The location of each fish was noted at six-minute intervals during each experiment. There was no screen present for the control treatment but the location of each fish within the flume, relative to the mid-point where a screen would usually be, was noted in an identical way to the screening treatments; the purpose of the control was to check whether species would attempt to move upstream in the absence of a screen (i.e., if there were no screen penetrations by a particular species it was because it was unable to pass through the screening material, not because the species showed no inclination to move upstream and attempt to penetrate it). At the end of each trial, all fish were collected and their lengths measured. There were five replicates conducted for each of the five species for each of the four screen treatments; two control replicates were conducted for each species (and produced identical results) and as all species showed they were motivated to swim upstream past the mid-point in the flume where a screen would be, five replicates were not undertaken given the obligations of our animal ethics permit to reduce unnecessary fish trials where possible.

Based on the results of the rock bund experiment, three species were also tested in overnight trials for the two rock screens (50–100 mm and 100–200 mm). These trials were run for 15 hours with the first three hours in light conditions followed by a period of 12 hours of dark. The location of fish within the flume was noted following the same process as the 30 minute experiments. The same number of fish were used in the overnight experiments as in the flume but only three species were tested and there were no control tests conducted.

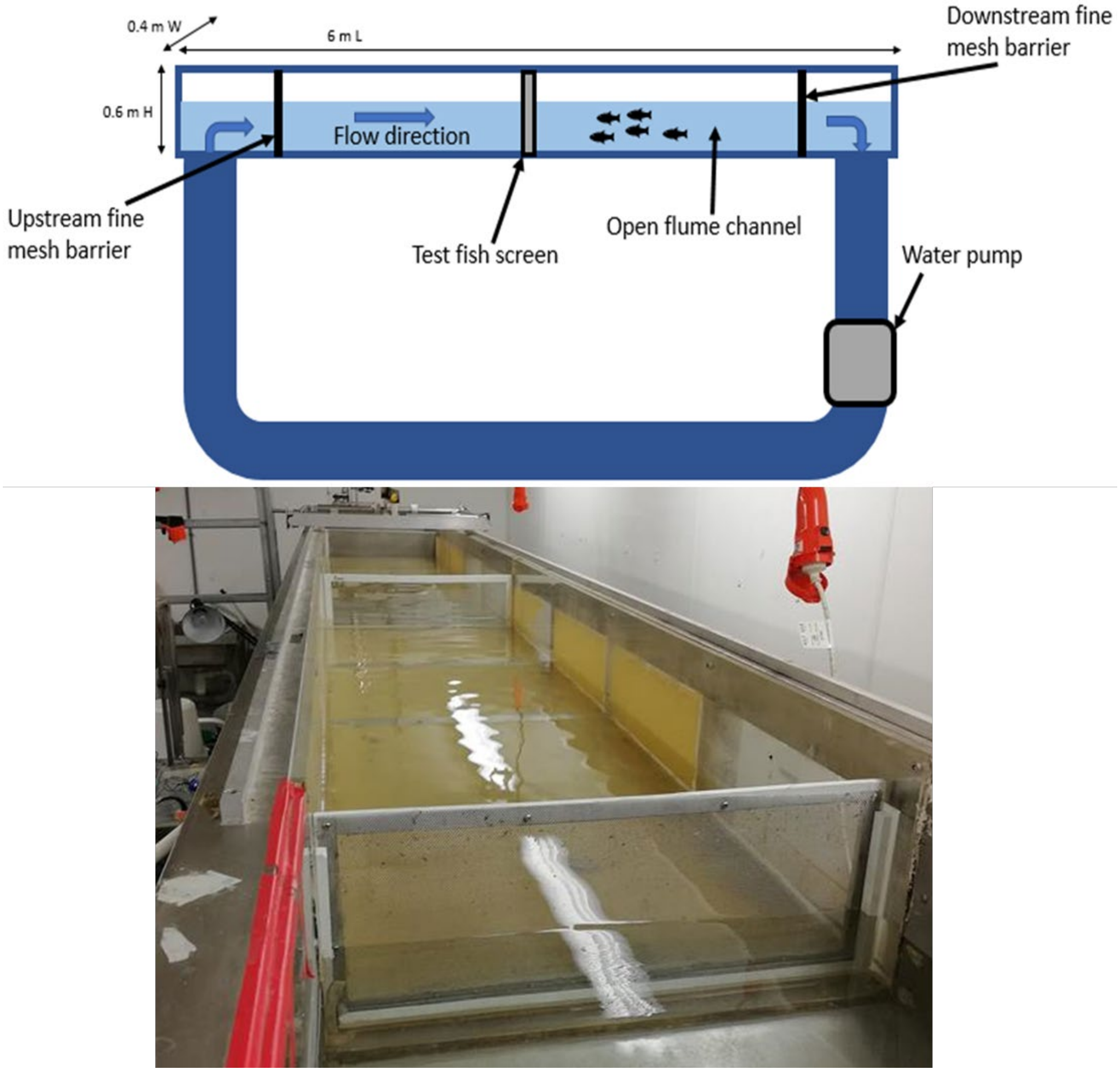

Figure 2: Schematic of indoor flume setup viewed from the side (top) and photograph with the downstream mesh barrier in the foreground looking longitudinally down the flume apparatus (bottom). In the bottom picture the 3 mm woven-wire mesh screen is being tested.

Figure 3: The three screen types tested in this study were: (a) rock bund, (b) woven wire mesh and (c) wedge-wire mesh. The left and centre panels show the experimental screening material used in the trials and the right panel shows examples of this material being used in New Zealand fish screens. Note, the two baskets of rocks in (a) show the 50–100 mm (left) and 100–200 mm (centre) rock treatments tested.

2.2.2 Outdoor stream simulator

The indoor flume trials tested several screen types whereas the outdoor stream simulator trials were considered refinement trials for the most appropriate screen type in a more 'real world' screening scenario. Stream simulator trials examined the effectiveness of two mesh sizes, for the leading screen type, under two 'approach' velocity treatments (0.12 m/s and 0.24 m/s). The stream simulator consisted of a header tank which released water into a fiberglass channel mounted above ground level and lined with 6 mm 'pea' gravel (Figure 4). Water flowed down the channel and then through either the fish screen or down a bypass channel into a sump where the water was then pumped back to the header tank by a submersible electric pump. Water was supplied to the channel at a constant flow rate by the adjustable gate valve on the header tank outlet. Exclusion screens were placed at either end of the channel to contain fish within the simulator although nets were in place at the downstream end to capture fish that had gone through the screen or down the bypass before contact with the exclusion screen.

In preliminary trials, the channel was lined with c. 60 mm diameter small cobbles to simulate a river environment, however, several species were immediately lost within the interstitial spaces and they did not leave this cover to interact with the screen. Consequently , a polythene lining was placed over the cobble layer and a thin lining of 6 mm pea gravel was placed on top to provide a more natural bed surface while also preventing fish from entering the coarser substrate. A section of fish screen (100 cm L x 30 cm H) was 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 was also a bypass channel that was 15% of the screen width, where fish moving downstream that did not penetrate the screen would be collected (Figure 4)— when entering the bypass, fish went through a notched section of a 'dam board' (which maintained the water level within the channel) and the combination of vertical drop and water velocity prevented fish from moving upstream again. Two cameras (GoPro™ Hero4 Silver) in waterproof housings were setup underwater to record footage of fish behaviour when interacting with the screen; one camera viewpoint was along the screen whereas the other camera viewed the screen from straight on (Figure 4).

As previously noted, two approach velocity treatments — 0.12 and 0.24 m/s — were also examined in the stream simulator experiments. The 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). 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 m/s of the intended treatment velocity. To ensure there was an appropriate sweep velocity along the screen, a notch had been cut into the 'dam board' at the end of the fish screen to create a sweep vector along the screen (and double as a bypass entry). 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 could not be as finely controlled in the outdoor simulator compared to the indoor flume as it 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 17°C water temperature of the indoor holding tanks. To maintain this water temperature standard, experiments were either ceased for the 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 17°C, was introduced into the header tank and then flowed through the experimental system until the water temperature reduced below 19°C. Experiments were not started unless the water temperature was less than 19°C.

At the beginning of each trial, five fish were released 2 m downstream of the top exclusion mesh in the centre of the channel. Each trial lasted 15 minutes and at the conclusion of the trial the nets were checked to examine how many fish had penetrated the screen compared to having entered the bypass. If fish were not in either net, then the stream simulator was checked to remove any remaining fish. All fish were measured for length (mm) and inspected for any visible injuries. Later, video footage was analysed for screen impingements and contacts. Impingements were defined as a fish visibly stuck in or on the screen for 10 seconds or more. Contacts were defined as any contact the fish made with the screen, whether by sitting against a screen, swimming along it, or actively trying to move through the screen. When a fish moved off a screen and returned, it was recorded as two separate contacts. Each screen treatment was replicated five times for each velocity treatment.

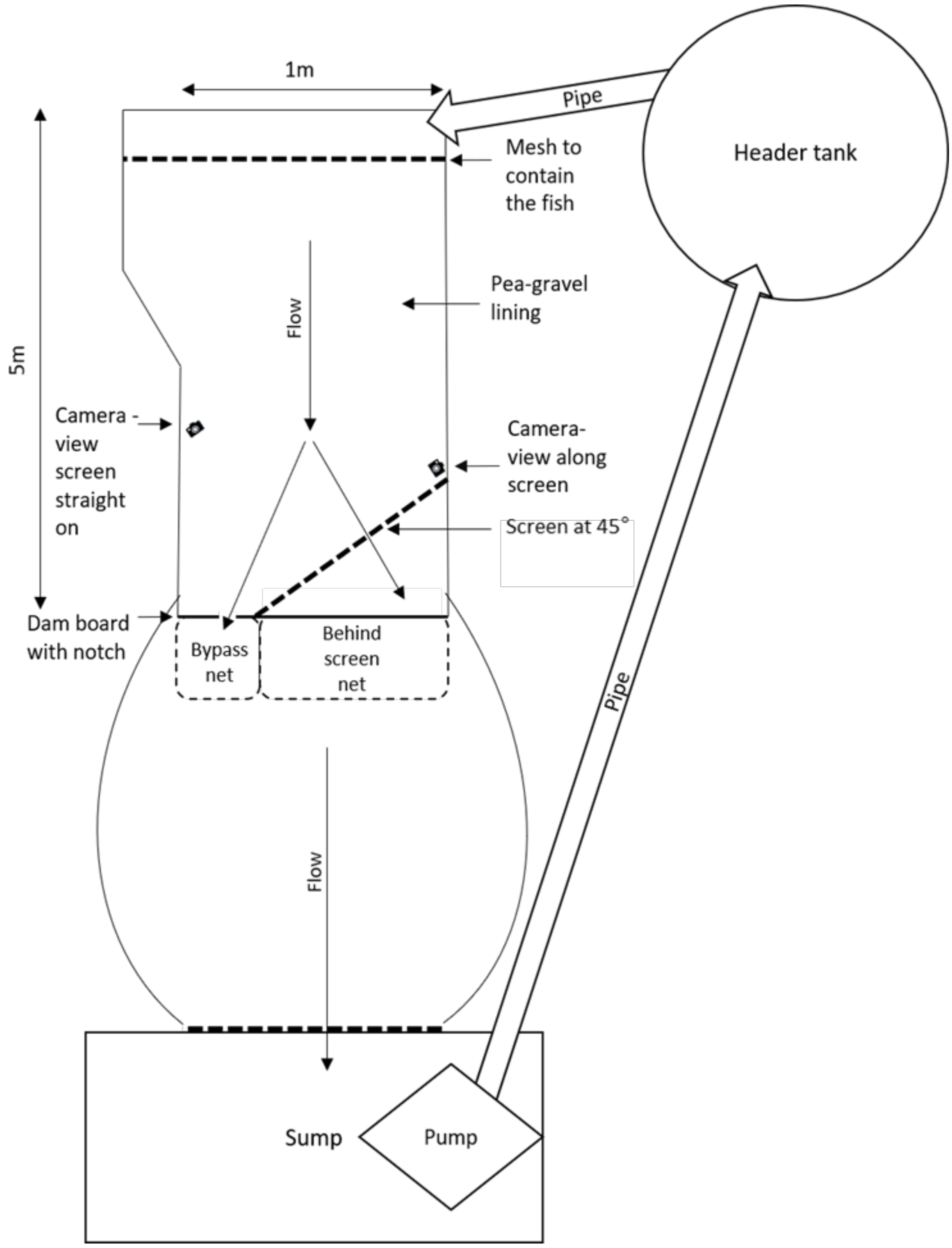

Figure 4: **Birds eye view diagram of the outdoor stream simulator.**

2.3 Statistical analysis

2.3.1 Indoor flume

The flume data were analysed using two approaches. The first approach was to analyse the maximum amount of screen penetration. The location of a fish was examined every six minutes and if a fish was recorded upstream of the screen during any of the five assessments during the 30-minute trial it was recorded as having penetrated the screen. For each replicate of a particular species, the proportion of the five fish that penetrated the screen was determined and then an average (and standard error) of the five replicates calculated for each screen type.

The second approach was a temporal analysis based on the location of each fish every six minutes. Fish location was analysed by dividing the flume into four zones: upstream of the screen, within the screen, downstream of the screen or on the back of the exclusion screen, and then calculating the average time a fish spent in each zone.

2.3.2 Outdoor stream simulator

Stream simulator data were analysed using two approaches. The first approach was to analyse the position and length of the fish at the end of the 15 minute trial. Fish were classified as being in one of three possible locations: screen net (i.e., the fish had penetrated the screen), bypass net (i.e., the fish had gone down the bypass) or simulator (i.e., was not in either net so was still in the simulator).

The second approach was to conduct video analysis from the two cameras. Videos were analysed for screen impingements and contacts. Impingements were defined as any fish being visibly stuck to the screen for 10 seconds or more. Contacts were defined as any contact the fish made with the screen, whether sitting by the screen, swimming along it, or actively trying to force their way through the screen.

For all stream simulator analyses, a two-way analysis of variance (ANOVA) was performed to determine whether species and either mesh size or velocity effects were influencing the response variable. Where appropriate/useful, a Tukey's test was used to test for significance in post-hoc pairwise comparisons. 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 by different screen types

Fish species and screen type had significant effects on the proportion of fish that penetrated each screen (Table 2). The presence of a screen significantly reduced the proportion of fish present in the upstream zone of the flume (Figure 5). The extent of a screen's effectiveness at preventing fish penetration was species-dependent and the control treatment, with no screen present, generally recorded the highest proportion of fish in the upstream zone (Figure 5). This indicated that all species tested were motivated to move upstream in the absence of a screen (Figure 5).

Rock-bund screens had a high proportion of bluegill bullies that had penetrated through both sizes of rock screen, with 60% penetration of the 50–100 mm rock screen (Figure 5). Only 32% of bluegill bullies penetrated the larger 100–200 mm rock screen, approximately half that of the smaller screen. The highest penetration through to the upstream zone by another species was 16% by Canterbury galaxias and no penetration through either size of screen was recorded for rainbow trout (Figure 5). Shortfin eel and common bully were not recorded in the upstream zone for any of the 50–100 mm rock screen experiments (Figure 5). However, these data were calculated by averaging the maximum penetration through the screen (i.e., whether a fish came out the other side of the screen) but the rock screens had a length of 0.5 m so these data do not illustrate the proportion of fish that entered/were within those screens that did not exit (i.e., penetrate). To examine this question, the percentage of time fish spent in different zones was analysed and revealed some quite different patterns about rock screen effectiveness. For example, screen penetration of 100–200 mm and 50–100 mm rock screens by shortfin eels was 4% and 0%, respectively but shortfins spent 63% of their time in the larger rock screens and 71% of their time in the 50–100 mm screens where no penetration was recorded (Figure 6). Even these percentage zonal data did not fully capture the movement and habitat use patterns of shortfin eels because several eels had actually swum through the half metre of the larger rock screen, penetrated into the upstream zone but had then gone back inside the rock screen before the first 'zone use' observation was made at six minutes (P.G. Jellyman, pers. obs.)[5]. A higher percentage of time spent within the rock screens rather than in the upstream zone was a pattern that was replicated across all five species, to varying extents (Figure 6). Bluegill bully were a slight anomaly in that despite spending more time within compared to upstream of the rock screens, a number of fish were in the upstream zone at the end of the trial resulting in them being over-represented in the screen penetration data (Figure 5) relative to the percentage of time they spent in the upstream zone (Figure 6).

Table 2: Two-way ANOVA comparing the proportion of different screen penetration by the five fish species tested in flume experiments. Significant P-values are shown in bold.

Predictor	d.f.	*F*	*P*-value
Screen	4	98.9	**<0.001**
Species	4	14.7	**<0.001**
Screen x Species	15	14.9	**<0.001**
Residuals	81		

[5] Many experiments had already been conducted before shortfin eel x rock screen experiments were undertaken so the methodology was not altered to capture this pattern, rather observational notes were taken.

Unlike the rock screens, fish were not able to be 'within' the 3 mm woven wire screen, they either did or did not penetrate the screen (Figure 6). There was no penetration of the woven wire screen by either Canterbury galaxias, common bully or rainbow trout (Figure 5). There was reasonable penetration of the woven wire screen by shortfin eels with 40% of fish getting through with eels that penetrated generally less than 75 mm. The only other species to have any individuals penetrate the screen was bluegill bully (4%); the single bluegill bully that penetrated the screen was 31 mm. As shortfins spent 19% of their time in the upstream zone and bluegill bullies 1.3%, the time in the upstream zone did not match the penetration data which indicated it took some time for most individuals to penetrate the screen (Figure 6).

With the exception of shortfin eels, there was no penetration of the 3 mm wedge-wire screen (Figure 5). As noted in Section 2.2.1, the effectiveness of a wedge-wire screen for rainbow trout was not examined. A number of shortfin eels easily penetrated the 3 mm wedge-wire and the swimming pattern of the smaller eels looked almost uninterrupted as they swam through the screen (P.G. Jellyman, pers. obs.). Whilst the bar spacing was effective for most species tested, it was observed that the more flexible body shape of shortfins meant the slot shape was easier to penetrate than the square grid of the 3 mm woven-wire screen (P.G. Jellyman, pers. obs.). Shortfins were able to weave their bodies through the wedge-wire in flume experiments and use the screen as refuge habitat (see Figure 7). Thus, similar to rock screens, the proportion of penetrations by shortfins at the end of the experiment over-represented their effectiveness because they were not present in the upstream zone (their bodies were woven onto both sides of the screen, Figure 7). The zonal analysis shows a more accurate reflection of the screen effectiveness with 14% of time spent upstream of the screen but also 53% of time spent woven within the screen (Figure 6).

There were also overnight rock-bund screen experiments conducted on bluegill bully, Canterbury galaxias and shortfin eel. These experiments were to examine whether the results obtained for the two types of rock-bund screens after 30 minutes differed markedly after testing for 15 hours. After 15 hours, a higher proportion of all three species were located in the upstream zone compared to the 30-minute experiments (Figure 8). The proportion of fish in this zone was slightly higher for all species in the 100–200 mm rock-bund treatment compared to the and 50–100 mm treatment. All treatment combinations had 80–95% of fish either in the screen or upstream of the screen after 15 hours (Figure 8).

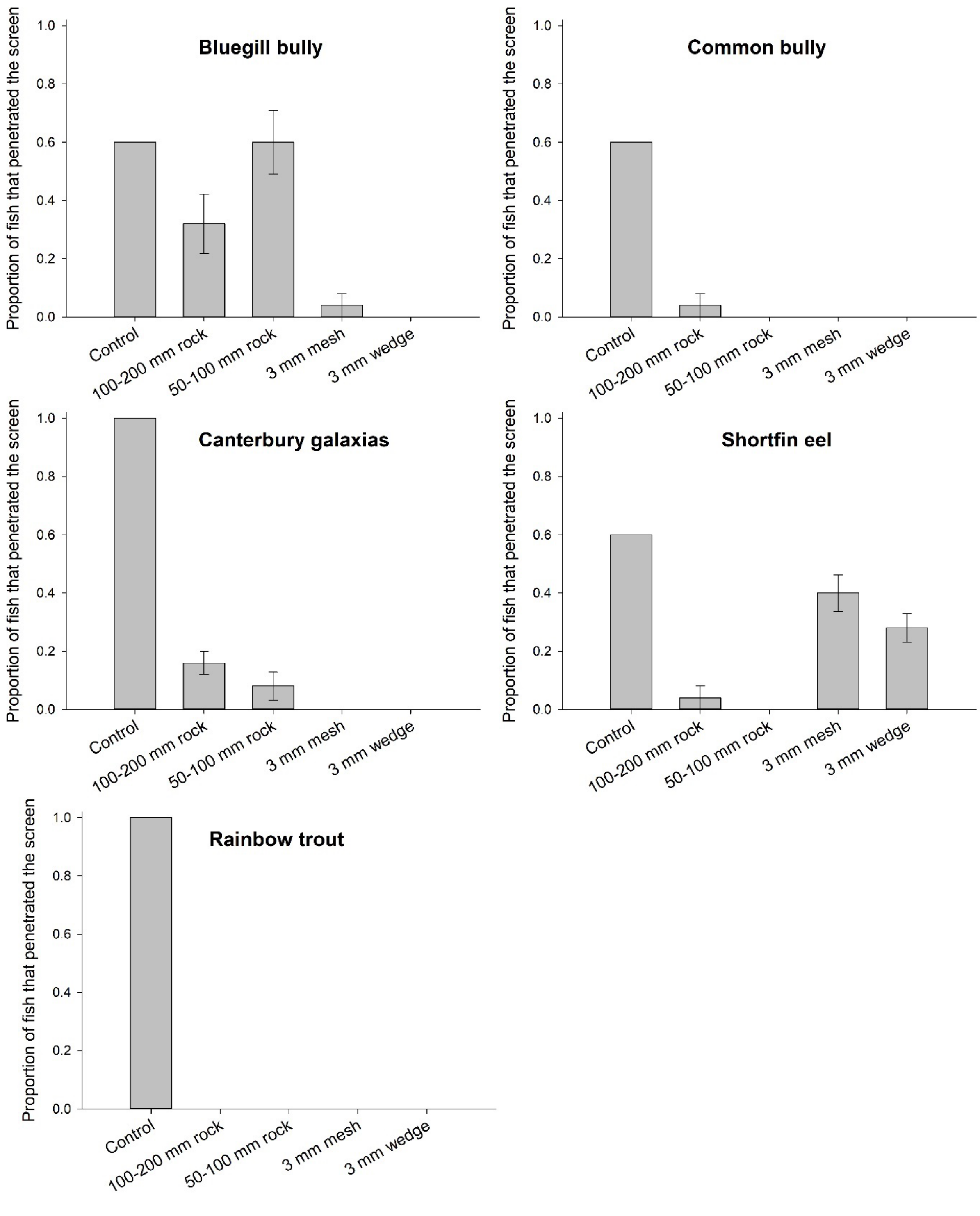

Figure 5: Mean proportion (±SE) of fish species that penetrated the treatment screens during the 30-minute trials. Note, several native fish species had high penetration of rock barriers but used the barriers for cover and as they did not exit upstream were not counted as having 'penetrated' the screen by the end of each trial, hence some proportions above are underestimates.

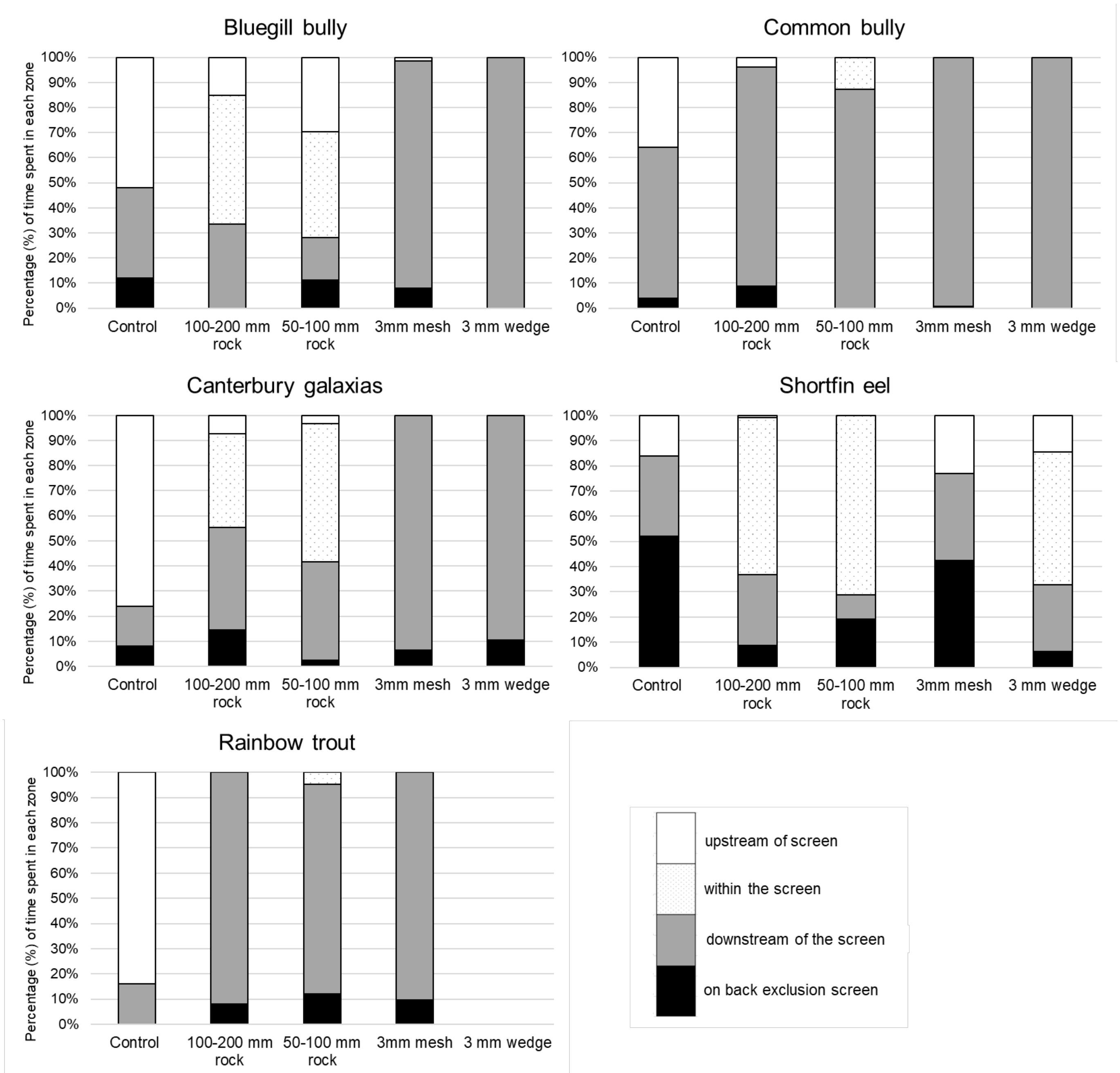

Figure 6: The average percentage of time spent in each zone for the different treatments. Note, there was no experiment conducted on 3 mm wedge-wire effectiveness for rainbow trout.

Figure 7: Shortfin eels would weave their bodies through the 3-mm wedge-wire as a spot to rest or to utilise as cover in the flume experiments.

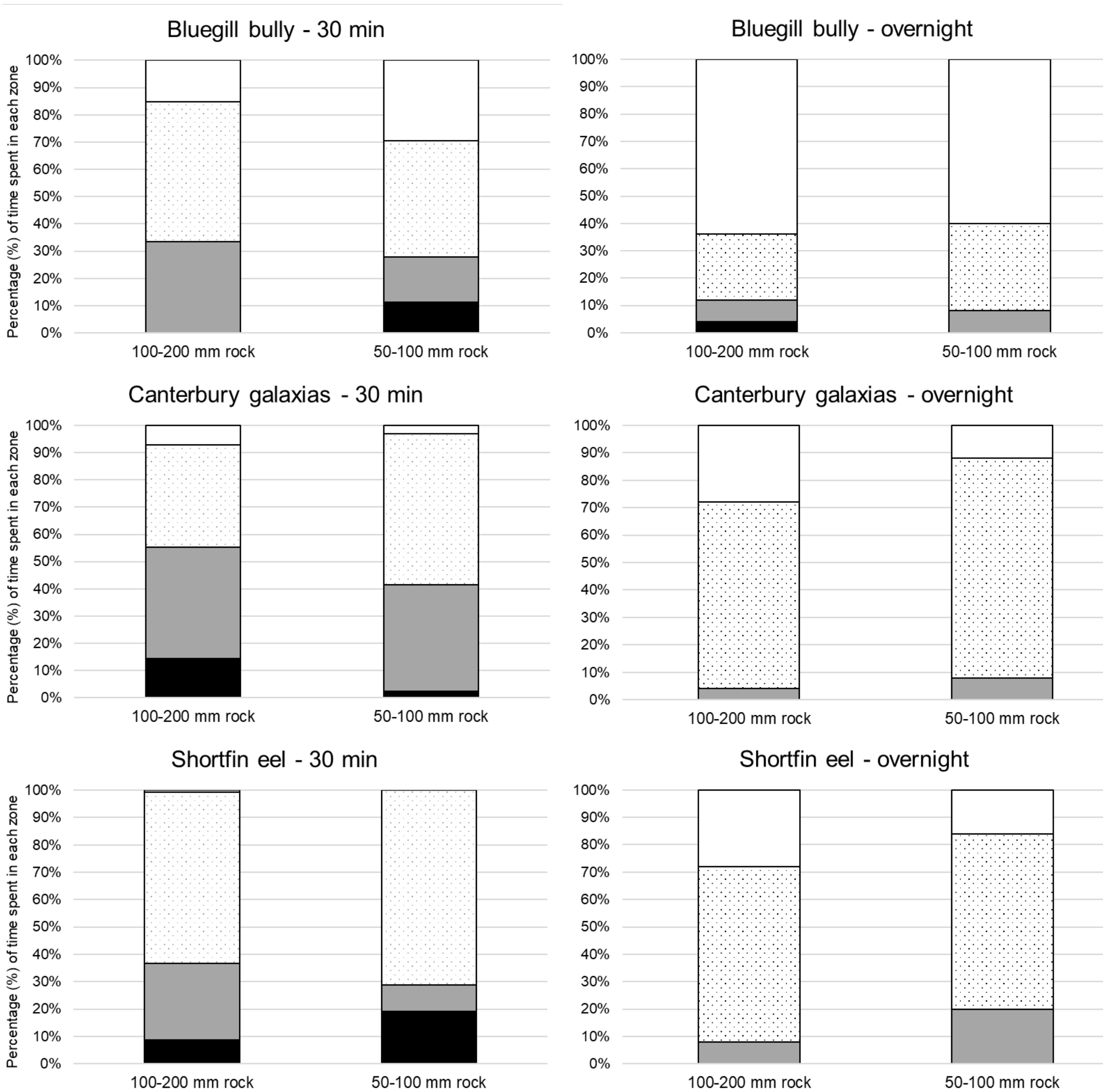

Figure 8: The time spent in each zone after 30 mins compared to where fish were found after being left for 15 hours overnight. The colour regime used to represent the different zones where fish were is the same as in Figure 6; white = upstream of the screen, dotted = within the screen, grey = downstream of the screen, black = on black exclusion screen.

3.2 Fish screening in stream simulator: 3-mm vs 2-mm wedge-wire

Based on the results of the flume experiments in Section 3.1, wedge-wire screens were selected for refinement experiments in the outdoor stream simulator (further rationale for this decision is provided in Section 4.2). There was a significant interaction between fish species and wedge-wire size on screen penetration ($F_{3,72}$ = 8.6; P < 0.001; Table 3). Both the 2 mm and 3 mm wedge-wire excluded all bluegill bullies, common bullies and Canterbury galaxias when tested in the stream simulator, however shortfin eels penetrated both screens (Figure 9).

As two velocity treatments were also being tested there were 10 experiments for each mesh size (i.e., 50 elvers at each mesh size). Eleven elvers (22%) penetrated the 3 mm screen ranging in size from 75–85 mm, whereas only two elvers (4%) that were 77 and 80 mm penetrated the 2-mm screen. Irrespective of mesh size, the elvers penetrating the wedge-wire screens were significantly smaller than the elvers that were retained in the simulator or were captured in the bypass ($F_{2,94}$ = 4.0; P = 0.02); the mean size of elvers that passed through the screen was 79 mm compared to 84 mm in the bypass. However, not all small fish went through the screen as the smallest elver in the bypass for the 3-mm screen was 75 mm and the smallest for the 2-mm screen was 72 mm.

Table 3: Two-way ANOVA results of screen penetration by four native species for different-sized wedge-wire in stream simulator experiments. Significant P-values are shown in bold.

Predictor	d.f.	*F*	*P*-value
Species	3	17.9	**<0.001**
Wedge-wire size	1	8.6	**0.005**
Species x Wedge-wire size	3	8.6	**<0.001**
Residuals	72		

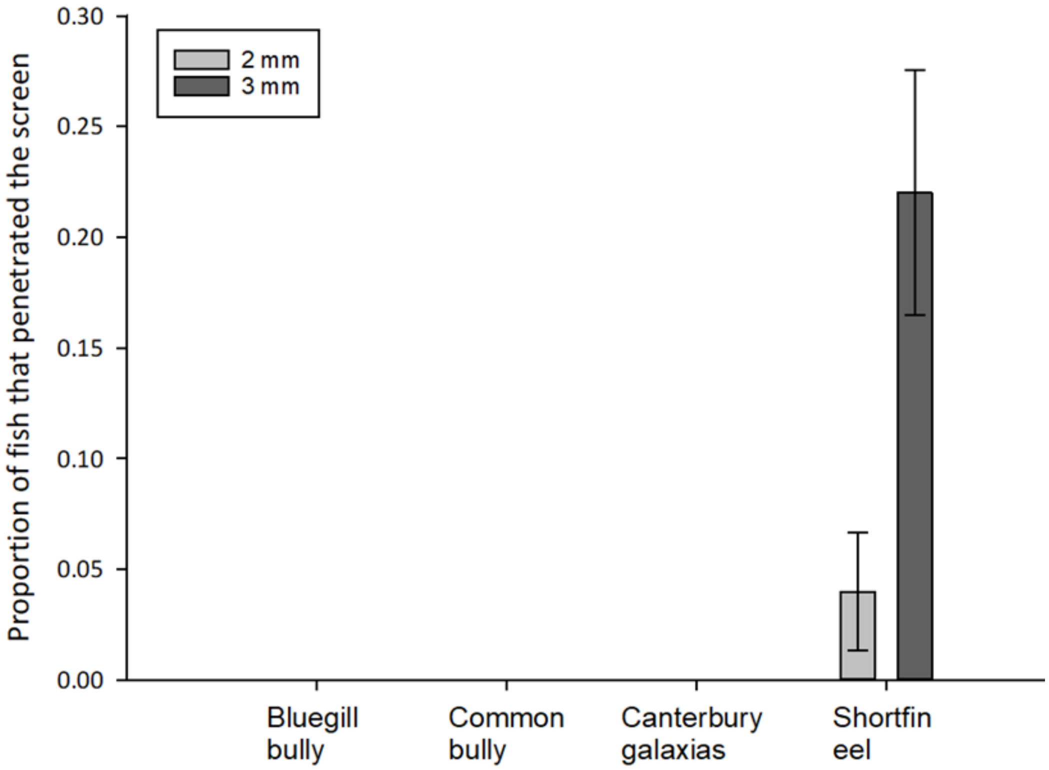

Figure 9: The mean (±SE) proportion of each species that penetrated the different sized wedge-wire screens. For clarity, a reduced y-axis is shown.

3.3 Velocity comparison: screen penetration, contacts and bypass use

3.3.1 Screen penetration

More shortfin eels penetrated the screen in the higher velocity treatment (Figure 10), however there was no significant difference in the mean proportion of screen penetrations between the two velocity treatments ($F_{1,72}$ = 0.7; P = 0.4; Table 4). Thus, there was no significant interaction between species and velocity effects on screen penetration ($F_{3,72}$ = 0.7; P = 0.6; Table 4). As highlighted in Section 3.2, shortfin eels were the only species to penetrate the screen resulting in the significant species effect in Table 4.

Table 4: Two-way ANOVA results examining fish species and velocity treatments on screen penetration. Significant P-values are shown in bold.

Predictor	d.f.	*F*	*P*-value
Species	3	12.6	**<0.001**
Velocity	1	0.7	0.4
Species x Velocity	3	0.7	0.6
Residuals	72		

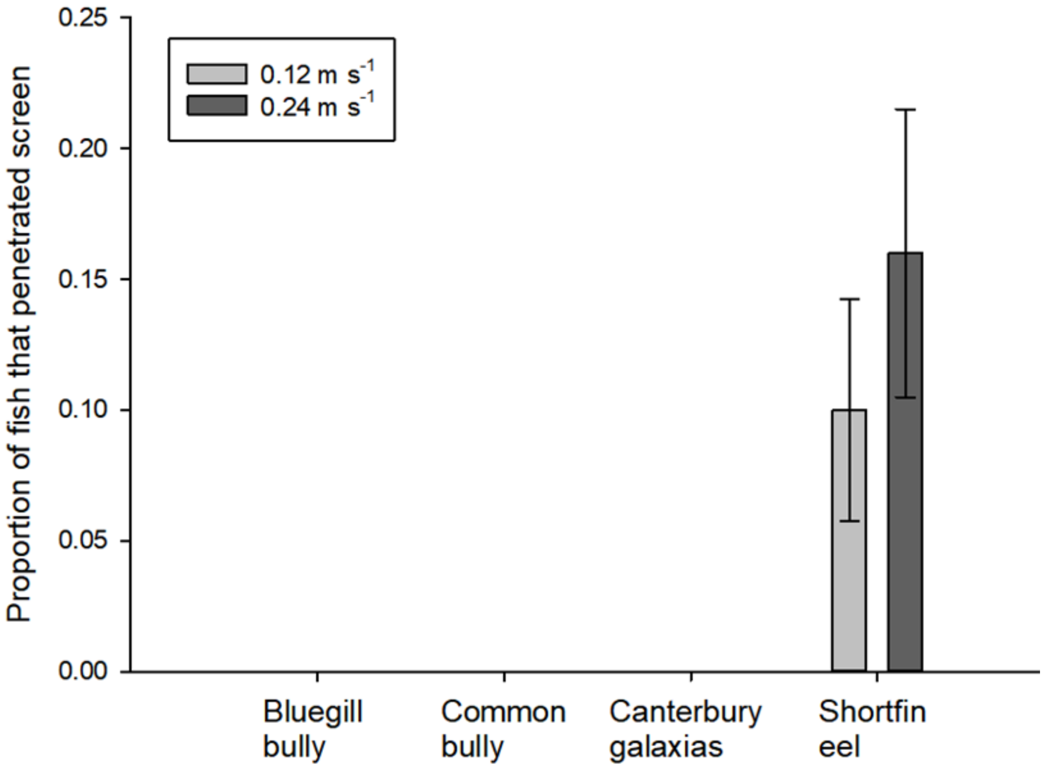

Figure 10: The mean (±SE) proportion of each species that penetrated the screen in the two velocity treatments. For clarity, a reduced y-axis is shown.

3.3.2 Bypass use

Water velocity did not appear to influence bypass use; the higher velocity treatment did not result in more fish entering the bypass. For all species, the mean proportion of fish in the bypass was slightly higher in the lower velocity treatment although there was no significant interaction between species and velocity effects on bypass use ($F_{3,72} = 0.4$; $P = 0.8$; Table 5). Neither was there a significant difference between velocity treatments in the mean proportion of fish in the bypass ($F_{1,72} = 2.9$; $P = 0.1$; Table 5). Conversely, there was a significant difference in the mean proportion of fish in the bypass between species ($F_{3,72} = 14.5$; $P < 0.001$; Table 5). The results of the post hoc Tukey's test, (Figure 11), showed that there were significantly more shortfin eels in the bypass compared to bluegill and common bullies. There were also significantly fewer common bullies in the bypass relative to the numbers of Canterbury galaxias.

Table 5: Two-way ANOVA results for species x velocity on proportion of fish in the bypass. For clarity, significant P-values are shown in bold type.

Predictor	d.f.	*F*	*P*-value
Species	3	14.5	**<0.001**
Velocity	1	2.9	0.1
Species x Velocity	3	0.4	0.8
Residuals	72		

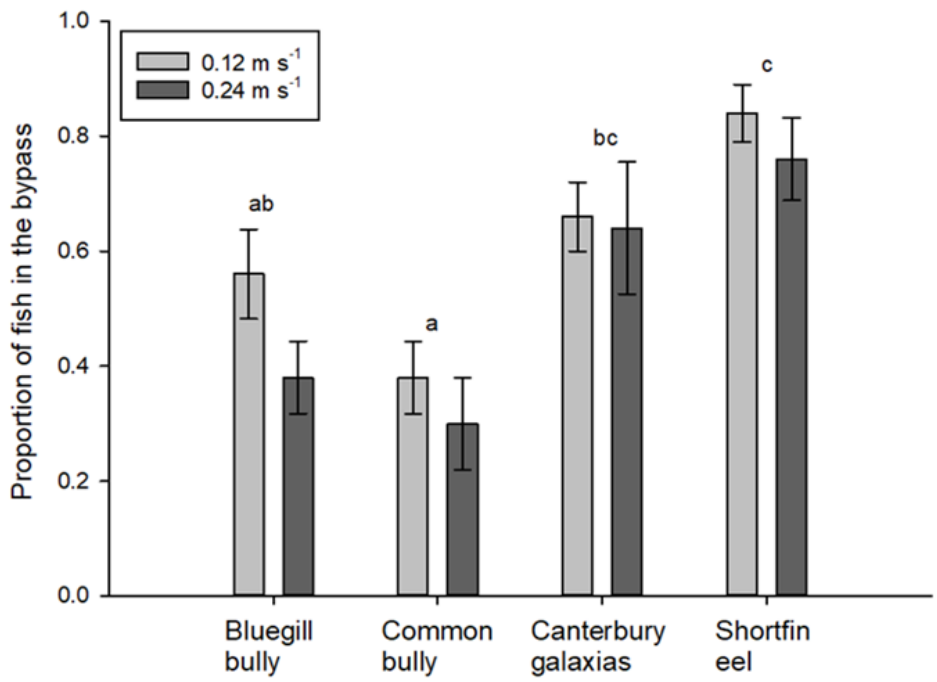

Figure 11: The mean (±SE) proportion of each species that were in the bypass for the two velocity treatments. Letters show significant differences in screen penetration between the different species from Tukey post hoc comparisons; the velocity treatments are pooled so letters are per species, instead of per bar.

3.3.3 Screen contacts

Video analysis revealed that all species showed some evidence of attempting to force their way through the screen, however, Canterbury galaxias and shortfin eels were much more persistent based on the average number of screen contacts (Figure 12). No impingements were observed for any of the species tested in the stream simulator, regardless of velocity treatment; Figure 13 shows some of the interactions observed and counted as contacts. Only one injury, a damaged tail fin, was observed throughout the trials, which could not be confirmed as related to screen contact from reviewing video footage. The higher velocity treatment did not result in more contacts and there was no significant interaction between species and velocity effects on contacts ($F_{3,65}$ = 1.3; P = 0.3; Table 6). There was also no significant difference in the mean number of screen contacts between the two velocity treatments ($F_{1,65}$ = 0.3; P = 0.6; Table 6). However, there was a significant difference between species ($F_{3,65}$ = 19.7; P < 0.001; Table 6 and Figure 12), with Canterbury galaxias having more screen contacts than any of the other three species. Canterbury galaxias was the only species to have markedly higher screen contacts in the higher velocity treatment (Figure 12). Screen contacts for shortfin eels for the two mesh sizes were similar to the velocity data (2 mm = 0.66 vs. 3 mm = 0.69).

Table 6: Two-way ANOVA results for species x velocity on screen contacts as a proportion. Significant P-values shown in bold.

Predictor	d.f.	*F*	*P*-value
Species	3	19.7	**<0.001**
Velocity	1	0.3	0.6
Species x Velocity	3	1.3	0.3
Residuals	65		

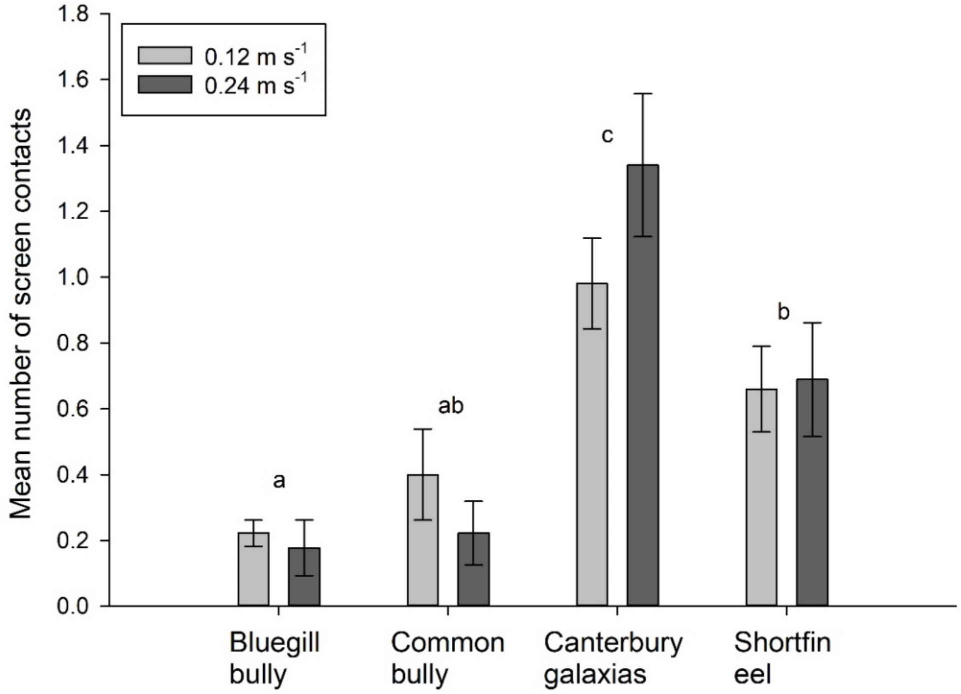

Figure 12: Mean (±SE) number of screen contacts for individual fish of each species in the two velocity treatments. Letters show significant differences in penetration between the different species from Tukey post hoc comparisons; the velocity treatments are pooled so there is only one letter per species, instead of per bar.

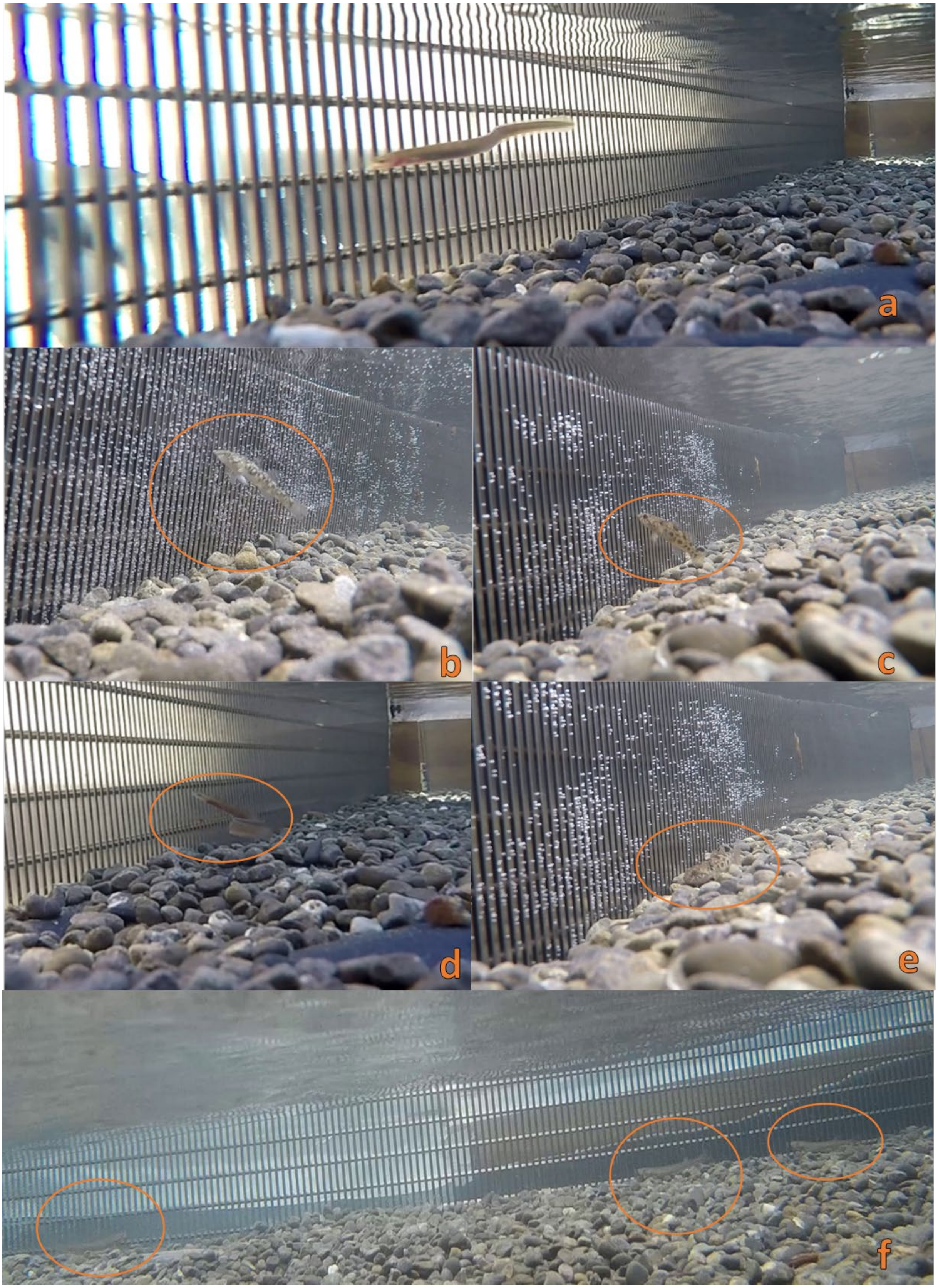

Figure 13: Examples of contacts viewed on camera footage. Images show: (a) shortfin eel swimming along the screen edge, (b) bluegill bully attempting to get through screen, (c) common bully attempting to get through screen, (d) shortfin eel attempting to penetrate screen, (e) common bully sitting next to screen and (f) three Canterbury galaxias sitting against the screen.

4 Discussion

Inappropriately screened water intake and diversion structures can result in the loss of fish species, which depending on the waterway and species' involved, has the potential for long-term impacts to fish populations. This research examined the behavioural responses of five of New Zealand's native and introduced fish species against three types of widely used fish exclusion screens and found markedly different species' responses to the screens tested.

4.1 Rock-bund screens

Rock-bund screens were tested 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. They have been proposed by consent applicants because they are cheaper to construct, relative to engineered concrete/metal screens, although they often come with high on-going maintenance costs for the scheme. If the rock bunds become heavily silted during the irrigation season — an issue for some, but not all rock bunds, as it is river and location dependent — they are usually deconstructed to remove silt and then remade resulting in short periods when no screen may be in place. Note, rock bunds can be built with a back-flushing capacity to desilt substrates but NIWA are not aware of New Zealand examples of where this capability was been installed. Field-based tests of rock-bund screens have found them to be relatively effective at excluding juvenile salmonids (e.g., Chinook salmon, 120–180 mm) (Webb and MacKenzie 2018). Our flume trials corroborated this finding for smaller rainbow trout (39–64 mm) as they, along with common bully, behaved quite differently to a rock-bund screen than other native species that were tested. Although the flume was a highly artificial testing environment, rainbow trout showed very little interest in wanting to enter the rock screen despite easily being able to fit into the gap. As an unscientific aside, after several of the trials had been completed an attempt was also made to 'spook' some of the rainbow trout to watch their reaction. Whilst they markedly increased their swimming activity in the flume zone downstream of the screen, they still showed no intention to flee into the rock bund. Provided there are not significant preferential flow paths through a rock-bund screen — which often develop over time based on observations of rock-bund screens exposed to high sediment loads in braided rivers (P. G. Jellyman, pers. obs.) — and there is a sufficient sweep velocity along the bund, then rock bunds should exclude the majority of salmonids that could potentially interact with the bund.

The concern with rock-bund screens is that they do not prevent native fish from entering an irrigation scheme/water distribution network because native fish can easily pass through the rock bund. There are additional concerns that because native fish may use the bunds as habitat that they may be injured or killed when deconstructing the rock bunds if they become clogged with sediment. Our flume results showed that the ubiquitous native fish, common bully, largely avoided entry into a rock-bund screen and there was only minor screen penetration recorded for the 100–200 mm rock treatment; no penetration was recorded for the 50–100 mm rock treatment. However, behavioural avoidance of the rock-bund screen was not evident for the other three native fish species tested. Bluegill bully, Canterbury galaxias and shortfin eel all spent, on average, at least 50% of their time in rock bunds across the two treatments based on the 30 minute experiments and this percentage was higher for Canterbury galaxias and shortfin eel based on the overnight trials (but lower for bluegill bully). With a high percentage of native fish still within the screen after 15 hours it would have to be assumed that crushing-related mortality of native fish during screen deconstruction is highly likely. Whilst rock-bund screens being used as habitat is important to note, the lack of 'screening' provided by rock bunds and the increase in the proportion of screen penetrations observed after 15 hours is of much greater concern for native fish conservation as it highlights the potential for a significant proportion of fish to be penetrating rock-bund screens.

4.2 Woven wire screens

When the woven wire screen is compared to a rock-bund screen the aperture size that a fish encounters is obviously far more consistent. The consistent sizing of the woven wire screen used in the flume experiments prevented Canterbury galaxias, common bully or rainbow trout from penetrating and all but one of the bluegill bully. The different body shape and behaviour of shortfins, relative to the other species tested, enabled 40% of these fish to pass through the 3 × 3 mm gap. The behaviour of eels differed in that these fish were often constantly searching across the screen width for a way to get upstream past the screen (Figure 14) — there was minor variation in the size of eels that could penetrate the woven wire screen but generally they were less than 75 mm.

Figure 14: Shortfin eels investigate the woven wire screen looking for a gap during flume experiments. This image is from a screen shot of a video file which is why it is a slightly lower resolution image.

Whilst the new woven wire screen tested was relatively effective, there are issues that occur with the types of rotating drum screens that typically woven wire as the screening material. The two main issues are: (1) that material gets caught in the mesh and because the wire can move, gaps larger than the original mesh size occur over time (Figure 15), and (2) woven wire is often used on rotating screens on smaller takes and the seals around the sides and bottom of these screen wear over time reducing the effectiveness of the device as a fish screen; this issue often goes unchecked/unnoticed as the user still sees a screen rotating in the diversion channel. There are other issues with the design of screens where woven wire is used such as these screens clogging at lower flows when not fully rotating, lifting/rotating impinged fish over the screen into the scheme, design challenges with drum screen types (relative to flat screens which can make drum screens more expensive) and their usability at sites where water surface elevations are not stable. For these reasons coupled with flume experiment results indicating woven wire screens were less effective than wedge-wire at excluding fish, the wedge-wire screening material was selected for refinement experiments.

Figure 15: A rotating drum screen where gaps appearing over time is an issue with this screen type. Note, the red circle is highlighting an area where the mesh has been stretched resulting in larger gaps.

4.3 Wedge-wire

Wedge-wire was as effective or more effective than others screening materials for four of the species tested. For the fifth species, shortfin eels, penetration results would also suggest it was the most effective screen but as Figure 7 showed, these results were skewed by shortfins using the wedge-wire as refuge habitat. It is also important to note that the wedge-wire flume experiments used markedly smaller shortfin eels than the other flume testing; generally only shortfins smaller than 75 mm penetrated the woven-wire screen and 75 mm was the largest fish used in the wedge-wire screen experiments. However, elvers have the ability to compress their body through bar spacings that are smaller than their body diameter (Environment Agency 2011), and based on the orientation tested, wedge-wire has a longer slot in a vertical direction which elvers can exploit to squeeze through whereas other fish species have a much more limited ability to do so. It is concluded from flume experiments that, with the potential exception of shortfin eels, wedge-wire was the most effective screening material and it had a number of advantages over woven-wire mesh as a screening material. It is acknowledged that it is more expensive per square metre than woven-wire mesh but the focus of this research was on determining what is most effective for fish.

The stream simulator provided a more accurate representation of how native fish could encounter and interact with a screen compared to flume experiments where screens were at 90° to the flow. The stream simulator results reinforced those from the flume experiments for bluegill bully, common bully and Canterbury galaxias with no penetration of 3 mm (or 2 mm) wedge-wire screen for these species. This was despite Canterbury galaxias exhibiting a strong behaviour to attempt to penetrate the screen with the highest number of screen contacts. It was more difficult to compare the flume and stream simulator results for shortfin eels but 28% penetrated the 3 mm screen in the flume compared to 22% in the simulator. However, as noted in the previous paragraph, it was problematic to quantify actual penetration when eels spent 50% of the time wrapped around the screen bars which was not a behaviour observed in the stream simulator. Shortfin eel screen contact rates indicated similar attempts to penetrate both screens, but significantly more were able to pass through the larger slot size. Screen penetration was not passive and all native fish species were filmed making attempts to force their heads through the screen but only the elvers were successful because of their slender head and body shape. Compared to elvers the body shape of other native species consisted of a wider head width, thinning towards the tail preventing them from penetrating the screen head-first. Whilst rainbow trout were not tested in the stream simulator work, field trials by Mueller et al. (1995) found that rainbow trout fry (23–27 mm) —markedly smaller than those tested in flume trials — could fit through 3.18-mm wedge-wire screens. Other studies have shown that wedge-wire screens need to be spaced 2.38 mm to exclude Chinook salmon fry greater than 30 mm in length (Kano 1982).

Head-first approaches by native fish are noted above because testing of salmonid fry has shown that fish with a head width greater than the gap size can fit through a wedge-wire screen if approaching in a tail-first direction. For example, Mueller et al. (1995) found wild Chinook salmon fry (36–42 mm) could fit through 3.18 mm wedge-wire when they approached it tail-first despite having a head widths ranging from 4.26 to 4.34 mm. Thus, if approach velocities were higher than those used in the stream simulator trials then it is possible that some native fish, of a size tested in our experiments, could approach a screen tail-first and possibly penetrate a 3 mm screen. However, the native fish species tested are benthic and spend most of their time on the river bed — whereas salmonid fry and juveniles are pelagic and spend most of their time in the water column — which should markedly decrease the likelihood that native fish will be swept into a screen tail-first because water velocity is lower on the bed than in the water column. In the absence of any tail-first entrainments observed in our experiments, 3 mm wedge-wire was found to be just as effective as 2 mm wedge-wire at excluding common bully >30 mm, bluegill bully >35 mm and Canterbury galaxias >42 mm.

Two different velocity treatments were tested in the stream simulator but with only one of the four species penetrating the screens there is probably limited inference that can be drawn from the effect of approach velocity on screen penetration from these experiments. However, it is noted that for the two different velocity treatments tested, 60% more shortfins penetrated wedge-wire screens at the higher velocity (0.24 m/s), although this difference was not statistically significant due to high variability between replicates. No impingements were noted for any species in either velocity treatment although video analysis also suggested that the setup had an appropriate sweep velocity that minimised the risk of impingement as individuals of all species were observed being swept along the screen, rather than being impinged onto it, and being directed into the bypass.

4.4 Bypass use

As mentioned previously, contacts with the screen were observed from video analysis as an active choice determined by fish behaviour rather than as a consequence of high water velocity forcing an interaction between fish and the screen. Elvers were observed being active for most of the experiment moving throughout the simulator and searching all areas. This likely mimicked their instinct to find any method (including climbing vertical surfaces) to continue their upstream migration, or to find suitable substrate in which to bury themselves to reduce predation risk (Williams et al. 2017). This constant searching behaviour meant they were swept into the bypass more often and it was observed that once an eel crossed in front of the bypass, they rarely managed to avoid entering it. The behaviour of shortfins largely reinforced how important regular maintenance of screens is because preliminary trials showed that small eels would find even the tiniest gaps if they were not properly. Bluegill bullies exhibited quite different behaviour to eels as they had the lowest rate of screen contacts but still often used the bypass. Video analysis showed bluegill bully sometimes moved straight for the bypass, with no screen interaction, which was almost never observed for shortfin eels or Canterbury galaxias.

All species showed some interest in exploring the upstream section of the artificial stream channel. Both bully species would often spend the whole trial upstream of the screens, which could explain lower screen contact incidence for those species, relative to Canterbury galaxias and shortfin eels, as well as the lower bypass use for common bully. Shortfin eels would explore the upstream section but normally make their way back down once they did not find an escape path or cover.

The size-dependent nature of fish screening meant that there was a slight bias towards larger eels in the bypass. The largest shortfin to penetrate the 3-mm screen in these trials was 85 mm long and this was 15 mm longer than the smallest eel to penetrate the screen. These fish were sourced from non-tidal sections of river more than 10 km inland which suggests that council plans that permit 3 mm screens in tidal areas will not be protecting many small eels in the lower reaches of rivers. The findings from this study suggest that 2 mm mesh could exclude five times the number of elvers from water diversion channels compared to 3 mm mesh, which has the potential to make a major difference to eel populations in recruitment-limited catchments.

5 Recommendations

Based on the results of the flume experiments it was concluded that:

- rock-bund screens should be effective at excluding salmonids, provided preferential flow paths through screens are not available;
- rock-bund screens are an ineffective fish screen for several native fish species tested, particularly bluegill bully, shortfin eel and Canterbury galaxias. Note, the species tested were anticipated to be representative of wider groups of fish, for example, results for shortfin eels should be highly applicable to longfin eels. Canterbury galaxias results should be applicable to other flathead and roundhead *Galaxias* species. It is acknowledged that rock-bund screens could become a screen for larger adult eels above a certain body length although the length at which a rock-bund becomes a screen will be relative to the size of rock used;
- woven-wire screens, when new, are likely to be a relatively effective screening material but because aperture size can change over time (i.e., within an irrigation season), there is concern about the potential for variable effectiveness with this screening material;
- with the potential exception of shortfin eels, wedge-wire was the most effective screening material and it had a number of advantages over woven-wire mesh as a screening material.

This summary is limited to the flume experiments. The Year 1 refinement experiments are not summarised because further testing in the stream simulator during Year 2 will result in a 'package' of recommendations from these experiments. Thus, all recommendations relating to the refinement experiments will be included in the Year 2 report scheduled for release in July 2021.

6 Acknowledgements

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Appendix A Summary of fish screening requirements in council plans from around New Zealand

Council	Screen on minor takes	Site location	Screen aperture		Approach velocity	Sweep velocity	Bypass provision	Bypass connectivity	Operation & maintenance	Individual consents reference guidelines	Notes
			Tidal river[1]	**Other rivers**							
Northland Regional Council	Yes	-	≤1.5 mm[2]	≤3 mm[2]	<0.12 m/s[2]	-	-	-	-	?	
Auckland Council	Yes	-	≤1.5 mm	≤1.5 mm	<0.3 m/s	-	-	-	-	?	
Waikato Regional Council	Yes	-	≤1.5 mm[3]	≤3 mm[3]	<0.3 m/s	-	-	-	-	?	
Bay of Plenty Regional Council	Yes[4]	-	≤3 mm	≤5 mm	<0.3 m/s[5]	-	-	-	-	?	
Gisborne District Council	Yes	-	≤3 mm	≤5 mm	<0.3 m/s	-	-	Yes	Yes	?	
Hawke's Bay Regional Council	No	-	-	-	<0.3 m/s	-	-	-	-	Yes	
Taranaki Regional Council	No	-	-	-	-	-	-	-	-	?	
Manawatu-Wanganui Regional Council	Yes	-	≤3 mm	≤3 mm	<0.3 m/s	-	-	-	-	?	[6]
Greater Wellington Regional Council	Yes	-	≤3 mm[7]	≤3 mm[7]	-	-	-	-	-	?	
Tasman Regional Council	Yes	-	<5 mm	<5 mm	<0.3 m/s	-	-	-	Yes	?	
Nelson City Council	Yes	-	<1.5 mm	<1.5 mm	0.5 L/s (?)	-	-	-	-	?	
Marlborough District Council	No	-	-	-	-	-	-	-	-	Yes	
West Coast Regional Council	Yes	-	-	-	-	-	-	-	-	?	[8]
Canterbury Regional Council	Yes	Yes	≤2 mm	≤3 mm	<0.12 m/s	Yes	Yes	Yes	Yes	Yes	
Otago Regional Council	No	-	-	-	-	-	-	-	-	Yes	[9]
Southland Regional Council	Yes	Yes	≤2 mm	≤3 mm	<0.12 m/s	Yes	Yes	Yes	Yes	Yes	[10]

[1]Also coastal rivers in some plans (e.g., <2 km from sea), [2]operative plan aperture ≤5 mm, sweep velocity <0.3 m/s, [3]for significant indigenous fisheries and fish habitat, otherwise 3 mm (<100 m.a.s.l) and 5 mm (<100 m.a.s.l), [4]under a current Plan Change this would be removed, [5]specified as 'velocity through the screen', [6]for larger takes council control the screening requirements, [7]operative plan has no mesh size specified – values are from the proposed plan, [8]previous Plan use to have more prescriptive fish screening criteria, [9]a standard consent condition is applied that is aligned with Jamieson et al., 2007 guidelines, [10]under the operative plan only the presence of a fish screen is required.