A touch too much – interactions of various species of freshwater fish and crustacea at a simulated fish protection screen

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A R T I C L E   I N F O

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Impingement
Entrainment
Ecohydraulics
Pump intake

A B S T R A C T

Fish protection screens are being increasingly applied to prevent fish entrainment at water diversions and intakes. Screen success is thought to depend upon selecting the most suitable mesh size and ensuring appropriate water velocities around the screen. It is generally hypothesised that if fish are smaller than the mesh size, they may become entrained through the screen or, if they are larger, become impinged upon the screen. Both situations can lead to injuries or mortality and need to be resolved for the fish protection screen to be effective.

Globally, abstraction of freshwater for human needs such as agriculture, industry or mining has a large impact on aquatic ecosystems (Moyle and Leidy, 1992; Closs et al., 2016; Baumgartner et al., 2019). Water diversion infrastructure has created a worldwide problem with the decline of freshwater fish species (Moyle and Williams, 1990). Suitable designed fish protection screens installed at water diversions can prevent fish from entering water intakes (McMichael et al., 2004; Baumgartner and Boys, 2012). Conversely, if poorly designed (i.e., without correct water velocities at the screen face), screens can fail to stop entrainment and contribute to fish impingement, which can lead to injury and/or mortality, ultimately transferring entrainment losses to the screen (Turnpenny, 1988; Montén, 1988; Calles and Greenberg, 2009; Calles et al., 2013; Maes et al., 2004; Patrick et al., 2014). The number of fish killed by prolonged impingement can be so large as to affect fish populations (Greenwood, 2008). For example, a study conducted at the intake point of a Swedish nuclear power plant determined that >31 million fish were killed over one year due to impingement (Brynh et al., 2013).

To reduce entrainment and impingement, a fish protection screen
requires mesh size to be small enough to physically exclude the smallest targeted individuals, and approach velocity (AV, defined as the perpendicular vector in front of the screen) to be low enough to enable fish to swim against for long enough to avoid impingement until they have passed the screen (Danley et al., 2002; Swanson et al., 2004; Boys et al., 2013a; Boys et al., 2021b).

While appropriate mesh size can be estimated based on fish morphometrics (Turnpenny, 1981), suitable AV to allow fish to escape impingement can vary significantly across species due to differences in swimming ability, life stage and fish behaviour (Kapodis, 1992; Boys et al., 2013b; Poletto et al., 2014). Understanding the appropriate AV for fish protection screens therefore relies on information relating to species-specific fish behaviour and swimming ability (Water Reuse Association, 2011; Mussen et al., 2014; Poletto et al., 2018; Jellyman et al., 2023). As AV increases, a fish will find it increasingly difficult to avoid entrainment or impingement (Swanson et al., 2005; Stocks et al., 2019). Therefore, fish swimming speed ($U_{sw}$) is often used to estimate entrainment and impingement susceptibility for different species (Hutchison et al., 2020). However, laboratory studies have also highlighted that various fish species exhibit distinct behavioural responses (e.g., rheotactic responses) that can assist with negotiating interactions with screens (Danley et al., 2002; Young et al., 2010; Boys et al., 2013a; Mussen et al., 2013; Poletto et al., 2014; Cooke et al., 2020).

Because swimming ability and behaviour varies between species and life history stage, the recommended maximum AV for fish protection screens can vary among species and countries. Approach velocities of 0.5 m/s are deemed suitable for some European fishes including barbel (Barbus barbus) or eel (Anguilla australis) to avoid impingement with a screen or at racks to prevent fish from entering turbines (Beck et al., 2020; DWA, 2005). Further studies suggest that an AV of 0.3 m/s is appropriate to prevent entrainment or impingement (e.g., for salmonid smolts) (Taft, 2000; DWA, 2005; Black and Perry, 2014; Kumar et al., 2017). However, it was shown that these velocities are too high for several species, e.g., delta smelt (Hypomesus transpacificus), with a recommended AV of $\approx 0.06$ m/s (California Fish and Game, 2010). An AV not exceeding 0.15 m/s appears to be suitable for juvenile northern pike (Esox lucius), Arctic grayling (Thymallus arcticus), walleye (Sander vitreus) or whitefish (Coregonus spp.) (Kapodis, 1992; NMFS, 1997; Peake, 2004). Approach velocities around 0.1 m/s or below appears to be an acceptable specification in several guidelines (e.g., NMFS, 1997; Bejakovich, 2006; U.K. Environment Agency, 2011; USFWS and NOAA, 2014) and offer reasonable protection to New Zealand natives, salmonid fry or glass eels and elvers (up to 140 mm) to reduce impingement.

Rarely do studies test a range of species to identify individual responses to these velocities; instead, they often focus on a limited selection of fish groups. For example, the first design specifications for fish screens in Australia dictate also that AV should not exceed 0.1 m/s (Boys et al., 2021b) but are largely based on the results of swimming performance studies using juveniles of three large-bodied native species (Murray cod, silver perch, golden perch) (Boys et al., 2013a; Stocks et al., 2019). However, the intent of the guidelines is to protect the entire native fish assemblage, including weak-swimming species (Boys et al., 2021b). It remains largely unclear whether the recommended AV caters to the diverse array of species with varying ecological characteristics within a diverse fish community, and whether exceeding that AV (e.g., 0.2 or 0.3 m/s) significantly reduces protection. Therefore, a broader understanding of a wider range of species such as that investigated for native species from New Zealand (Jellyman et al., 2023) or the United Kingdom (Turnpenny, 1981) should be incorporated, rather than designing screens that rely on studies that focus on a few specific species or taxa groups.

Most international fish protection screen studies are focused on salmonids and subsequent data are not always transferable to other species and fish assemblages, similar to the challenges faced when transferring knowledge about salmonid use of fishways to other taxa (Mallen-Cooper and Brand, 2007; Baumgartner and Boys, 2012). This study attempts to resolve the critical AV required to minimise impingement at fish protection screens for a variety of aquatic species from a broad range of different families, body types and habitat types. Fish species are evolutionarily adapted to different river environments, resulting in different ecological characteristics that can significantly influence a species’ swimming ability, morphometrics and behaviour (Branco et al., 2013; Romao et al., 2017). The best way to understand the influence of these differences is to test various species, representing different specialisations and ecological characteristics, under controlled and standardised conditions (i.e., velocities).

The main objective of this study was to examine the screen interactions of seventeen Australian freshwater fish species and two crustacean species at a 3 mm wedge-wire screen across a range of AVs using a laboratory flume.

This was assessed with two subsidiary aims delivered through two targeted experiments:

1. Quantify screen approaches, screen contact and impingement for 16 fish species for a 10-min duration across a range of AVs (0 to 0.3 m/s) (Experiment 1).

2. At the highest AV, quantify impingement, screen detachment frequency and 24 h survival of groups of individuals across 17 fish and two crustacean species for a 15-min duration (Experiment 2).

2. Methods

2.1. Experimental setup and fish husbandry

A custom-made rectangular flume (3996 mm × 232 mm × 211 mm) was used in this study (AWMA Water Control Solutions; awmawatercontrol.com.au, Cohuna, Victoria, Australia). The flume was fully enclosed by a lid allowing for the system to recirculate water via two in-line pumps (H3000M Davey Hurricane® Turbo Pump) installed with two in-line flow meters (MAG 5000 electromagnetic transmitter, Siemens® Munich, accuracy 0.2%). Individual variable flow adjustment valves allowed for velocities to be controlled between 0 and 0.3 m/s. The 3 mm wedge-wire mesh screen test panel (250 mm × 250 mm) was positioned in the middle of the flume, perpendicular to the flow (Fig. 1). A 3 mm wedge-wire screen was tested as this is currently applied at several fish protection screen installations within the Murray-Darling Basin (MDB), Australia, and where the majority of the fish and crustacean species occur (Boys et al., 2021a; Bretzel et al., 2023).

Water was recirculated through the flume via a 1000 L reservoir fitted with a heater-chiller unit to maintain water temperatures at 21 °C (range 20.2–22.6 °C) throughout the experiments, except for the salmonid species where the temperature was 12 °C (range 10.8–13.8 °C). A laminar flow in the flume was generated at the upstream end of the flume through a 0.1 mm diffuser screen and delivered through the flume and back to the 1000 L reservoir through another downstream 0.1 mm screen (as a physical barrier so fish remain in the flume). Fish were added to the flume through a fish delivery tube located upstream of the test screen panel. The critical zone was defined by the area up to 8 cm in front of the screen, since screen design guidelines are commonly standardised to AV at this specified distance from the screen (NMFS, 1997; Boys et al., 2021b) and applied previously laboratory studies (Boys et al., 2013a).

Three cameras were installed; Two security cameras (5 MP IR Eyeball Network Security Cameras (Zhejiang Dahua Vision Technology Co., Ltd., Hangzhou, China)) were mounted outside the clear Plexiglas viewing windows upstream and downstream of the test screen panel and another camera (GoPro Hero 8, San Mateo, California) was fixed viewing over the screen to record all experiments.

In total, this study involved 17 fish species and two crustacean species sourced from hatcheries or live fish suppliers, except freshwater shrimp and G. holbrooki, which were collected from the wild (Appendix, Table A.1). Species were chosen to represent a range of fish ecological characteristics and body shapes (Table 1). Fish were kept for at least 24 h
in specialised recirculating aquaculture systems (600–1000 L) after
arrival at the CSU Fish Laboratory. All fish were maintained at a constant
temperature suited to their biology (Australian natives: 18–21 °C; sal-
monids: 11–12 °C) and fed daily (depending on species with blood-
worms, artemia or pellets). Tested fish received their last feed 6 h before
the trials. Water changes of 30% were conducted every two days. Water
quality parameters (total ammonia, nitrite, nitrate, dissolved oxygen,
salinity, water temperature, pH) were monitored daily.

2.2. Experimental procedure

After the test AV in the flume was established, the fish were released
into the flume via the fish delivery tube for the desired experimental
duration. Two experiments were conducted; single trials (n = 1 indi-
vidual per trial, Experiment 1), which assessed 16 fish species, and
group trials (n = 6 individuals per trial, Experiment 2) which assessed 17
fish species and two crustacean species. The tested fish ranged between
21 and 68 mm standard length (SL) except for A. australis, which ranged
from 64 to 120 mm (Appendix, Table A.1). Species were selected to
reflect a broad range of different families, body types, and habitat types.
The crustacean species and C. auratus were only tested in Experiment 2,
due to time restrictions using the setup.

2.2.1. Experiment 1: Single trials

To quantify screen approaches, contacts, impingement or avoidance
of individual fish, 16 fish species (n = 12 individuals per species) were
randomly exposed to one of five standardised AVs (0, 0.05, 0.1, 0.2 and
0.3 m/s) for 10-min durations and observed throughout this time.
Approach velocities at 0.05 and 0.1 m/s were tested since they meet the
current prescribed guidelines for screen design for Australian species
(AV ≤ 0.1 m/s; Boys et al., 2021b), while velocities of 0.2 and 0.3 m/s
are still considered to prevent impingement or entrainment for some
marine and freshwater species (Taft, 2000; Black and Perry, 2014;
Kumar et al., 2017). The 10 min duration was chosen as Stocks et al.
(2019) considered this the time when impingement-related mortality
begins. While 15 out of the 16 species were tested for all five velocities,
R. semoni was tested only for 0.1 m/s.

There were four potential outcomes for fish in each trial. First, they
could stay outside the critical zone of influence of the screen. Second,
they could contact the screen and move off. Third, they could become
impinged on the screen. Fourth, they could be entrained (i.e., pass
through the screen). To count and observe the fish encounters with the
screen, each trial was documented using real-time observations. Video
footage was reviewed for number of screen approaches, contacts, im-
ingements, entrainment and to explain any fish species responses to the
screen

(Table 2). Rheotaxis was observed and quantified immediately after
the fish were released in the flume, irrespective of velocity. Fish that did
not enter the critical zone were then excluded from the screen encounter
related analysis, since they were not subject to screen impingements and
contacts.

For the screen interaction analysis, approaches and avoidance, con-
tacts, and impingement were quantified (Table 2). Volitional contacts
were noted since they provide insights about specific behaviour at the
screen across the different velocities. Further observations recorded
were the direction the fish positioned when entering the critical zone;
body part and time of the first interaction, time of first impingement
since release and entrainment (Table 2). Jellyman et al. (2023) observed
that fish may rest at the screens, which was also noted in the present
study.

2.2.2. Experiment 2: Group trials

To quantify impingement, screen detachment frequency and 24 h
survival of a group of individuals at the highest AV (0.3 m/s), 17 fish and
On completion of each 15 min trial, all fish and crustaceans were significantly increased for impingement durations (2019) and Peake (2004), have reported that rates of fish mortality of this velocity was chosen and confirmed with a pilot using Impingements and detachments (Table 2), entrainment number, highest velocity of 0.1 m/s, were also omitted. To elucidate approach fate (Table 2) and the probability of contacts or impingement when entering the critical zone across a spectrum of velocities, a basic Bayesian network (BN) model was employed. BN models provide a graphical representation of the joint probability distribution of random variables (such as velocity, fish species, impingements and non-volitional contacts), facilitating the identification of possible associations between these variables (Kjaerulff and Madsen, 2008). Within this graphical framework, each variable is denoted as a node, with directed edges indicating the underlying dependency relationships. The model, constructed using Netica software (Norsys software Corp. Netica 6.09, 2021), offers a mathematically coherent framework to predict inter-variable connections, whether and when the fish was entrained was recorded.

### Table 1

<table>
<thead>
<tr>
<th>Species name</th>
<th>Body shape</th>
<th>Swimming ability</th>
<th>Flow habitat</th>
<th>Migratory type</th>
<th>Depth zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Short-finned eel (Anguilla australis)</td>
<td>Elongated, eel-like</td>
<td>Strong</td>
<td>Lotic</td>
<td>Catadromous</td>
<td>Benthic</td>
</tr>
<tr>
<td>Golden perch</td>
<td>Compressiform</td>
<td>Weak</td>
<td>Lotic</td>
<td>Potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Murray cod (Macquaria ambigua)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lotic</td>
<td>Potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Silver perch (Bidyanus bidyanus)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lotic</td>
<td>Potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Eel-tailed catfish (Tandanus taudanus)</td>
<td>Compressiform</td>
<td>Weak</td>
<td>Lotic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Benthic</td>
</tr>
<tr>
<td>Firetail gudgeon (Hypseleotris guli)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Benthic</td>
</tr>
<tr>
<td>Southern pygmy perch (Nannoperca australis)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Australian smelt (Retropinna semoni)</td>
<td>Elongate, fusiform</td>
<td>Strong</td>
<td>Lotic</td>
<td>Potamodromous, amphidromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Crimsonsprotted rainbowfish (Melanotaenia duboulayi)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous;</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Olive perchlet (Ambassis australis)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lotic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Spangled perch (Leiopotherapon unicola)</td>
<td>Compressiform</td>
<td>Strong</td>
<td>Lotic</td>
<td>Potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Australian bass</td>
<td>Depressiform</td>
<td>Strong</td>
<td>Lotic</td>
<td>Catadromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Trout cod (Maculolochella macquariensis)</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lotic</td>
<td>Potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Goldfish</td>
<td>Compressiform</td>
<td>Moderate</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Pelagic</td>
</tr>
<tr>
<td>Eastern mosquitofish (Gambusia holbrooki)</td>
<td>Elongate, compressiform</td>
<td>Weak</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Surface</td>
</tr>
<tr>
<td>Brown trout (Salmo trutta)</td>
<td>Elongate, fusiform</td>
<td>Strong</td>
<td>Lotic</td>
<td>Potamodromous, anadromous</td>
<td>Benthic</td>
</tr>
<tr>
<td>Rainbow trout (Oncorhynchus mykiss)</td>
<td>Elongate, fusiform</td>
<td>Strong</td>
<td>Lotic</td>
<td>Potamodromous, anadromous</td>
<td>Benthic</td>
</tr>
<tr>
<td>Yabby crayfish (Chersx destructor)</td>
<td>Elongate, cylindrical</td>
<td>Weak</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Benthic</td>
</tr>
<tr>
<td>Freshwater shrimp (Paratya australis)</td>
<td>Elongate, cylindrical</td>
<td>Weak</td>
<td>Lentic</td>
<td>Sedentary/small scale potamodromous</td>
<td>Benthic</td>
</tr>
</tbody>
</table>

Two crustacean species were tested. Each group trial contained six replicates (n = 6 fish/crustacean per replicate), all of which were recorded and analysed on video recordings. Fish were released into the flume as a group at a constant velocity of 0.3 m/s for 15 min. It is assumed that testing several individuals simultaneously reduces the costs of swimming by gaining a net energetic benefit, as well as physiological processes by schooling (Ralph et al., 2012; Marras et al., 2015), Stocks et al. (2019) identified 0.3 m/s as the minimum velocity required for 100% impingement to occur within 1 min for grouped M. ambigua; therefore this velocity was chosen and confirmed with a pilot using G. holbrooki. The 15 min duration was chosen since other studies such as Stocks et al. (2019) and Peake (2004), have reported that rates of fish mortality significantly increased for impingement durations >10 min at 0.3 m/s. On completion of each 15 min trial, all fish and crustaceans were transferred into their holding containers in small net cages (155 × 140 × 150 mm) and kept for 24 h before they were inspected for mortality, as conducted by Boys et al. (2013a).

Time of first impingement (in seconds (s)), total number of impingements and detachments (Table 2), entrainment number, highest number of impinged fish at once and how many fish were impinged each minute (minute-by-minute impingement) were noted throughout the 15 min duration. Standard length (SL) for fishes and total length (TL) for crustaceans were measured to nearest millimetre after each trial, and whether and when the fish was entrained was recorded.

### 2.3. Data analysis

#### 2.3.1. Experiment 1: Single trials

Rheotaxis was analysed by chi-square tests to determine the association or independence between species and velocities. For investigation into screen interactions, the focus was on fish that entered the designated critical zone, where they would be most susceptible to impingement. The aim was to discern the correlation between impingement (the dependent variable) and various factors including velocity, species, swimming direction, fish length, and the entry point into the critical zone (independent variables). To achieve this, binomial regression analysis was conducted. This approach was used to explore the influence of these variables on impingement and to identify potential species-specific effects. Anguilla australis were excluded due to their notably high entrainment rates, while R. semoni, subjected only to a single velocity of 0.1 m/s, were also omitted. To elucidate approach fate (Table 2) and the probability of contacts or impingement when entering the critical zone across a spectrum of velocities, a basic Bayesian network (BN) model was employed. BN models provide a graphical representation of the joint probability distribution of random variables (such as velocity, fish species, impingements and non-volitional contacts), facilitating the identification of possible associations between these variables (Kjaerulf and Madsen, 2008). Within this graphical framework, each variable is denoted as a node, with directed edges indicating the underlying dependency relationships. The model, constructed using Netica software (Norsys software Corp. Netica 6.09, 2021), offers a mathematically coherent framework to predict inter-variable connections,
there was a correlation between percentage of time impinged at the
dividuals at the same time. This formula was suitable to indicate species
(Nx2) - D + H, where N is the total number of impingements, D the
total number of detachments and H the highest number of impinged in-
dividuals at the same time. This formula was suitable to indicate species
impingement susceptibility by combining several of the measured
factors of impingement. For impingment/detachment analysis, trials
where entrainment occurred were excluded. Kruskal-Wallis tests were
conducted to test whether there were significant differences among
species and the Impingement factor I, detachments, and the highest
number of simultaneously impinged fish. Entrainment was quantified by
examining total number, species, and the standard lengths (SL) of the
tested fish entrained.

3. Results

3.1. Screen approaches

In total, 52.0% (475) of all tested fish did not enter the critical zone
and swam upstream in the flume, avoiding approaching the critical zone
and the screen. Species varied in the number of screen approaches at
tested velocities, with eight species demonstrating a higher number
of screen approaches with increasing velocities (Fig. 2). Of the 732 indi-
vidual fish across 16 species tested at all velocities ≥0.05 m/s, 79.6%  
showed positive rheotaxis after being released in the flume, while
negative rheotaxis occurred for 16.5%. For three species (M. peelii,  
L. unicolour, A. agassizii) negative rheotaxis occurred or increased as AV
increased, while M. duboulayi, T. tandanus and O. mykiss always
exhibited negative rheotaxis across all tested velocities. This occurrence
of negative rheotaxis was not statistically significant ($X^2$, df = 6, $p = 0.410$).

3.1.2. Impingment

For all fish (excluding A. australis) tested at all AVs, 89.1% of all
impingements and 93.9% of all long-term impingements occurred at 0.2
or 0.3 m/s. No impingement occurred at 0 m/s (Fig. 2). The BN model
revealed that the probability of impingement of all fish that entered
the critical zone was more than three times higher at 0.3 m/s than at 0.1 m/s
(Table 3). For six species, impingement was observed at 0.05 m/s
(maximum at two replicates per species) but made up only 2.7% of all
long-term impingements. For all species except P. novemaculeata,
impingement occurred at 0.3 m/s (Table 4). The binomial regression
model revealed that velocity ($\beta = 15.31, p < 0.001$), swimming
direction, and species (both $p < 0.001$) were all significant predictors of
impingement in general, while fish length ($\beta = 0.023, p = 0.615$) and
the way the fish entered the critical zone ($p = 0.532$) did not show a signif-
inificant relationship with impingement. The model demonstrated good
fit to the data ($\chi^2 = 389.69, df = 21, p < 0.01$; Nagelkerke $R^2 = 0.574$).

At all tested AVs, all species entered the critical zone except for
M. peelii at 0 m/s and M. macquariensis at 0.1 m/s, which showed
no screen approaches. Of all fish within the critical zone (8 cm), there was
a significant positive correlation between AV and %ZI (Spearman, $r = 0.171, p < 0.001$, $n = 404$). Impingment time, occurrence of
impingement, and long-term impingements increased with increasing
velocity. For impinged fish, a significant correlation was also found
between AV and %ZI (Spearman, $r = 0.238, p = 0.01, n = 115$) (Fig. 3).
The GLM (Likelihood ratio $\chi^2$: 56.703, $df = 20; p < 0.001$) including all
fish (except A. australis and R. semoni) entering the critical zone showed
that only AV had an effect on %ZI (Wald $\chi^2 = 43.2; p < 0.001$), while
species ($p = 0.323$), part of first screen contact ($p = 0.419$) and body
position when entering the critical zone ($p = 0.426$) showed no signifi-
cant correlation with %ZI (Intercept: $B = 83.2, p < 0.001$).

3.1.3. Contacts

Non-volitional contacts did not increase with increasing velocities
for all species, except A. agassizii and O. mykiss, which showed more non-
volitional screen contacts at velocities > 0.1 m/s (Fig. 4). All species
except M. peelii showed volitional contacts, with T. tandanus,  
P. novemaculeata, G. holbrooki, S. trutta and O. mykiss having the highest
frequencies. Anguilla australis conducted volitional contacts, particularly
at velocities < 0.2 m/s. With increasing velocity, the number of

<table>
<thead>
<tr>
<th>Table 2</th>
<th>Definitions of observations of fish behaviour throughout the trials, either with single fish (n = 1, Experiment 1) or a group of fish (n = 6, Experiment 2) in the flume.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observation</td>
<td>Definition</td>
</tr>
<tr>
<td>Entering the flume</td>
<td>The intentional swimming direction immediately after release in the flume noted as “upstream” (positive rheotaxis, head first into the flow), “downstream” (negative rheotaxis, head first with the flow) and “vertical” (no rheotactic response, sideways with the flow).</td>
</tr>
<tr>
<td>Swimming direction (Initial rheotaxis)</td>
<td></td>
</tr>
<tr>
<td>Entering the critical zone of influence</td>
<td>When a fish moved to the “critical zone”: defined as within 8 cm in front of the screen</td>
</tr>
<tr>
<td>Screen approach</td>
<td>How fish entered the critical zone: by head, tail, or on the side.</td>
</tr>
<tr>
<td>Entering critical zone</td>
<td>Contact where the fish appeared to actively swim against the screen or penetrates the slots head first</td>
</tr>
<tr>
<td>Approach time</td>
<td>The probability that approaches would result in either a contact or impingement</td>
</tr>
<tr>
<td>Approach fate</td>
<td></td>
</tr>
<tr>
<td>Screen interactions</td>
<td></td>
</tr>
<tr>
<td>Time of first interaction</td>
<td>Time (mm:ss) from release and first interaction (contact or impingement) with the screen</td>
</tr>
<tr>
<td>Screen contact</td>
<td>When a fish touched the screen for ≤3 s</td>
</tr>
<tr>
<td>Volitional screen contact</td>
<td>Contact</td>
</tr>
<tr>
<td>Non-volitional screen contact</td>
<td>The fish contacted the screen after exhibiting some avoidance behaviour</td>
</tr>
<tr>
<td>Impingement</td>
<td>Prolonged contact of a fish with the screen &gt;3 s</td>
</tr>
<tr>
<td>Short term impingement</td>
<td>Impingements &gt;10 s</td>
</tr>
<tr>
<td>Long term impingement</td>
<td>Impingements &gt;10 s</td>
</tr>
<tr>
<td>Impingement time</td>
<td>Total time (sec) of impingement</td>
</tr>
<tr>
<td>Minute-by-minute impingement</td>
<td>Number of fish impinged (prolonged contact &gt;3 s at the screen minute by minute after the release)</td>
</tr>
<tr>
<td>Body part of first interaction</td>
<td>Body part of the fish at the first interaction with the screen panel: by head, tail, or on the side.</td>
</tr>
<tr>
<td>Zone-impingement percentage “%ZI”.</td>
<td>The proportion of time between the fish in the critical zone (approach time) and time impinged at the screen.</td>
</tr>
<tr>
<td>Resting</td>
<td>Parts or all of the fish, were touching, but not forced against the screen &gt;3 s.</td>
</tr>
<tr>
<td>Detachment</td>
<td>When a fish could freely itself from impingement at the screen and showed no screen interaction for at least 3 s.</td>
</tr>
<tr>
<td>Entrainment</td>
<td>When fish passed entirely through the screen panel</td>
</tr>
</tbody>
</table>

Aiding in the assessment of impingement likelihood. To test whether
there was a correlation between percentage of time impinged at the
screen of total time in the critical zone (%ZI) and AV or species,
Spearman tests were applied. A generalised regression model (GLM) was
generated to quantify relationships between %ZI (dependent variable)
and species, velocity, body part of first screen contact (independent
variables) and how the fish were entering the critical zone. To test the
relationship between species and velocity on volitional contacts,
Spearman rank tests were generated.

2.3.2. Experiment 2: Group trials

To quantify the impingement and detachment rates at a higher AV
(0.3 m/s), Impingement factor I was determined by the formula: $I = (N x 2) - D + H$, where $N$ is the total number of impingements, $D$ the
total number of detachments and $H$ the highest number of impinged in-
dividuals at the same time. This formula was suitable to indicate species
impingement susceptibility by combining several of the measured

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volitional contacts decreased for all species. Specifically, at AV 0 m/s, 59.9% of all observed volitional contacts occurred, followed by 32.2% at 0.05 m/s, 6.6% at 0.1 m/s and 1.1% at 0.2 m/s. There was a statistically significant correlation between the frequency of volitional contacts and AV (Spearman, \( r = 0.238 \), \( p < 0.05 \), \( n = 104 \)). When independent of velocity, the tested species showed a difference in the number of volitional contacts, whereby these differences showed borderline significance (Spearman, \( r = 0.191 \), \( p = 0.052 \), \( n = 104 \)).

### 3.2. Experiment 2: Group trials

Overall, there was a significant difference among species in ‘Impingement factor I’ and ‘Highest individual number impinged at the same time’ (Kruskal-Wallis, \( H = 37.103 \), \( df = 17 \), \( p < 0.003 \), entrained cases excluded). For example, the two crustacean species and *G. holbrooki* showed the lowest detachment rates (0–21.5%) and could not free themselves from the screen once impinged (Fig. 6). Also, for *T. tandanus* only 33.3% of impingements detached. High detachment rates were shown by *H. galii* (96.3%), *A. agasizii* (88.0%), *S. trutta* (83.3%) and *Bidyanus bidyanus* (71.2%) (Appendix, Table A.2). The total number of impinged and detached fish varied by species when assessed minute-by-minute over the 15-min duration (Appendix, Fig. A.1).

Post-impingement (24 h) mortality occurred in six species, *G. holbrooki* (13.8%), *M. macquariensis* (11.1%), *M. duboulayi* (5.6%) and *B. bidyanus*, *R. semoni* and *P. australiensis* (2.8%). The 3 mm slot wedge-wire was sufficiently small enough to prevent the entrainment of most of the individuals tested. A total of 1.9% of tested fish (excluding *A. australis*) between 22 and 31 mm were entrained through the screen. Over 94% of all *A. australis* (n = 36) were entrained.

### 4. Discussion

Across the broad range of species tested, screen interactions were strongly influenced by AV and species-specific behavioural factors and swimming ability. An AV of \( \leq 0.1 \) m/s can significantly reduce impingement across a range of fish and crustacean species at a 3 mm screen. However, for some species, such as eels, AV was not as decisive for screen responses as body shape or behaviour. As AV increased in the trials (\( > 0.1 \) m/s), significantly greater rates of impingement occurred, with varying responses observed across the species tested in their ability
to detach from the screen. At an AV of 0.3 m/s, species-specific responses to impingement, detachment and post-impingement mortality were detected. Thus, exceeding the AV of 0.1 m/s at a fish protection screen could lead to significant levels of impingement, but this is also highly dependent on species-specific traits such as swimming ability, body shape and behaviour. These traits could lead to adverse outcomes for some species of fish, especially if they are unable to detach from the screen.

4.1. Role of AV in screen encounters

For those fish entering the critical zone in front of the screen, AV had a high influence on impingement, but this varied across the species tested. The present results indicate AVs > 0.1 m/s are too high for a large proportion of the tested species to avoid impingement and reduces the chance for fish to free themselves. Conversely, at ≤ 0.1 m/s, fish have greater success at escaping the screen or could maintain their position in the critical zone in front of the screen without impingement. Some species (T. tandanus, B. bidyanus) could avoid impingement at AV up to 0.2 m/s, but were impinged at an exceptionally higher frequency and for a longer duration at 0.3 m/s. This suggests that minor increases in AV (e.g., 0.1 m/s increase) may result in substantially higher impingement rates. Screen contacts (≤ 3 s) decreased with increasing velocities for several fish species (P. novemaculeata, S. trutta, B. bidyanus, H. galii, T. tandanus). This observation may be attributed to the resultant reduction in contacts due to prolonged impingement periods but could also be linked to behavioural responses to the increasing velocity (Boys et al., 2013a; Poletto et al., 2014).

<p>| Table 4 | Mean percentage ± SD of time a fish is impinged at the screen as a proportion of the total time in the critical zone (%ZI) for each tested species. The number of individuals entering the zone per velocity treatment (top row) is in parentheses and the mean ± SD total impingement time (s) of fish that entered the critical zone is in italics. Trials with entrainment were excluded (Salmo trutta, 0.3 m/s, n = 2 and A. australis). Darker shading indicates a higher proportional time impinged at the screen (Shade intervals: &lt; 1%; 1–10%; 11–20%; 21–30%; 31–50%; 51–70%; &gt; 70%). |</p>
<table>
<thead>
<tr>
<th>Species</th>
<th>0 m/s</th>
<th>0.05 m/s</th>
<th>0.1 m/s</th>
<th>0.2 m/s</th>
<th>0.3 m/s</th>
</tr>
</thead>
<tbody>
<tr>
<td>Southern pygmy perch (Nannoperca australis)</td>
<td>0 (4)</td>
<td>19.8 ± 39.6 (4)</td>
<td>26.6 ± 45.5 (3)</td>
<td>18.4 ± 39.0 (6)</td>
<td>9.1 ± 1.3 (5)</td>
</tr>
<tr>
<td>Eastern mosquitofish (Gambusia holbrooki)</td>
<td>0 (8)</td>
<td>0.7 ± 2.0 (8)</td>
<td>8.1 ± 18.9 (6)</td>
<td>36.4 ± 41.3 (12)</td>
<td>95.3 ± 10.1 (12)</td>
</tr>
<tr>
<td>Golden perch (Macquaria ambigua)</td>
<td>0 (1)</td>
<td>0 (1)</td>
<td>0 (4)</td>
<td>36.1 (4)</td>
<td>94.4 ± 7.6 (10)</td>
</tr>
<tr>
<td>Trout cod (Maccullochella macquariensis)</td>
<td>0 (2)</td>
<td>0 (3)</td>
<td>- (0)</td>
<td>3.1 ± 6.8 (7)</td>
<td>67.3 ± 46.8 (10)</td>
</tr>
<tr>
<td>Silver perch (Bidyanus bidyanus)</td>
<td>0 (7)</td>
<td>0 (6)</td>
<td>0 (2)</td>
<td>8.7 ± 15.3</td>
<td>395.1 ± 274.7</td>
</tr>
<tr>
<td>Murray cod (Maccullochella peeli)</td>
<td>- (0)</td>
<td>0 (1)</td>
<td>0 (2)</td>
<td>62.1 ± 51.9 (5)</td>
<td>66.0 ± 40.2 (9)</td>
</tr>
<tr>
<td>Firetail gudgeon (Hypseleotris galii)</td>
<td>0 (8)</td>
<td>11.6 ± 14.0 (4)</td>
<td>16.5 ± 19.1</td>
<td>9.8 ± 14.3 (5)</td>
<td>54.3 ± 42.9 (5)</td>
</tr>
<tr>
<td>Eel-tailed catfish (Tandanus tandanus)</td>
<td>0 (7)</td>
<td>0.3 ± 0.8 (8)</td>
<td>11.7 ± 20.0 (7)</td>
<td>26.9 ± 63.9</td>
<td>0 (9)</td>
</tr>
<tr>
<td>Rainbow trout (Oncorhynchus mykiss)</td>
<td>0 (10)</td>
<td>0 (6)</td>
<td>0 (9)</td>
<td>15.0 ± 28.6 (11)</td>
<td>33.9 ± 47.3 (11)</td>
</tr>
<tr>
<td>Brown trout (Salmo trutta)</td>
<td>0 (9)</td>
<td>0.4 ± 0.9 (5)</td>
<td>1.0 ± 2.2</td>
<td>49.6 ± 70.1 (2)</td>
<td>139.5 ± 229.5</td>
</tr>
<tr>
<td>Crimsnspotted rainbowfish (Melanotaenia duboulayi)</td>
<td>0 (4)</td>
<td>16.1 ± 36.7 (7)</td>
<td>84.4 ± 217.3</td>
<td>0 (4)</td>
<td>17.8 ± 156.0</td>
</tr>
<tr>
<td>Olive perchlet (Ambassis agassizi)</td>
<td>0 (6)</td>
<td>0 (3)</td>
<td>0 (6)</td>
<td>24.8 ± 40.8 (10)</td>
<td>17.8 ± 36.6 (9)</td>
</tr>
<tr>
<td>Spangled perch (Leipoatheron unicolor)</td>
<td>0 (3)</td>
<td>0 (3)</td>
<td>11.8 ± 16.6 (2)</td>
<td>2.0 ± 2.8</td>
<td>93.6 ± 189.6</td>
</tr>
<tr>
<td>Australian bass (Percaidae novemaculeata)</td>
<td>0 (8)</td>
<td>0 (10)</td>
<td>6.3 ± 18.1 (8)</td>
<td>8.1 ± 23.0</td>
<td>19.6 ± 43.4 (5)</td>
</tr>
<tr>
<td>Australian smelt (Retrospinna semoni)</td>
<td>-</td>
<td>-</td>
<td>3.4 ± 8.9 (7)</td>
<td>0.6 ± 1.5</td>
<td>-</td>
</tr>
<tr>
<td>All fish</td>
<td>0 (77)</td>
<td>3.6 ± 15.5 (69)</td>
<td>13.0 ± 74.3</td>
<td>5.4 ± 15.2 (66)</td>
<td>20.7 ± 36.4 (92)</td>
</tr>
</tbody>
</table>

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4.2. Role of species-specific traits in screen encounters

All species exhibited negligible or very low impingement rates at AVs ≤ 0.1 m/s, except *N. australis*, *H. galii* and *M. duboulayi*. The observed vulnerability of these species to impingement could be attributed to their preference for inhabiting lentic wetland-type habitats, while, additionally, *N. australis* has a low swimming performance ($U_{crit}$) compared to other Australian species of similar size (Tonkin et al., 2008; Watson et al., 2019). The higher impingement rates observed in these species may also be attributed to flow-related behavioural traits, i.e., displaying less avoidance at these lower velocities, as suggested by Poletto et al. (2014). Additionally, the wetland specialist *G. holbrooki* exhibited generally high susceptibility to impingement, likely due to its lower $U_{crit}$ compared to other species of similar size, even those within the same taxonomic family or genus (Srean et al., 2017). Small-bodied species adapted to lentic habitats with low flow velocity tolerances may display heightened susceptibility to impingement or entrainment, especially if pump intakes are located in their preferred habitat (Plaut, 2001; Donaldson et al., 2013; Shiau et al., 2020). Other habitat aspects, such as the preferred depth zones of species within the water column, have been demonstrated to affect screen encounters (Moursund et al., 2003; Kumar et al., 2017). Despite impingement occurring for some species at the lowest velocity, it was still in a very low range and fish could usually detached after a short time. This underscores the importance of considering lower velocities (< 0.1 m/s) in fish screen installations, especially in areas where multi-species assemblages are prevalent. With respect to multi-species fish communities, it is therefore imperative to consider species-specific swimming abilities, habitat preferences and behavioural responses when assessing impingement risks at fish screens.

Compared to species adapted to lentic habitats, lotic species often have higher swimming abilities (Yan et al., 2013). Both trout species (*O. mykiss* and *S. trutta*) tested showed lower impingement susceptibility. Nevertheless, the results confirm that AV $\geq$0.2 m/s is not suitable to avoid impingement for either species in the early parr stage (Katopodis, 1992; Bejakovich, 2006). The results also show that the juvenile native Australian percichthyid species (*M. peelii*, *M. macquariensis* and *M. ambigua*) showed a low velocity tolerance to avoid impingement. However, *Carassius auratus* was the only cyprinid tested and showed a
much higher threshold and detachment ability. Despite it being considered as a lentic species and poor swimmer among cyprinids, e.g. compared to common carp (*Cyprinus carpio*) (Fu et al., 2013), it is still capable of achieving swimming speeds comparable to some Australian riverine species (Starrs et al., 2017; Watson et al., 2019). As such, some juvenile Australian native species may be more susceptible to impingement and entrainment than some introduced species.

Some of the species tested with low impingement susceptibility are known for diadromous lifecycles. Both tested trout species showed a strong threshold, while *Percalates novemaculeata*, a catadromous species with strong swimming abilities, displayed the lowest impingement at all tested velocities (Rodgers et al., 2014). Diadromous species are often characterised by high swimming capabilities, morphological (body shape) and physiological traits appropriate for long and difficult migrations (Bernatchez and Dodson, 1987; Larinier, 2001), which may explain lower impingement rates in this study. Conversely, freshwater resident fish with small home ranges are considered to be less adapted to sustained swimming and show lower swimming performance (Peake et al., 1997; Dalziel et al., 2012; Crespel et al., 2017). Consequently, it may be often more challenging to screen for sedentary fish species than for diadromous species.

The AVs recommended by the Australian screen design specifications (Boys et al., 2021a), were sufficient to reduce or minimise impingement for most tested Australian native pelagic species, which inhabit various lotic and lentic habitats. At 0.1 m/s, very low impingement occurred for the strong swimming species *R. semoni* (Watson et al., 2019; Svozil et al., 2020). *Ambassis agassizi* and *L. unicolor* had low rates of impingement at all velocities tested. For *L. unicolor*, this may be attributed to its strong swimming performance (*U_{crit}*) (Watson et al., 2019; Koehn et al., 2020). All three species were found to be highly susceptible to entrainment into unscreened diversions, which was assumed to be due to behavioural migration aspects or a shoaling nature in the vicinity of intake structures (Hutchison et al., 2022; Boys et al., 2021a). The sustained swimming speed of fish species is also commonly recommended as a reference for the AV of a screen installation (Turnpenny and O’Keeffe, 2005; Ebel, 2016; Meister et al., 2022). Our results indicate that additionally species-specific behaviour influence screen encounters, highlighting the importance of these factors alongside physical design properties (mesh...
width or material) when designing and installing screens.

In the present study, fish size had no significant effect on impingement rates, although we acknowledge that we focused on a relatively small range of juvenile and small-bodied fish. Fish size and shape (e.g., eels) can have substantial consequences for entrainment when considering exclusion morphometrics at a screen (Turnpenny and O’Keeffe, 2005). It has been previously noted that fish length may influence recommended AV (Katopodis, 1992) and fish swimming performance (Haro et al., 2004). This may be further complicated by inter-specific differences in swimming performance are not solely due to fish length (Rogers et al., 2014; Watson et al., 2019; Shiu et al., 2020; Jones et al., 2020). Therefore, when developing fish screening criteria, river managers should aim to incorporate the widest range of species to account for their behaviour and swimming abilities, rather than only using fish morphometrics.

Detachment rates varied between species and were not uniformly related to impingement susceptibility (e.g., T. tandanus, H. gali). Some fish species were more capable of freeing themselves from the screen once impinged at 0.3 m/s (e.g., fish species were more capable of freeing themselves from the screen for their behaviour and swimming abilities, rather than only using fish swimming performance (Harj et al., 2004). This may be further complicated by inter-specific differences in swimming performance that are not solely due to fish length (Rogers et al., 2014; Watson et al., 2019; Shiu et al., 2020; Jones et al., 2020). Therefore, when developing fish screening criteria, river managers should aim to incorporate the widest range of species to account for their behaviour and swimming abilities, rather than only using fish morphometrics.

Post-impingement mortality was low in the present study compared to other studies (Boys et al., 2013a; Stocks et al., 2019). This is likely a result of fish not being continually exposed to impingement across the full experimental time. Impingement duration can increase the likelihood of mortality (Stocks et al., 2019), and fish can often be impinged until mortality occurs (Turnpenny, 1988; Black and Perry, 2014; Boys et al., 2021a). Regarding the limited time of the trials, it is expected that in the present study, post-impingement mortality may have been higher under conditions of more direct exposure to the screen or longer experimental durations. Indirect mortality can also occur as impinged fish can become susceptible to predation due to their inability to escape. Furthermore, increased screen encounters may also lead to adverse behavioural responses due to the effects of increased stress hormone levels (Olla et al., 1992; Poletto et al., 2014). The impingement results suggest that velocities of ≥0.3 m/s can lead to higher impingement rates that could then expose fish to direct or indirect (stress responses and predation) mortality for particular species, even for those with a high detachment ability, as demonstrated in Experiment 2.

4.5. Other factors

While all fish were tested under similar light conditions (artificial light over the flume), it is important to note that screen encounters could differ in darkness or high turbidity as visual cues can play a significant role in avoiding contact with screens (Swanson et al., 2004; Poletto et al., 2014). In Boys et al. (2013a), M. ambigua actively avoided areas of higher velocity in front of the screen by engaging in positive rheotaxis, increasing with higher velocities, while B. bidyanus were more likely to approach the screen, resulting in a higher probability of encounters. Higher velocities could initiate a greater motivation to swim against the current by an augmented rheotactic response with strong positive rheotaxis, thus moving away from the screens (Coombs et al., 2020). Similarly, studies including white sturgeon (Acipenser transmontanus) and green sturgeon (Acipenser medirostris) in laboratory flumes demonstrated a prompt response to faster velocities by exhibiting upstream swimming behaviour (Webber et al., 2007; Poletto et al., 2014; Poletto et al., 2018). These results indicate that water velocity and screen avoidance responses are species-specific, and that screen approaches occur due to a combination of behavioural and hydraulic factors (Boys et al., 2013a; Kammerlander et al., 2020; Carter et al., 2023).

4.4. Entrainment & post-impingement mortality

The 3 mm mesh width excluded most of the tested fish, with only occasional entrainment, except for A. australis, which showed a high rate of entrainment at all AVs. Although mesh size plays a crucial role in reducing entrainment rates (Bøstgen et al., 2004; Turnpenny and O’Keeffe, 2005), it has been demonstrated that for overall screen functionality, sweeping and approach velocities remain the primary consideration (Boys et al., 2013a, 2013b).

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4.3. Rheotaxis and screen approaches

Species-specific rheotactic response behaviour was observed when fish were exposed to the velocities in the flume. Additionally, this behaviour was changing with increasing AVs for several species (e.g., L. unicolour, A. agassizii, T. tandanus). At AVs < 0.2 m/s, an additional behavioural pattern was shown by several species (O. mykiss, S. trutta, T. tandanus, G. holbrooki, P. novemaculeata, A. agassizii), by exploration of the new environment (in this case, the flume), simultaneous with a high frequency of voluntary contacts, but a linear swimming behaviour for maintaining their position in the current at velocities ≥0.2 m/s, resulting in varying screen encounter outcomes among species. In previous laboratory studies, rheotactic behaviour had an influence on how close a fish came to the screen and therefore affected the contact with the screen and impingement rates (Swanson et al., 2004; Poletto et al., 2014). In Boys et al. (2013a), M. ambigua actively avoided areas of higher velocity in front of the screen by engaging in positive rheotaxis, increasing with higher velocities, while B. bidyanus were more likely to approach the screen, resulting in a higher probability of encounters. Higher velocities could initiate a greater motivation to swim against the current by an augmented rheotactic response with strong positive rheotaxis, thus moving away from the screens (Coombs et al., 2020). Similarly, studies including white sturgeon (Acipenser transmontanus) and green sturgeon (Acipenser medirostris) in laboratory flumes demonstrated a prompt response to faster velocities by exhibiting upstream swimming behaviour (Webber et al., 2007; Poletto et al., 2014; Poletto et al., 2018). These results indicate that water velocity and screen avoidance responses are species-specific, and that screen approaches occur due to a combination of behavioural and hydraulic factors (Boys et al., 2013a; Kammerlander et al., 2020; Carter et al., 2023).

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4.5. Other factors

While all fish were tested under similar light conditions (artificial light over the flume), it is important to note that screen encounters could differ in darkness or high turbidity as visual cues can play a significant role in avoiding contact with screens (Swanson et al., 2004; Poletto et al., 2014; Young et al., 2010; Boys et al., 2013a; Mussen and Cech Jr, 2019). For eels, however, Carter et al. (2023) found no difference in behavioural screen avoidance and impingement rates between day and night, probably linked to the migrating urge cues of eels (Jellyman et al., 2023).

Only AV was investigated in the present study, which represents the worst-case scenario for fish since they are exposed to a contact with a vertically oriented structure with no sweeping velocity (SV, vector parallel to the screen face) (Zydlewski and Johnson, 2002). It was shown that SV plays an important role in guiding fish away from direct interactions with fish screens and guidance rack systems (Albayrak et al., 2020; Maddahi et al., 2022), and more protection for fish occurs when the SV is the same or higher than the recommended AV (White et al., 2010; Baumgartner and Boys, 2012). When screened intakes are located in rivers where flows align parallel to the screen (creating a SV), distinct
recommendations for AV could arise, as observed in various field cases (Danley et al., 2002; Swanson et al., 2004). However, in lentic or slow-flowing waters, an adequate SV is not always present (Bretzel et al., 2023). Studies incorporating different screen inclinations and flow angles have shown that these design criteria can affect general screen functionality in protecting fish (Harbicht et al., 2022; Lemkecher et al., 2022), but may also have little effect on the velocity field (Meister et al., 2020; Raynal et al., 2014). We therefore recommend future research especially to incorporate the influence of SV in relation to AV across various fish species.

5. Conclusion

In this study we provide quantitative evidence, derived from flume-based experiments, for 17 juvenile and small-bodied fish species and two crustacean species with diverse ecological traits, evaluated across a range of approach velocities using a 3 mm wedge-wire screen. To minimise impingement of aquatic organisms at screened intakes used for industrial water supply, irrigation, hydropower generation and flood defence, we recommend AVs not exceeding 0.1 m/s at the screen surfaces.

Although we detected various responses from fish species, an approach velocity exceeding 0.2 m/s is deemed excessive for the protection of a diverse fish community. We emphasise the significance of species-specific behavioural and ecological factors in influencing screen approaches, encounters, and detachment rates. This broader understanding is crucial for devising effective strategies to mitigate impingement and entrainment at fish protection screens, as different species within a fish community may exhibit varying responses to screen installations. Further research conducted at field diversions and intake sites, also considering SV, is warranted to validate the findings presented here and to ascertain their applicability to natural fish behaviours. This study contributes to enhancing our understanding of hydraulic and behavioural influences on fish impingement, thereby facilitating the refinement of global screening design criteria and considerations at water intakes.

Data sharing and data availability

The data that support the findings of this study are available from the authors. Restrictions apply to the availability of these data, which were used under licence for this study. Data are available from the corresponding author with the permission of Charles Sturt University.

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Appendix A. Supplementary data

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References


Declaration of competing interest

The authors have no conflict of interest to declare.

Data availability

Data will be made available on request.