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FINAL REPORT

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Summary for public release

Executive Summary	This report represents a continuation of "Impacts and Solutions: A scoping study on the relative impacts of irrigation infrastructure on fish in the Fitzroy Basin" (Hutchison et al. 2022). This original study was initiated to understand how different types of irrigation infrastructure and hydrological conditions contributed to entrainment of fishes into irrigation systems. This knowledge assisted with development of a prioritisation matrix, to direct mitigation measures to where there was the greatest need. In the current study, supplementary data was collected to boost the statistical power of the original data set. The aim was to determine if the patterns observed in the original study were maintained and supported by statistical significance to provide more confidence in the recommendations from the original report. The increased data set and revised statistical analyses would also assist with refinement of the original prioritisation matrix. Analysis of the enhanced data set largely confirmed the patterns observed in the original study. A comparison of a gravity fed and pumped offtakes from Fairbairn Dam in the original data set indicated that fish were entrained at greater rates through the gravity fed diversion than the pumped diversion (Hutchison et al. 2022). With the inclusion of the supplementary data, this was statistically significant for several species and size classes, and across all species combined. Inlet flow rates had little impact on this result. Gravity fed diversions should be a high priority for mitigation with modern self-cleaning screening systems. For irrigation systems that pump water from rivers, there was a general tendency for increased numbers of fish to be entrained per unit time as pumping rate (ML per day) increased. The number of different species entrained per unit time also increased with pumping rate. This trend was consistent across many species, although not statistically significant for most due to high variability in catch rates between different flow events. The steepness of the relationship

	between pump rate and fish entrained per unit time varied between species. When considering entrainment rates on a volumetric basis, there was still a positive relationship evident, but the upward trend was more gradual than might have been expected. These results suggest that pumping rate does have an impact on entrainment rates, but the effect of pumping rates is probably less important than some other factors such as flow type and intake location and depth. The current study confirmed that flow type has a significant influence on entrainment rates. In the original study, entrainment rates were found to be very low on overbank (flood) flows. This trend continued with the addition of supplementary data. Low entrainment rates on flood flows are probably partly due to the dilution effect of large volumes of water and partly due to fish inhabiting habitats inundated over the banks and away from the irrigation intakes. When water levels drop back to the main river channel, fish are more vulnerable to entrainment. In the original study it was suggested that natural within bank flows had a tendency for marginally higher entrainment rates than allocated (supplemental) within-bank flows. With the addition of the supplementary data, it is apparent that natural within-bank flows can lead to entrainment rates approximately double that of entrainment rates on allocated (supplemental) flows. This is probably because fish migrations are more likely to be triggered on natural flow events. In general, larvae are entrained at higher rates on natural flow events, although carp gudgeon larvae are entrained more frequently on allocated flows. This probably reflects the fact that species with pelagic larvae tend to spawn on natural flow events. The current study also confirmed that for most species and size classes of fish (including overall entrainment rates for all species combined), bankside shallow intakes generally entrained far fewer fish than other inlet types (e.g., bankside deep intakes, mid-channel deep intakes and intakes from side channels perpendicular to the river). Inlet location and depth appears to be more important than pump rate. Based on these findings a prioritisation matrix has been developed to assist with decision making on where investment in mitigation measures (e.g. screening with modern self-cleaning fish screens) should be directed to have the most impact. The matrix is virtually identical to that produced by Hutchison et al. (2022) with some minor changes to one of the factors. The factors used in the matrix include pumping rate, pump intake position and depth (intake configuration), flow types pumped and annual licensed allocation (total volume licensed to pump of any flow type).The metrics used for three of the four factors remain unchanged from Hutchison et al. (2022), but within the factor flow type, the weighting for natural within-bank flows has been updated to reflect that these flows on average have double the entrainment rate of allocated (supplemental) flows. By cross multiplying the metrics for these different categories, an overall score can be derived for different pumps in a river. The highest scoring pumps will be those predicted to be in the greatest need of mitigation action. However, for mitigation actions, feasibility and cost, based on the specific site characteristics also need to be considered. In some cases, better outcomes for fish per unit cost may be achieved by screening several slightly lower ranked pumps, rather than expending a large amount of

	resources on a single highly ranked pump that is logistically difficult or expensive to screen. A more cost-effective time to consider screening can be when pumps have reached the end of their useful life and require replacement. The following recommendations have been derived from this research project. 1. Data from this project suggests that gravity fed diversions have a high impact, but only one such diversion was monitored. Further investigations into impacts of riverine gravity fed diversions are recommended. 2. Pumped diversions can be prioritised using a four-part scoring system that considers flow type being pumped, intake configuration (location and depth), pump rate and total volume pumped per annum. Consideration also needs to be given to the costs and feasibility of screening a site as part of the prioritisation process. 3. Future pumped irrigation developments should consider factoring in screening at the design and construction phase when it will be most cost-effective to install screens, compared to retrofitting them later. When existing pumps reach the end of their useful life, screening of the replacement pump should also be considered because it will be more cost effective.
Objectives	• To collect supplementary data to improve statistical power to provide more confidence in the trends observed in the original "Impacts and solutions" report. This was to support the objective from the original impacts and solutions report • Evaluate the relative impact of different irrigation infrastructure types and practices on fish
Background	The original impacts and solutions report was produced based on the following. The cotton industry is under constant scrutiny from the public and the government, particularly in relation to its water use and the impacts that this may have or be perceived to have on the environment. It had recently been recognised that irrigation infrastructure was entraining native fish. Native fish are an environmental asset highly valued by the public. Fish form the basis of recreational fishing activities, are key environmental condition indicators, and are of social, economic and cultural significance. Recent drought related fish kills in the Murray-Darling Basin heightened the public's focus on fish in regulated rivers. Actions that can be taken to maintain or increase the productivity of fish populations will be viewed favourably by the general community and serve to promote a positive image regarding the sustainability of the cotton industry. This project was developed to assist the cotton industry to understand the scope of the issue and to guide where mitigation efforts should be focused. The supplementary report was run in response to a recommendation from the original report which is as follows. Further replication of sampling will provide more confidence in the metrics for flow type being pumped, intake location and depth, and pump rate.

Research activities	This project continued the research from the original impacts and solutions project, using identical sampling methods. The addtional data collected were added to the original data set for statistical analyses. This work was field based research that evaluated the relative impact of different types of irrigation infrastructure on fish entrainment rates. Types of infrastructure examined included gravity fed diversions and pumped diversions. For pumped diversions, factors such as intake position (bankside, mid-river channel, side-channel) and depth, pumping rate and flow type (natural or allocated) were investigated. This work enabled development of a prioritisation matrix to help guide the industry where to invest in mitigation measures. the increased data set led to more statistically significant results and an improved understanding of the patterns observed. Data analyses comparing entrainment rates through different infrastructure and under different flow conditions used generalized linear models, and susceptibility of different species and size classes to entrainment was analysed by one way ANOVA.
Outputs	This project found that gravity fed diversions tend to entrain more fish than pumped diversions, although it is recommended this is investigated further in other catchments where gravity fed diversions are more prevalent, to provide better replication. Within pumped diversions, pumping rate, flow type pumped, and inlet configuration (position and depth) can all influence the number of fish entrained. Bankside shallow pumped intakes seemed to have the least impact. Intake configuration found to have a significant influence on entrainment rates. Pumping from within-bank natural flows tended to entrain more fish than pumping during allocated (supplemental) flows. Pumping during overbank flood flows entrained the least amount of fish. Using the results of this work a prioritisation matrix for riverine pumps was developed that considers pump inlet location and depth, pumping rate (ML per day), flow type pumped and total annual allocation (extraction) for that pump. · The relative impacts are summarised in an information sheet. · The final report contains worked examples of the prioritisation process and these are also presented in an information sheet. Following the recommendations of the final report should assist in directing investment to reduce entrainment of fish in the most beneficial and cost-effective way.
Impacts	This research has identified the types of irrigation infrastructure and flow events that are more likely to lead to entrainment of high numbers of fish. Low risk infrastructure has also been identified. This has led to the development of a prioritisation matrix that can assist with directing where mitigation measures should be implemented. The matrix has been refined from that presented in the original study but is broadly similar. This should lead to improving cotton's environmental footprint in the most cost-effective way. Links to mitigation options are provided.

Key publications	There are no major publications submitted to journals to date, but it is possible that some journal publications may appear in the future with CRDC consent.

Impacts and solutions: A scoping study on relative impacts of irrigation infrastructure on fish in the Fitzroy Basin

Supplementary report

Queensland Government

This publication has been compiled by Michael Hutchison, David Nixon, Jenny Shiau and Haydn Turner of Agri-Science Queensland, Department of Agriculture and Fisheries

The Department of Agriculture and Fisheries proudly acknowledges all First Nations peoples (Aboriginal peoples and Torres Strait Islanders) and the Traditional Owners and Custodians of the country on which we live and work. We acknowledge their continuing connection to land, waters and culture and commit to ongoing reconciliation. We pay our respect to their Elders past, present and emerging.

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Summary

This report represents a continuation of “Impacts and Solutions: A scoping study on the relative impacts of irrigation infrastructure on fish in the Fitzroy Basin” (Hutchison *et al*. 2022). This original study was initiated to understand how different types of irrigation infrastructure and hydrological conditions contributed to entrainment of fishes into irrigation systems. This knowledge assisted with development of a prioritisation matrix, to direct mitigation measures to where there was the greatest need.

In the current study, supplementary data was collected to boost the statistical power of the original data set. The aim was to determine if the patterns observed in the original study were maintained and supported by statistical significance to provide more confidence in the recommendations from the original report. The increased data set and revised statistical analyses would also assist with refinement of the original prioritisation matrix.

Analysis of the enhanced data set largely confirmed the patterns observed in the original study. A comparison of a gravity fed and pumped offtakes from Fairbairn Dam in the original data set indicated that fish were entrained at greater rates through the gravity fed diversion than the pumped diversion (Hutchison *et al*. 2022). With the inclusion of the supplementary data, this was statistically significant for several species and size classes, and across all species combined. Inlet flow rates had little impact on this result. Gravity fed diversions should be a high priority for mitigation with modern self-cleaning screening systems.

For irrigation systems that pump water from rivers, there was a general tendency for increased numbers of fish to be entrained per unit time as pumping rate (ML per day) increased. The number of different species entrained per unit time also increased with pumping rate. This trend was consistent across many species, although not statistically significant for most due to high variability in catch rates between different flow events. The steepness of the relationship between pump rate and fish entrained per unit time varied between species. When considering entrainment rates on a volumetric basis, there was still a positive relationship evident, but the upward trend was more gradual than might have been expected. These results suggest that pumping rate does have an impact on entrainment rates, but the effect of pumping rates is probably less important than some other factors such as flow type and intake location and depth.

The current study confirmed that flow type has a significant influence on entrainment rates. In the original study, entrainment rates were found to be very low on overbank (flood) flows. This trend continued with the addition of supplementary data. Low entrainment rates on flood flows are probably partly due to the dilution effect of large volumes of water and partly due to fish inhabiting habitats inundated over the banks and away from the irrigation intakes. When water levels drop back to the main river channel, fish are more vulnerable to entrainment. In the original study it was suggested that natural within bank flows had a tendency for marginally higher entrainment rates than allocated (supplemental) within-bank flows. With the addition of the supplementary data, it is apparent that natural within-bank flows can lead to entrainment rates approximately double that of entrainment rates on allocated (supplemental) flows. This is probably because fish migrations are more likely to be triggered on natural flow events. In general, larvae are entrained at higher rates on natural flow events, although carp gudgeon larvae are entrained more frequently on allocated flows. This probably reflects the fact that species with pelagic larvae tend to spawn on natural flow events.

The current study also confirmed that for most species and size classes of fish (including overall entrainment rates for all species combined), bankside shallow intakes generally entrained far fewer fish than other inlet types (*e.g*., bankside deep intakes, mid-channel deep intakes and intakes from side channels perpendicular to the river). Inlet location and depth appears to be more important than pump rate.

Based on these findings a prioritisation matrix has been developed to assist with decision making on where investment in mitigation measures (*e.g*. screening with modern self-cleaning fish screens) should be directed to have the most impact. The matrix is virtually identical to that produced by Hutchison *et al*. (2022) with some minor changes to one of the factors.

The factors used in the matrix include pumping rate, pump intake position and depth (intake configuration), flow types pumped and annual licensed allocation (total volume licensed to pump of any flow type).The metrics used for three of the four factors remain unchanged from Hutchison *et al*. (2022), but within the factor flow type, the weighting for natural within-bank flows has been updated to reflect that these flows on average

have double the entrainment rate of allocated (supplemental) flows. By cross multiplying the metrics for these different categories, an overall score can be derived for different pumps in a river. The highest scoring pumps will be those predicted to be in the greatest need of mitigation action. However, for mitigation actions, feasibility and cost, based on the specific site characteristics also need to be considered. In some cases, better outcomes for fish per unit cost may be achieved by screening several slightly lower ranked pumps, rather than expending a large amount of resources on a single highly ranked pump that is logistically difficult or expensive to screen. A more cost-effective time to consider screening can be when pumps have reached the end of their useful life and require replacement.

The following recommendations have been derived from this research project.

1. Data from this project suggests that gravity fed diversions have a high impact, but only one such diversion was monitored. Further investigations into impacts of riverine gravity fed diversions are recommended.
2. Pumped diversions can be prioritised using a four-part scoring system that considers flow type being pumped, intake configuration (location and depth), pump rate and total volume pumped per annum. Consideration also needs to be given to the costs and feasibility of screening a site as part of the prioritisation process.
3. Future pumped irrigation developments should consider factoring in screening at the design and construction phase when it will be most cost-effective to install screens, compared to retrofitting them later. When existing pumps reach the end of their useful life, screening of the replacement pump should also be considered because it will be more cost effective.

Introduction

Justification for collection of supplementary data

In 2022, DAF submitted a final report to the Cotton Research and Development Corporation (CRDC) outlining results and recommendations of a scoping study on the relative impacts of irrigation infrastructure on fish in the Fitzroy Basin in the vicinity of Comet and Emerald (Hutchison *et al*. 2022). This project investigated entrainment of fish through riverine pumps and whether pumping rate and pump intake position (proximity to bank and depth) made any difference to entrainment rates of fish. The research project also investigated whether fish were more susceptible to entrainment through riverine pumps on different levels of natural flow events or supplementary flows releases from irrigation dams. In addition, the study examined entrainment of fish in pumped and gravity fed irrigation channels originating from Fairbairn Dam. This work led to the following recommendations.

1. Gravity fed diversions should be considered a high priority for mitigation of impacts to fish. Further investigations into impacts of riverine gravity fed diversions are recommended.
2. Pumped diversions can be prioritised using a four-part scoring system that considers flow type being pumped, intake location and depth (intake configuration), pump rate and total volume pumped per annum. Consideration also needs to be given to feasibility of screening a site (including cost) as part of the prioritisation process.
3. Future pumped irrigation developments should consider factoring in screening at the design and construction phase when it will be cheaper to install screens, compared to retrofitting them later.
4. Further replication of sampling will provide more confidence in the metrics for flow type being pumped, intake location and depth, and pump rate.
5. Further research needs to be conducted into the cost-benefits of screening to provide irrigators confidence that pump screening will not significantly impact on their financial position.

Point five in the above list is now being addressed through research by the NSW Department of Primary Industries. Point four recommended further replication of sampling to provide more confidence in the metrics for flow type being pumped, intake location and depth, and pump rate. This recommendation came about because although there were clear patterns and trends repeated across several different species, high variation in catch rates and sampling rates of fish (which is typical of fisheries data) resulted in not all patterns being statistically significant for many species. One such pattern was that near bank shallow water pump intakes tended to entrain fewer fish than other intake types. Multiple lines of evidence and some significant findings for some fish species gave some confidence in the data, but it was felt that further replication would give more power to the data interpretation and strengthen the robustness of recommendations. This current project has collected some supplementary data to add to the original data set compiled by Hutchison *et al.* (2022). This combined data set has been reanalysed to determine if the patterns remain consistent with the original findings and if any further statistically significant findings are detected to improve confidence in the use of the prioritisation metrics developed in the 2022 report.

Key patterns observed in the 2022 report.

Some of the patterns reported by Hutchison *et al*. 2022 included the following:

1. The numbers of fish entrained across several species tended to be lower through bankside shallow inlets. However, despite the pattern being consistent, this was only statistically significant for a limited number of species and size classes. The lack of significance was mainly driven by high variability in entrainment rates across the other inlet types, rather than through large variation at the bankside shallow sites.
2. The number of species entrained per unit time was significantly less at bankside shallow sites. The number of species and the number of individual fish entrained (across many species) tended to increase as pump rates increased, but this trend was only statistically significant for the number of species entrained and for bony bream greater than 100 mm fork length (FL).

3. Very few fish were entrained during over-bank natural flows. Entrainment rates were higher during within-bank flows.
4. There was no significant difference across most species for entrainment rates between natural and allocated within-bank flows, but there was a tendency for more large fish to be entrained on natural flow events and for golden perch larvae to be entrained on natural flow events.
5. Entrainment rates for spangled perch showed no tendency to increase as pump rates went up. This suggested spangled perch (especially large-spangled perch) may actively swim into lateral offtake currents. Fish entrained per megalitre (ML) was marginally positive across most species as pumping rates increased.
6. The original report also examined if there were any significant differences in the size (length frequency) distribution of fish in the river versus the size of fish being entrained. In general, within species, smaller-sized fish were generally more susceptible to entrainment than larger fish, and this was usually statistically significant. There were some exceptions. Larger spangled perch and olive perchlet were significantly over-represented in some pump samples compared to riverine samples, especially during the warmer months. This suggests that pumps may have intercepted these species during a spawning migration. Both species spawn in off-river wetlands, so these fish may have been seeking currents lateral to the river flow, to lead them into wetlands and may have actively swum into the irrigation offtakes.

Fish size frequency comparisons between river or impoundment reference site samples and entrained fish samples will not be further investigated in this supplementary report as the data collected previously was already clear cut and mostly statistically significant. The original report also ranked fish species and size classes by their susceptibility. This is revisited in this current report, especially to provide a ranking for some of the rarer riverine species that may have been caught too infrequently in the original survey for an accurate ranking. Also, some additional species and size classes were entrained during supplementary data collection, enabling a more comprehensive list of species that are entrained to be compiled.

The current document should be treated as a companion document to Hutchison *et al*. (2022). The main objective is to either confirm trends through statistical modelling observed in the original study or to identify any new trends and information detected through collection of supplementary data.

The sampling and statistical methods used in this study are essentially identical those used in the original study by Hutchison *et al.* (2022).

Methods

As outlined above, the methods used in this study were identical to those used in the original study by Hutchison *et al.* (2022). The data from the original study and the supplementary study were combined into a single comprehensive dataset. The methods from the original report are reprinted here for the convenience of the reader, with some updates to include the additional sampling. The statistical method that examined length frequency distributions of fish in the original study is excluded from the current study as length frequency data required no further investigation. Given the higher water levels in Fairbairn Dam during the supplementary period compared to the original data collection period, “dam capacity %” has been added as an additional variable to be investigated for its influence on entrainment of fish into the diversion channels exiting Fairbairn Dam.

Experimental design

This project opportunistically sampled pump outlets on cotton farms for entrained fish during natural and allocated flows in the period from October 2023 to March 2024. These data were combined with data collected by Hutchison *et al*. (2022) between January 2021 and March 2022 for analyses. The pumps extracted water from the Nogoa, Mackenzie and Comet Rivers. For privacy reasons we have not identified the individual farms involved in this survey, but Figure 1 shows a map of the general region where the surveys were completed. A diverse range of pump sizes were selected, ranging from extraction rates of 14 megalitres (ML) per day up to 164 ML per day (Table 1). Intake positions included bankside, mid-river channel (at least several metres from the bank edge), and within an excavated side channel perpendicular to the river (Figure 2). The pump intakes were set at various water depths. Intakes where the top of the intake was situated less than 1 m below the water surface during normal allocated flow or base flow levels were classified as shallow, and intakes where the top of the intake site sat greater than 1 m below the surface on a baseflow or normal allocated flow were classified as deep. This resulted in four intake position and depth configurations in this study: bankside shallow, bankside deep, mid-river channel deep and side channel shallow.

Pumping events were monitored from allocated flows released from Fairbairn Dam, and from natural flows, which included both within bank and overbank flows. Overbank flows were where water covered at least the riverside bench. The number of samples collected was limited by the number of growers pumping on any given flow, and by the frequency of flows. Rainfall events that helped water crops and generated overland flows that allowed growers to fill storage tanks, meant that there were fewer pumping events from the rivers than anticipated during the supplementary sampling period. The key factors investigated were pump size, pump intake location and depth, and flow type.

Entrainment of fish into irrigation diversion channels originating from Fairbairn Dam (Figure 3) were also evaluated (Table 1). There are two irrigation diversions, the Selma Channel and the Weemah Channel, which have different intake configurations. Depending on the water level in Fairbairn Dam, the Selma channel is either gravity fed (>68% dam capacity) or fed by three variable discharge pumps (<68% dam capacity). During the study period Fairbairn Dam levels varied between 14% and 44% capacity.

Table 1: Summary of pumps, diversion channels and flow events monitored

Pump site code	Intake type (position and depth)	Extraction rate (ML/day)	Allocated flows (count)	Natural flows (count)
1	Bankside deep	100	1	2
3	Side-channel shallow	42-51	1	3
4	Mid-river channel deep	27-56	1	2
7	Bankside shallow	80-164	2	3
8	Bankside deep	100	2	1
9	Bankside shallow	22.5-30	2	
11 (Selma Channel)	Pumped diversion from dam	75-420	6	
12 (Weemah Channel)	Gravity diversion from dam	75-259	6	
13	Mid-river channel deep	88.5	1	
15	Bankside shallow	90-140	2	
16	Bankside deep	90-100		2
17	Mid-river channel deep	14-14.5	3	
19	Side-channel shallow	80-100	1	1

Therefore, the Selma channel was supplied solely by pumping during sampling. The Weemah channel is always gravity fed through a 6 m diameter pipe at the bottom of the dam wall, with flow rates set using control gates in the intake tower (Figure 3). Key variables examined for the diversion channels were outlet flow rate (changing according to irrigator demand) and outlet type. Monitored discharge rates ranged from 75 ML per day to 400 ML per day. Seasonal variation was also considered, as the thermocline (which forms in summer usually at a depth between 4 - 8 m below the surface) could possibly influence where fish sit in the water column relative to the channel intakes. Most fish are likely to avoid the deoxygenated water below the thermocline. Water temperatures may also affect fish activity levels (Volkoff and Rønnestad 2020) and therefore susceptibility to entrainment. During the study period, low water levels in Fairbairn Dam meant that the intake site for the Weemah diversion and the pump intake for the Selma channel were probably above the thermocline on at least four out of the 6 sampling occasions and possibly for all 6 sampling occasions. Nevertheless, the dam levels (dam capacity %) have been included as a variable to account for differences in intake depths. An increase in intake depth might limit entrainment of species that may favour surface waters.

Fish were sampled in riverine or impoundment sites adjacent to pumped irrigation infrastructure and the diversion channels so that entrained fish numbers could be referenced against fish abundances in the source water. This is discussed in further detail below.

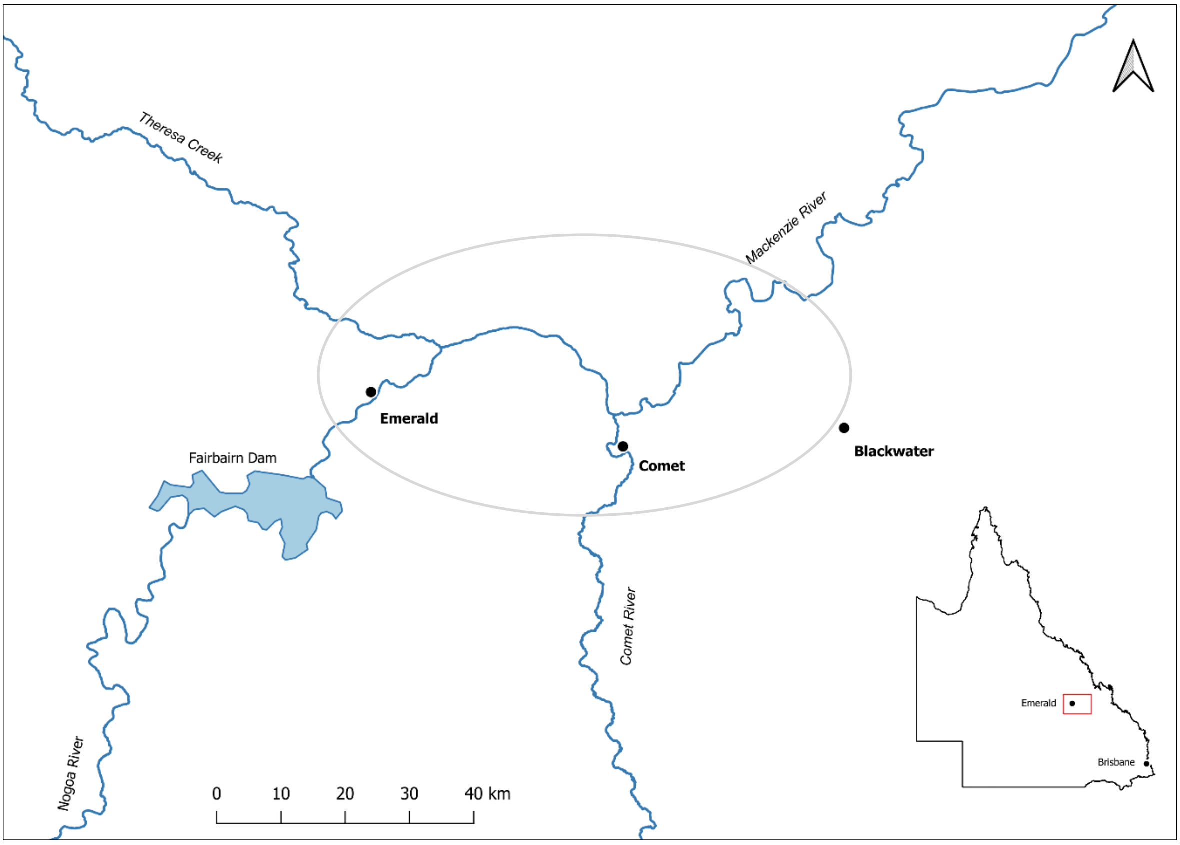

Figure 1: Map of the waterways where pump intakes were located. Sampling was completed along the Nogoa, Mackenzie and parts of the lower Comet River within the area circled between Emerald and Blackwater. Sampling also took place within Fairbairn Dam and in the two diversion channels exiting from Fairbairn Dam. Natural flow events originated from upper Theresa Creek and the upper Comet River. Allocated flows originated from Fairbairn Dam.

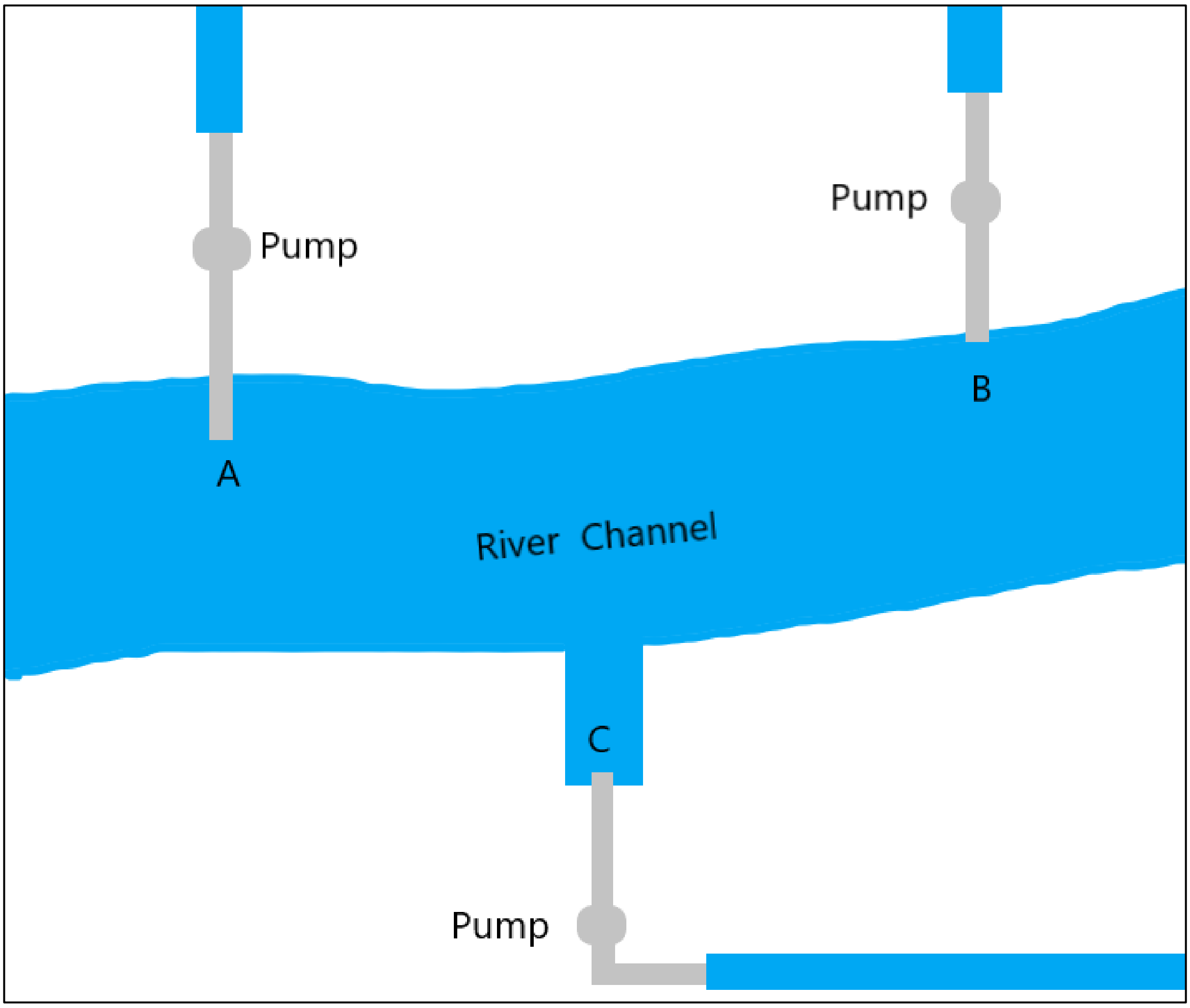

Figure 2: Schematic diagram of different river pump intake types. A: Mid-river channel intake that extends several metres out from the bank. B: Bankside intake that is close to or flush with the riverbank. C: Intake that draws water from an excavated side channel. Pump outlets run into irrigation channels (as illustrated) or directly into a ring tank. Note, mid-river channel intakes extend three or more metres from the bank but may not necessarily reach the middle of the river, especially in wider reaches.

Figure 3: Satellite image showing intakes for diversion channels from Fairbairn Dam. Selma Channel intake (upper left) when gravity fed, or when pumped into the channel at dam levels below 68% capacity. Alternatively, water passes from the intake (lower right) through the bottom of the dam wall to be released into either the Nogoa River, or the Weemah Channel.

Irrigation outlet sampling

Outlet netting

To monitor irrigation outlets, a custom-made net was set across the outlet channel, 15-20 m downstream of the irrigation pump outlet (Figure 4). Where rock armouring was present on the sides of the channel, the net was positioned immediately downstream of the rocks to prevent it from being snagged or torn. The net was constructed from 4 mm mesh, with two 15 m wings that had a 5 m drop. The top of the wings had a row of floats, and the bottom of each wing contained a lead line. In the centre of the net, between the two wings, was a 5 m long 2 mm mesh pocket with a tied cod end. To ensure the bottom of the net did not lift off the channel substrate in the water current, 10 m of 8 mm chain was attached to the lead line across the centre of the net. Additional floats (pool noodles) were added to the float-line in the centre of the net above the pocket to ensure the top of the net was not dragged under due to the flow velocity. The net was held in place by steel stakes or alternatively tied to a bull bar of a vehicle (Figure 4). Once the net was secured in the flow, it was drifted backwards until taut. The net was set for 100 min and captured the entire outlet flow for that set period. After 100 min, the net was carefully hauled in by both wings, ensuring that the lead line remained on the bottom. When the net was almost fully hauled in, the lead line was scooped up to stop fish escaping and all the net contents were shaken into the pocket. The cod-end was emptied into aerated bins to be processed. All captured fish were identified and counted, and the mortality rate for each species was estimated. Within each net shot, a maximum of 40 fish from each species were measured (fork length) to give an indication of size-frequency. Catch rates were recorded as catch per 100 min and catches were also standardised to catch per megalitre of water diverted.

Figure 4: Outlet sampling net in place. Note the float line and extra floatation across the centre of the net.

Larval netting

A larval net was also set downstream of the pump outlet for a period of 20-30 min. The duration of a set depended on the current velocity and debris load. Larval nets were made from 200 µm mesh and contained a fine nylon fabric pocket. The net opening had a diameter of 56 cm and was fitted with a flow meter. By using the start and finish readings from the current meter counter, it was possible to estimate the volume of water that had passed through the larval net during the period it was set. At the end of the set period, the contents of the larval net were emptied into a bucket. Any non-larval fishes were removed from the bucket and returned directly to the channel for processing in the larger outlet net sample. The remaining contents were sieved through a plastic jar with 200 µm mesh panels. The contents of the jar were then flushed with alcohol, washed into storage jars and diluted with clean water to approximately 60% alcohol content. These jars were then labelled and stored in a portable refrigerator for later analysis back at the Bribie Island Research Centre laboratory.

River and impoundment sampling

River reaches and Fairbairn Dam were sampled by a combination of boat electrofishing and overnight sets of fyke nets. These 'reference sites' were sampled to provide an indication of the species composition and abundance of fish and fish larvae present in the source waterbody. When reference site catch is compared with outlet catch from nearby irrigation pumps or channel diversions, it can provide an indication of how susceptible different species and different sizes classes of fish may be to entrainment. For example, some fish common in the reference site catch may be only rare in the outlet catch, indicating they are not highly susceptible to entrainment or vice-versa. Evaluating abundance of fish at reference sites also allows for more equitable comparisons of the different types of irrigation infrastructure when reference site catch is used as a covariate in statistical analyses.

Sampling locations

Reference sites were located as close as possible to pump intakes. The nearest possible access site on the river where an electrofishing boat could be safely launched and operated was used. Sites were used in the Nogoa, Mackenzie and Comet Rivers, and in Fairbairn Dam. The Fairbairn Dam site was close to the dam wall and the diversion channel intakes. Most reference sites were sampled either on the same day as the associated pump outlet (or outlets) or within one day of outlet sampling, to reflect as closely as possible the relative abundance of fish in that reach of the river during water extraction. On one occasion, sampling at a reference site (during data collection for Hutchison *et al.* 2022) had to be delayed by one week due to exceptionally high flow rates leading to safety concerns and road access difficulties.

Boat electrofishing

Electrofishing is an active form of sampling that uses a pulsed DC electric current to stun fish. Anodes are set on booms on the front of the boat and lowered to the water during electrofishing (Figure 5), while the metal hull acts as a cathode. An electric field is set up around the boat between the anodes and cathode. Fish within two to three metres of the boat are temporarily stunned by the current. Stunned fish are dip-netted from the water for identification and measurement. After processing, the fish are released back unharmed into the river.

Five electrofishing shots were conducted at any given reference site, with each shot consisting of 300 seconds of power on time, applied over a 50 m x 15 m area. Most shots were conducted around bankside and instream structure, sampling representative habitat for the site.

Figure 5: Electrofishing boat in operation on the Mackenzie River.

Fyke netting

Four fyke nets were set in back-to-back pairs in the late afternoon and cleared the next morning. The fykes each had 2 x 5 metre wings, leading to funnels that led into a cod-end. The nets were constructed from 2 mm knotless mesh. The entrance to each fyke was fitted with a turtle excluder, consisting of 10 cm wide stainless steel wire grills. The turtle excluders prevent large turtles from entering the fyke net and preying on trapped fish. A float was placed in the cod-end of each net to provide an air pocket for air breathing aquatic animals that might pass through the turtle excluder. Fyke nets were set out of the main current in sheltered edge areas or backwaters (Figure 6). Fykes are a passive sampling method and rely on fish moving for foraging or migration. The wings guide the fish into the net, where they are then trapped in the cod-end by a series of funnels.

Figure 6: A fyke net set along a bank. Note wings leading to an entrance and a float in the cod end to provide an air pocket should any air breathing animals pass the turtle excluder.

Larval netting

If sufficient current velocity was present, larval nets were set in the river using the same methodology as in the irrigation channels. When flow was slower, larval nets were slowly towed behind the electrofishing boat for 10 min or approximately 600 m. Samples from Fairbairn Dam were always collected by towing. A flow meter set in the mouth of the net enabled calculation of the volume of water sampled. The larval net samples were processed the same way as those from larval nets set in the irrigation channels.

Identifying larval samples

In the laboratory, larvae were viewed through a binocular microscope fitted with a camera linked to a computer monitor. Larvae were identified to species level where possible using descriptions and images from the published literature. Those that could not be identified to species level had their size recorded and were photographed for later identification. Newly hatched yolk-sac larvae or damaged larvae were sometimes difficult to identify to species level, but most advanced larvae were able to be identified to the species or family. Fish eggs were also recorded. Without the aid of genetic sampling eggs could not be identified to species, but the size of the eggs can give some indication as to what species groups the eggs may have belonged to. Larval and egg catches were standardised to catch per unit volume sampled.

Data management and susceptibility indices

Data entry and management

Data was entered into an Excel spreadsheet, with tables for shot details, site characteristics, fish catch and fish size. Species specific tables were constructed to export the data into Genstat for analyses (see statistical analyses below). Additional tables were established for calculation of susceptibility indices for fish, larval fish and eggs (see methods below).

Susceptibility indices

Susceptibility indices were calculated for each species present in the reference site adjacent to irrigation infrastructure intakes. For larger species, separate indices were calculated for fish ≤100 mm in fork length and >100 mm in fork length. The index was calculated from the catch per megalitre entrained through the infrastructure divided by the total catch of that species or size class from the reference site, as collected by standardised electrofishing and fyke netting. For example, if the entrainment rate for a given fish species and size class was 5 per megalitre and the total catch from the reference site for the same species and size class was 10 fish, then the susceptibility score would be 0.5. If the species was present in the reference site, but not entrained through the infrastructure, then it was given a susceptibility score of zero. Occasionally a species would be found entrained in the irrigation infrastructure but was not captured in the reference site. To have been entrained through the infrastructure the species must have been present in the reference site, so in this scenario the reference site was given a count of 0.5 to enable calculation of an index score. The arbitrary count of 0.5 was to indicate rarity, but not absence. If for example 5 fish of that species were entrained, and none caught in the reference site, then the susceptibility score would have been calculated as 5/0.5 =10. If a species was not encountered in either the reference site or the outlet site, then no score was recorded for that occasion. As catch per megalitre is generally lower than the standardised river catch, most index values were <1. The rank order of the indices gives an indication of the relative susceptibility of the different species.

To calculate susceptibility for fish larvae (or fish eggs) entrained through irrigation infrastructure, the catch of fish larvae per cubic metre (m^3) was divided by the catch per cubic metre from the reference site. If the larvae of a species were present in the reference site, but not entrained, then a susceptibility score of zero was recorded. If the larvae of a species were entrained, but not detected in the reference site, the river catch per cubic metre was designated as 0.01. Note 0.01 larvae per cubic metre is equivalent to 10 larvae per megalitre. This is approximately half of the lowest (non-zero) count recorded for larvae of any species during this project. This figure was to represent presence, but rarity and to enable calculation of a susceptibility score. If the larvae of a species were recorded neither in the irrigation infrastructure nor in the reference site during a sampling event, then no susceptibility score was calculated. Therefore, if the catch of larvae in the irrigation infrastructure was 0.06 per cubic metre and the catch rate in the reference site was 0.08 per cubic metre, then the susceptibility score would be 0.06/0.08 =0.75. If the same catch rate was detected in the infrastructure, but no larvae were detected in the river, then the score would be 0.06/0.01 = 6.

Statistical analyses

Key variables analysed

For each species and size class (>100mm and ≤100mm) the catch of fish per 100 min of sampling and per megalitre (ML) were evaluated as the dependant variables. The following factors: pump rate (ML pumped per day), pump location and depth, and flow type were assessed as explanatory variables. Additional continuous explanatory variables considered in the statistical analyses were water temperature, turbidity (Secchi depth) and conductivity. Pump intake depth was recorded as the depth of the top of the intake pipe from the surface during normal allocated flow levels and this depth was fixed across all flow types. Intakes less than 1 m below the surface were classed as shallow and intakes over 1 m below the surface were classed as deep. The reason for using a fixed rather than a variable depth method is that it is an easier variable to measure for site assessments when collecting information for prioritisation of irrigation infrastructure for mitigation actions. River or impoundment catch of the same species and size class of fish was included as a covariate (Table 2). The same factors and explanatory variables were used for larval fish and fish egg entrainment data respectively, but larval river catch and larval entrainment rates were expressed as catch per unit volume sampled only.

Table 2: Factors and variables considered for inclusion in statistical models of entrainment through irrigation infrastructure.

Dependent variables analysed	Factors	Continuous explanatory variables	Covariates
• Catch per 100 min • Catch per ML	• Pump location and depth • Flow type • Season	• Pump rate (outlet flow rate) ML per day • Water temperature • Secchi depth • Conductivity • Impoundment capacity % (for Selma and Weemah channels data only)	• River or impoundment reference site background fish catch

Generalised linear models

Generalised linear models (GLMs) (McCullagh and Nelder 1989) were used to analyse the catch rate data for adult, juvenile and larval fish in GenStat® (22^{nd} edition, VSN International UK) . A model was generated for each species and size class for which there was sufficient catch data. The Poisson distribution with the log-link function was adopted for catches (discrete counts), with over-dispersion where warranted. The Normal distribution with the identity-link function was used for catch rates (catches per ML). Residual plots were used to check the assumptions of homogeneous variances and low skewness. Alternate models were trialled and simplified as appropriate for the somewhat-limited numbers of observations in some analyses. The primary fixed effects were pump location and depth, and flow-type. Season, pump-rate (on a log-basis), background fish levels at reference sites, temperature, salinity, Secchi-depth and conductivity were also considered. Season was split into two categories, cool season and warm season. The cool season was winter and early spring when temperatures were 20ºC or less and the warm season was late spring through to autumn when temperatures exceeded 20ºC. If temperature was run as a variable, season was dropped from the model. For the diversion channels exiting Fairbairn dam, "dam capacity %" was also considered as a fixed effect.

Interactions between the fixed effects were screened but proved to be non-significant. However, dam catch rate and dam capacity % were correlated for some species of fish, so these variables were not included in the same model. Adjusted means (and their standard errors) were estimated and subjected to unprotected post-hoc pairwise testing with a Fisher's protected least significant difference test.

Some species were only recorded infrequently at pump outlets, and some species or size classes that were recorded in the adjacent waterway were never recorded at pump outlets. These fish could not be analysed by GLM. However, all species recorded in either adjacent waterways or at irrigation outlets were tabulated. Models run for the channels exiting Fairbairn Dam were over-paramatised if both impoundment level and background fish catch were run in the same model. These were therefore run separately in different models. Pump our outlet flow rate was dropped for most models for the Fairbairn Dam outlet channels as extremely high catch rates for some species on one sampling occasion for flow rates of 100 ML per day meant there was no relationship between flow or pump rate for most species, and other parameters were more important for explaining entrainment rates. See the Results section for more details.

Similar approaches were used for larval fishes. Model. For larvae entrained from Fairbairn dam, most species were detected too infrequently for any analyses. A combination of all larvae detected was analysed by GLM using a Poisson distribution and Log link function. Terms included in the model included dam capacity, temperature, natural log (ln) of channel inlet flow rate and dam catch of fish larvae as a covariate. Temperature was not significant and was dropped from the model. There was some correlation between dam catch of fish larvae and dam capacity, so these terms were run in alternative models.

Comparison of mean susceptibility indices scores

Susceptibility indices were designed to enable comparisons between species and size classes, and to adjust for localised species abundances when comparing different infrastructure sizes and configurations. The indices can also be used to rank the susceptibility of different species to entrainment. Those species present in the river but never entrained received equal low-ranking scores of zero. A species had to be encountered in the adjacent river or coming through the pump for it to receive a count for the calculation of *"n"* for the estimation of the mean. The value of "n" refers to the number of occasions a species or size class was detected at a reference site, or if not at the reference site, entrained through a pump adjacent to that reference site, as these were occasions when a susceptibility score could be calculated. Absence from both the reference site and pump on a pumping event did not contribute to estimation of the mean value. Very rarely encountered species (n<5) were not included in statistical comparisons of the mean susceptibility scores. For those species and size classes with five or more susceptibility scores, analyses were completed using Genstat®. Analyses were by one way ANOVA of Log_{10} +1 transformed data, followed by a post-hoc pairwise comparison of the means using a Fisher's protected least significant difference test.

Results

To make the results more user friendly to the reader, many of the statistical models have been placed in the appendices. This section focuses on the key patterns detected and highlights factors or results that were statistically significant. For the GLM outputs, the predicted mean value outputs were presented rather than the tabulated model outputs which can be found in the appendix. Predicted means (also known as adjusted means) are determined from the actual patterns in the data and hold other factors in the model constant for the prediction. They make it easier to visualise and interpret what the data is showing.

Species caught

Table 3 shows the range of species and size classes captured at riverine reference sites and whether these species and size classes were ever found entrained during the study. Some species and size classes were only rarely detected in the reference sites, so it was to be expected that they may not be detected at irrigation outlets. Table 4 shows species and size classes found in the Fairbairn Dam reference site and whether those species or size classes were ever found entrained in the Fairbairn Dam irrigation diversion channels. Species for which no size class is indicated are all ≤100 mm in fork length (for round tailed species such as gudgeons and juvenile golden perch this measure is equivalent to total length).

Species or size classes commonly recorded in the river reference sites but not found entrained through riverine pumps were saratoga >100 mm, and golden perch ≤ 100 mm. Juvenile golden perch were present in relatively low numbers at riverine reference sites compared to sites the authors have sampled previously in the northern Murray-Darling Basin. Fish entrained during the supplementary data collection period that were not found to be entrained during the original data collection period included golden perch >100 mm, saratoga ≤100 mm, barred grunter >100 mm and freshwater catfish ≤100 mm. These fish were not a common catch in pump outlets in the supplementary data collection period and juvenile freshwater catfish were also rare in the river sites.

In contrast to the riverine pumps, golden perch were entrained in both the pumped Selma Diversion Channel and the gravity fed Weemah Diversion Channel. Juvenile golden perch were relatively common in Fairbairn Dam during the original data collection period, with good recruitment evident from an upstream flow event. However, they were less common in the dam during the supplementary data collection period.

Table 5 shows detection of fish larvae and fish eggs in irrigation pump outlets and their river reference sites and Table 6 shows detection of fish larvae and fish eggs in impoundment diversion channels and the Fairbairn Dam reference site. Fewer larvae and fish eggs were detected at the impoundment site and the associated diversion channels than were detected in riverine sites and riverine pump outlets. Larvae were typically only seasonal in occurrence, with most larvae being detected in warmer months.

Table 3: Fishes (excluding larval stages) recorded either entrained through riverine irrigation pump outlets or from surveys of the adjacent river reference sites. Larger species are broken into two size classes, ≤100mm or >100 mm. All other species were <100 mm. Some size classes were not recorded either in the river or entrained through the pumps (e.g., freshwater longtom ≤100 mm) during this project and these have been excluded from the table. * Denotes an introduced species

Size class	Common name	Species name	Entrained through pump	Captured in river
>100 mm	Long-finned eel	*Anguilla reinhardtii*	no	yes
	Southern saratoga	*Scleropages leichardti*	no	yes
	Bony bream	*Nematalosa erebi*	yes	yes
	Freshwater catfish	*Tandanus tandanus*	no	yes
	Hyrtl's tandan	*Neosilurus hyrtlii*	yes	yes
	Rendahl's tandan	*Porochilus rendahli*	yes	no
	Blue catfish	*Neoarius graeffii*	yes	yes
	Freshwater longtom	*Strongylura krefftii*	no	yes
	Golden perch	*Macquaria ambigua oriens*	yes	yes
	Murray cod	*Maccullochella peelii*	no	yes
	Leathery grunter	*Scortum hillii*	no	yes
	Barred grunter	*Amniataba percoides*	no	yes
	Spangled perch	*Leiopotherapon unicolor*	yes	yes
	Sleepy cod	*Oxyeleotris lineolatus*	yes	yes
	Goldfish*	Carassius auratus	no	yes
≤100 mm	Southern saratoga	*Scleropages leichardti*	yes	yes
	Bony bream	*Nematalosa erebi*	yes	yes
	Freshwater catfish	*Tandanus tandanus*	yes	no
	Hyrtl's tandan	*Neosilurus hyrtlii*	yes	yes
	Rendahl's tandan	*Porochilus rendahli*	yes	no
	Blue catfish	*Neoarius graeffii*	yes	yes
	Golden perch	*Macquaria ambigua oriens*	no	yes
	Leathery grunter	*Scortum hillii*	yes	yes
	Spangled perch	*Leiopotherapon unicolor*	yes	yes
	Barred grunter	*Amniataba percoides*	yes	yes
	Sleepy cod	*Oxyeleotris lineolatus*	yes	yes
<100 mm	Fly-specked hardyhead	*Craterocephalus stercusmuscarum*	yes	yes
	Eastern rainbowfish	*Melanotaenia splendida splendida*	yes	yes
	Olive perchlet	*Ambassis agassizii*	yes	yes
	Fly-specked hardyhead	*Craterocephalus stercusmuscarum*	yes	yes
	Purple-spotted gudgeon	Mogurnda adspersa	yes	yes
	Carp gudgeon species	*Hypseleotris* spp.	yes	yes
	Flat-headed gudgeon	*Phylipnodon grandiceps*	yes	yes
	Dwarf Flat-headed gudgeon	*Phylipnodon macrostomus*	yes	no
	Mouth almighty	*Glossamia aprion*	no	yes
	Mosquitofish*	*Gambusia holbrooki*	yes	yes
	Platy*	*Xiphophorus maculatus*	yes	yes

Table 4: Fishes (excluding larval stages) recorded either entrained in the Weemah or Selma diversion channels or in the adjacent Fairbairn Dam reference site. Larger species are broken into two size classes, ≤100mm or >100 mm. All other species were <100 mm. Some size classes were not recorded either in the river or entrained through the pumps (e.g., barramundi ≤100 mm) during this project. Those size classes have been excluded from the table.

Size class	Common name	Species name	Entrained in diversion channel	Captured in impoundment
>100 mm	Long-finned eel	*Anguilla reinhardtii*	no	yes
	Bony bream	*Nematalosa erebi*	yes	yes
	Hyrtl's tandan	*Neosilurus hyrtlii*	no	yes
	Rendahl's tandan	*Porochilus rendahli*	yes	no
	Barramundi	*Lates calcarifer*	no	yes
	Golden perch	*Macquaria ambigua oriens*	yes	yes
	Murray cod	*Maccullochella peelii*	no	yes
	Leathery grunter	*Scortum hillii*	yes	yes
	Spangled perch	*Leiopotherapon unicolor*	yes	yes
	Barred grunter	*Amniataba percoides*	yes	yes
	Sleepy cod	*Oxyeleotris lineolatus*	Yes	yes
≤100 mm	Bony bream	*Nematalosa erebi*	yes	yes
	Hyrtl's tandan	*Neosilurus hyrtlii*	no	yes
	Golden perch	*Macquaria ambigua oriens*	yes	yes
	Leathery grunter	*Scortum hillii*	yes	yes
	Spangled perch	*Leiopotherapon unicolor*	yes	yes
	Barred grunter	*Amniataba percoides*	yes	yes
	Sleepy cod	*Oxyeleotris lineolatus*	yes	yes
<100 mm	Fly-specked hardyhead	*Craterocephalus stercusmuscarum*	yes	yes
	Eastern rainbowfish	*Melanotaenia splendida splendida*	yes	yes
	Olive perchlet	*Ambassis agassizii*	yes	yes
	Carp gudgeon species	*Hypseleotris* spp.	yes	yes
	Flat-headed gudgeon	*Phylipnodon grandiceps*	yes	yes
	Dwarf Flat-headed gudgeon	*Phylipnodon macrostomus*	yes	yes

Table 5: Larval fish and fish eggs recorded in river reference sites and/or entrained at irrigation pump outlets. *Terapon perches (Terapontidae) includes spangled perch, barred grunter and leathery grunter. Their early larval stages are difficult to separate without the aid of genetic methods.

Common name	Species name	Entrained through pump	Captured in River
Bony bream	*Nematalosa erebi*	yes	yes
Fly-specked hardyhead	*Craterocephalus stercusmuscarum*	no	yes
Eastern rainbowfish	*Melanotaenia splendida splendida*	no	yes
Golden perch	*Macquaria ambigua oriens*	yes	yes
Terapon perches*	Terapontidae	yes	yes
Carp gudgeon species	*Hypseleotris* spp.	yes	yes
Flat-headed gudgeon	*Phylipnodon grandiceps*	yes	no
Sleepy cod	*Oxyeleotris lineolatus*	no	yes
Unidentified larvae		yes	yes
Unidentified yolk sac larvae		yes	no
Unidentified fish eggs		yes	yes

Table 6: Larval fish and fish eggs recorded in the Fairbairn Dam reference site and/or entrained in the Weemah or Selma irrigation diversion channels.

Common name	Species name	Entrained through pump	Captured in Impoundment
Bony bream	*Nematalosa erebi*	yes	yes
Carp gudgeon species	*Hypseleotris* spp.	no	yes
Flat-headed gudgeon	*Phylipnodon grandiceps*	yes	no
Sleepy cod	*Oxyeleotris lineolatus*	yes	yes

Range of entrainment rates

Diversion channels

Pumping and outlet flow rates sampled in the diversion channels ranged from 75 ML to 410 ML per day. Entrainment rates of adult and juvenile fish varied between sampling occasions, flows and infrastructure types.

Entrainment rates in the pumped Selma diversion channel ranged from 56 fish per 100 min sampled to 1007 fish per 100 min sampled. On a per unit volume basis, catches ranged from 7.114 fish per ML to 35.37 fish/ML, with a mean catch of 13.326 fish per ML. Based on prevailing pumping rates, extrapolated entrainment rates per day ranged from 806 to 14,501 fish per day. Larval entrainment rates ranged from 0 to 128.9 larvae per ML. Based on pumping rates the highest extrapolated daily entrainment of larvae recorded was 52,849 larvae per day (range 0 to 52,849).

Entrainment rates in the gravity fed Weemah diversion channel ranged from 237 fish per 100 min sampled to 4,351 fish per 100 min sampled. On a per unit volume basis catch rates ranged from 27.304 fish per ML to 626.950 fish per ML, with a mean catch of 143.29 fish per ML. Based on diversion rates, extrapolated entrainment rates ranged from 3,413 to 62,695 fish per day. The maximum entrainment rate of larval fish recorded was 38.68 larvae per ML (range 0 to 38.68 larva per ML). Based on prevailing diversion rates, the highest extrapolated daily entrainment rate for fish larvae was 4,641 larvae per day (range 0 to 4,641 larvae per day).

Riverine pumps

Sampled riverine pumps varied considerably in size, with pumping rates ranging from 14 ML per day to 164 ML per day. Across all riverine pumps, catch rates ranged from 0 fish per 100 min sampled to 793 fish per 100 min sampled. On a per unit volume basis, catch rates ranged from 0 fish per ML to 137.233 fish per ML, with a mean of 22.658 fish per ML. Extrapolating catch per unit volume figures showed potential daily fish entrainment rates through riverine pumps ranging from 0 to 5,794 fish per day. Entrainment rates of larval fish through riverine pumps ranged from 0 per ML to 1,028 per ML. Based on daily pumping rates, extrapolated daily entrainment rates for fish larvae ranged from 0 to 102,790 fish larvae per day. If fish eggs entrained are added to the totals, then combined fish egg and fish larval entrainment rates ranged from 0 per ML to 2,056 per ML. More detailed breakdowns of entrainment rates by species are provided in the GLM results below.

Generalised linear model outputs

This section focuses on the predicted (adjusted) means generated by the GLMs and the role of key factors and covariates in the models. Tabulated outputs of the various GLM models are in the Appendix.

Adult and juvenile fish entrainment in impoundment diversion channels

Intake type (pumped or gravity fed)

For most groups or size classes of fish analysed, intake type was a factor that partially explained variation in entrainment rates. Several species and size classes of fish exhibited significant differences in entrainment rates per 100 min between the Selma (pumped) Diversion Channel and the Weemah (gravity fed) Diversion channel, with entrainment rates for most species being greater in Weemah Channel (see Figure 7).

Instances where mean entrainment rates were higher in the gravity fed Weemah Channel included Rendahl's tandan (p<0.05), the combined catch of all fish ≤100 mm (p=0.016), the combined catch of all fish (p=0.017), carp gudgeon spp. (p=0.008), bony bream ≤100 mm (p=0.006), barred grunter >100 mm (p< 0.05). In the case of barred grunter <100 mm, significantly more fish were captured per 100 min in the Selma Channel (p=0.002). For most other species or size classes no significant differences between the pumped and gravity fed channel were detected.

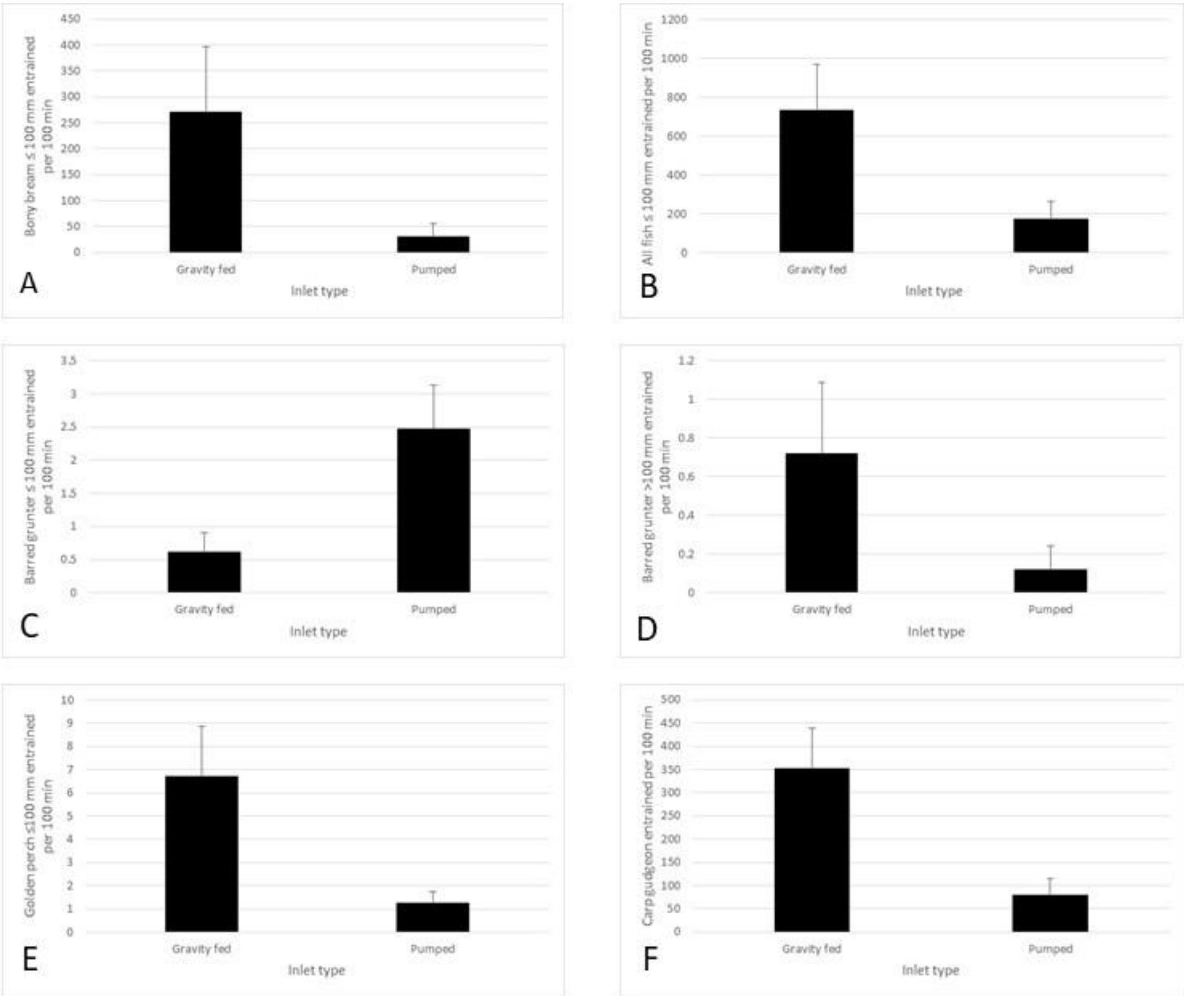

Figure 7: Examples of significantly different (P<0.05) entrainment rates per 100 min between pumped and gravity fed diversion channels leading from Fairbairn Dam. Entrainment rates are shown for (A) bony bream ≤100 mm, (B) All fish ≤100 mm, (C) barred grunter ≤100 mm, (D) barred grunter >100 mm, (E) golden perch ≤100 mm, and (F) carp gudgeon spp. Values shown are adjusted means. Error bars show one standard error of the mean. Note vertical scales are different on each graph, and in most cases, values are significantly higher in the gravity fed channel.

Pump rate

The influence of pump or diversion flow rate on entrainment rates showed no consistent patterns. A high spike in catch rates for several species and size classes in February 2022, when inlet flow rates were 100 ML per day, meant for most species there was no discernible pattern between pump rate and entrainment rate. Therefore, pump or inlet flow rate was dropped as a factor from most models, except for golden perch ≤100 mm. For this species, a significant correlation (p<0.001) existed between intake or pump flow rate and entrainment rate (Figure 8).

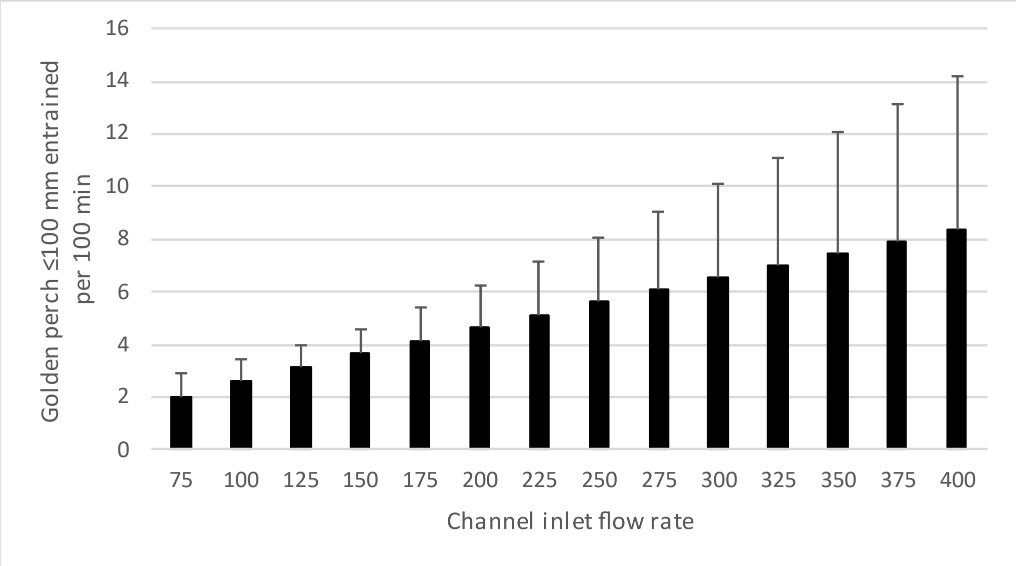

Figure 8: Adjusted mean entrainment rates by channel inlet flow rate for golden perch ≤100 mm. Error bars show one standard error of the mean. Means were estimated by holding other factors in the model constant.

Temperature, dam catch rates and dam capacity (per cent full)

As noted above, the pump or inlet flow rate did not explain entrainment rates for most fish in the impoundment diversion channels. For several species or groups of fish, temperature and catch rates in the impoundment (an indicator of fish abundance in the dam) or a combination of both parameters explained much of the variation. Dam capacity (per cent full) also explained some variation in entrainment rates, but this factor could not be run with the background catch rates in the impoundment due to over-parameterisation of the models. Catch rates and dam capacity had some correlation for some species or groups of fish.

Species and groups of fish where temperature was shown to have a significant positive effect included the combined catch of all fish ≤100 mm ($p=0.003$), combined catch of all fish of all sizes ($p=0.003$), carp gudgeon spp. ($p=0.004$), flathead gudgeon ($p=0.011$) and bony bream ≤100 mm ($p<0.001$) (see Figure 9). For some other species the temperature effect was not statistically significant, but there was still a positive trend for increasing entrainment rates with increasing temperature. This included bony bream >100 mm. Other species such as eastern rainbowfish and barred grunter >100 mm had a no relationship between entrainment rates and temperature, whereas golden perch ≤100 mm had a non-significant ($p=0.061$) negative relationship between the two variables.

Species and groups of fish where the impoundment catch rate covariate had a significant ($p<0.05$) positive influence on entrainment rates included bony bream ≤100 mm, flathead gudgeon ≤100 mm, barred grunter ≤100 mm, barred grunter >100 mm, and golden perch ≤100 mm. For other species and size classes abundant enough for the covariate impoundment catch rate to be included in the model, there was no significant effect, but for most the trend was positive.

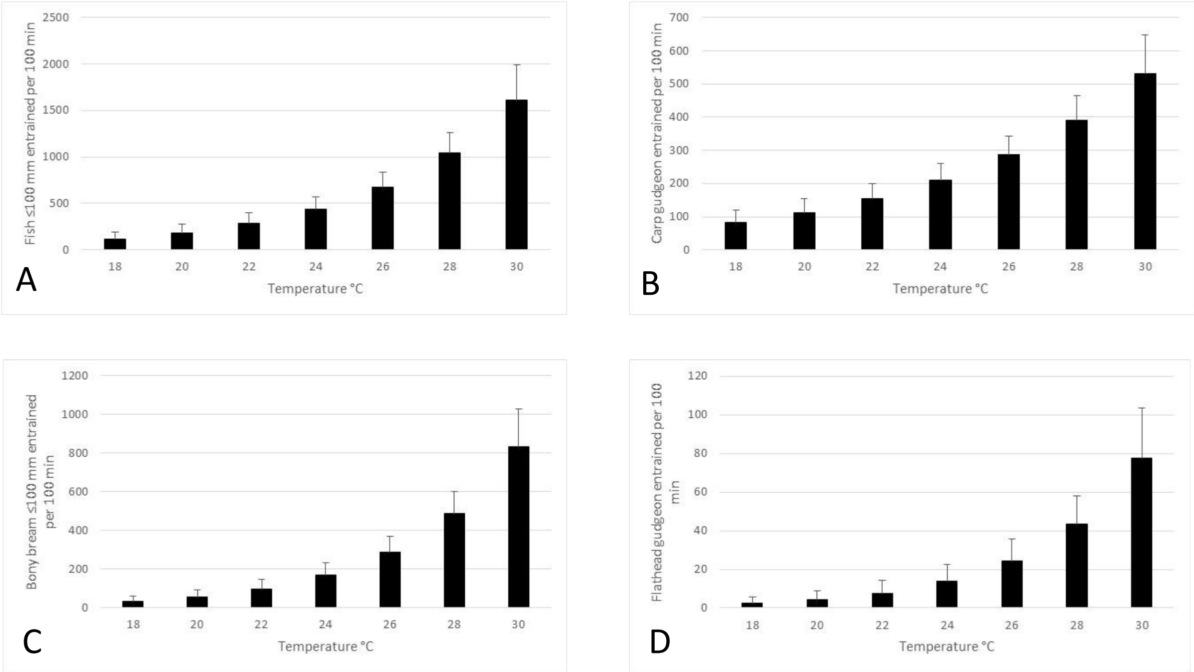

Figure 9: Relationship between entrainment rates per 100 min and temperature in diversion channels leading from Fairbairn Dam. Entrainment rates are shown for (A) All fish ≤100 mm, (B) carp gudgeon spp., (C) bony bream ≤100 mm, and (D) flathead gudgeon. Values shown are adjusted means. Error bars show one standard error of the mean. Note vertical scales are different on each graph.

Dam capacity was found to have a significant ($p<0.05$) positive effect on entrainment rates of flathead gudgeon (Figure 10), but there was a significant ($p<0.05$) negative relationship between dam capacity and entrainment rate for golden perch ≤100 mm, barred grunter ≤100 mm (Figure 10) and barred grunter >100 mm. The relationship between dam capacity and entrainment rates was also negative (but not statistically significant) for bony bream ≤100 mm and carp gudgeon spp. The relationship between dam capacity and entrainment rates for eastern rainbowfish was positive but not statistically significant. Most other relationships between entrainment rates and dam capacity were non-significant with essentially no trends.

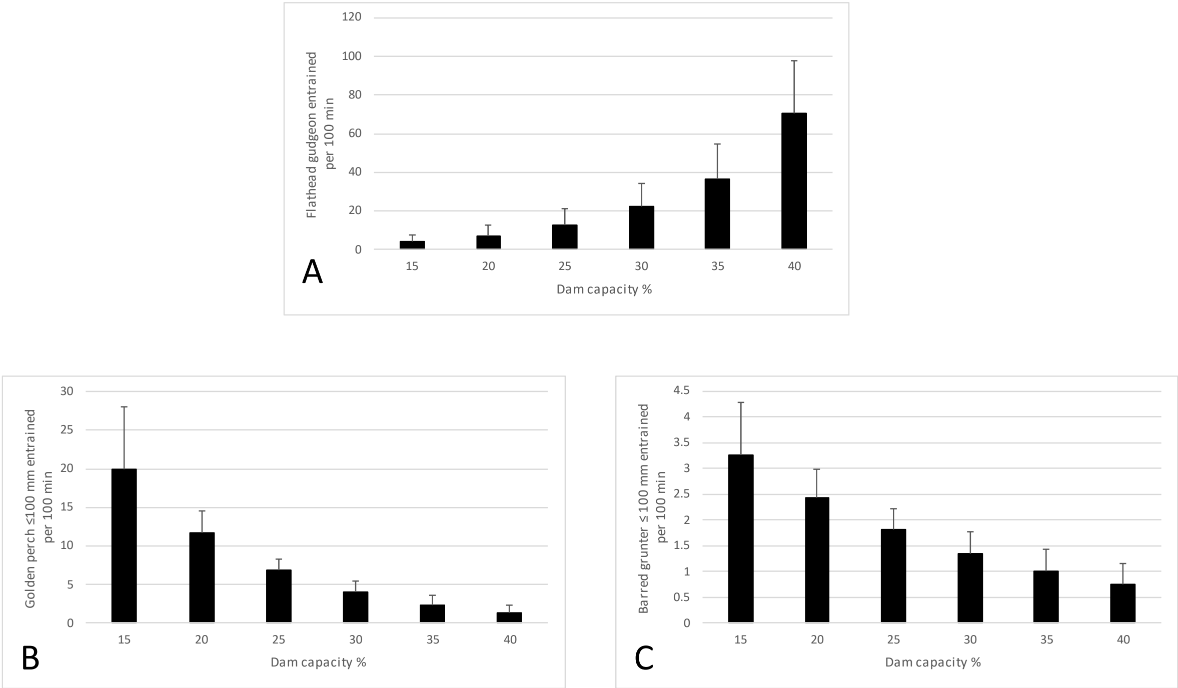

Figure 10: Examples of significant relationships between dam capacity and entrainment rates. (A) flathead gudgeon, (B) golden perch ≤100 mm, and (C) barred grunter ≤100 mm. Values are adjusted means. Error bars show one standard error of the mean. Note vertical scales vary between graphs.

Larval fish entrainment in impoundment diversion channels

Larval catches were irregular and infrequent for most species in Fairbairn Dam and impoundment diversion channels. Most species of larvae were detected too infrequently to develop reliable models. Results for combined catches of all larvae are presented below.

Inlet flow rate was found to be significant ($p<0.001$) with a trend for increasing entrainment rates per day with increasing flow rates (Figure 11). There was no significant difference between the gravity fed Weemah Channel and the pumped diversion Selma Channel ($p=0.357$) but the adjusted mean entrainment rate in the gravity fed Weemah Channel was triple that of the pumped Selma Channel. Variability in catch rates was high, leading to large error bars (Figure 12). Entrained larval numbers were higher when the dam capacity was higher ($p=0.004$) (Figure 13). The catch rate of larvae in the dam reference site (covariate) also had a significant positive effect on larval entrainment rates ($p<0.001$).

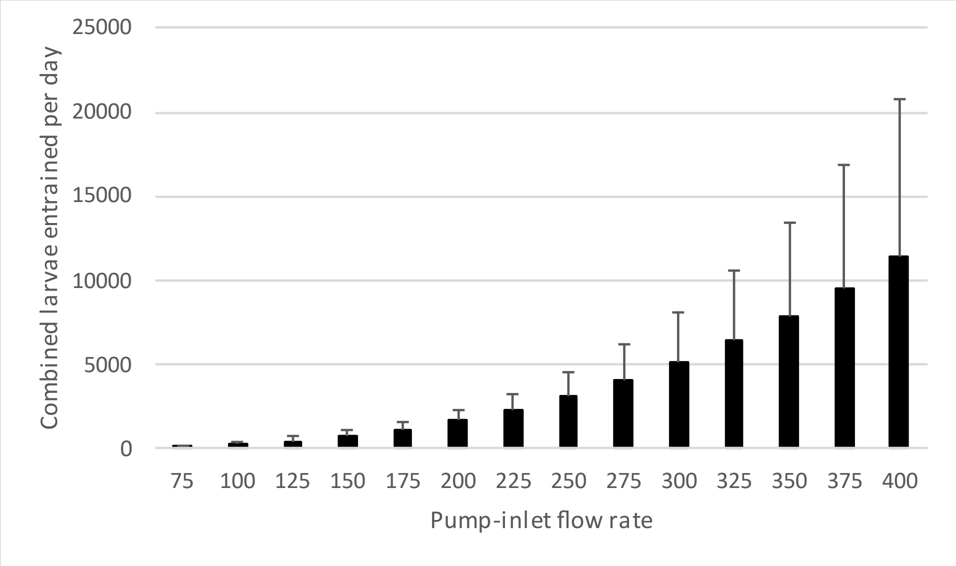

Figure 11: The relationship between impoundment diversion channel pump-inlet flow rate and number of larvae entrained per day. Values are adjusted means. Error bars show one standard error of the mean.

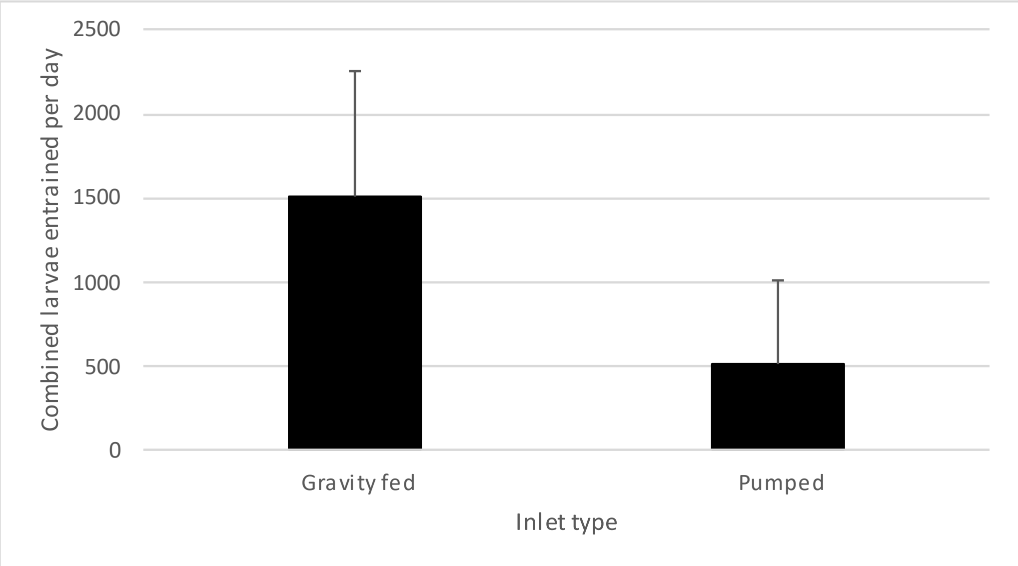

Figure 12: Larval entrainment rates (larvae per day) for the different diversion channel offtake types. Values shown are adjusted means. Error bars show one standard error of the mean.

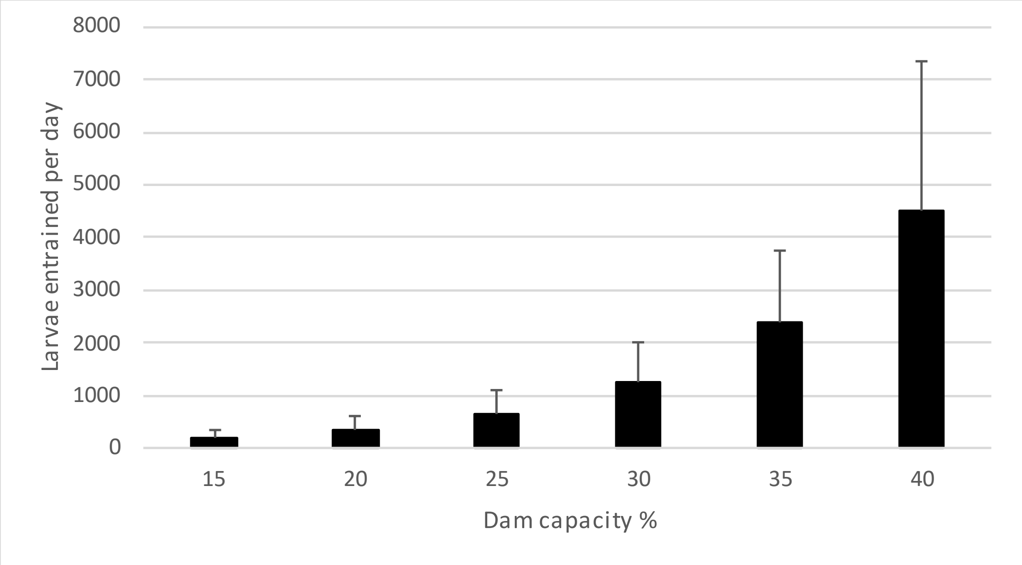

Figure 13: The relationship between Dam capacity (%) and the number of larvae entrained per day. Values are adjusted means. Error bars show one standard error of the mean.

Adult and juvenile fish entrainment through riverine pumps

To analyse fish entrainment per 100 min through riverine pumps, the generalised linear models (GLM) used a Poisson distribution for most species. However, for some species, where appropriate, a normal distribution model was used. The covariate riverine catch was retained in models if positive in effect, and pump rate was retained throughout as natural log (ln) transformed data. Intake location and depth, and flow type were retained in all models as factors. Season (warm or cool) was also retained in models for some of the more commonly entrained species and size classes (see original report by *Hutchison et al*. 2022). Some species and size classes entrained (see Table 3) were detected too infrequently to be evaluated by any GLMs at all. For some species with reduced frequencies of capture some simplified GLM models without pump rate were run to see if any trends in the effect of flow type, intake position and depth, and season could be detected.

Riverine catch rates had a positive relationship to entrainment rates for blue catfish ≤100 mm, eastern rainbowfish, olive perchlet, spangled perch and bony bream ≤100 mm, but it was only significant for spangled perch >100mm ($P<0.001$) and bony bream ≤100 mm ($P=0.01$).

GLMs for fish entrainment per unit volume pumped were also run. Entrainment rates per megalitre generally showed flatter trends than entrainment rates per 100 min, but the overall patterns for the effects of the different variables in these models were similar to those for catches per 100 min. However, the focus is on fish entrained per 100 min, as this was found to be more useful for detecting trends. The per unit volume entrainment models are not presented in this results section, except for modelled entrainment rate per megalitre across all fish and all fish >100 mm. GLM models used to produce the outputs in this results section can be found in the Appendix.

Pump rate

Pump rate had a significant ($P<0.025$) positive relationship with the number of species of native fish entrained per 100 minutes. For most species, the general trend was for increasing numbers of fish to be entrained per 100 minutes as pump rate increased. Although this trend was consistently positive it wasn't significant for most species, probably due to variability in catch rates between flow events. Pump rate had a significant ($P<0.001$) positive impact on entrainment rates for eastern rainbowfish and it appears that at pump rates less than 80 ML/day entrainment of this species is low. Some species, such as spangled perch and carp gudgeons, exhibited little change in entrainment rates as pump rates increased. For carp gudgeons the trend was weakly negative.

Plots of adjusted mean entrainment rates for the number of native fish species entrained, and adjusted mean entrainment rates for various species and size classes of fish are shown in Figure 14. As noted above, entrainment rates per unit volume pumped were just weakly positive as pump rate increased, although for fish >100 mm in length the positive trend was more evident. Figure 15 shows the examples of the combined adjusted mean entrainment rate of all fish and for all fish >100 mm.

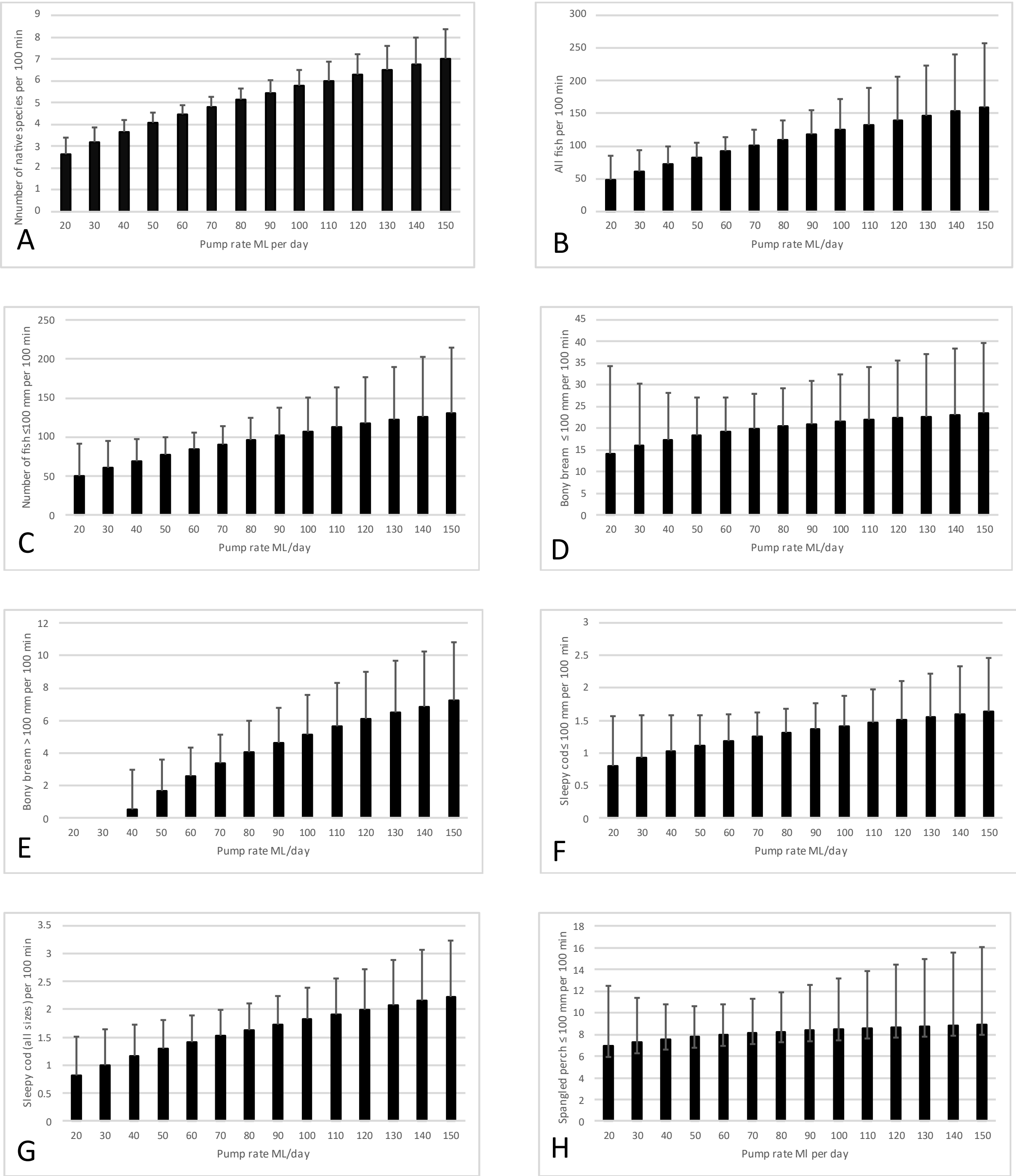

Figure 14: Adjusted mean entrainment rates per 100 min for different pump rates (ML per day). (A) Number of species entrained per 100 min, (B) all fish entrained per 100 min, (C) All fish ≤100 mm entrained per 100 min, (D) Bony bream fish ≤100 mm entrained per 100 min (E) Bony Bream >100 mm entrained per 100 min, (F) sleepy cod ≤100 mm entrained per 100 min (G) Sleepy cod all size entrained per 100 min, (H) Spangled perch ≤100 mm entrained per 100 min. Error bars show one standard error of the mean. Note the vertical axis scales are different in each graph. Other factors in the models were held constant for estimation of adjusted means.

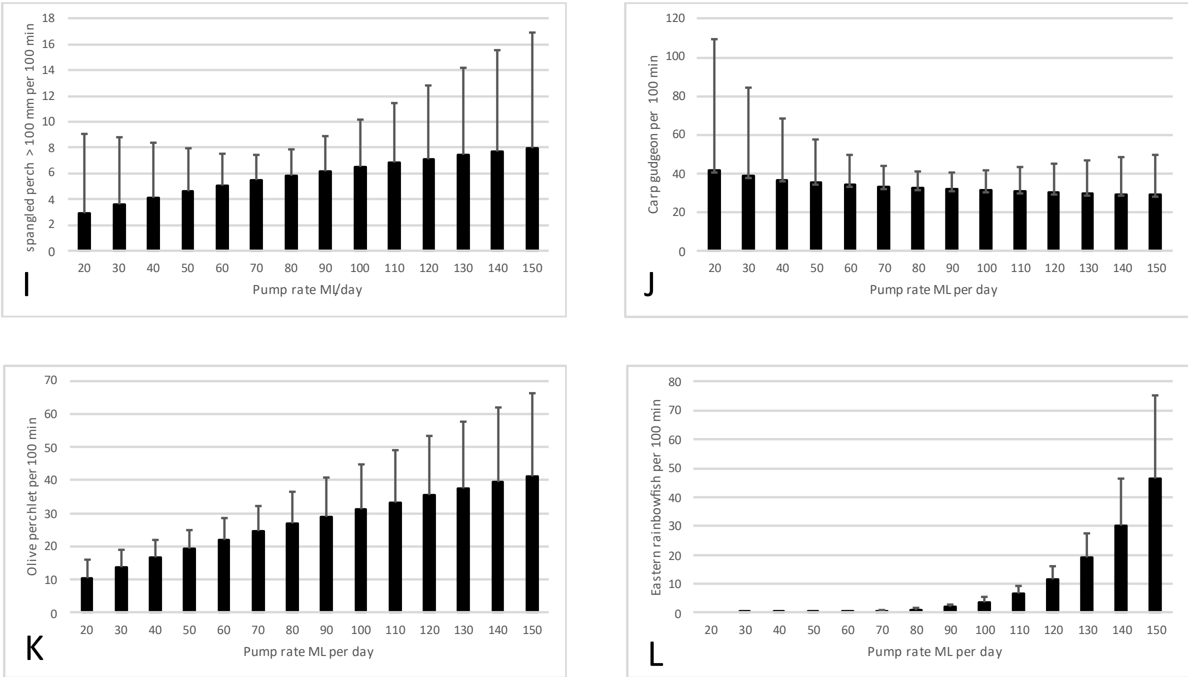

Figure 14 continued: Adjusted mean entrainment rates per 100 min for different pump rates ML per day. (I) Spangled perch >100 mm entrained per 100 min, (J) Carp gudgeon entrained per 100 min, (K) Olive perchlet entrained per 100 min, (L) Eastern rainbowfish entrained per 100 min. Error bars show one standard error of the mean. Note the vertical axis scales are different in each graph. Other factors in the models were held constant for estimation of adjusted means.

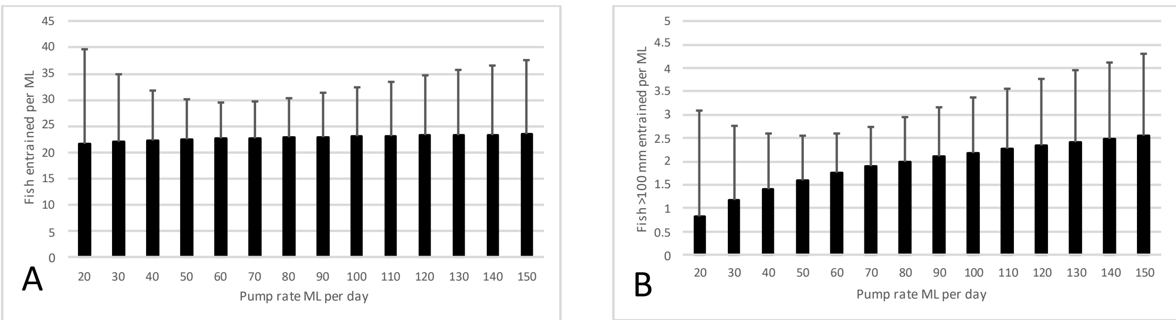

Figure 15: Adjusted mean entrainment rates (fish per ML) by pump rate (ML per day). (A) All fish, (B) All fish >100 mm. Error bars show one standard error of the mean. Other factors in the model were held constant for estimation of adjusted means.

Flow type

There was a general trend across most species and size classes of fish for adjusted mean entrainment rates per 100 minutes to have higher values during natural within bank flows than for allocated (supplemental) within bank flows and natural overbank flows. Entrainment rates were generally lowest on natural overbank flows (flood events). Flow type wasn't always statistically significant, but it was significant for some species and size classes. The number of native species of fish entrained was also significantly higher on natural within bank flow events (P=0.004).

Flow type was significant when considering all fish entrained (P=0.043). The adjusted mean entrainment rate for all fish during natural within bank flows was approximately double that of the adjusted mean entrainment rates during allocated (or supplemental) flow events and nearly eight times the adjusted mean entrainment rate of fish during overbank flow events. Flow type was also significant for spangled perch >100 mm (P<0.001) and blue catfish (P<0.001), with entrainment being most prevalent on natural within bank flows.

There were two species (olive perchlet and eastern rainbowfish) where entrainment rates tended to be higher on allocated flows, but not statistically significant. In the case of eastern rainbowfish, the adjusted mean entrainment rate was less than 0.5 fish per 100 minutes across all flow types, so the impact was relatively low. Note, other parameters in the model such as pump rate and inlet type were held constant to estimate the adjusted means for the different flow types.

The adjusted mean entrainment rates per 100 minutes for the number of native species entrained and for several different species and size classes are presented in Figure 16.

Inlet location and depth

Inlet location and depth was a significant factor in several of the GLM models. For example it was significant for all species (combined, $P < 0.05$), spangled perch >100 mm ($P < 0.001$), or carp gudgeon spp. ($P=0.005$), eastern rainbowfish ($P=0.002$), barred grunter ≤100 mm ($P=0.01$), blue catfish ≤100 mm ($P=0.039$) and in post-hoc pairwise comparison tests for bony bream >100 mm ($P<0.05$). The combined species data also includes the rarer species for which it was not possible to run a GLM. Across most species, even for those where intake location and depth was not statistically significant, shallow bankside intakes tended to have the lowest or one of the lowest two mean entrainment rates (Figure 17). Across all species combined, including when split by size class, the shallow bankside intakes also showed this trend. There were some species and size classes within species where shallow bankside intakes tended to have higher entrainment rates than other inlet and depth combinations. This included eastern rainbowfish (which had very low adjusted mean entrainment rates across all intake types), sleepy cod ≤100 mm and blue catfish ≤100 mm. With regard to the number of species entrained per 100 min, shallow bankside intakes also tended to entrain the least number of species (Figure 17).

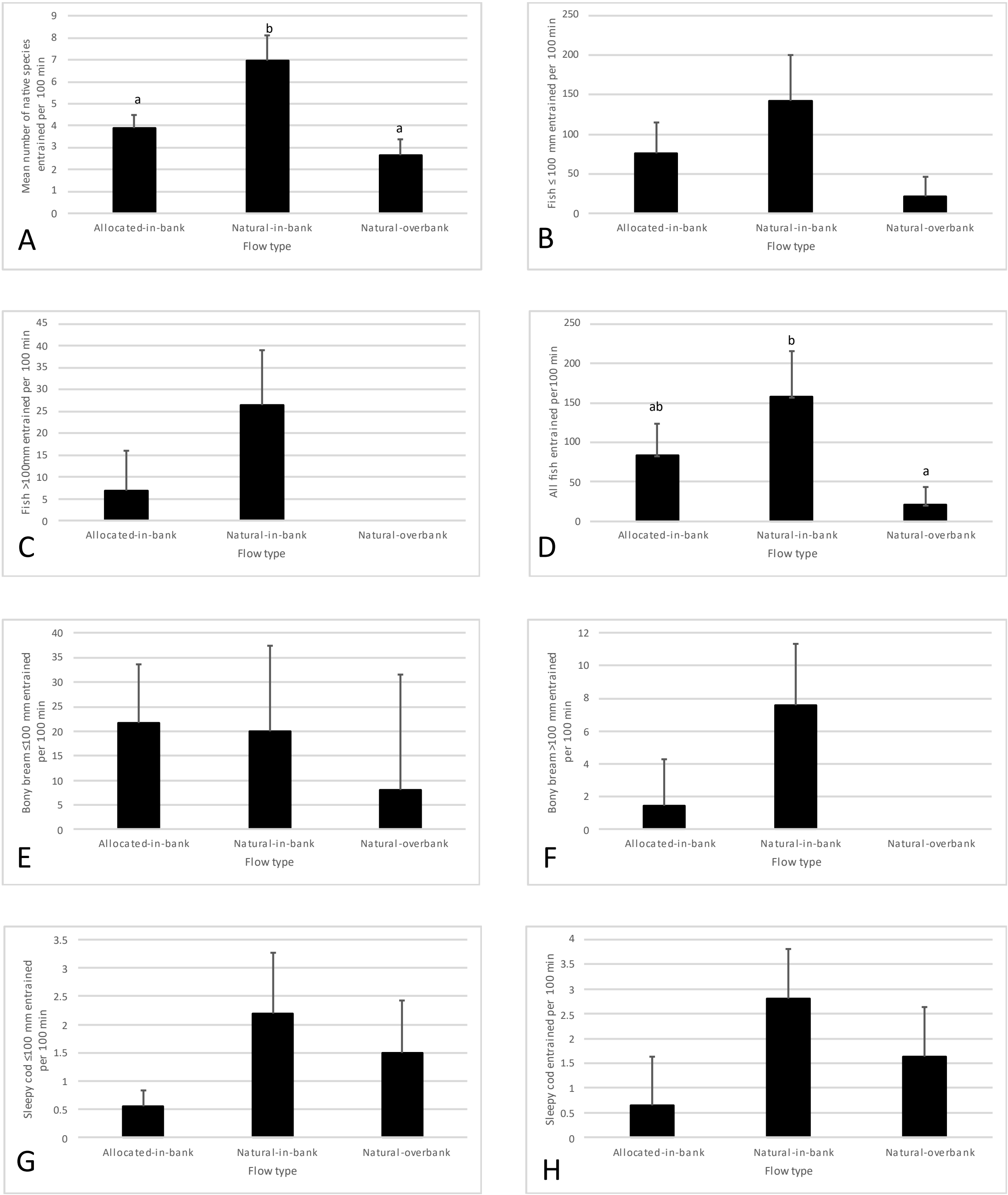

Figure 16: Adjusted mean entrainment rates per 100 min for different flow types across different groups of species and size classes. In each graph, flow types not sharing the same letter are significantly different (P<0.05) as estimated by post-hoc pairwise testing with a Fisher's protected least significant difference test. Other parameters in the models have been held constant to estimate the adjusted means. Error bars show one standard error of the mean. Vertical scales are different for each graph. (A) Number of native species entrained per 100 min, (B) Fish ≤100 mm entrained per 100 min, (C) Fish >100 mm entrained per 100 min, (D) all fish entrained per 100 min, (E) Bony bream ≤ 100 mm entrained per 100 min,(F) bony bream >100 mm entrained per 100 min, (G) sleepy cod ≤ 100 mm entrained per 100 min, (H) all sleepy cod entrained per 100 min

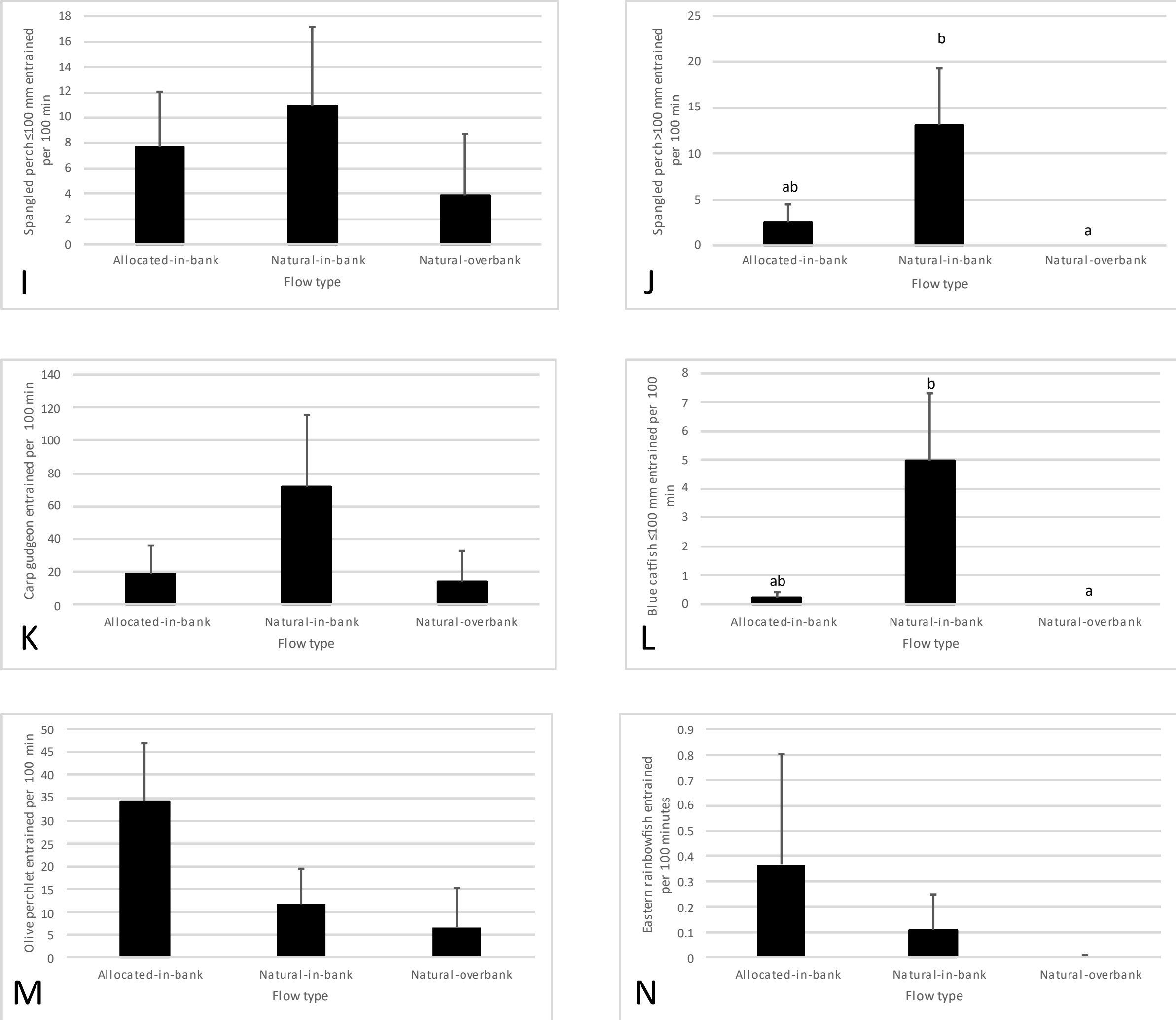

Figure 16 continued: Adjusted mean entrainment rates per 100 min for different flow types across different groups of species and size classes. In each graph, flow types not sharing the same letter are significantly different ($P<0.05$) as estimated by post-hoc pairwise testing with a Fisher's protected least significant difference test. Other parameters in the models have been held constant to estimate the adjusted means. Error bars show one standard error of the mean. Vertical scales are different for each graph. (I) Spangled perch ≤100 mm entrained per 100 min, (J) Spangled perch >100 mm entrained per 100 min, (K) Carp gudgeon entrained per 100 min, (L) Blue catfish ≤ 100 mm entrained per 100 min, (M) Olive perchlet entrained per 100 min, (N) eastern rainbowfish entrained per 100 min

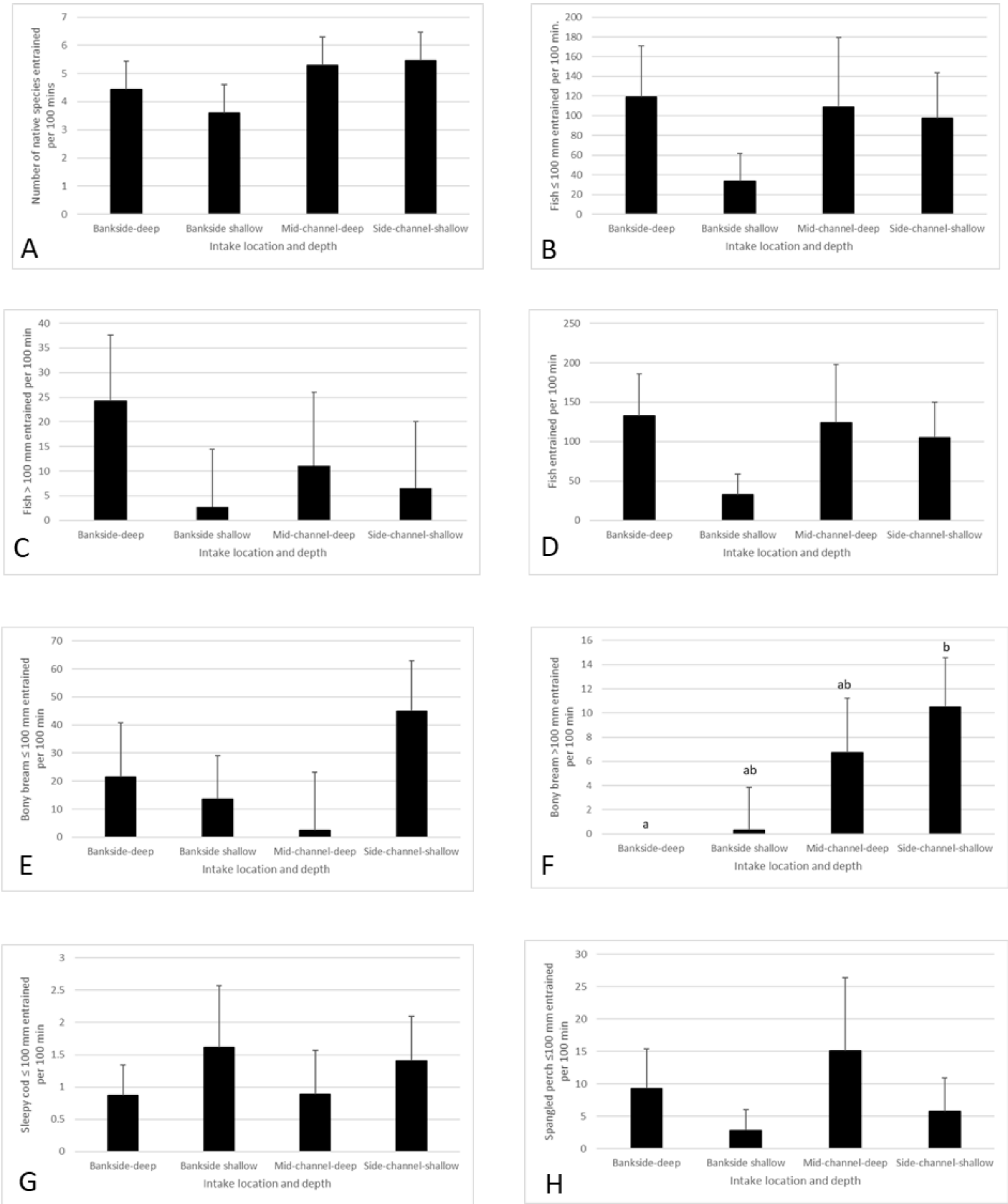

Figure 17: Adjusted mean entrainment rates per 100 min for different intake locations and depths across different groups of fish species and size classes. In a graph, intake types not sharing the same letter are significantly different (P<0.05) as estimated by post-hoc pairwise testing with a Fisher's protected least significant difference test. However, intake position and depth was statistically significant in numerous GLM models (see results text). Other parameters in the models have been held constant to estimate the adjusted means. Error bars show one standard error of the mean. Note, vertical scales are different for each graph. (A) Number of native species entrained per 100 min, (B) Fish ≤100 mm entrained per 100 min, (C) Fish >100 mm entrained per 100 min, (D) all fish entrained per 100 min, (E) Bony bream ≤ 100 mm entrained per 100 min,(F) bony bream >100 mm entrained per 100 min, (G) sleepy cod ≤ 100 mm entrained per 100 min, (H) Spangled perch ≤100 mm entrained per 100 min.

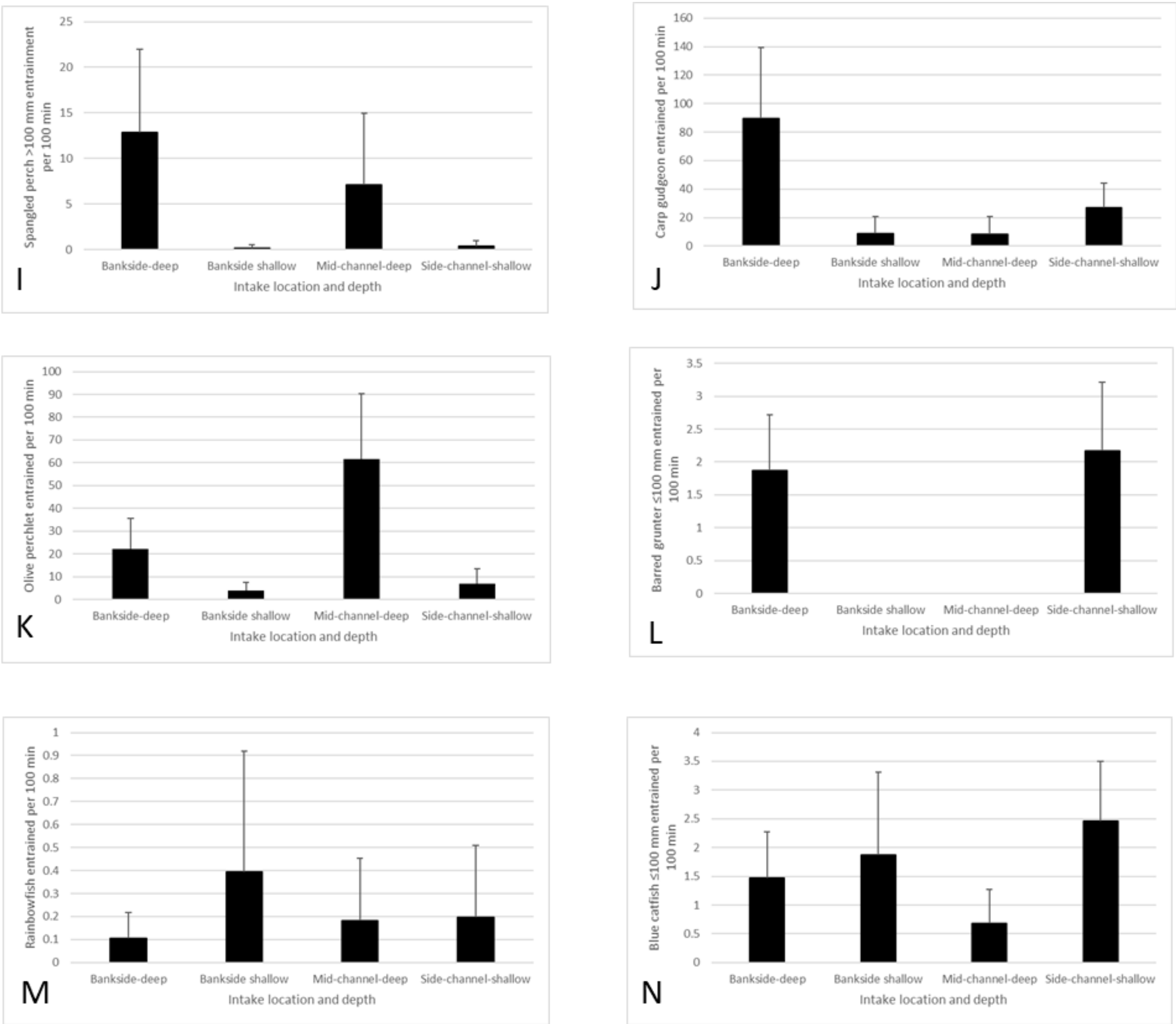

Figure 17 continued: Adjusted mean entrainment rates per 100 min for different intake locations and depths across different groups of species and size classes. Intake position and depth was statistically significant in numerous GLM models (see results text). Other parameters in the models have been held constant to estimate the adjusted means. Error bars show one standard error of the mean. Vertical scales are different for each graph. (I) Spangled perch >100 mm entrained per 100 min, (J) Carp gudgeon spp entrained per 100 min, (K) Olive perchlet entrained per 100 min, (L) Barred grunter ≤100 mm entrained per 100 min, (M) Eastern rainbowfish entrained per 100 min, (N) Blue catfish ≤100 mm entrained per 100 min.

Entrainment of larval fish and eggs through riverine pumps

Entrainment of eggs and larvae were analysed using projected entrainment rates per day based on the number of larvae entrained per megalitre. The models included the factors ln pump rate, flow type, and inlet location and depth. Temperature in lieu of season was trialled but was not significant in any model, so was dropped. Catches of larvae in the river were run initially as a covariate in the models, but the covariate was never significant and was partly aliased with flow type, so was dropped from the models. The final models can be found in the Appendix.

Pump rate

Pump rate was not significant, but there was generally a slight positive trend for increasing numbers of larvae to be entrained per unit time as pump rates increased. Figure 18 shows the trend across all larvae combined. No positive trend was detected for fish eggs with increasing pump size, so pump size was excluded from the model for fish eggs.

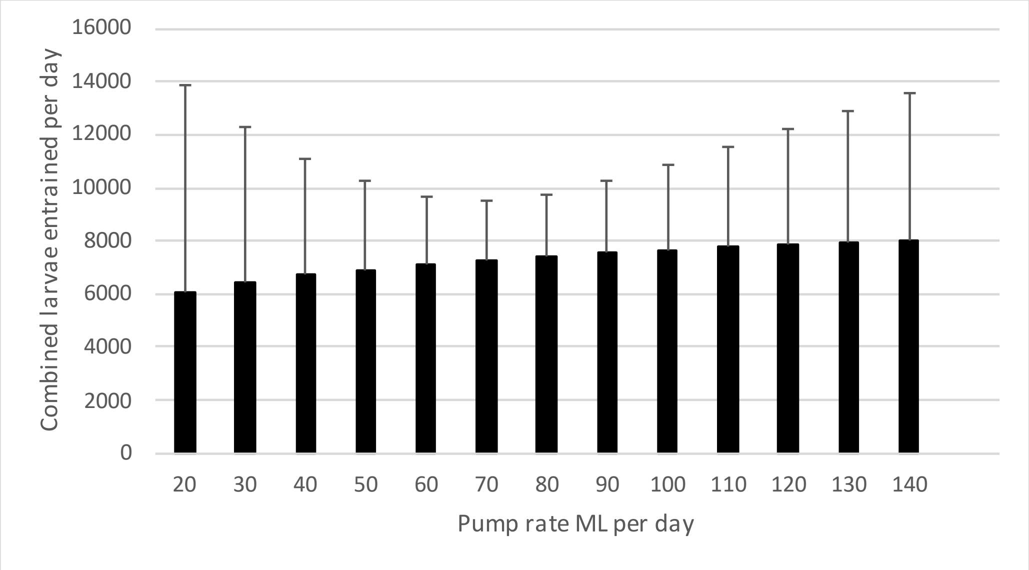

Figure 18: Adjusted mean entrainment rates of all larvae combined (larvae per day) by pump (rate ML per day). Other factors in the model were held constant to estimate the adjusted means. Error bars show one standard error of the mean.

Flow type

Entrainment of fish larvae tended to be greatest on natural within bank flows and least on natural overbank flows (Figure19). For species of larvae and larvae combinations for which there were enough data points to run the GLM, flow type was always significant (p<0.05). Golden perch larvae were only ever entrained on within bank natural flows (P<0.001). In the case of carp gudgeon larvae, entrainment was more prevalent on within bank allocated flows and this was statistically significant (P=0.011). Fish egg entrainment was most likely to occur on natural flow events, especially during within-bank natural flows. Eggs tended to be >2 mm in diameter and pelagic. Eggs were least likely to be recorded on allocated (supplemental) flow events (Figure19).

Intake position and depth

Intake position and depth showed similar patterns for entrainment rates to those for non-larval fishes (Figure 20). The bankside shallow intakes generally had the lowest or second lowest entrainment rates. This was statistically significant for golden perch larvae (P<0.05). Pelagic fish eggs showed a different pattern, with entrainment rates tending to be higher in bankside deep and bankside shallow intakes compared to the other intakes (P<0.05).

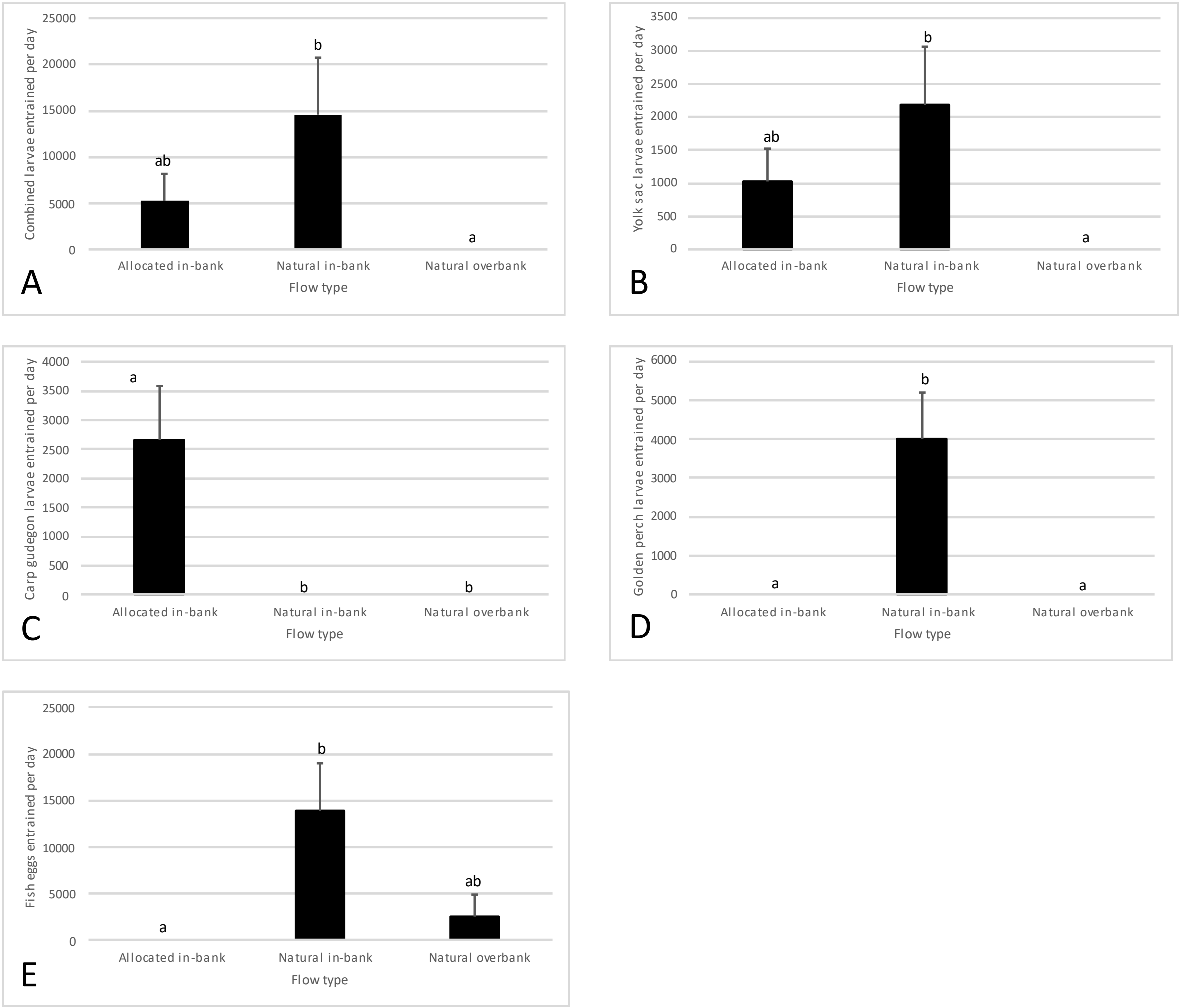

Figure 19: Adjusted daily mean entrainment rates of fish larvae and fish eggs for different flow types. Other parameters in the models have been held constant to estimate the adjusted means. Error bars show one standard error of the mean. Vertical scales are different for each graph. (A) All larvae combined, (B) unidentified yolk sac larvae, (C) Carp gudgeon larvae, (D) Golden perch larvae, (E) Fish eggs. In a graph, flow types not sharing the same letter are significantly different (P<0.05) as estimated by post-hoc pairwise testing with a Fisher's protected least significant difference test.

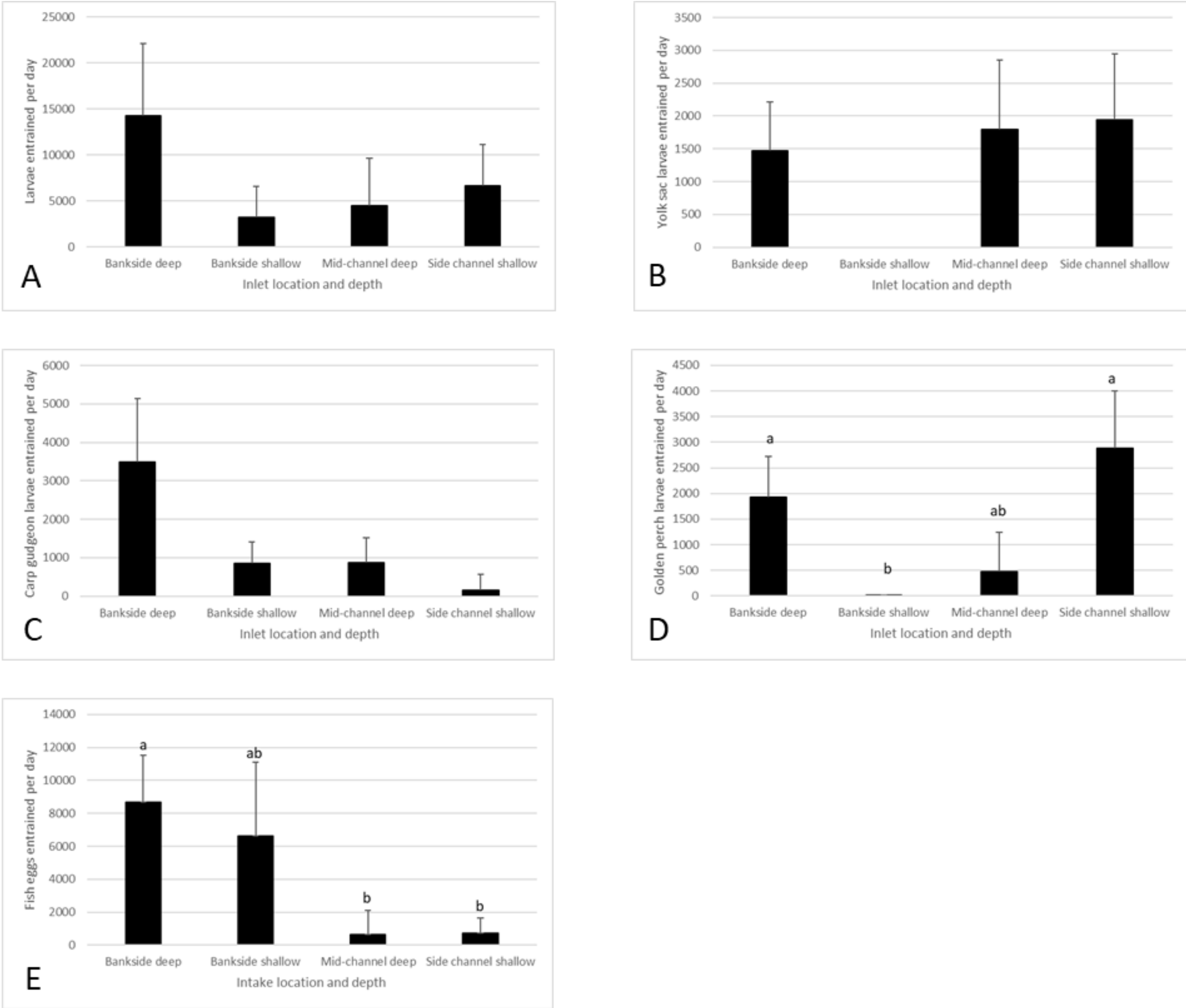

Figure 20: Adjusted mean entrainment rates of fish larvae and fish eggs per day for intake positions and depths. Other parameters in the models have been held constant to estimate the adjusted means. Error bars show one standard error of the mean. Vertical scales are different for each graph. (A) All larvae combined, (B) Unidentified yolk sac larvae, (C) Carp gudgeon larvae, (D) Golden perch larvae, (E) Fish eggs. In a graph, intake types not sharing the same letter are significantly different (P<0.05) as estimated by post-hoc pairwise testing with a Fisher's protected least significant difference test.

Susceptibility indices

Analyses of susceptibility of non-larval fish to entrainment through the diversion channels suggests that flathead gudgeon are the most susceptible species to entrainment from Fairbairn Dam, followed by carp gudgeon, bony bream ≤100 mm and golden perch ≤100 mm. Numerous lower ranked species and size classes were not significantly different to each other. Several species and size classes were detected or entrained too infrequently for statistical analyses. Rankings of all species and size classes by their mean susceptibility score are shown in Table 7. However, for those species caught too infrequently for statistical analyses, their position in the rankings needs to be treated with considerable caution, as it could change up or down with further detections.

Larval fish were found too infrequently in the diversion channels for any statistical comparisons to be made. Only bony bream larvae were sampled on at least five occasions in the channels. The mean susceptibility score for bony bream larvae was 6.397, for flathead gudgeon larvae it was 0.699, for sleepy cod larvae it was 0.340 and for carp gudgeon larvae it was 0. Carp gudgeon larvae were detected in the dam, but never in the channels when present in the dam. Without additional data, ranking these is pointless.

Table 7: Untransformed mean susceptibility to entrainment scores for fish species and size classes entrained in irrigation channels exiting Fairbairn Dam. Scores are ranked from least susceptible to most susceptible. Scores with N values less than 5 (greyed out) cannot be ranked with confidence. Rankings not sharing the same letter a significantly different (P<0.05) based on post hoc Fishers protected least significance difference test of log transformed scores.

Species	Size class	N	Mean susceptibility score	S.E.M	Significance (p<0.05)
Long-finned eel	>100 mm	2	**0**	0	
Hyrtl's tandan	≤ 100 mm	2	**0**	0	
Hyrtl's tandan	>100 mm	2	**0**	0	
Murray cod	>100 mm	4	**0**	0	
Barramundi	>100 mm	8	**0**	0	a
Sleepy cod	>100 mm	12	**0.00002**	0.00002	a
Spangled perch	≤100 mm	8	**0.0005**	0.0005	a
Sleepy cod	≤100 mm	12	**0.0007**	0.0004	a
Golden perch	>100 mm	12	**0.0011**	0.0011	a
Olive perchlet		4	**0.0020**	0.0020	
Eastern rainbowfish		12	**0.0052**	0.0027	a
Barred grunter	>100 mm	12	**0.0077**	0.0033	a
Fly specked hardyhead		12	**0.0079**	0.0047	a
Spangled perch	>100 mm	12	**0.0100**	0.0075	a
Bony bream	>100 mm	12	**0.0208**	0.0138	ab
Barred grunter	≤100 mm	10	**0.0213**	0.0073	ab
Leathery Grunter	>100 mm	8	**0.0212**	0.0212	ab
Leathery grunter	≤100 mm	7	**0.0517**	0.0407	abc
Dwarf Flat-headed gudgeon		2	**0.0575**	0.0575	
Golden perch	≤100 mm	12	**0.0728**	0.0315	bc
Bony bream	≤100 mm	12	**0.0812**	0.0466	bcd
Carp gudgeon spp		12	**0.1198**	0.0480	cd
Flat-headed gudgeon	≤100 mm	12	**0.1413**	0.0478	d
Rendahl's tandan	>100 mm	3	**0.2100**	0.0518	

For non-larval fish in the river, the most susceptible species to entrainment were olive perchlet and spangled perch (Table 8). All other species and size classes were not significantly different to each other or were recorded on too few occasions to be confident about their ranking. Larval fish and fish eggs in the river were mostly not significantly different to each other in susceptibility to entrainment or were encountered too infrequently to be confident of their susceptibility ranking. Unidentified larvae were significantly more vulnerable to entrainment than at least three other species (See Table 9).

Table 8: Untransformed mean susceptibility index scores, with standard errors of the mean (SEM) and frequency of encounters (N), for native fish and size classes at riverine pump or adjacent riverine sites. Scores are ranked from least susceptible to most susceptible. Scores with N values less than 5 (greyed out) cannot be ranked with confidence. Rankings not sharing the same letter are significantly different (P<0.05) based on post hoc Fishers protected least significance difference test of log transformed scores.

Species	Size class	N	Mean susceptibility score	S.E.M	Significance (p<0.05)
Long-finned eel	>100 mm	1	**0**	0	
Murray cod	>100 mm	2	**0**	0	
Freshwater longtom	>100 mm	3	**0**	0	
Freshwater catfish	>100 mm	6	**0**	0	a
Golden perch	≤100 mm	7	**0**	0	a
Leathery grunter	>100 mm	13	**0**	0	a
Saratoga	>100 mm	20	**0**	0	a
Blue catfish	>100 mm	23	**0.0003**	0.0003	a
Sleepy cod	>100 mm	30	**0.0026**	0.0013	a
Hyrtl's tandan	>100 mm	23	**0.0116**	0.0051	a
Bony bream	>100 mm	27	**0.0207**	0.0110	a
Golden perch	>100 mm	22	**0.0219**	0.0219	a
Barred grunter	>100 mm	14	**0.0257**	0.02571	a
Sleepy cod	≤100 mm	29	**0.0260**	0.0105	a
Bony bream	≤100 mm	29	**0.0413**	0.0149	a
Eastern rainbowfish		29	**0.0705**	0.0427	a
Fly-specked hardyhead		21	**0.1525**	0.1237	a
Flat-headed gudgeon		4	**0.2850**	0.1646	
Barred grunter	≤100 mm	19	**0.2843**	0.2106	a
Freshwater catfish	≤100 mm	1	**0.2880**	0	
Blue catfish	≤100 mm	18	**0.3097**	0.1317	a
Rendahl's tandan	≤100 mm	1	**0.3260**	0	
Carp gudgeon spp		30	**0.324**	0.1617	a
Purple spotted gudgeon		3	**0.528**	0.2092	
Hyrtl's tandan	≤100 mm	3	**0.5767**	0.5767	
Saratoga	≤100 mm	1	**0.6400**	0	
Rendahl's tandan	>100 mm	3	**0.6847**	0.2446	
Spangled perch	≤100 mm	19	**1.4400**	0.7064	b
Spangled perch	>100 mm	14	**1.8805**	1.0585	b
Olive perchlet		27	**2.5733**	1.2481	b
Leathery grunter	≤100 mm	3	**3.650**	2.0802	

Table 9: Untransformed mean susceptibility index scores, with standard errors of the mean (SEM) and N values for frequency of encounters, for different larval native fish and fish eggs at riverine pumps and adjacent river sites. Scores are ranked from lowest to highest. Greyed categories were not encountered frequently enough for statistical analyses. Mean scores sharing the same letter are not significantly different at the 5% probability level.

Egg or larval category	N	Mean susceptibility score	S.E.M	Significance (p<0.05)
Fly-specked hardyhead larvae	3	**0**	0	
Eastern rainbowfish larvae	2	**0**	0	
Sleepy cod larvae	1	**0**	0	
Bony bream larvae	10	**0.2258**	0.161	a
Golden perch larvae	8	**0.4036**	0.294	a
Terapontidae (Terapon perches) larvae	6	**1.0890**	0.751	ab
Fish eggs	10	**5.0448**	1.921	abc
Carp gudgeon spp larvae	10	**5.7923**	3.347	bc
Unidentified larvae	9	**8.2269**	3.153	c
Flathead gudgeon	1	**10.0600**	0	
Unidentified yolk sac larvae	2	**50.1215**	43.337	

Discussion

General observations

Entrainment rates

Non-larval fish

As noted in the original report for this study (Hutchison *et al*. 2022) various researchers have examined entrainment of fish through irrigation infrastructure in Australia (*e.g.*, O'Connor *et al*. 2008; Baumgartner *et al*. 2009; Boys *et al*. 2013; Norris 2015; Norris *et al*. 2020). This current study combines data from the work by Hutchison *et al.* (2022) and data collected in 2023-24. This combination of data has enabled comparison of entrainment rates through multiple irrigation intake types to develop generalisations which can be used to prioritise where mitigation measures should be undertaken. Not all the previous studies in Australia directly quantified rates of entrainment, but of those that did, Norris *et al*. (2015) found maximum entrainment rates of 3,293 fish per ML (94,838 per day) through a pumped diversion on Oakey Creek in the Condamine catchment, whilst Baumgartner *et al*. (2009) recorded a maximum entrainment rate of only 232 fish per day through a pumped diversion. Some of the variation between these past studies is probably due to factors such as the local abundance of fish in the river system, the diversion type, position and depth of the intake, pumping rate and the flow event type being monitored. The current project recorded entrainment rates through riverine pumps ranging from 0 fish/ML to 137.23 fish/ML equating to 0 to 5,794 fish per day. In a pumped diversion from an impoundment this study recorded entrainment rates of 7.11 fish/ML to 35.37 fish/ML (806 to 14,501 fish per day). The impoundment diversion pumped at a considerably higher maximum rate (420 ML/day) than any of the riverine pumps examined (maximum 164 ML/day) but still had a lower maximum rate of entrainment than the riverine pumps.

In the current study the highest entrainment rates were recorded in the gravity fed Weemah irrigation channel. Entrainment rates ranged from 27.30 fish/ML to 626.95 fish/ML. Extrapolated entrainment rates ranged from 3,413 to 62,695 fish per day. O'Connor *et al*. (2008) also monitored a gravity fed diversion, and although they did not but did not quantify entrainment rates per unit time or per unit volume, electrofishing surveys indicated high abundance of native and introduced fish species in the diversion channel. Jones and Stuart (2008) have also indicated that gravity fed diversions can entrain high numbers of fish.

It appears that non-larval fish are more susceptible to entrainment through gravity fed diversions, than through pumped diversions, although it should be noted this study only compared one gravity fed diversion with an adjacent pumped diversion. Gravity fed diversions should probably be a high priority for mitigation, but it would be worth doing more research comparing gravity fed with pumped diversions in other river basins, especially where both pumped, and gravity fed diversions share the same river channel. Pumped diversions can subsequently be prioritised based on criteria developed in this study. Gravity fed diversions and prioritisation of pumped diversions will be elaborated on further in sections below.

Larval fish

Larval fish and fish eggs were detected far more intermittently than non-larval fish. This is to be expected as fish spawning tends to be cued by various environmental factors, including temperature, flow, and day length (King *et al*. 2016, Lintermans 2023, Šmejkal *et al*. 2023), thus larvae and fish eggs are present in the ecosystem intermittently. Therefore, entrainment rates of zero were frequently recorded in riverine pumped diversions, in an impoundment pumped diversion and, in an impoundment,-based gravity diversion. The maximum entrainment rate recorded from the pumped diversion from Fairbairn Dam into the Selma channel was 128.9 larvae/ML and the maximum daily entrainment rate was estimated to be 52,849 larvae per day.

The maximum entrainment rate recorded in the gravity fed Weemah diversion channel was 38.68 larvae per ML Based on prevailing diversion rates the highest extrapolated daily entrainment rate for fish larvae was 4,641 larvae per day. The maximum larval entrainment rate was therefore recorded from a pumped, rather than gravity fed diversion. However, occurrence of fish larvae and fish eggs in the Fairbairn Dam was irregular. More frequent sampling for larvae across the year is probably required to detect irruptions of larvae and develop a more informative indication of trends in entrainment of fish eggs and fish larvae. Such an undertaking would be time consuming and therefore expensive.

The maximum recorded rate of larval fish through riverine pumps was 1,028 larvae per ML, generating a daily maximum extrapolated entrainment rate of 102,790 larvae per day. If fish eggs entrained are added to the totals, then the maximum combined fish egg and fish larval entrainment rate was 2,056 per ML. Pelagic eggs and larvae drift on flow events. Thus, it is not surprising that riverine pumps had a higher maximum larval entrainment rate than pumped and gravity diversions from Fairbairn Dam. The general lack of currents in the Fairbairn Dam would require active swimming by larvae or wind generated water movements to put larvae in proximity of irrigation inlets. Spawning events for most species tend to occur in the warmer months of the year, which is often the time when demands for water for irrigation are also at their highest. It is therefore likely that some riverine pumping events will coincide with pulses of larvae. The maximum recorded loss of 102,790 larvae from the river through one pump on a single day does not equate to the loss of 102,790 mature fish, because larval mortalities are naturally high for many species, but even if just 1% of larvae made it through to the adult stage, then the loss of so many larvae would equate to the loss of over 1,000 adult fish, and if survival is just 0.1% from larvae to adult, then the loss of so many fish from the river equates to 100 adult fish per day through a single pump. Fortunately, modern self-cleaning fish screens can substantially reduce loss of fish larvae (Stocks *et al*. 2024).

Species entrained

Compared with the findings of Hutchison *et al*. (2022), some additional species and size classes were recorded to be entrained through riverine pumps in the current project. This included golden perch >100 mm, saratoga ≤100 mm, barred grunter >100 mm and freshwater catfish ≤100 mm. These fish were not a common catch in pump outlets in the supplementary data collection period and juvenile freshwater catfish were also rare in the river sites. Juvenile saratoga were not captured in the river during the original sampling for this project, but small numbers were found in the 2023-2024 sampling period. This probably explains why they were only recently detected being entrained through riverine pumps. Adult saratoga have been detected at riverine sites throughout both periods of this project but have not yet been found entrained. Despite detecting golden perch >100 mm being entrained through riverine pumps; this project did not detect any entrainment of juvenile golden perch through the same pumps. This is possibly due to the relatively low abundance of golden perch fingerlings in the adjacent river, which suggests recent recruitment has been poor. Larval golden perch were detected on some flow events in 2021-2022 and pelagic eggs (possibly golden perch eggs) were also detected in both stages of the project, both in the river and entrained through pumps. Hutchison *et al*. (2022), found juvenile golden perch were entrained through offtakes from Fairbairn

Dam. This coincided with high numbers of juvenile golden perch in Fairbairn Dam in the first phase of this project.

The detection of juvenile freshwater catfish entrained through a riverine pump is significant. Only adults of this species were detected in the river, suggesting juvenile freshwater catfish were in low abundance. This species is threatened in the Murray-Darling Basin (Lintermans 2023). Juvenile catfish have also been found to be entrained through pumps in the Condamine catchment (Norris 2015, Norris *et al.* 2020). Olive perchlet and purple spotted gudgeon were also entrained through riverine pumps across both phases of this project and these species are also threatened in the Murray Darling Basin (Lintermans 2023). Additionally, olive perchlet were detected for the first time below outlets from Fairbairn Dam, although entrainment of this species through the dam diversion channels was less frequent than through riverine pumps.

Some fish present in dam or river sites were not observed to be entrained. This included freshwater long tom, Murray cod, adult saratoga and barramundi. Freshwater longtom and adult saratoga are both surface species and this behaviour may keep them away from most riverine pump intakes. The smallest Murray cod sampled in reference sites were beyond fingerling size, and no fingerling size barramundi were detected in reference sites during sampling. Most barramundi detected were large fish. None of our sampling events coincided with recent releases of stocked barramundi fingerlings. The juvenile stages of both Murray cod and barramundi can be expected to be more vulnerable to entrainment. Experiments and sampling in the Murray-Darling Basin have shown that juvenile Murray cod can be vulnerable to entrainment (O'Connor *et al*. 2008, Stocks *et al*. 2024).

The diversity of larval fish species found entrained in both riverine and impoundment offtakes is relatively low (Tables 5 and 6) compared to the range of non-larval species entrained (Tables 3 and 4). This probably in part reflects the smaller windows of time that fish larvae are in the system. The range of species of larvae entrained was higher in the riverine pumps than in the impoundment diversions. This is most likely because larvae are washed past pump intakes during flow events in a riverine environment, whereas in the impoundment, where there are generally no currents, larvae would need to actively swim past intakes or be moved there by wind generated currents when the wind is blowing in the right direction. A greater diversity of larvae was also detected in riverine reference sites compared to Fairbairn Dam and some species of larvae detected in the river sites were not recorded being entrained.

Factors influencing entrainment rates

Diversion type

Hutchison *et al*. (2022) noted that the pumped Selma diversion and the gravity fed Weemah, diversion originating from the same water body, consistently showed less fish in total being entrained through the pumped diversion than the gravity fed diversion. This trend continued with the addition of supplementary data. For the combined totals of all fish species and for all fish ≤100 mm this was statistically significant ($P<0.05$). This trend was also statistically significant for several small bodied species and for smaller size classes of several species. The one exception was barred grunter ≤100 mm, which were entrained at a significantly higher rate per unit time into the pumped diversion. In the case of fish for which there were no statistically significant differences, the trend was generally for the adjusted mean value to be higher for fish entrained through the gravity fed diversion. Entrainment rates of larger fish in impoundment diversions were generally much lower, suggesting these fish may be better at avoiding entrainment. As noted by Hutchison *et al*. (2022) some of the differences between the two diversions might be explained by the rocky channel leading to the Selma intake, compared to the more open water around the Weemah intake. The rocks potentially could offer refugia from the intake current. However, the Selma intake channel was a highly productive area for sampling fish by electrofishing both in phases one and two of this project, suggesting fish were numerous near the intake point. Even when the water extraction rates were much higher in the Selma Channel than in the Weemah Channel, the Weemah Channel entrained more fish per unit time. Pump noise might deter some fish from approaching the Selma intake, whereas the gravity fed Weemah diversion would only have natural sounds related to flow akin to that of a natural entrance to an anabranch or a cascade. As noted in the original report (Hutchison *et al*. 2022), the sampling location in the Selma channel had to be set below a section of rock lined channel for safety and logistical reasons. It is possible that some entrained fish injured or killed passing through the Selma pump may have settled in rock crevices before reaching the sampling net and this may have biased catch rates downwards. Adjusted mean entrainment rates for larvae (all larvae combined) was three times higher in the gravity fed Weemah channel than in the pump fed Selma channel. Although not statistically significant, due to high variability in catch rates between events, this trend is consistent with that for most of the non-larval fishes sampled.

Whilst not originating from the same waterbody as the Weemah Channel, at comparable intake flow rates, the riverine pumps monitored in this study generally had lower entrainment rates per volume of water pumped compared to the Weemah Channel. This suggests gravity fed diversions may be a higher priority for mitigating fish entrainment. Comparative studies of other pumped and gravity fed diversions, especially gravity fed diversions leaving from river channels are required to support this concept.

Other researchers have also suggested that gravity fed diversions leading off rivers have the potential to entrain large numbers of fish (*e.g*., Jones and Stuart 2008; O'Connor *et al*. 2008). Fish are known to make downstream migrations (*e.g*. O'Connor *et al*. 2003, Hutchison *et al*. 2008,). In coastal rivers this includes catadromous species of fish like Australian bass, sea mullet and barramundi (Allen *et al*. 2002). Juvenile fish have been shown to make downstream movements in the Murray-Darling Basin, and adult fish after heading upstream on rising flows often head back downstream on falling flows (Hutchison *et al*. 2008). It is plausible that these fish could swim downstream into a diversion channel. In these situations, downstream migrating fish, including juveniles and drifting larvae would be highly susceptible to entrainment in gravity fed diversions (Boys *et al*. 2021), which would behave much like an anabranch channel and therefore potentially divert many fish from the river.

It would be informative to see if entrainment rates are increased in the Selma Channel when it operates as a gravity fed diversion during higher lake levels but unfortunately dam levels did not reach the critical level of 60% capacity during this study.

Dam capacity

During the original phase of this project the level of Fairbairn Dam ranged from 14% to 26% and when collecting the supplementary data, it ranged from 35% to 42%. As the increased depth would alter the depth of the intakes, dam capacity (used as a substitute for depth) was tested as a factor in the GLM models for entrainment rates through the channel inlets. Our hypothesis was that if the intake was located below the thermocline in a hypoxic layer of water, then entrainment rates would be low due to the absence of fish in the zone from which water was drawn. However, the results suggest that neither intake was below the thermocline during the extended study period, as fish continued to be entrained through both inlets.

Dam capacity explained some variation in entrainment rates of non-larval fishes but was partially aliased with dam catch rates of various size classes and species of fish. Therefore, it is difficult to draw any conclusions on the direct influence of dam level. Similarly for entrainment rates of larval fish, dam capacity seemed to have an influence on entrainment rates. The catch rates of fish larvae from the dam were also positively correlated with the dam capacity and larval entrainment rates were higher when the dam capacity was higher. It seems likely that dam capacity may have had an indirect influence on entrainment rates by influencing the abundance or density of fish in the dam. Higher water levels may have favoured recruitment of some species (*e.g*. flathead gudgeon), leading to increased entrainment rates, or led to production of larvae which increased their entrainment rates. However, for some species of fish (e.g. golden perch ≤100 mm and barred grunter ≤100 mm), increases in dam levels led to decreases in entrainment. This could possibly have been due to the dilution effect of the increased volume of water in the dam, or alternatively as the intakes became deeper below the surface, they may have entered a zone these fish did not occupy as frequently.

Temperature

Within the diversion channels exiting from Fairbairn Dam, temperature was shown to have a significant positive effect on the entrainment rates of various non larval fishes. These included the combined catch of all fish, combined catch of all fish ≤100 mm, carp gudgeon spp., flathead gudgeon and bony bream ≤100 mm. For some other species the temperature effect was not statistically significant, but a positive trend for increasing entrainment rates with increasing temperature was present. Golden perch ≤100 mm exhibited a non-significant negative relationship between temperature and entrainment rates.

In general, as temperatures increase, feeding activity levels and metabolic rates of fish tend to increase, although there is a point where temperatures can become too high, and fish become stressed (Volkoff and Rønnestad 2020). Dissolved oxygen levels also decline with increasing temperatures. As the Fitzroy catchment occupies the tropics and sub-tropics, most species of native fish in the system would be well adapted to warm waters. Therefore, it can be expected that most fish in this catchment would be more active in the warmer months of the year. Increased activity levels are more likely to lead to increased probability of interaction with irrigation intakes, and therefore entrainment rates can be expected to be higher when waters are warm. In static waters such as Fairbairn Dam, activity levels of fish activated by temperature are probably more significant for bringing fish into contact with an intake, compared to within a river, where cues such as flow may trigger movements provided temperatures are above a critical threshold, and where flows can result in passive movements of larval fish, fish eggs and small juveniles through downstream drift.

For non-larval fishes, no significant effect of season on entrainment rates through riverine pumps was detected for any of the size classes or species for which this factor was run in GLMs. However, most pumping events were sampled in the warmer months of the year, as this tended to be the peak irrigation time for cotton. Thus, it is possible that under-representation of cool season events may have masked any trends. Temperature was also not found to be significant for entrainment of fish larvae through riverine pumps. Again, this is probably the result of too few samples being collected in the cooler months. Most native lowland non-diadromous species of fish in Australia tend to spawn in the warmer months (spring-summer). Therefore, it would be expected that entrainment of larvae should be higher in the warmer times of the year. A combination of too few cool season samples and only patchy spawning events in the warmer months (resulting in some zero entrainment results) could mask the importance of temperature or season for rates of entrainment of larval fish in a river system.

Reference site catch rates

The catch rate of larvae in the dam reference site was significantly correlated with larval entrainment rates. Increased density of larvae in the dam increased the probability of larvae being entrained in the Selma and Weemah Channels. Similar trends occurred for non-larval fishes in Fairbairn Dam. Species and groups of fish where the covariate impoundment catch rate had a significant positive influence on entrainment rates included bony bream ≤100 mm, flathead gudgeon ≤100 mm, barred grunter ≤100 mm, barred grunter >100 mm, and golden perch ≤100 mm. For other species there was no significant effect, but for most the trend was still positive.

Riverine catch rates had a positive relationship to entrainment rates for blue catfish ≤100 mm, eastern rainbowfish, olive perchlet, spangled perch and bony bream ≤100 mm, but it was only significant for spangled perch >100mm and bony bream ≤100 mm). For most other fish there was no apparent relationship between catch in the riverine reference site and entrainment rates. The reason for this is uncertain. One possibility is that the riverine sampling methods used may not have adequately detected certain species. Our fyke nets were generally set in less than one metre depth and electrofishing is usually not very effective in depths greater than two to three metres, especially in turbid waters. Thus, relative abundance of some species occupying deeper waters may have been an underestimated. There also could be behavioural differences driving these changes in entrainment rates. For example, some species may be in low abundance, but their behaviour in a riverine environment, may make them more likely to approach an irrigation inlet. Other species, although quite abundant may have behavioural traits that make them less likely to approach intakes and thus be entrained, Behaviour within species groups and size classes may also vary seasonally or with various environmental factors, so this could potentially break down relationships between abundance in the river and entrainment rates.

Pump rate

Impoundment diversion channels

For both the pumped and gravity fed diversions originating from Fairbairn Dam, pump rate (or gravity fed extraction rate) was not always positively correlated with entrainment rate. There were some instances of negative relationships. It is likely that factors other than pump rate were contributing more strongly to the entrainment of fish. Water temperature, dam level and abundance of fish in the reference site have all been demonstrated to influence entrainment rates, and for many species and size classes in the impoundment this may have had a greater influence than the water extraction rate. Golden perch ≤100 mm were an exception to this trend and there was a significant correlation between intake or pump flow rate and entrainment rate for this species.

Inlet flow rate was found to be significantly correlated with larval fish entrainment rates into the channels leading from Fairbairn Dam. The trend was for increasing entrainment rates per day with increasing flow rates. Given larval fish have poor swimming abilities, if larvae are within the proximity of an irrigation inlet, they are highly likely to be entrained. Thus, for a static waterbody like Fairbairn Dam, provided larvae are present in the dam, as intake flow rates increase, the number of larvae entrained per unit time can also be expected to increase.

Riverine pumps

For many species and size classes of fish, there was a positive relationship between fish entrained per unit time and pump rates. However, for most fish this was not statistically significant. Pump rate had a significant positive effect on the number of different species entrained per unit time and for the number of eastern rainbowfish entrained per unit time. For some species of fish, there was no relationship, or it was weakly negative. For those species with very weak trends, other factors must be influencing entrainment rates to break down the relationship between pump rate and entrainment. Some of these factors were discussed in the original report for this project (Hutchison *et al*. 2022) and included the possibility that some species may actively swim into intakes. Other species may also be very good at avoiding intakes.

When entrainment rates were considered per unit volume of water pumped, a weak positive relationship was evident for many individual species of fish and overall, when they were pooled. This suggests that the number of fish entrained per megalitre only increases slowly as pump rates increase. The trend was a little stronger for larger size classes (fish >100 mm) of fish. Entrainment patterns suggested larger fish were generally capable of avoiding entrainment at lesser pumping rates but become more likely to be entrained at higher pumping rates.

Pooled data for all riverine larvae showed a weak positive (but not statistically significant) relationship between entrainment rates per unit time and pump rate. For fish eggs, no relationship was detected. This was unexpected. For eggs and larvae which can be expected to drift passively on river flows, you would normally expect a positive relationship between pump rate and entrainment rate per unit time. There must be other factors at play in the river which have reduced the intensity of this relationship. The sporadic nature of larval entrainment, which is linked to timing of spawning events, probably meant there was less statistical power to demonstrate the effect of pump rate on this life history stage.

Overall, when pooling data for all species, and considering the weak positive relationship between fish larvae entrainment and pump rates, it seems that pumping rate does have an influence on entrainment rates, but the impact of pumping rate may be less important than other factors and this needs to be considered when applying weightings to a prioritisation matrix.

For most species entrainment rates per unit volume of water pumped increased only marginally with increasing pump rate. Generally, farms with larger pumps have larger storages and are therefore likely to pump greater total volumes of water. Given entrainment rates increase per unit time as pumping rates increase, it can be expected that the total number of fish entrained will be greater on farms with larger pumps, although intake position and depth, and flow type may have a greater influence on the total number of fish entrained than pump rate (see below).

Flow type

Flow type was statistically significant for several species, including the pooled entrainment catch across all species and size classes. It was quite clear from the results that fish and larvae are less likely to be entrained through riverine pumps on overbank flow events. This trend for low catches on overbank flows was consistent across multiple species and size classes, providing some confidence that the effect is real. Entrainment rates as low as zero fish per 100 min were recorded on some overbank events. Fewer species were likely to be entrained on overbank flow events. Variability in catch rate was low on overbank flows, but the considerable variability in entrainments rates with the other flow types made it difficult to show a statistically significant difference across all species.

There could be at least two reasons for reduced entrainment rates on overbank flows. Firstly, the greater volume of water on overbank flows compared to within bank flows means that the density of fish per unit volume of water would be reduced. Secondly, during overbank flows it is likely that most fish will avoid the strong currents of the main river channel and will be sheltering or moving through the quieter water on the vegetated margins, which would be located behind or well above any riverine irrigation intake. On overbank flows our fykes were set in these areas and they caught good numbers of fish. It is unlikely that irrigators extract water from rivers solely on overbank flows. However, if they do extract water when the flow is over the riverbank (*i.e*., during flood flows), then this activity will have low direct impact on fish through entrainment.

Prior to this work it was expected that more non-larval fish would be entrained on within bank natural flow events than on allocated flow events. Previous work by Hutchison *et al*. (2008) found that most non-larval fish were more likely to move up or downstream during natural flow events than during allocated flow events. Murray-Darling rainbowfish were an exception to this rule. Therefore, it would be expected that most non-larval fish could be more vulnerable to entrainment during natural within bank flows. Analyses using the additional data collected now confirm that expectation. In the original study by Hutchison *et al*. (2022), within-bank natural flows were only marginally higher in adjusted mean entrainment rates than within bank allocated flow entrainment rates. However, the addition of extra data has demonstrated that entrainment on average is twice as likely on within-bank natural flow events than it is on within bank allocated flow events. This trend was reversed for eastern rainbowfish, which were much more likely to be entrained on allocated flow events than natural flow events. This result aligns with the observations of Hutchison *et al*. (2008) for Murray-Darling rainbowfish. Olive perchlet had a similar pattern to eastern rainbowfish, although variability was very high for olive perchlet.

Olive perchet, although still relatively common in coastal catchments, has declined significantly in the Murray-Darling Basin and is absent from large parts of its former range (Lintermans 2009). Based on these results their recovery could be at risk from pumping on allocated flows in parts of the Murray-Darling Basin while pumps remain unscreened. There was a tendency for fish of various species greater than 100 mm in length to be entrained more readily on natural within bank flow events than on allocated flow events. This included spangled perch and bony bream. It is possible that some of these fish could have been undertaking movements related to spawning when entrained. From a biological perspective, entrainment of fish undertaking spawning movements could be considered more significant than entrainment of juveniles.

Data for fish larvae and eggs generally matched the trend for non-larval fishes. Golden perch larvae were only entrained on natural within bank flow events. Golden perch are known to spawn on natural flow events but have also been recorded breeding on environmental flow releases (Stuart and Sharpe 2020). Their buoyant eggs and larvae then drift downstream (Stuart and Sharpe 2020) and at this stage they would be highly vulnerable to entrainment. Golden perch are of significant social and economic value. Entrained pelagic eggs were most prevalent on natural within bank flows. Of the more commonly entrained larvae, only carp gudgeon spp. larvae were entrained more frequently of allocated flow events. Carp gudgeon guard and fan their eggs (Lintermans 2023), so spawning is most likely to occur in low flow periods, which would explain why carp gudgeon larvae are more prevalent on allocated flow events, than during natural flow events.

It appears that flow type is more significant than pumping rate and that pumping on overbank flows has little direct impact on fish via entrainments. Overall, entrainment rates are approximately doubled (across all species pooled) when pumping from natural-within-bank flows, compared to pumping from allocated within-bank flows.

Intake position and depth

The current work (including that by Hutchison *et al*. 2022) is the first to look in detail at the effect of riverine pump intake position and depth on entrainment rates. Previous work by Norris *et al.* (2015) monitored two pumps of similar capacity on opposite banks of the same river reach. Catch rates varied considerably between the two intakes. Comparison of intake position and depth was not the objective of Norris *et al.* (2015) but the observations did suggest that intake position and depth might have an influence on entrainment rates.

The current study strongly supports the concept that intake position and depth can influence entrainment rates. With the addition of the supplementary data from this project’s extension, the general trends observed for pump intake position have remained consistent with the original findings. However, with the additional data several more species, size classes or species combinations were found to be statistically significant for this factor. For example, it was significant for all species (combined) entrained, for spangled perch >100 mm, for carp gudgeon spp., eastern rainbowfish, barred grunter ≤100 mm, blue catfish ≤100 mm and it was also significant in post-hoc pairwise comparison tests for bony bream >100 mm. The combined species data also includes the rarer species for which it was not possible to run a GLM model.

There were some exceptions to the overall trend for less entrainment through bankside shallow intakes. For example, eastern rainbowfish were significantly more likely to be entrained through shallow bankside intakes than other intakes. Sleepy cod ≤100 mm and blue catfish ≤100 mm also tended to be entrained more frequently through bankside shallow intakes, but entrainment rates of these species were relatively low. On balance, shallow bankside intakes have the lowest risk of entraining native fish.

The trend for relatively low entrainment rates through bankside shallow intakes was also reflected in the data for larval fishes, but pelagic fish eggs had higher adjusted mean entrainment rates through bankside shallow and bankside deep intakes.

The differences between the other intakes varied between species. Considering all species and size classes pooled, there was little difference between the other three intake types.

Most of these differences in entrainment rate between intake types are probably related to behavioural traits of the different species of fish, which would determine how likely they are to encounter the location of a particular intake type. For example, the higher entrainment rates of olive perchlets from mid-river channel intakes, suggests that during flow events that a significant number of olive perchlets are likely to be moving mid-river channel, perhaps migrating with the flow. The high prevalence of spangled perch >100 mm in bankside deep intakes and mid-river channel deep intakes, suggests that adult spangled perch may migrate during within bank flow events reasonably deep in the water column. The prevalence of bony bream entrainment through side channel intakes may indicate bony bream seeking shelter from the river currents.

Susceptibility of different species and size classes to entrainment

As the susceptibility index was calculated from a relationship between the number of fish entrained per megalitre and the number of fish of the same species and size class captured by standardised sampling in the river or impoundment reference site, it could be prone to some biasing by the catchability of that species or size class by electrofishing and fyke netting. In general, the combination of electrofishing and fyke netting should give a reasonable estimate of relative abundance, but it is still possible that some fish species may be over or under-represented by these sampling methods.

If the standardised sampling methods give reasonable representation of relative abundance, then within the irrigation channels exiting Fairbairn Dam, Flat-headed gudgeon, carp gudgeon spp, bony bream ≤100 mm and golden perch ≤100 mm appear to be the most vulnerable to entrainment. These represent small species of fish or small size classes of larger fish. Thus, some of their vulnerability may be due to swimming ability. Smaller fish may have more difficulty avoiding the approach velocities within the vicinity of pumps (Boys *et al.* 2013). This result is closely aligned to the result reported by Hutchison *et al*. (2022). Most other species and size classes were not significantly different to each other, although some fish species or size classes were sampled too infrequently to be included in the statistical analysis.

For riverine pumps, olive perchlet, spangled perch >100 mm and spangled perch ≤100 mm appear to be the most vulnerable to entrainment. All other species and size classes sampled frequently enough for statistical analyses were not significantly different to each other. It is possible that these fish were entrained at high rates relative to their abundance because of migratory behaviour. Both species are known to move laterally into wetlands during flow events (Hutchison *et al*. 2008). Entrained olive perchlets and spangled perch were also found to have a significantly different size distribution to fish captured in adjacent riverine reference sites (Hutchison *et al*. 2022). This suggests that these fish could be mature fish undergoing a spawning migration. Their migratory behaviour on flow events may make them more vulnerable to entrainment in a riverine situation. As olive perchlet are threatened in the Murray-Darling Basin, entrainment during a spawning migration could impact on recovery of this species.

Larval fish entrained in irrigation channels exiting Fairbairn Dam were encountered too infrequently to warrant any discussion. Within riverine offtakes, unidentified larvae were the most vulnerable to entrainment. Mostly these larvae were early-stage larvae, which is why identification was difficult. Early-stage larvae are likely to be poorer swimmers than more advanced larvae, which may explain why they are entrained more frequently.

Prioritising mitigation

The evidence from this study suggests that gravity fed diversions could have a higher impact than pumped diversions. Based on this current work and some observations published in the literature, gravity fed diversions are likely to be a high priority for mitigation actions in a catchment. Further studies in catchments where gravity fed diversions are more prevalent are required to compare entrainment rates between pumped and gravity fed diversions to confirm this. Depending on the size of the gravity fed diversion, they could be screened with a bank of cone screens or by a large vertical panel, self-cleaning wedge wire screen incorporating a bypass channel back to the river as is commonly done in the USA. Screening gravity fed diversions may be very expensive, but as these diversions generally service multiple irrigators, the cost per individual user may not be that high. For example, in the Emerald irrigation district, it is not just cotton growers who are serviced by a gravity fed diversion, but also citrus, grape and cereal producers. Alternatively, government grants may be able to fund or subsidise some mitigation projects.

Pumped diversions also have significant impacts on fish, but the impact is highly variable. Combining the data from Hutchison *et al*. (2022) with the supplementary data from the current study, an evidence-based prioritisation matrix has been developed that can help community groups, NRM groups, government agencies and irrigators prioritise mitigation of pumped irrigation infrastructure within a catchment or across multiple catchments. As many of the species of fish used to generate this data also occur in the Murray-Darling Basin, the prioritisation matrix should have applicability across a wider geographical area than just the Fitzroy Basin. The results should be applicable to the Murray-Darling Basin, Burnett River Basin, and Burdekin River Basin in addition to the Fitzroy Basin. Overall, this prioritisation matrix is very similar to that presented by Hutchison *et al*. (2022), but some adjustments to the weightings of flow type have been made to reflect the findings from the additional data collected.

It is anticipated that some of the future fish entrainment mitigation will be funded by government or not-for-profit grants. It is important that the funding is used wisely so that the greatest benefit can be achieved for the available investment. There is limited benefit in screening infrastructure that is currently having a minimal impact on fish or expending large amounts of resources on a logistically difficult site, when the same funding could achieve a better outcome for fish at either higher priority or more logistically feasible sites. Some irrigators may opt to self-fund installation of fish screens on their properties for reasons other than fish entrainment mitigation, such as achieving a more reliable flow of water, reducing pump maintenance. or cleaner water that does not clog sprinkler or centre pivot systems.

Modern self-cleaning screens currently available in Australia have been demonstrated to substantially reduce fish and fish larvae entrainment (Boys *et al*. 2021a; Stocks *et al*. 2024), while maintaining pumping efficiency. The Fishscreens.org website features some of the screening options available and case studies of the current fish-screening sites around Australia (https://fishscreens.org.au). Additionally, two useful publications available for irrigators considering screening intakes are. “The practical guide to modern fish-protection screening in Australia” (https://fishscreens.org.au/wp-content/uploads/2021/11/A-guide-to-modern-fish-protection-screening-in-Australia_FINAL_WPA.pdf) compiled by Boys *et al*. (2021b) and “Design specifications for fish-protection screens in Australia” (https://fishscreens.org.au/wp-content/uploads/2021/11/Design-specifications-for-fish-protection-screens_FINAL_WPA.pdf) compiled by Boys (2021).

Prioritisation matrix

The prioritisation matrix for identifying pumped water offtakes likely to be having the greatest impacts on fish is based on a scoring system derived from the trends observed in the data presented in this report. The aim of the matrix is to assist with deciding which pumped irrigation infrastructure should be the highest priority for mitigation of fish entrainment within a particular irrigation district. Potential options for prioritising between districts are also discussed. Potential users of the matrix may include state and federal government agencies, community groups (e.g., Landcare) and NRM groups, irrigators, agricultural companies, and peak bodies representing irrigators.

The scoring system relies on four main parameters:

1) the type of flow or flows the irrigator is licensed to pump
2) the pump size or capacity in ML/day
3) the pump intake location and depth

4) the maximum annual allocated volume the irrigator is licensed to take from that pump.

Shallow intakes are considered those where the top of the intake pipe sits less than 1 metre below the surface when measured during base flow events or typical allocated flow events (they may be further below the surface in bank full flow events). Deep intakes have intake pipes where the top of the intake sits more than one metre below the surface on a baseflow or typical allocated flow event.

Scoring for the flow type, pump rate and intake position and depth focusses around the total number of fish entrained. Individual species impacted were a lesser consideration, as these may vary between catchments and this matrix is intended to have cross catchment application. However, some consideration was given to impacts on larger fish, as some of the fish larger than 100 mm (especially among the small to medium sized species) could represent fish in breeding condition or on spawning migrations. These differences were most evident for intake location and flow type. Entrainment rates of pelagic larvae were also considered. Pelagic larvae frequently belong to recreationally or socio-economically important species such as golden perch, or some of the terapon perches, which outside the Fitzroy catchment may include species like silver perch. Pelagic larvae tended to be more prevalent on natural flow events. More generalist common species like carp gudgeon spp and bony bream tended to have larvae present on all pumped flows, as they may spawn readily even in non-flowing conditions.

The scores reflect the general trends observed in the data to enable separation of the scoring categories. Larger differences between categories are reflected where they exist. For example, to mimic the trends observed in entrainment rate (fish per megalitre) data by pump rate, the increments between categories expanded as the score increased gradually to represent the asymptotic curve of the entrainment rate/ML data. In contrast the total allocated volume scores are strictly linear, reflecting how total volume taken will directly influence the number of fish entrained in a linear fashion for a given pumping rate.

The lowest impact score in each category is scored as a 1. As the categories are cross multiplied to derive a final score, this ensures that the lowest impact score in each category categories does not lead to any increase in the final score. The weightings of the maximum score are similar across the three categories based on the field-derived data, although the maximum for pump rate is lower than the other two field categories, to reflect the lesser impact of this category identified in the research findings. However, volume allocated was given a higher maximum score than the other categories because the variations in total allocations are extreme. Extraction of very large volumes will still entrain many fish, even if the rate entrained per megalitre is low. The final score is derived from multiplication because of the way each category interacts has a multiplier effect in the field, rather than an additive effect.

Flow type the irrigator is licensed to harvest

The following weightings are given to different flow types:

- Overbank natural flows only = 1
- Allocated flows only = 2
- Natural flows only = 4
- Both natural and allocated flows = 2.5, 3 or 3.5.
  For predominantly allocated (supplemental) flows by volume use 2.5, predominantly natural flows by volume use 3.5, approximately equal amounts of allocated and natural flows pumped by volume use 3.

Justification: It is unlikely that any irrigator is licensed to take just overbank flows. However, fish and larval fish entrainment rates from overbank flows were used a baseline to help derive the scores for allocated flows and natural within-bank flows. The low probability of entrainment during overbank flows, means this flow type is given a rating of 1. Higher weighting has been given to natural within bank flows than to allocated within-bank flows, because on average the survey data found twice as many fish were entrained during natural within bank flows than during allocated within-bank flows. A similar pattern was also recorded for entrainment of fish larvae. Therefore, the weighting for within-bank natural flows is double that for allocated within-bank flows. In Hutchison *et al.* (2022) natural flows were weighted slightly higher than allocated flows, but with the collection of additional data and evidence of statistically significant differences, this weighting has been increased.

Most irrigators that pump on natural flow events would pump on both within-bank and overbank flows, with most pumping occurring from within-bank flows. If the irrigator is not located on a river reach with allocated flow releases from a dam or weir, then they would only be taking natural flows. Irrigators located downstream of weirs and dams that allocate water for pumping may be licensed to take allocated flows only, or they may be licensed to take both natural and allocated flows. Dual access pumps can be scored 2.5, 3 or 3.5 depending on the approximate proportions of allocated versus natural flows harvested by volume (see above).

Pump rate ML/day

The following weightings are given to different pumping rates:

- ≤ 30 ML/day = 1.0
- 31-60ML/day = 1.5
- 61-120ML/day = 2.0
- ≥121 ML/day =2.5

Justification: Pump rate scoring has been left unchanged from the scoring used in Hutchison *et al*. (2022). Pump rate was found to have a positive relationship with number of fish entrained per unit time across multiple species. There was slight positive trend for fish pumped per megalitre, and this was more notable for fish > 100 mm. However, error bars were quite large, especially for the higher pumping rates. When calculating annual impacts, the number of fish pumped per megalitre is more important than fish entrained per unit time if considering the total amount of water pumped. The score increases with increasing pump rate to reflect the positive trends observed, but the maximum score is relatively low, to reflect the lesser impact of pump rate compared to the other factors in the prioritisation matrix (flow type, pump intake location and depth, and total volume extracted per annum). The width between categories of pumping rates increases as the score rises which reflects the asymptotic curve of entrainment rates by pump rate.

Many farms operate twin pumps (or more pumps) in tandem from the same extraction point and these twin pumps normally have a common outlet point. In scoring these pumps the combined pumped volume is used. A farm operating widely separated pumps on different sections of the river with separate outlet points can consider those pumps independently.

Intake position and depth

The following weightings are given to different intake positions and depth combinations:

- Bankside shallow = 1
- Mid-river channel deep = 3
- Bankside deep = 3
- Side channel = 3

Justification: The weightings for this factor have not changed from those used by Hutchison *et al*. (2022). The additional data collected in the current project confirmed the trend for bankside shallow intakes to have the lowest impact. Intake position and depth was statistically significant for several species and size classes of fish. Just as outlined in Hutchison *et al*. (2022) the relative impacts of the other intake types were difficult to separate. For mid-channel deep, bankside deep and side channel shallow intakes, there were frequently no statistically significant differences between these three categories, whereas bankside shallow intakes were often significantly different to one or more of these three categories. Which of these three categories had the greatest impact was highly variable between species. This was also true for fish larvae. When data are pooled across species of fish and size classes the entrainment rates for these three categories were very similar.

Annual pumping allocation

The following weightings are given to different annual pumping volumes:

- ≤1500 ML/annum = 1
- 1501-3000 ML/annum = 2
- 3001-4500 ML/annum = 3
- 4501-6000 ML/annum = 4
- 6001-7500 ML/annum = 5
- 7501-9000 ML/annum = 6
- 9001-10,500 ML/annum = 7
- 10,501-12,000 ML/annum = 8
- 12,001-13,500 ML/annum = 9
- 13,501-15,000+ ML/annum = 10

Justification: The matrix scores used for annual pumping allocation remain unchanged from Hutchison *et al.* (2022). The justification also remains unchanged and is repeated here. The figures used are based on annual supplemented (allocated flows) and unsupplemented (natural flows) amounts of water able to be taken by irrigators using pumps from rivers in Queensland. The larger totals are generally pumped from unsupplemented (natural) flows in Queensland, and it is probably the same in other states. Some properties have volumetric limits well above 25,000 ML per annum. Most growers should have good knowledge of how much water a particular pump takes per year. For properties that have pumps at several locations, the annual pumping rate metric needs to be applied to the pump in question and not to the property's overall volumetric limit. Pump intake location will have a bearing on entrainment of fish, thus pumps on a property pumping from separate locations need to be considered separately. Whereas twin or multiple pumps extracting from the same intake location will need to be considered as one unit. Most growers should know what the annual pumped amount is for each pump location. The greater the amount of water pumped per annum, the greater the number of entrained fish will be, but the total number of fish and the biological impact will be influenced by the pump size, pump intake location and depth and the flow type from which the water is pumped. For variable use of twin pumps see other considerations below.

Table 10: Scoring metrics for the different pump intake prioritisation categories

Flow type pumped		**Intake position and depth**		**Pump rate**		**Annual pumping rate** (licensed take)	
Overbank only	1	Bankside shallow	1	≤ 30 ML /day	1	≤ 1500 ML/annum	1
Allocated flows only	2	Bankside deep	3	31-60 ML/day	1.5	1501-3000 ML/annum	2
Mixed: Mostly allocated by volume, some natural	2.5	Mid- river channel deep	3	61-120 ML/day	2	3001-4500 ML/annum	3
Mixed: Approx. equal volumes of natural and allocated flows	3	Side channel shallow	3	≥121 ML/day	2.5	4501-6000 ML/annum	4
Mixed: Mostly natural flows by volume, some allocated flows	3.5					6001-7500 ML/annum	5
Natural flows only: within and overbank	4					7501-9000 ML/annum	6
						9001-10,500 ML/annum	7
						10,501-12,000 ML/annum	8
						12,001-13,500 ML/annum	9
						13,501-15,000+ ML/annum	10

Score calculations

To calculate the final score for a particular pump, the score from each category is cross multiplied. Referring to the score metrics for each category in Table 10 use the following procedure to derive the score:

Total pump prioritisation score = flow type score x intake position and depth score x pump rate score x annual pumped volume score

Based on the assumption that no grower pumps solely from overbank flows, then the lowest score that can be achieved using the four-step prioritisation matrix will be 2, and the highest possible score that can be achieved is 300. The score achieved can be used to rank pumps from least concern (lowest score) to the greatest concern (highest score)

A grower who pumps only from allocated flows (2) with a bankside deep intake (3), with a 50 ML/day pump rate (1.5) and less than 1500 ML annual allocation (1) would receive a score of:

Total pump prioritisation score = 2 x 3 x 1.5 x 1
= 9.0

A grower who uses a pump for a mixed take of natural and allocated (supplemented) flows, but mostly natural flows by volume (3.5), with a bankside shallow pump intake (1), a 100 ML/day pump rate (2) and an annual allocation of 3,100 ML (3) would receive a score of

Total pump prioritisation score = 3.5 x 1 x 3 x 3
= 31.5

If the grower had a side channel shallow intake, then their score would be

Total pump prioritisation score = 3.5 x 3 x 3 x 3
= 94.5

Other considerations

The following information was also presented in Hutchison *et al*. (2022). It is re-presented here, with some minor updates to reflect the revised scoring system.

Variable use of twin and multiple pumps at intake points

It has already been noted that some irrigators use twin pumps or multiple pumps at a single intake location, and it has been recommended above to consider their combined pumping rate for the prioritisation process. However, there may be some flows where only one pump is operated and other occasions where all pumps are operated. These twin or multi-pump units can be scored using a two-step process. Most growers should have a good knowledge of the average annual total volume they pump using a single pump or multiple pumps at a site.

The worked example below shows how to come up with a prioritisation score in such situations. In this example the farmer has four 100ML/day pumps that he operates together on natural flow events to fill a large irrigation storage. (*i.e*., the farmer pumps at a rate of 400 ML per day). The farmer's total annual allocation for pumping from natural flows is 4,000 ML. The farmer can also pump from allocated (supplementary flows), but to pump from these flows the farmer uses only one of the 100 ML/day pumps. Their total annual allocation for allocated flows using the single pump is 1,000 ML. All the intakes are bankside deep intakes.

Referring to Table 19, the score for the four pumps operating together on natural flows is therefore

Total pump prioritisation score = 4 x 3 x 2.5 x 3
= 90

The score for the single pump operating on allocated flows is

Total pump prioritisation score = 2 x 3 x 2 x 1
= 12

Summing the two gives a score of 102.

If we had just considered the total allocated volume pumped (5,000 ML), which is mostly natural flow, and just treated all four pumps as a single unit, whether all were in use all the time or not, then the default score would have been

Total pump prioritisation score = 3.5 x 3 x 2.5 x 4
= 105.

The combined score of 102 is smaller than the default score and provides a more realistic assessment of the overall impact of the use of the combined pumping system in a year. Should the combined score exceed the default score, which is extremely rare, then the default score can be used.

Feasibility

The score achieved from the prioritisation matrix will identify pumps as the highest priority for mitigation as a first step, but as outlined in Hutchison *et al.* (2022), the feasibility of screening pumps identified as a high priority still needs to be considered. Other factors such as accessibility, available power supply, and how the existing infrastructure is configured (for example the intake may be contained within some underwater concrete structure) that could affect how feasible it is to screen an intake need to be considered. Site inspections should be undertaken by a screening expert to evaluate the feasibility and cost of screening a particular intake. Some locations may end up being prohibitively expensive to screen; in which case the funding available for mitigation may be better spent at two or more slightly lower priority locations where it is more cost effective install a screen. This would achieve a better overall outcome for the same cost. It can be cheaper to install screens when a new pump is installed, rather than try to retrofit a screen to an existing system. When existing pumps reach the end of their useful life and require replacing, this would be an opportune time to consider installing a screen. Modern self-cleaning fish screens can reduce debris problems and the need for back flushing that are experienced by many current trash racks or trash screen systems, so there can be operational advantages to fitting modern self-cleaning fish screens.

Between catchment prioritisations

The above four-part matrix is designed for prioritisation within an irrigation district or single catchment. When prioritising within a particular irrigation area, consideration of individual species impacted is not generally an issue because all pumps in an area are likely to be exposed to the same suite of species. The current project was not able to produce susceptibility scores for all species likely to be exposed to entrainment in Australia but has identified olive perchlet as a species highly susceptible to entrainment. This species has declined or become regionally extinct in parts of the southern Murray-Darling Basin. In catchments of the Murray-Darling Basin where recovery programs for this species are underway, special consideration could be given to the impacts of pump entrainment of this species. In such cases, perhaps a higher weighting could be given to mid-river channel irrigation intakes, where higher numbers of this species were found entrained in the current project.

If prioritising pumps between catchments, consideration may also be given to the species composition of the different catchments being considered. For example, catchments might be scored based on the number of endangered species present in the reaches where water extraction is taking place or the number of recreationally or economically important species present in the pumped reach. As knowledge grows on the susceptibility to entrainment of different species, some species may eventually be able to be weighted more highly than others during inter-catchment prioritisation. Species scores could be used as additional multipliers to the overall prioritisation model or simply used to derive a priority score for catchments and then pump mitigation work can be directed to catchments in priority order. Alternatively, catchments could be classed as high, medium, or low priorities, which could then be used to generate a 3-, 2-, or 1-times multiplier to be applied to the overall model.

Recommendations

1. Data from this project suggests that gravity fed diversions have a high impact, but only one such diversion was monitored. Further investigations into impacts of riverine gravity fed diversions are recommended.
2. Pumped diversions can be prioritised using a four-part scoring system that considers flow type being pumped, intake configuration (location and depth), pump rate and total volume pumped per annum. Consideration also needs to be given to the costs and feasibility of screening a site as part of the prioritisation process.
3. Future pumped irrigation developments should consider factoring in screening at the design and construction phase when it will be most cost-effective to install screens, compared to retrofitting them later. When existing pumps reach the end of their useful life, screening of the replacement pump should also be considered because it will be more cost effective.

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Appendix

Statistical models

Generalised linear models for adult and juvenile fish

Impoundment diversion channel fish

All fish ≤100 mm entrained per 100 min

Response variate: All fish ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	3412.2	3412.2	9.24	0.016
Dam catch	1	324.9	324.9	0.88	0.376
Temperature	1	6830.2	6830.2	18.49	0.003
Residual	8	2954.8	369.3		
Total	11	13522.2	1229.3		

All fish entrained per 100 min

Response variate: All fish **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	3393.9	3393.9	9.11	0.017
Dam catch	1	401.7	401.7	1.08	0.330
Temperature	1	6707.4	6707.4	18.00	0.003
Residual	8	2981.6	372.7		
Total	11	13484.7	1225.9		

Carp gudgeon spp entrained per 100 min

Response variate: Carp gudgeon spp. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	1427.8	1427.8	12.56	0.008
Dam catch	1	45.8	45.8	0.40	0.543
Temperature	1	1763.2	1763.2	15.51	0.004
Residual	8	909.4	113.7		
Total	11	4146.2	376.9		

Bony bream ≤100 mm entrained per 100 min

Response variate: Bony bream ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	3119.4	3119.4	13.65	0.006
Dam catch	1	5318.4	5318.4	23.27	0.001
Temperature	1	395.7	395.7	1.73	0.225
Residual	8	1828.5	228.6		
Total	11	10662.1	969.3		

Bony bream >100 mm entrained per 100 min

Response variate: Bony bream >100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	2.039	2.039	0.43	0.529
Dam catch	1	1.515	1.515	0.32	0.586
Temperature	1	1.744	1.744	0.37	0.560
Residual	8	37.650	4.706		
Total	11	42.948	3.904		

Barred grunter ≤100 mm entrained per 100 min

Response variate: Barred grunter ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	9.637	9.637	9.64	0.002
Dam catch	1	16.974	16.974	16.97	< 0.001
Temperature	1	0.082	0.082	0.08	0.774
Residual	8	9.706	1.213		
Total	11	36.400	3.309		

Barred grunter >100 mm entrained per 100 min

Response variate: Barred grunter >100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	3.9624	3.9624	3.96	0.047
Dam catch	1	4.7776	4.7776	4.78	0.029
Temperature	1	0.0225	0.0225	0.02	0.881
Residual	8	4.3287	0.5411		
Total	11	13.0911	1.1901		

Golden perch ≤100 mm entrained per 100 min

Response variate: Golden perch ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Ln pump rate, Dam catch (covariate), Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	29.055	29.055	14.29	0.007
Ln pump rate	1	76.570	76.570	37.65	<0.001
Dam catch	1	21.903	21.903	10.77	0.013
Temperature	1	10.15	10.15	4.99	0.061
Residual	7	14.237	2.034		
Total	11	151.915	13.810		

Impoundment diversion channel fish (models including dam capacity %)

Flathead gudgeon entrained per 100 min

Response variate: Flathead gudgeon. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam capacity %, Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	161.38	161.38	5.13	0.053
Dam capacity %	1	565.42	565.42	4.78	0.003
Temperature	1	342.58	342.58	0.02	0.011
Residual	8	251.74	31.47		
Total	11	1321.12	120.10		

Bony bream ≤100 mm entrained per 100 min

Response variate: Bony bream ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam capacity %, Temperature.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	3119.4	3119.4	13.65	0.005
Dam capacity %	1	154.2	154.2	23.27	0.414
Temperature	1	5728.4	5728.4	1.73	<0.001
Residual	8	1660.1	207.5		
Total	11	10662.1	969.3		

Barred grunter ≤100 mm entrained per 100 min

Response variate: Barred grunter ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Dam capacity %, Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	9.637	9.637	9.64	0.002
Dam capacity %	1	9.037	9.037	9.04	0.003
Temperature	1	0.082	0.082	0.08	0.370
Residual	8	16.923	2.115		
Total	11	36.400	3.309		

Golden perch ≤100 mm entrained per 100 min

Response variate: Golden perch ≤100 mm. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet type (pumped or gravity), Ln inlet flow rate, Dam capacity %, Temperature

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	1	29.055	29.055	10.69	0.014
Ln inlet flow rate	1	76.570	76.570	28.16	0.001
Dam capacity %	1	26.654	26.654	9.80	0.017
Temperature	1	0.602	0.602	0.22	0.652
Residual	7	19.034.	2719		
Total	11	151.915	13.810		

Fish entrained through riverine pumps

Number of native species entrained per 100 min

Response variate: Number of native species **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, Season.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	11.021	3.674	3.44	0.035
Flow type	2	15.023	7.512	7.02	0.004
Ln pump rate	1	6.207	6.207	5.80	0.025
Season	1	0.104	0.104	0.10	0.758
Residual	22	23.525	1.069		
Total	29	55.881	1.927		

All fish ≤100 mm entrained per 100 min

Response variate: All fish ≤100 mm **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, Season.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	949.5	316.5	2.16	0.122
Flow type	2	739.6	369.8	2.52	0.103
Ln pump rate	1	65.8	65.8	0.45	0.510
Season	1	6.8	6.8	0.05	0.831
Residual	22	3224.5	146.6		
Total	29	4986.2	171.9		

All fish >100 mm entrained per 100 min

Response variate: All fish >100 mm **Distribution:** Normal **Link Function:** Identity

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, Season.

Change	d.f.	Sum of squares	Mean squares	variance	F pr.
Inlet type	3	3884	1295	1.28	0.305
Flow type	2	3778	1899	1.87	0.177
Ln pump rate	1	148	148	0.15	0.706
Season	1	317	317	0.31	0.581
Residual	22	22199	1009		
Total	29	30326	1046		

All fish entrained per 100 min

Response variate: All fish **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, Season.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	1228.8	409.6	3.10	0.047
Flow type	2	962.7	481.3	3.65	0.043
Ln pump rate	1	97.6	97.6	0.74	0.399
Season	1	17.4	17.4	0.13	0.720
Residual	22	2902.7	131.9		
Total	29	5209.2	179.6		

Bony bream ≤100 mm entrained per 100 min

Response variate: Bony bream ≤100 mm **Distribution:** Normal **Link Function:** Identity

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch (covariate).

Change	d.f.	Sum of squares	Mean squares	Variance	F pr.
Inlet type	3	9269	3090	1.71	0.197
Flow type	2	6230	3115	1.72	0.203
Ln pump rate	1	85	85	0.05	0.831
River catch	1	14745	14745	8.14	0.010
Residual	21	38051	1812		
Total	28	68380	2442		

Bony bream >100 mm entrained per 100 min

Response variate: Bony bream >100 mm **Distribution:** Normal **Link Function:** Identity

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch (covariate).

Change	d.f.	Sum of squares	Mean squares	variance	F pr.
Inlet type	3	451.61	150.54	1.65	0.206
Flow type	2	198.53	99.26	1.09	0.353
Ln pump rate	1	216.91	216.91	2.38	0.137
River catch	1	64.07	64.07	0.07	0.410
Residual	22	2002.35	91.02		
Total	29	2933.47	101.15		

Sleepy cod ≤100 mm entrained per 100 min

Response variate: Sleepy cod ≤100 mm **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch (covariate).

Change	d.f.	Deviance	Mean Deviance	Deviance ratio	Approx. F pr.
Inlet type	3	4.244	1.415	0.69	0.568
Flow type	2	12.123	6.062	2.95	0.073
Ln pump rate	1	.0637	0.637	0.31	0.583
River catch	1	0.138	0.138	0.07	0.798
Residual	22	45.164	2.053		
Total	29	62.306	2.148		

Spangled perch ≤100 mm entrained per 100 min

Response variate: Spangled perch ≤100 mm **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	70.19	23.4	0.86	0.477
Flow type	2	18.89	9.44	0.35	0.711
Ln pump rate	1	0.89	0.89	0.03	0.859
River catch	1	0.20	0.20	0.01	0.932
Residual	22	598.89	27.22		
Total	29	689.06	23.76		

Spangled perch >100 mm entrained per 100 min

Response variate: Spangled perch >100 mm **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	439.21	146.4	13.97	<0.001
Flow type	2	229.15	114.58	10.93	<0.001
Ln pump rate	1	8.32	8.32	0.79	0.383
River catch	1	182.86	182.86	17.44	<0.001
Residual	22	230.63	10.48		
Total	29	1090.18	37.59		

Carp gudgeon spp entrained per 100 min

Response variate: Carp gudgeon spp. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, Season.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	1350.62	450.21	5.76	0.005
Flow type	2	407.27	203.63	2.60	0.097
Ln pump rate	1	1.22	1.22	0.02	0.902
Season	1	1.51	1.51	0.02	0.891
Residual	22	1720.36	78.2		
Total	29	3480.98	120.03		

Olive perchlet entrained per 100 min

Response variate: Olive perchlet **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	234.39	78.13	2.00	0.144
Flow type	2	68.94	34.47	0.88	0.429
Ln pump rate	1	85.66	85.66	2.19	0.153
River catch	1	105.56	105.56	2.7	0.115
Residual	22	861.28	39.15		
Total	29	1355.82	46.75		

Eastern rainbowfish entrained per 100 min

Response variate: Eastern rainbowfish **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, Ln pump rate, River catch

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	111.219	37.073	6.95	0.002
Flow type	2	34.966	17.483	3.28	0.057
Ln pump rate	1	196.678	196.678	36.89	<0.001
River catch	1	5.956	5.956	1.12	0.302
Residual	22	117.277	5.331		
Total	29	466.097	16.072		

Blue catfish ≤ 100 mm entrained per 100 min

Response variate: Blue catfish ≤100 mm **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), flow type, River catch

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	18.660	6.220	3.27	0.039
Flow type	2	44.538	22.269	11.72	<0.001
River catch	1	2.317	2.317	1.22	0.281
Residual	23	43.690	1.90		
Total	29	109.205	3.766		

Barred grunter ≤100 mm entrained per 100 min

Response variate: Barred grunter ≤100 mm **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type)

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	42.823	14.274	4.68	0.010
Residual	26	79.326	3.051		
Total	29	122.149	4.212		

Fly-specked hardyhead entrained per 100 min

Response variate: Fly-specked hardyhead **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type)

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	24.601	8.200	5.37	0.005
Residual	26	39.713	1.527		
Total	29	64.314	2.218		

All fish entrained per ML

Response variate: All fish **Distribution:** Normal **Link Function:** Identity

Fitted terms: Constant, Inlet location and depth (type), Flow type Ln pump rate, Season

Change	d.f.	Sum of squares	Mean squares	variance	F pr.
Inlet type	3	4415	1472	1.07	0.383
Flow type	2	3052	1526	1.11	0.348
Ln pump rate	1	0.	0.	0.	0.990
Season	1	215.	215.	0.16	0.697
Residual	22	30326	1378		
Total	29	3807	1311		

All fish > 100 mm entrained per ML

Response variate: All fish >100 mm **Distribution:** Normal **Link Function:** Identity

Fitted terms: Constant, Inlet location and depth (type), Flow type Ln pump rate, Season.

Change	d.f.	Sum of squares	Mean squares	variance	F pr.
Inlet type	3	73.44	24.48	1.15	0.353
Flow type	2	77.59	38.80	1.82	0.186
Ln pump rate	1	2.75	2.75	0.13	0.723
Season	1	8.33	8.33	0.39	0.539
Residual	22	470.01	21.36		
Total	29	632.12	21.80		

Generalised linear models larval fish and eggs

Impoundment diversion channel larval fish

All fish larvae entrained per day with "Dam catch" included in the model

Response variate: All larval fish. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Ln inlet flow rate, Dam catch (covariate) Inlet type (pumped or gravity).

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Ln Inlet flow rate	1	126222	126222	62.93	<0.001
Dam catch	1	79034	79034	39.40	<0.001
Inlet type	1	1916	1916	0.96	0.357
Residual	8	16046	2006		
Total	11	223218	20293		

All fish larvae entrained per day with "dam capacity %" included in the model

Response variate: All larval fish. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Ln inlet flow rate, Dam capacity %, Inlet type (pumped or gravity).

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Ln Inlet flow rate	1	126222	126222	31.77	<0.001
Dam capacity %	1	61876	61876	15.57	0.004
Inlet type	1	3336	3336	0.84	0.386
Residual	8	31783	3973		
Total	11	223218	20293		

Fish larvae and eggs entrained through riverine pumps

All fish larvae entrained per day

Response variate: All larval fish. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Ln pump rate, Flow type, Inlet location and depth (type).

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Ln pump rate	1	29584	29584	1.37	0.254
Flow type	2	213206	106603	4.93	0.017
Inlet type	3	57022	19007	0.88	0.467
Residual	23	497424	21627		
Total	29	797236	27491		

Unidentified fish larvae entrained per day

Response variate: Unidentified larval fish. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Flow type, Inlet location and depth (type).

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Flow type	2	25730	12865	3.72	0.039
Inlet type	3	20168	6723	1.94	0.149
Residual	24	82954	3456		
Total	29	128852	4443		

Carp gudgeon larvae entrained per day.

Response variate: Carp gudgeon larvae. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Flow type, Inlet location and depth (type).

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Flow type	2	47577	23789	5.48	0.011
Inlet type	3	23876	7959	1.83	0.168
Residual	24	104200	4342		
Total	29	175653	6057		

Golden perch larvae entrained per day.

Response variate: Golden perch larvae. **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Flow type, Inlet location and depth (type).

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Flow type	2	135196	67598	15.73	<0.001
Inlet type	3	22186	7395	1.72	0.189
Residual	24	103153	4298		
Total	29	260535	8984		

Fish eggs entrained per day.

Response variate: Fish eggs **Distribution:** Poisson **Link Function:** Log

Fitted terms: Constant, Inlet location and depth (type), Flow type.

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Inlet type	3	168187	56062	4.8	0.009
Flow type	2	218906	109453	9.37	<0.001
Residual	24	280291	11679		
Total	29	667384	25013		

ANOVA Tables

Susceptibility to entrainment of Impoundment adult and juvenile fish

Variate: Log susceptibility score +1. **Term:** Species and size class group

Source of variation	d.f.	Sum of squares	Mean squares	variance	F pr.
Species and size class	16	0.0531698	0.0033231	3.74	<0.001
Residual	172	0.1526941	0.0008878	9.37	
Total	188	0.2058640			

Susceptibility to entrainment of riverine adult and juvenile fish

Variate: Log susceptibility score +1. **Term:** Species and size class group

Source of variation	d.f.	Sum of squares	Mean squares	variance	F pr.
Species and size class	20	3.23480	0.16174	6.78	<0.001
Residual	416	9.92868	0.02387		
Total	436	13.16348			

Susceptibility to entrainment of riverine fish larvae and fish eggs

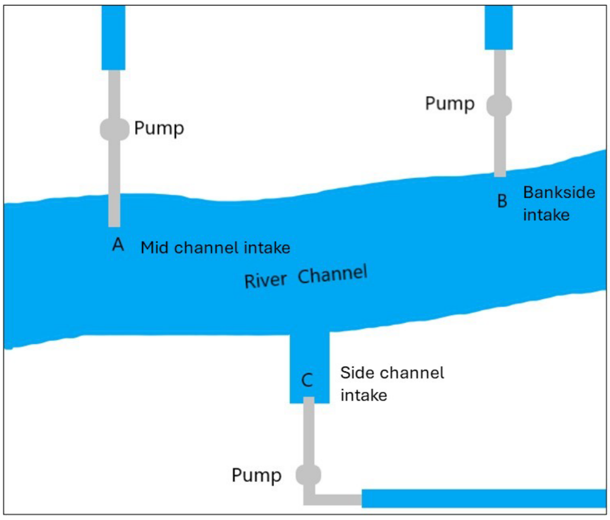
Variate: Log susceptibility score +1. **Term:** Species group

Source of variation	d.f.	Sum of squares	Mean squares	variance	F pr.
Species group	5	3.4916	0.6983	4.25	0.003
Residual	47	7.7216	0.1643		
Total	52	11.2133			

Prioritising pumps to mitigate impacts on native fish

Irrigation pumps can remove native fish from our rivers with the water they extract. Some pumps entrain very few fish, whereas others can entrain high numbers of fish and larvae. Recent research has shown that the position and depth (configuration) of the pump intake and type of river flow that is being pumped from have a greater influence on the number of fish entrained than the pumping rate.

In the research, the position of pump intakes assessed were categorised as: bankside (A), mid-river channel (at least several metres from the bank edge) (B), and within an excavated side channel (C) perpendicular to the river (see diagram). During normal allocated or base flow levels, if the top of the intake was less than 1 m below the water surface, pumps were classified as shallow, whilst if the top of the intake was greater than 1 m below the surface they were classified as deep.



Bankside shallow intakes generally entrain far fewer native fish than other pump intake configurations. Entrainment rates of the other intake configurations vary between species, but overall, they have similar total impacts to each other.

Flows in the river can be classed as natural within-bank, natural overbank (floods) or allocated (supplemental) within bank. Pumping from flood flows entrains very few fish, but pumping from natural within bank flows tends to entrain more fish, more fish larvae and more large fish. Pumping from allocated within bank flows still entrains fish, but at about half the rate of pumping from equivalent natural flows.

Pumping rate has some influence on the number of fish entrained per unit time, but the number of fish entrained per unit volume of water only increases marginally as rate of pumping increases. The volume of water extracted by a pump in a year also influences total fish entrainment, with higher native fish impacts occurring at higher total extraction volumes.

This knowledge can be used to score and compare different irrigation intakes within a catchment or within a business. The process can be used to help direct investment on mitigating impacts to native fish to where it will have the greatest impact.

Queensland Department of Agriculture and Fisheries researchers have developed a scoring matrix (next page) to assist with identifying which pumps should be prioritised for mitigation actions to reduce their impacts on native fish populations.

Scoring metrics for the different pump intake prioritisation categories

Flow type pumped		**Intake position and depth**		**Pump rate**		**Annual pumping limit** (licensed take)	
Overbank only	1	Bankside shallow	1	≤ 30 ML /day	1	≤ 1500 ML/annum	1
Allocated flows only	2	Bankside deep	3	31-60 ML/day	1.5	1501-3000 ML/annum	2
Mixed: mostly allocated by volume, some natural	2.5	Mid- river channel deep	3	61-120 ML/day	2	3001-4500 ML/annum	3
Mixed: approx. equal volumes of natural and allocated flows	3	Side channel shallow	3	≥121 ML/day	2.5	4501-6000 ML/annum	4
Mixed: mostly natural flows by volume, some allocated flows	3.5					6001-7500 ML/annum	5
Natural flows only: within and overbank	4					7501-9000 ML/annum	6
						9001-10,500 ML/annum	7
						10,501-12,000 ML/annum	8
						12,001-13,500 ML/annum	9
						13,501-15,000+ ML/annum	10

Score calculations

The following procedure will enable the total pump prioritisation score to be derived. The total pump prioritisation score for a particular pump is calculated by multiplying the score from each category in the above table.

Total pump prioritisation score = flow type score x intake position and depth score x pump rate score x annual pumped volume score

Based on the assumption that no-one pumps only from overbank flows, the lowest score that can be achieved using the four-step prioritisation matrix will be 2, and the highest possible score achievable is 300. The total pump prioritisation scores can be used to rank pumps from least concern (lowest score) to greatest concern (highest score)

Examples:

A grower who pumps only from allocated flows (2) with a bankside deep intake (3), at a rate of 50 ML/day (1.5) with less than 1,500 ML annual limit (1) would receive a score of:

2 x 3 x 1.5 x 1 = 9.0

A grower who uses a pump for a mixed take of natural and allocated flows, but mostly pumps from natural flows by volume (3.5), with a bankside shallow pump intake (1), 100 ML/day pump rate (2) and an annual limit of 3,100 ML (3) would receive a score of:

3.5 x 1 x 3 x 3 = 31.5

If the grower had a side channel shallow intake, then their score would be:

3.5 x 3 x 3 x 3 = 94.5

Other considerations

Some irrigators use twin or multiple pumps at a single intake location, and it is recommended to consider their combined pumping rate for the prioritisation process. However, there may be flows where only one pump is operated and other occasions where all pumps are utilised. These multi-pump units can be scored using a two-step process. Most growers should have a good knowledge of the average annual total volume they pump using a single pump or multiple pumps at a site.

The worked example below shows how to calculate a prioritisation score in such situations. In this example the farmer has four 100ML/day pumps that are operated together on natural flow events to fill a large irrigation storage. (*i.e.*, the farmer pumps at a rate of 400 ML per day). The farmer's total annual limit for pumping from natural flows is 4,000 ML. The farmer can also pump from allocated flows, but in these instances, they only use one of the 100 ML/day pumps. Their total annual limit for allocated flows using the single pump is 1,000 ML. If all the intake configurations are bankside deep, then the score for the four pumps operating together on natural flows is:

4 x 3 x 2.5 x 3 = 90

The score for the single pump operating on allocated flows is

2 x 3 x 2 x 1 = 12

Summing the two gives a score of 102.

If we had just considered the total volume limit pumped (5,000 ML), which is mostly natural flow, and treated all four pumps as a single unit, whether all were in use all the time or not, then the default score would have been:

3.5 x 3 x 2.5 x 4 = 105

The combined score of 102 is slightly less than the default score and is a more realistic assessment of the overall impact of the use of the combined system in a year. Should the combined score exceed the default score, which is extremely rare, then the default score can be used.

Feasibility

The score achieved from the prioritisation matrix will identify the highest priority pumps for mitigating fish entrainment, but the feasibility of screening those pumps still needs to be considered. Factors such as accessibility, available power supply, and the existing infrastructure configuration can affect how feasible it is to screen an intake. Site inspections by a screening expert would be needed to evaluate the feasibility and cost of screening a particular intake. Some locations may end up being prohibitively expensive to screen. In which case the funding available for mitigation may be better spent at two or more slightly lower priority locations where it is more cost effective to install screens to achieve a better overall outcome for the same investment.

It is typically more cost-effective to install screens when a new pump is installed, rather than try to retrofit a screen to an existing pump. An opportune time to consider fitting a screen is when existing pumps require replacing. There can be advantages to fitting modern self-cleaning fish screens beyond the benefits to fish. Modern self-cleaning fish screens can reduce debris problems and the frequency of back flushing, compared to many current trash racks or trash screen systems. More information on self-cleaning screens can be found on the Fish Screens Australia website. https://fishscreens.org.au

For further information on how the prioritisation matrix was developed, refer to "Impacts and solutions: A scoping study on relative impacts of irrigation infrastructure on fish. (Supplementary report)" by Hutchison *et al.* 2024. This should be available on request from the CRDC.