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

Final report

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Contents

Summary **1**
Introduction **3**
Methods **4**
Experimental design 4
Irrigation outlet sampling 8
Outlet netting 8
Larval netting 9
River and impoundment sampling 9
Sampling locations 10
Boat electrofishing 10
Fyke netting 11
Larval netting 11
Identifying larval samples 12
Data management and susceptibility indices 12
Data entry and management 12
Susceptibility indices 12
Statistical analyses 13
Key variables analysed 13
Generalised linear models 13
Comparison of size distributions 14
Comparison of mean susceptibility indices scores 15
Results **15**
Species caught 15
Range of entrainment rates 18
Diversion channels 18
Riverine pumps 18
Generalised linear model outputs 18
Adult and juvenile fish entrainment in impoundment diversion channels 18
Intake type (pumped or gravity fed) 18
Pump rate 19
Larval fish in impoundment diversion channels 21
Adult and juvenile fish entrainment through riverine pumps 22
Pump rate 22
Intake location and depth 24
Flow type 27
Other variables 27
Larval fish and fish egg entrainment through riverine pumps 29

Intake location and depth 29
Flow type 30
Season 30
Differences in length frequencies between entrained fish and fish in references sites 30
Susceptibility indices 35
Adult and juvenile fish 35
Larval fish 38
Discussion 39
General observations 39
The role of diversion type, pump size, flow and intake position and depth 40
Diversion type 40
Pump rate 41
Impoundment diversion channels 41
Riverine pumps 41
Flow type 42
Intake position and depth 43
Fish size and Susceptibility 44
Key findings 46
Mitigation options 47
Prioritising mitigation 51
Prioritisation matrix 51
Flow type the irrigator is licensed to harvest 52
Pump rate ML/day 53
Intake position and depth 53
Annual pumping rate 54
Score calculations 54
Other considerations 55
Recommendations 57
Acknowledgments 57
References 58
Project Outputs 60
Appendices 61
Appendix I: GLM summary tables 61
Impoundment diversion GLMs 61
Adult and juvenile fish entrained per 100 min 61
Response variate: All fish ≤100 mm 61
Response variate: All fish >100 mm 62
Response variate: All fish all sizes 63
Response variate: Carp gudgeon 64

Response variate: Eastern rainbowfish 65
Response variate: Flat-headed gudgeon 66
Response variate: Bony bream ≤ 100 mm 67
Response variate: sleepy cod ≤ 100 mm..... 68
Response variate: sleepy cod > 100 mm 69
Response variate: Barred grunter ≤ 100 mm..... 70
Response variate: Barred grunter > 100 mm 71
Response variate: Leathery grunter all sizes 72
Response variate: Golden perch ≤100 mm 73
Response variate: Golden perch all sizes 74
Response variate: Rendahl's tandan> 100 mm..... 75
Fish larvae..... 76
Response variate: All larvae estimated daily entrainment rate 76
Response variate: Bony bream larvae estimated daily entrainment rate 76
Response variate: Flat-headed gudgeon larvae estimated daily entrainment rate 77
Response variate: All larvae entrainment rate per ML 77
Response variate: Bony bream larvae entrainment rate per ML 77
Response variate: Flat-headed gudgeon larvae entrainment rate per ML 78
Riverine pump GLMs accumulated analyses of deviance or variance 78
Adult and juvenile fish entrained per 100 min..... 78
Response variate: All fish ≤100 mm 78
Response variate: bony bream ≤100 mm..... 79
Response variate: bony bream >100 mm..... 79
Response variate: Sleepy cod ≤100 mm..... 80
Response variate: spangled perch ≤100 mm 80
Response variate: spangled perch >100 mm 81
Response variate: carp gudgeon..... 81
Response variate: Olive perchlet..... 82
Response variate: Eastern rainbowfish 82
Response variate: Blue catfish ≤ 100 mm 83
Response variate: Sleepy cod > 100 mm..... 83
Response variate: barred grunter ≤100 mm 83
Response variate: Hyrtl's tandan >100 mm..... 84
Response variate: Rendahl's tandan >100 mm..... 84
Response variate: Fly-specked hardyhead 84
Response variate: Number of native species 85
Larval fish entrained per 100 min 85
Response variate: All larvae combined projected catch per day..... 85
Response variate: Unidentified larvae projected catch per day 86

Response variate: Carp gudgeon larvae projected catch per day ... 86
Response variate: Golden perch larvae projected catch per day ... 87
Selected adult and juvenile fish entrained per ML ... 87
Response variate: All fish ≤100 mm ... 87
Response variate: All fish >100 mm ... 88
Response variate: Bony bream ≤100 mm ... 88
Response variate: Bony bream >100 mm ... 89
Response variate: Olive perchlet ... 89
Response variate: Eastern rainbowfish ... 90
Larval fish entrained per ML ... 90
Response variate: All larvae combined projected catch per ML ... 90
Response variate: Unidentified larvae catch per ML ... 91
Response variate: Carp gudgeon larvae catch per ML ... 91
Response variate: Golden perch larvae catch per ML ... 92
Appendix II: Additional plots of fish entrainment rates per ML ... 93
Bony bream >100 mm entrainment rate per ML by pump rate ... 93
Eastern rainbowfish entrainment rate per ML by pump rate ... 93
Appendix III: Length frequency histograms of entrained fish and fish in adjacent reference sites ... 94
Commonly encountered fish at riverine pump or reference sites on natural flow events by site and flow event. ... 94
Pump site 3 vs Ref site 5, 14/01/21. Pump rate 49 ML/day. Side-channel intake ... 94
Pump site 3 vs Ref site 5, 27/11/21. Pump rate 49 ML/day. Side channel intake ... 95
Pump site 3 vs Ref site 5, 20/03/21. Pump rate 51 ML/day. side channel intake ... 96
Pump site 4 vs Ref site 5, 14/01/21. Pump rate 54 ML/day. Mid-river channel intake ... 97
Pump site 4 vs Ref site 5, 21/03/21. Pump rate 56 ML/day. Mid-river channel intake ... 98
Pump site 16 vs Ref site 2, 16/11/21. Pump rate 90ML/day. Bankside deep intake. ... 99
Pump site 1 vs Ref site 2, 13/01/21. Pump rate 100 ML/day. Bankside deep intake ... 100
Pump site 1 vs Ref site 2, 16/11/21. Pump rate 100 mL/day. Bankside deep intake ... 101
Pump site 8 vs Ref site 6, 21/03/21. Pump rate 100 ML/day Bankside deep intake ... 102
Pump site 7 vs Ref site 6, 27/11/21. Pump rate 100 ML/day. Bankside shallow intake. ... 103
Pump site 7 vs Ref site 6, 20/03/21. Pump rate 150 ML/day bankside shallow intake ... 104
Commonly encountered fish at riverine pump or reference sites on allocated flow events by site and flow event. ... 105
Pump site 17 vs Ref site 18, 25/02/22. Pump rate 14 ML/day. Mid-river channel intake ... 105
Pump site 17 vs Ref site 18, 22/01/22. Pump rate 14.5 ML/day. Mid-river channel intake ... 106
Pump site 9 vs Ref site 6, 01/06/21. Pump rate 23 ML/day. Bankside shallow intake. ... 107
Pump site 4 vs Ref site 14, 22/02/22. Pump rate 27 ML/day. Mid-river channel intake. ... 108
Pump site 3 vs Ref site 14, 22/02/22. Pump rate 42 ML/day. Side-channel intake. ... 109
Pump site 7 vs Ref site 6, 26/02/22. Pump rate 50 ML/day. Bankside shallow intake. ... 110

Pump site 13 vs Ref site 6, 19/06/21. Pump rate 88.5 ML/day. Mid-river channel intake 111
Pump site 8 vs Ref site 6, 20/06/21. Pump rate 100 ML/day. Bankside deep intake. 112
Pump site 8 vs Ref site 6, 18/09/21. Pump rate 100 ML/day. Bankside deep intake 113
Pump site 1 vs Ref site 2, 28/09/21. Pump rate 100 ML/day. Bankside deep intake 114
Pump site 15 vs Ref site 6, 02/11/21. Pump rate 140 ML/day. Bankside shallow intake. 115
Examples of combination histogram plots from combined flow events, including some less commonly encountered fish at riverine pump or reference sites 116
Pump site 1 and reference site combined length frequency histogram plots. Bankside deep intake. 116
Pump site 3 and reference sites combined length frequency histogram plots. Side-channel intake. 117
Pump site 4 and reference sites combined length frequency histogram plots. Mid-river channel intake 118
Pump site 8 and reference site combined length frequency histogram plots. Bankside deep intake. 119
Pump site 7 and reference site combined length frequency histogram plots. Bankside shallow intake 120
Commonly encountered fish in the Weemah or Selma diversion channels, or in the adjacent Fairbairn Dam reference site 121
Length frequencies in Selma Channel and Fairbairn Dam 29/09/2021. Pumped intake, 75 ML/day. 121
Length frequencies in Selma Channel and Fairbairn Dam 18/06/2021. Pumped intake, 140 ML/day. 122
Length frequencies in Selma Channel and Fairbairn Dam 24/01/2022. Pumped intake, 340 ML/day. 123
123
Length frequencies in Selma Channel and Fairbairn Dam 24/02/2022. Pumped intake, 400 ML/day. 124
Length frequencies in Weemah Channel and Fairbairn Dam 30/09/2021. Gravity fed intake, 75 ML/day. 125
Length frequencies in Weemah Channel and Fairbairn Dam 23/02/2022. Gravity fed intake, 100 ML/day. 126
Length frequencies in Weemah Channel and Fairbairn Dam 19/06/2021. Gravity fed intake, 120 ML/day. 127
Length frequencies in Weemah Channel and Fairbairn Dam 24/01/2022. Gravity fed intake, 259 ML/day. 128
Combined length frequencies in Selma Channel and Fairbairn Dam. Pumped intake 129
Combined length frequencies in Weemah Channel and Fairbairn Dam. Gravity fed intake 130
Appendix IV: Kolmogorov-Smirnov tables 131
Glassfish *Ambassis agassizii* (AMBAGA) 131
Barred grunter *Amniataba percoides* (AMNPER) 132

Carp gudgeon species *Hypseleotris* spp. (HYPSPP) 133
135
Spangled perch *Leiopotherapon unicolor* (LEIUNI) 135
Golden perch *Macquaria ambigua oriens* (MACAMB) 136
Eastern rainbowfish *Melanotaenia splendida splendida* (MELSPL) 137
Bony bream *Nematalosa erebi* (NEMERE) 138
Blue catfish *Neoarius graeffei* (NEOGRA) 140
Sleepy cod Oxyeleotris lineolatus (OXYLIN) 140
Flat-headed gudgeon *Philypnodon grandiceps* (PHIGRA) 140
Leathery grunter Scortum hillii (SCOHIL) 141

List of figures

Figure 1: Map of the rivers where pump intakes were located. 6
Figure 2: Schematic diagram of different river pump intake types. 7
Figure 3: Satellite image showing intakes for diversion channels from Fairbairn Dam. 8
Figure 4: Outlet sampling net in place. 9
Figure 5: Electrofishing boat in operation on the Mackenzie River. 10
Figure 6: A fyke net. 11
Figure 7: The relationship between entrainment rates per 100 min for fish ≤ 100 mm in length by pump or flow rate and intake type. Top of dam, pumped (Selma Channel) and bottom of dam gravity fed (Weemah Channel). 20
Figure 8: The relationship between entrainment rates per 100 min for fish > 100 mm in length by pump or flow rate and intake type. Top of dam, pumped (Selma Channel) and bottom of dam gravity fed (Weemah Channel). 20
Figure 9: a). Adjusted mean daily entrainment rates of bony bream larvae in an irrigation diversion channel by flow rate (p=0.052) and b). by intake type (p<0.05): 21
Figure 10: a). Adjusted mean daily entrainment rates of all larvae combined in an irrigation diversion channel by flow rate and b). by intake type Pumped upper channel diversion (Selma channel) and gravity fed lower channel diversion (Weemah Channel). 21
Figure 11: Adjusted mean entrainment per 100 min of various fish species and size classes by pump rates (ML/day). Error bars show standard errors of the mean. 23
Figure 12: Adjusted mean entrainment per ML for a. All fish ≤100 mm b. All fish >100 mm c. Bony bream <100 mm and d. Olive perchlets.. 24
Figure 13: Adjusted mean entrainment per 100 min by intake location and depth for various fish species and size classes 25
Figure 13 (continued): Adjusted mean entrainment per 100 min by intake location and depth for various fish species and size classes.. 26
Figure 14: Entrainment rates per 100 min by flow type. 28
Figure 14 (continued): Entrainment rates per 100 min by flow type. 29

Figure 15: Adjusted mean entrainment rate (per 100min) of all fish ≤100 mm by season.. 29
Figure 16: Adjusted mean entrainment rates of golden perch larvae through pumped riverine intakes, by intake type and depth and season. 30
Figure 17: Histogram showing differences between length-frequency distribution of golden perch entrained into the Weemah channel (blue) and in Fairbairn Dam (red) on 24 January 2022.). 32
Fig 18: Histogram showing differences between length-frequency distribution of entrained spangled perch at pump outlet 1 (blue) and fish sampled in the adjacent reference site (red).. 33
Figure 19: A diagram of a cone screen showing internal workings. 48
Figure 20: Installation of cone screens. 48
Figure 21: A diagram of a brush cleaned T style wedge-wire cylinder screen 49
Figure 21: A T style retrievable wedge-wire self-cleaning cylinder screen in the raised position......... 50

List of tables

Table 1: Summary of pumps, diversion channels and flow events monitored …………….………… 5
Table 2: Factors and variables considered for inclusion in statistical models of entrainment through irrigation infrastructure ……………………………………………………………………………… 13
Table 3: Fishes (excluding larval stages) recorded either entrained through riverine irrigation pump outlets or from the adjacent river reference sites …………………………………………………………16
Table 4: fishes (excluding larval stages) recorded either entrained in the Weemah or Selma diversion channels or in the adjacent Fairbairn Dam reference site ………………………………………………. 17
Table 5: larval fish and fish eggs recorded in river reference sites and/or entrained at irrigation pump outlets ……………………………………………………………………………………………………… 17
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 ………………………………………………………… 17
Table 7: K-S probabilities for flat-headed gudgeon on discrete sampling events and combined …… 31
Table 8: K-S probabilities for golden perch on discrete sampling events and combined events ……. 32
Table 9: K-S probabilities for spangled perch on discrete sampling events …………………………… 34
Table 10: K-S probabilities for olive perchlet on discrete sampling events……………………………...34
Table 11: K-S probabilities for entrained golden perch larvae on discrete sampling events at pump outlets and associated reference sites …………………..………………………………………………… 34
Table 12: K-S probabilities for carp gudgeon on discrete sampling events in diversion channels and Fairbairn Dam ……………………………………………………………………………………………..……. 35
Table 13: Summary of one-way ANOVA for susceptibility indices scores for different species and size classes entrained through riverine pumps ………………………………………………………………... 35
Table 14: Mean susceptibility index scores for different native fish and size classes at riverine pump locations …… 35
Table 15: Summary of one-way ANOVA for susceptibility indices scores for different species and size classes entrained in diversion channels originating from Fairbairn Dam ……………………………… 37

Table 16: Mean susceptibility scores for different native fish and size classes at Fairbairn Dam irrigation diversion channels …………………………………………………………………………… 38

Table 17: Summary of one-way ANOVA for susceptibility indices scores for different species of fish larvae and fish eggs entrained through riverine pumps …………………………………………………. 39

Table 18: Mean susceptibility index scores for different larval native fish and fish eggs at riverine pumps ………………………………………………………………………………………………………. 39

Table 19: Scoring metrics for the different pump prioritisation categories …………………………..… 55

Summary

Entrainment of native fish through irrigation systems is an environmental impact of irrigation activities. Entrained fish are almost always permanently lost to the river system and fish can also suffer significant mortalities as they pass through offtakes. In this study, entrainment rates of fish through different irrigation intake systems were evaluated. Various riverine pumps on the Comet, Nogoa and Mackenzie rivers and the irrigation diversion channels originating from Fairbairn Dam were compared. Irrigation outlets were sampled during natural and allocated flow events with specialised nets to capture all fish entrained over a 100-minute period. Entrainment rates were calculated as fish per unit time and as fish per megalitre (ML) extracted. Larval nets with flow meters were also set to calculate the number of fish larvae entrained per ML.

Nearby river and impoundment reference sites were sampled during the same flow events. Catch rates from the reference sites were used as a covariate in generalised linear models to harmonise comparisons between irrigation systems. Reference site catch rates, when compared with entrainment rates also helped identify species and size classes of fish that were more or less susceptible to entrainment.

The results from the diversion channels originating from Fairbairn Dam suggest that gravity fed diversions entrain significantly more fish per ML and per unit time than pumped diversions. The water extraction rate was far less important than whether the channel was gravity fed or pump fed.

Several factors were considered when comparing riverine pumps, including pump rate (ML/day), intake location and depth (intake configuration), and flow type pumped (allocated flow, natural within-bank flow or overbank flow). For most species there was a general trend for increasing entrainment rates as pump rates increased, although the fish entrained per ML increased at a lesser rate than fish entrained per unit time as pump rate increased. Pump intake position and depth significantly impacted entrainment rates, with shallow bankside intakes generally entraining far fewer fish than bankside deep, mid-river channel or side-channel pump intakes. Some very large pumps with shallow bankside intakes entrained far fewer fish than some smaller pumps nearby with different intake configurations. There was some variation between species and size classes on which intake locations and depth had the greatest impact, but for most species and size classes, entrainment through bankside shallow intakes was consistently low.

Pumping from overbank flows (flows where the river covers the bench) entrained far fewer fish than pumping from both natural within-bank flows and allocated flows. However, it is highly unlikely that any irrigator pumps solely from overbank flows. There was no statistically significant difference between allocated flows and natural within bank flows in terms of total numbers of fish entrained. Allocated flows tended to entrain more small fish, whereas fish >100 mm length appeared to be more susceptible to entrainment on natural within-bank flows. The pelagic larvae of golden perch were only entrained on natural within bank flows. Pumping natural within bank flows probably has a marginally higher biological impact on fish than pumping from allocated flows. Further replication would help determine these differences more conclusively.

Based on individual pump licenses and operations it is possible to predict the likely severity of impact of a pump. This can be done by considering pumping rate, pump intake position and depth (intake configuration), flow type(s) pumped and annual licensed allocation (total volume licensed to pump of any flow type). By cross multiplying score metrics for these different categories, a score can be derived for different pumps in a river system. The scores can help prioritise pumps for mitigation

actions such as screening. 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 site characteristics also need to be considered. Any group, agency or peak body wishing to invest in pump screening, in some cases may achieve better outcomes for fish per unit cost by screening several slightly lower ranked pumps, rather than expending a large amount of money on a single highly ranked pump that is logistically difficult and thus expensive to screen.

The following recommendations have been derived from this research project.

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.

Introduction

Cotton is an important agricultural industry in Australia, and there are over 1,500 cotton farms across the country. The cotton industry employs more than 12,000 people and operates primarily in New South Wales and Queensland, with small areas of production in Victoria, the Northern Territory and Western Australia. Much of the cotton crop relies on an irrigated water supply and the industry has become increasingly water efficient (Cotton Australia, 2020). The Cotton Research and Development Corporation (CRDC) has developed a strategic RD&E plan for the period 2018-2023 (CRDC 2018) with the objective of increasing economic, social, and environmental benefits for the Australian cotton industry and wider community, by investing in knowledge, innovation and its adoption. One part of the plan focuses on investments in RD&E that ensure Australian cotton continues to be produced to the highest environmental and social standards, with an improved environmental footprint.

One area where the cotton industry can reduce its environmental footprint is through improvements to fish friendly cotton production. Australian freshwater fishes are of social, economic and cultural value (Cottingham *et al*. 2020). The potential for native freshwater fish to be entrained through Australian irrigation systems, including pumped diversions and gravity fed diversions, has been recognised since early this century. Blackley (2003), the MDBC (2004), Baumgartner (2005), Baumgartner *et al*. (2007) and King and O'Connor (2007) were among the first to draw attention to this potential impact on fish in Australia. Subsequent research on pumped diversions (*e.g.,* Baumgartner *et al.* 2009; Boys *et al.* 2012; Norris 2015) has demonstrated that Australian freshwater fish are indeed susceptible to entrainment through irrigation systems and can suffer significant injuries and mortalities. Some fish may survive their passage through irrigation infrastructure, although these are still permanently lost from the ecosystem, and can no longer contribute to reproduction and recruitment of their species in the riverine environment. Some species and size classes appear to be more susceptible to entrainment than others, and this may be in part due to swimming ability, behaviour, and the location of the offtake (Ehrler and Raifsnider 2000; Baumgartner *et al.* 2009; Norris *et al.* 2020).

To date, there has been very little quantified information published on the rate of fish loss through irrigation infrastructure in Australia, and the role that intake configuration has in dictating entrainment rates. There is also a paucity of information on *in situ* susceptibilities of different Australian native fish species and size classes, on both allocated and natural flows. Such information is important for minimising impacts and prioritising mitigation expenditure. Mitigation options can be expensive, so efforts should be focussed on the least fish friendly irrigation infrastructure.

In recognition that cotton irrigation has the potential to entrain native fish, the Queensland Department of Agriculture and Fisheries (DAF) Animal Science group were engaged by the CRDC to examine the relative impact of different infrastructure types, with the aim of developing Best Management Practices to minimise future impacts of irrigation infrastructure on fish. As part of this process, DAF prepared a literature review on current known impacts of irrigation infrastructure and theoretical susceptibility of different native fish species and size classes (see Hutchison *et al*. 2020, available on the CRDC website) based on existing data on their swimming abilities. For many species or life stages, there was no data available.

DAF also examined what is currently documented for different mitigation technologies, including various screening options. Some modern self-cleaning screen options show promise for delivering good flow rates (Hutchison *et al*. 2020). DAF identified a gap in the knowledge of the economic impacts of screens on irrigated agriculture (both positive and negative), but this is currently being addressed by research being completed in New South Wales (NSW) by the Department of Primary Industries (DPI).

To better understand how irrigation infrastructure affects fish, the authors of this report designed a study to investigate the effects of flow type, pump size (pumping rate) and pump intake configuration (position and depth) on fish. For more details refer to the methods section below.

The Emerald region in Queensland was chosen to run these investigations because the fish fauna in this area contains a mix of tropical and temperate freshwater fish species of economic, social, cultural and conservation importance. Therefore, some of the results from this study can be applicable to both northern tropical rivers like the Burdekin River, and to southern temperate rivers such as those in the Murray-Darling Basin. The study was designed to collect data that could be used to objectively prioritise mitigation efforts. It was also designed so that it could provide objective guidance on optimal position and depth configuration of any new intake infrastructure, with a view towards minimising future impacts on fish populations. This report focuses on the relative impact (on different species and size classes of fish) of various infrastructure types under both natural and allocated flows and introduces a prioritisation scoring system to guide mitigation efforts. Several potential mitigation options are also discussed.

Methods

Experimental design

This project opportunistically sampled pump outlets on cotton farms for entrained fish during natural and allocated flows in the period from January 2021 to March 2022. 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. We selected a diverse range of pump sizes, ranging from an extraction rate 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. We classified intakes where the top of the intake sat less than 1 m below the water surface during normal allocated flow or base flow levels 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 as deep. We ended up with four intake position and depth configurations in this study. They were as follows, bankside shallow, bankside deep, mid-river channel deep and side channel shallow.

Pumping events from allocated flows released from Fairbairn Dam, and from natural flows, which included both within bank and overbank flows were monitored. Overbank flows are where water covers at least the bench. The number of samples collected was limited by the number of growers pumping on any given flow, and by the frequency of flows. The key factors investigated were pump size, pump intake location and depth and flow type.

Entrainment of fish in 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, and both 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

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	Natural flows
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	1	2
8	Bankside deep	100	2	1
9	Bankside shallow	22.5	1	
11 (Selma Channel)	Pumped diversion from dam	75-400	4	
12 (Weemah Channel)	Gravity diversion from dam	75-259	4	
13	Mid-river channel deep	88.5	1	
15	Bankside shallow	140	1	
16	Bankside deep	90		1
17	Mid-river channel deep	14-14.5	2	

27% capacity. Therefore, the Selma channel was supplied solely by pumping. 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) could possibly influence where fish sit in the water column relative to the channel intakes, with most fish likely to avoid the deoxygenated water below the thermocline. Water temperatures may also affect fish activity levels and susceptibility to entrainment. During the study period, low water levels in Fairbairn Dam meant that the intake site for the Weemah diversion was always above the thermocline, thus this influence could not be investigated.

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

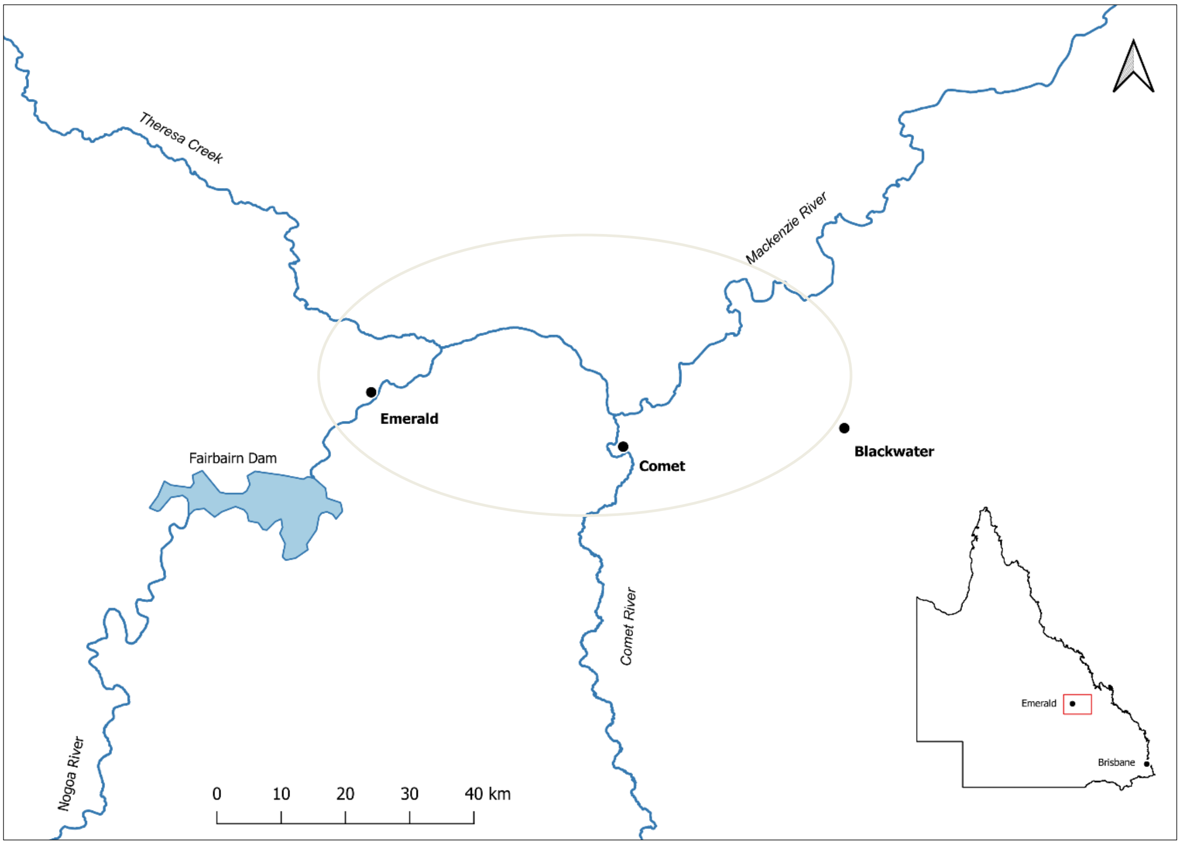


Figure 1: Map of the rivers where pump intakes were located. Sampling was completed along the Nogoa, Mackenzie and parts of the lower Comet River within the area circled between Emerald and Blackwater. Sampling also took place within Fairbairn Dam and in the two diversion channels exiting from Fairbairn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

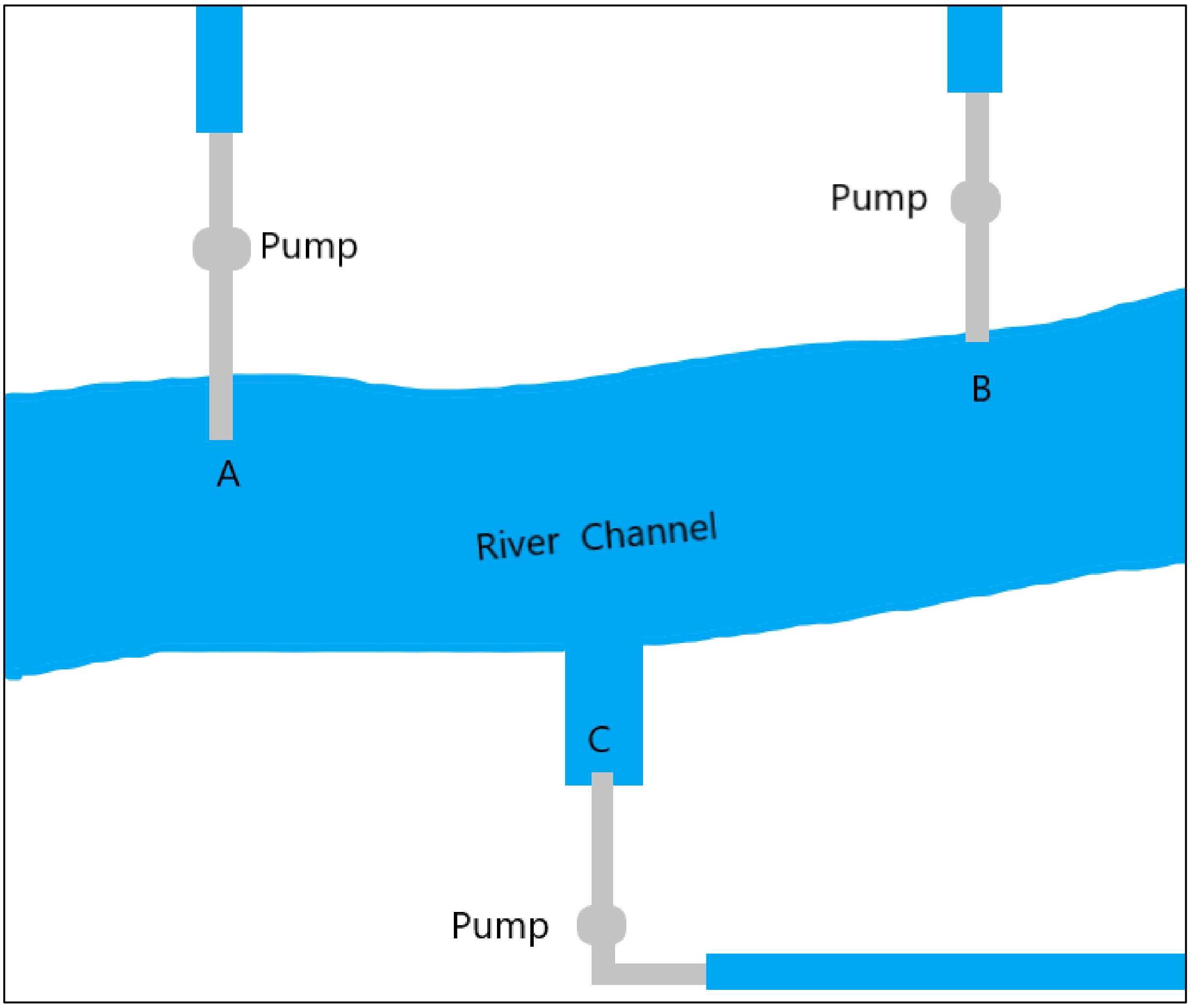


Figure 2: Schematic diagram of different river pump intake types. A: Mid-river channel intake that extends several metres out from the bank. B: Intake that is close to or flush with the riverbank. C: Intake that draws water from an excavated side channel. Pump outlets run into irrigation channels (as 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.

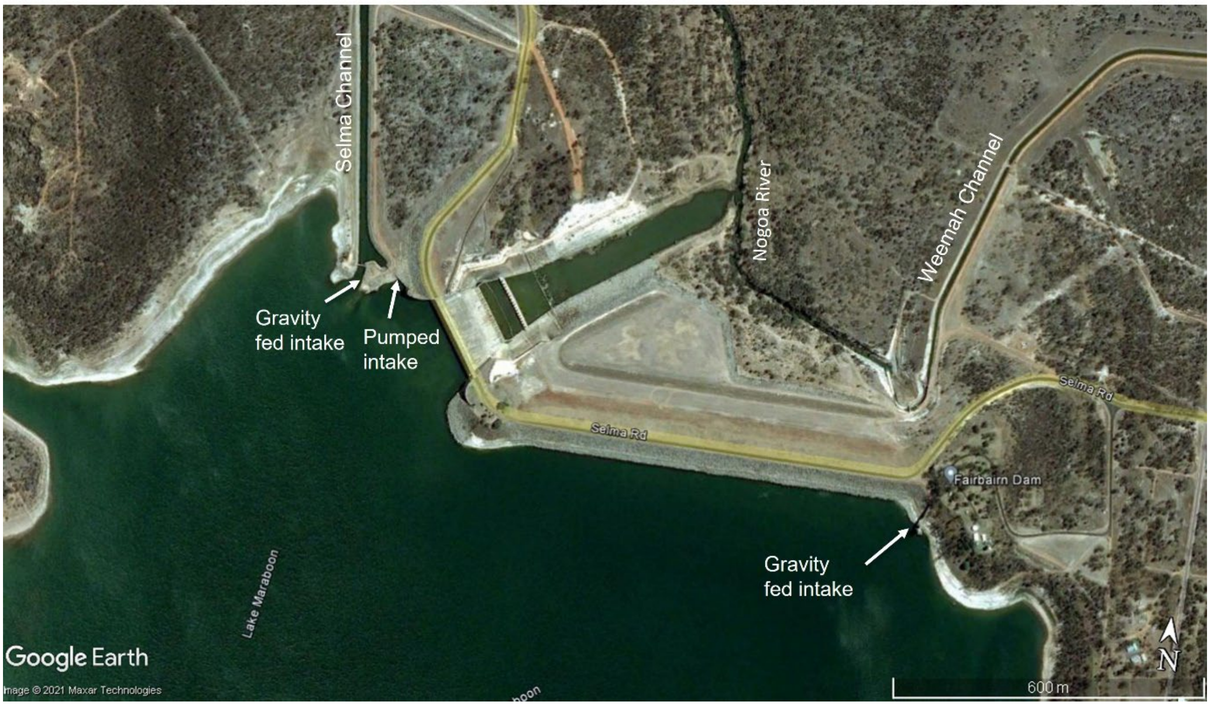


Figure 3: Satellite image showing intakes for diversion channels from Fairbairn Dam. Selma Channel intake (upper left) when gravity fed, or when pumped into the channel at dam levels below 68% capacity. Alternatively, water passes from the intake (lower right)) through the bottom of the dam wall to be 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, including the entrance of the pocket. 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 pump outflow velocity. The net was held in place by steel stakes (star pickets) or alternatively tied to a bull bar of a vehicle (Figure 4). Once the net was secured in the flow it 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 ML.

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

Larval netting

A larval net was also set downstream of the pump outlet for a period of 20 to 30 min. The duration of a set depended on the current velocity and debris load. Larval nets were made from 200 µm mesh and had a fine nylon fabric pocket. The net opening had a diameter of 56cm and the entry to the larval net was fitted with a current meter. By using the start and finish readings from the current meter counter, it was possible to estimate the number of cubic metres of water that had passed through the larval net in the set period. At the end of the set period the contents of the larval net were emptied into a bucket. Any non-larval fishes were picked 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 give some indication of the species composition and abundance of fish and fish larvae 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 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 and 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 can be dip-netted from the water for measurement and identification. 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 and sampled representative habitat for the reach.

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 excluder was to prevent large turtles from entering the fyke net and preying on captured 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.

Figure 6: A fyke net. 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 there was sufficient current velocity, larval nets were set in the river using the same methodology as in the irrigation channels, alternatively larval nets were towed behind the electrofishing boat while travelling at low speed for 10 min or approximately 600 m. Samples from Fairbairn Dam were always collected by towing. A current meter set in the mouth of the net enabled calculation of the exact 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. Some 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 species or family level. 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 Excel tables, with tables for shot details, site characteristics, fish catch and fish size. For statistical analyses species specific tables were set up in a format that could be imported in Genstat for analyses (see statistical analyses below). Additional tables were set up for automated 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 for fish >100 mm in fork length. The index was based on the catch per ML 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 ML 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 ML is generally lower than the standardised river catch, most index values will be <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 m^3 was divided by the catch m^3 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 m^3 was designated as 0.01. Note 0.01 larvae per m^3 is equivalent to10 larvae per ML. 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 m^3 and the catch rate in the reference site was 0.08 per m^3, 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. Note the larval susceptibility index can be expected to exceed a value of 1 more frequently than the index for adult and juvenile fish.

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 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, Secchi depth (turbidity) 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. See Table 2 for details. 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 ML per day Water temperature Secchi depth Conductivity	River or impoundment reference site catch

Generalised linear models

Generalised linear models (GLM) (McCullagh and Nelder 1989) were used to analyse the catch rate data for adult, juvenile and larval fish in GenStat (2021). 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.

Interactions between the fixed effects were screened, but none proved to be significant. Adjusted means (and their standard errors) were estimated and subjected to unprotected post-hoc testing.

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.

Comparison of size distributions

Length frequency histograms were prepared for the more abundant species captured in the river or found passing through irrigation infrastructure. This was to provide a visual comparison of the size distributions between river or impoundment fish and the fish entrained through the adjacent irrigation infrastructure. This was done for each piece of irrigation infrastructure each sampling occasion. Most of these histograms are presented in the Appendices. They also show species that may have been abundant in the reference location, but rarely entrained through pump infrastructure.

Length distributions of fish from irrigation infrastructure and the adjacent river or impoundment sites were also compared statistically in Genstat® (18^{th} edition, VSN International UK), using the non-parametric Kolmogorov-Smirnov (K-S) test. K-S tests were used for individual fish species, to compare the length distribution of entrained fish at pump outlet sites with the length distribution at the adjacent reference site. The K-S test produces a probability value (p), which indicates the probability of the two size distributions being the same. We used a p of ≤ 0.05 to indicate a significant difference.

These tests were only possible where sufficient numbers of a species were recorded at both the entrainment site and the associated reference site during contemporaneous sampling. Many species occurred commonly in the reference sites while occurring only infrequently in the entrainment sites, and the opportunities to conduct K-S tests for these species were limited. However, additional K-S tests for these species were achieved by combining the measurements from several sampling events on the same flow type at individual sites.

Initial K-S tests included all length data for a species, including measurements of larval fish (<15mm TL). A second round of K-S tests were conducted with larval measurements omitted to evaluate the contribution of larvae to probability values. Length-frequency histograms showing fish distribution at pump outlet sites and at the adjacent reference sites were also evaluated alongside K-S results. This helped to identify the shape and direction of significant differences, visually demonstrating whether entrained fish at pump outlet sites were larger or smaller than fish sampled in the adjacent reference sites.

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. 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® (18th edition, VSN International UK). Analyses were by one way ANOVA followed by a post-hoc pairwise comparison of the means using Fisher's protected LSD test or a Tukey test.

Results

To make this section more user friendly to the reader, many of the statistical models and other outputs have been placed in the appendices. In this section we have chosen to focus on the key patterns detected and to highlight factors or results that were statistically significant. For the GLM outputs we have chosen to present the predicted mean value outputs rather than the tabulated model outputs. The tabulated outputs can be found in the appendices. 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. Adjusted means 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 in this study and whether these species and size classes were ever found entrained during this 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.

Species or size classes recorded quite regularly in the river reference sites but not found entrained through riverine pumps were saratoga >100 mm, barred grunter >100 mm and golden perch both > 100 mm and ≤ 100 mm. However 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.

In contrast to the riverine pumps, golden perch were found entrained in both the pumped Selma Diversion Channel and the gravity fed Weemah Diversion Channel. Juvenile golden perch were relatively common in Fairbairn Dam, with good recruitment evident from an upstream flow event.

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 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. Those size classes 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*	no	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	Bony bream	*Nematalosa erebi*	yes	yes
	Hyrtl's tandan	*Neosilurus hyrtlii*	no	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
	Rendahl's tandan	*Porochilus rendahli*	yes	no
	Barramundi	*Lates calcarifer*	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	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
	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*	no	yes
Sleepy cod	*Oxyeleotris lineolatus*	no	yes
Unidentified larvae		yes	yes
Unidentified yolk sac larvae		yes	yes
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	no
Carp gudgeon species	*Hypseleotris* spp.	yes	yes
Flat-headed gudgeon	*Phylipnodon grandiceps*	yes	no
Sleepy cod	*Oxyeleotris lineolatus*	yes	yes

Range of entrainment rates

Diversion channels

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 256 fish per 100 min sampled. On a per ML basis catches ranged from 7.114 fish/ML to 10.748 fish/ML. The mean catch per ML was 9.084 fish. Based on prevailing pumping rates, extrapolated entrainment rates per day ranged from 806 to 3686 fish per day. Larval entrainment rates ranged from 0 to 17.5 larvae/ML. Based on pumping rates the highest extrapolated daily entrainment of larvae recorded was 7000 larvae per day (range 0 to 7000).

Entrainment rates in the gravity fed Weemah diversion channel ranged from 327 fish per 100 min sampled to 4351 fish per 100 min sampled. On a per ML basis catch rates ranged from 30.932 fish/ML to 626.950 fish/ML. The mean catch per ML was 196.93 fish. Based on diversion rates extrapolated entrainment rates ranged from 3866 to 17377 fish per day. The maximum entrainment rate of larval fish recorded was 18.6 larvae per ML (range 0 to 18.6 larva/ML). Based on prevailing diversion rates the highest extrapolated daily entrainment rate for fish larvae was 2325 larvae per day.

Riverine pumps

Sampled riverine pumps varied considerably in size (see GLM results below for effect of pump rate on catch) with pumping rates ranging from 14 ML/day to 164 ML per day. Across all riverine pumps catch rates ranged from 1 fish per 100 min sampled to 793 fish per 100 min sampled. On a per ML basis, catch rates ranged from 0.614 fish/ML to 137.233 fish/ML. The mean catch per ML across all samples was 28.99 fish. Extrapolating catch per ML figures showed potential daily entrainment rates of fish through riverine pumps ranging from 43 to 5794 fish per day. Entrainment rates of larval fish through riverine pumps ranged from 0 per ML to 2878 per ML. Based on daily pumping rates, extrapolated daily entrainment rates for fish larvae ranged from 0 to 42,111 fish larvae per day. More detailed breakdowns of entrainment rates by species are provided in the GLM results below.

Generalised linear model outputs

In this section the focus is on the predicted 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 Appendix I.

Adult and juvenile fish entrainment in impoundment diversion channels

Intake type (pumped or gravity fed)

For most species and size classes of fish there were 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 the gravity fed Weemah Channel. Significant differences where mean entrainment rates were higher in the Weemah Channel included the combined catch of all fish ≤100 mm ($p<0.001$), carp gudgeon ($p=0.002$), bony bream <100 mm ($p<0.001$), barred grunter >100 mm ($p< 0.001$), Rendahl's tandan >100 mm ($p< 0.001$) and golden perch <100 mm ($p=0.005$). In the case of barred grunter <100 mm, significantly more fish were captured per 100 min in the Selma Channel ($p=0.040$). For most other species >100 mm there were no significant differences.

Pump rate

Pump or diversion flow rate showed no consistent patterns in entrainment rates. For some species entrainment rates increased with pump rate or flow rate but increases or decreases were not consistent between the two channels. The pump or flow rate was significant for some species but not others. The differences in the effect of pump or flow rate between the two diversion channels is summarised in Figure 7 which shows the relationship between pump or flow rate and all fish ≤100 mm (this includes combined juveniles of the larger species and all the small species that are <100 mm) in each diversion channel type and in Figure 8 which shows the relationship between pump rate and all fish >100 mm in each diversion channel type. Note the entrainment rate of the smaller fish (Figure 7) is far greater than that of larger fish (Figure 8). Those species and size classes for which a significant effect was detected for flow or pump rate on the number of fish entrained per 100 min were barred grunter <100 mm (p=0.041), sleepy cod <100 mm (p=0.003), eastern rainbowfish (p=0.006) and bony bream <100 mm (p< 0.001). Some of these relationships were negative and there was also a significant interaction between channel intake type and pump rate for eastern rainbowfish.

The GLMs that used catch per ML rather than catch per 100 min for entrainment rates did not reveal any patterns that were considerably different to those above, with catch rates in the Weemah channel being generally higher than those in the Selma Channel. When using catch per ML, flow or pump rate was less useful as a predictor of catch, so the catch per ML models were not considered further here for the impoundment diversion channels.

It is possible other influences were having a greater effect on entrainment rates per 100 min than the pumped or gravity fed flow rates to the diversion channels (see discussion). Other significant influences on entrainment rates included temperature for carp gudgeon spp. (p=0.003) (where entrainment rates were increased with increasing temperature) and the number of fish in the reference site, where increased abundance of fish in the reference site led to more fish entrained in the diversion channels.   Examples for the latter include all fish ≤100 mm combined (p<0.001), eastern rainbowfish (p=0.003), Flat-headed gudgeon ≤100 mm (p=0.034), bony bream ≤100 mm (p<0.001), sleepy cod ≤100 mm (p = 0.037) and barred grunter ≤100 mm (p= 0.049).

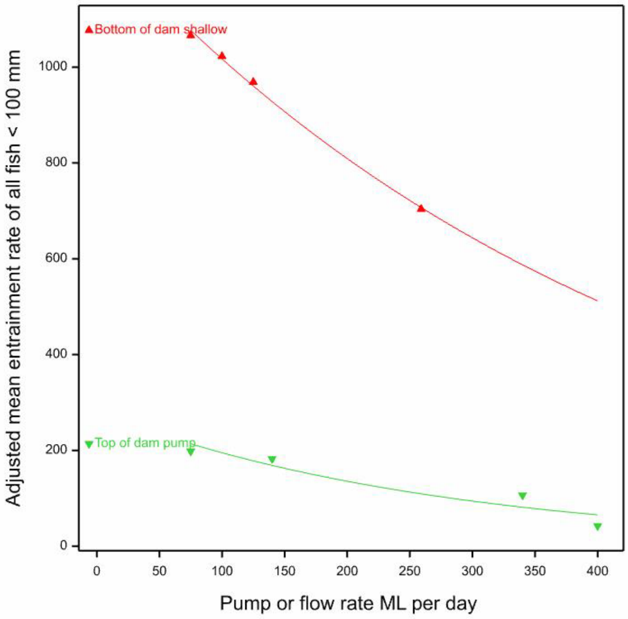


Figure 7: The relationship between entrainment rates per 100 min for fish ≤ 100 mm in length by pump or flow rate and intake type. Top of dam, pumped (Selma Channel) and bottom of dam gravity fed (Weemah Channel).

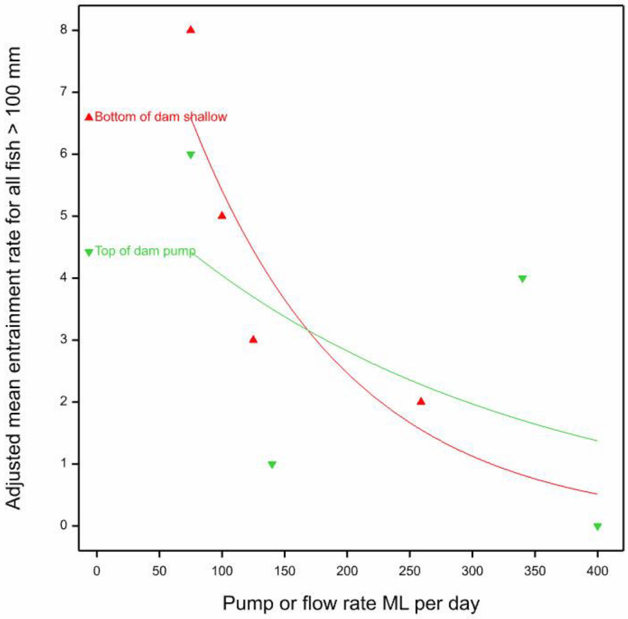


Figure 8: The relationship between entrainment rates per 100 min for fish > 100 mm in length by pump or flow rate and intake type. Top of dam, pumped (Selma Channel) and bottom of dam gravity fed (Weemah Channel).

Larval fish in impoundment diversion channels

Only two species of larvae, bony bream and flat-headed gudgeon were captured in sufficient numbers and/or on sufficient occasions for any statistical analyses to be completed. Combined catch of all species of larvae (to include the more rarely caught species) was also analysed.

Bony bream larvae showed a tendency to have increased entrainment rates with increased gravity fed flow rate ($p=0.052$) (Figure 9a) and there was a significant difference in entrainment rate between the gravity fed Weemah Channel and the pumped Selma Channel, with all bony bream larvae being recorded in the gravity fed channel (Figure 9b) ($p<0.05$).

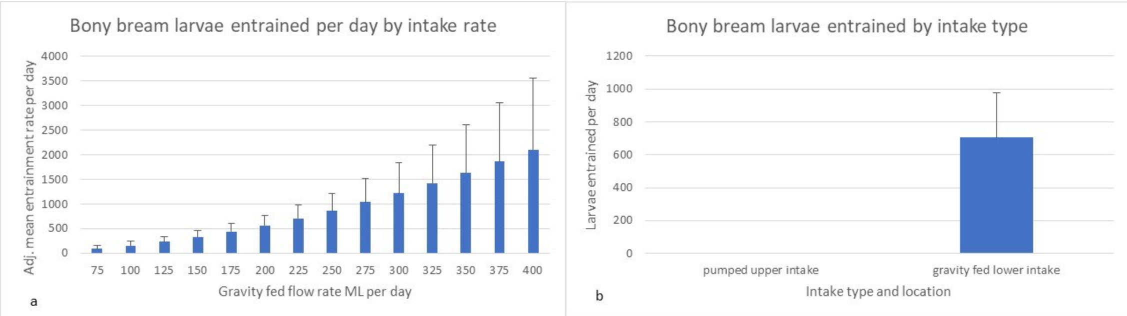


Figure 9: a). Adjusted mean daily entrainment rates of bony bream larvae in an irrigation diversion channel by flow rate ($p=0.052$) and **b).** by intake type ($p<0.05$): Pumped upper channel diversion (Selma channel) and gravity fed lower channel diversion (Weemah Channel). Error bars show one standard error of the mean.

Flat-headed gudgeon larvae tended to be more common in the gravity fed Weemah channel, but differences between the two channels were not statistically significant. Catch rates were too low to include pump rate in the model.

Combining all larvae into a single model showed a tendency for more larvae to be entrained with increasing pump or flow rate into the diversion channels (Figure 10a) and for more larvae to be entrained in the gravity fed Weemah Channel (Figure 10 b). However, neither result was statistically significant.

Larvae entrained per ML rather than per day as the dependant variable made no appreciable difference to the observed patterns. Catch per ML tended to increase with increased flow rate and although showing a positive trend was a flatter plot and not significant.

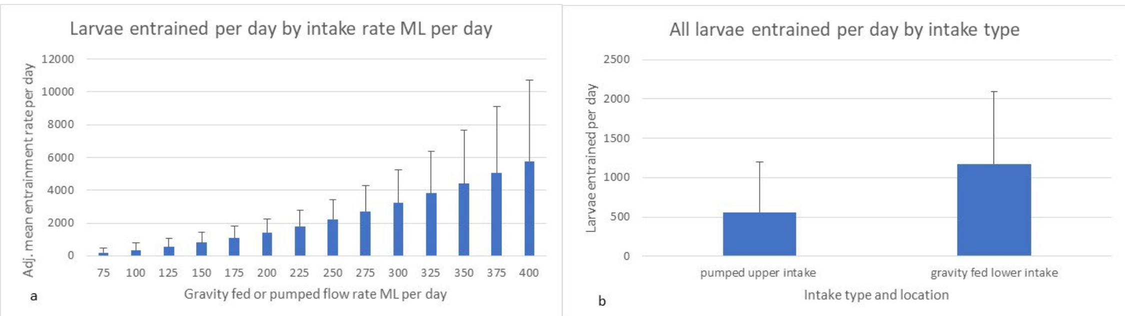


Figure 10: a). Adjusted mean daily entrainment rates of all larvae combined in an irrigation diversion channel by flow rate and **b).** by intake type: Pumped upper channel diversion (Selma channel) and gravity fed lower channel diversion (Weemah Channel). Error bars show one standard error of the mean. Neither plot was statistically significant

Adult and juvenile fish entrainment through riverine pumps

There were common patterns for many of the species and size classes captured regularly enough at riverine pump outlets for statistical analyses. Although not all patterns observed were significant, repetition of similar patterns across several species and/or size classes provides weight of evidence. There were some species that had markedly different results to others, and these may be explained by some behavioural traits (see discussion).

Pump rate

For most species pump rate was not statistically significant for number of fish entrained per 100 min, yet for most species there was still a positive trend evident for increasing rates of entrainment with increasing pump rate (Figure 11). Note the vertical axis scale is different for each species and size class in Figure 11, but the trends are generally consistent. The positive trend was statistically significant for bony bream >100 mm ($p<0.05$) (Figure 11d) but the entrainment rates were much higher overall for bony bream ≤100 mm (Figure 11c). The temporal variability in catch rates has influenced the statistical result for most species. Spangled perch juveniles showed a much flatter trend than other species and size classes of fish, suggesting that their entrainment rate was less influenced by pump rate (Figure 11g). Larger spangled perch showed a slight positive trend for increasing entrainment with increasing pump rate (Figure 11f) but the positive trend was more pronounced for other species. The pooled entrainment rate for all fish over 100 mm in length also showed only a weak positive trend with increasing pump rate (Figure 11 a) but the pooled entrainment rate for all fish ≤100 mm showed a relatively strong positive relationship with pump rate (Figure 11b). Note some of the species used in the pooled data in Figure 11 were captured too infrequently at pump outlets to be evaluated separately. The number of different species entrained per 100 min increased with pump rate (Figure 11j) and this was statistically significant ($p <0.05$).

Using number of fish entrained per ML as the dependent variable did not alter patterns greatly. Figure 12 shows some typical examples. For most species there was still a slightly positive but non-significant trend for increasing entrainment rates with increasing pump rates, but patterns were generally asymptotic, with catch rates increasing most steeply for pump rates between 20 and 50 ML per day, then flattening off. The generally flatter or asymptotic nature of the catch per ML with increasing pump rate is supportive of using catch per ML for development of the susceptibility indices of different species and size classes for comparative purposes (see susceptibility indices below). Fish entrained per ML is not considered any further as a dependent variable in any more of the GLM analyses presented here as it did not add anything significant to our understanding of entrainment of fish. However, observed patterns of change in catch per ML by pump rate were used in development of prioritisation criteria, because catch per ML cross multiplied with total volume pumped was useful for predicting relative impacts of different pumps. Some additional catch per ML plots against pump rate are presented in Appendix II.

Further surveys may provide more statistical power to demonstrate significant differences between pump rates and add more support to the consistent trends across multiple species and size classes observed.

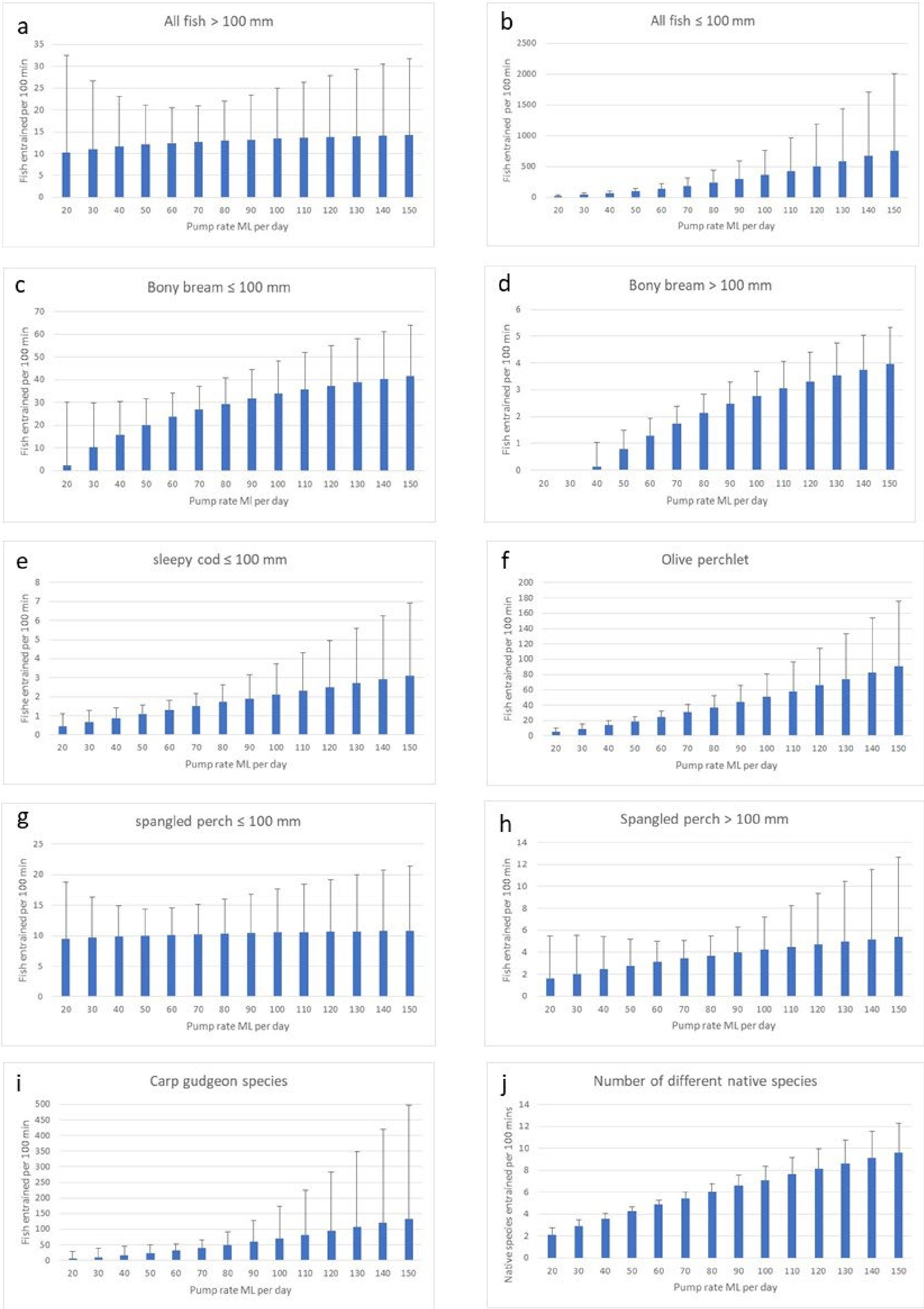


Figure 11: Adjusted mean entrainment per 100 min of various fish species and size classes by pump rates (ML/day). Error bars show standard errors of the mean. 11d & 11j are significant p<0.05)

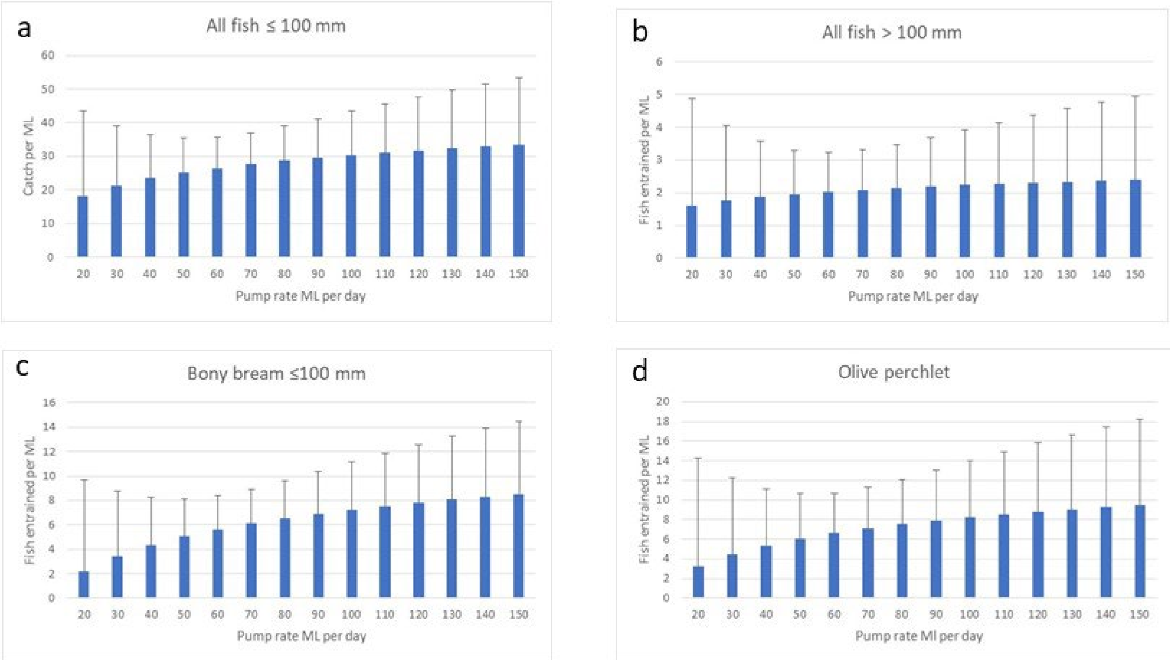


Figure 12: Adjusted mean entrainment per ML for **a.** All fish ≤100 mm **b**. All fish >100 mm **c.** Bony bream ≤100 mm and **d.** Olive perchlets. Error bars show standard errors of the mean.

Intake location and depth

Intake location and depth or intake configuration had a significant influence on entrainment rates for several species and size classes (Figure 13). For those species or size classes where intake location and depth were not significant, there was often a similar trend in the data to those for which this factor was significant. There were some species for which the patterns were different and sometimes still significant. The reasons for these differences are explored in the discussion.

The most common pattern across most species and size classes is for bankside shallow intakes to have low entrainment rates. Species and size classes for which bankside shallow intakes had significantly lower entrainment rates ($p<0.05$) compared to some of the other intake position and depths were bony bream >100 mm, spangled perch >100 mm, carp gudgeons, olive perchlet, barred grunter ≤100 mm and Rendahl's tandan >100 mm. For most other species the adjusted mean entrainment rate was lowest or one of the lowest at the bankside shallow intake. Generally, for those species and size classes where there was no significant difference, the standard error of the mean was quite small relative to the size of the mean at the bankside shallow intake, suggesting consistently low entrainment rates, but high variability at the other intake types prevented a significant difference from being detected. Examples of this include the pooled data for all fish ≤100 mm (Figure 13b) and sleepy cod >100 mm (Figure 13m). Significantly fewer species were entrained per 100 min through bankside shallow intakes ($p<0.05$) (Figure 13e).

There were some exceptions to the pattern above. For eastern rainbowfish (Figure 13j) the adjusted mean entrainment rate was highest at bankside shallow intakes ($p<0.05$) and blue catfish ≤100 mm (Figure 13l), also had the highest mean entrainment rate (not significant) at bankside shallow intakes. In the case of blue catfish, the standard error of the mean was larger than the mean for entrainment through this intake type.

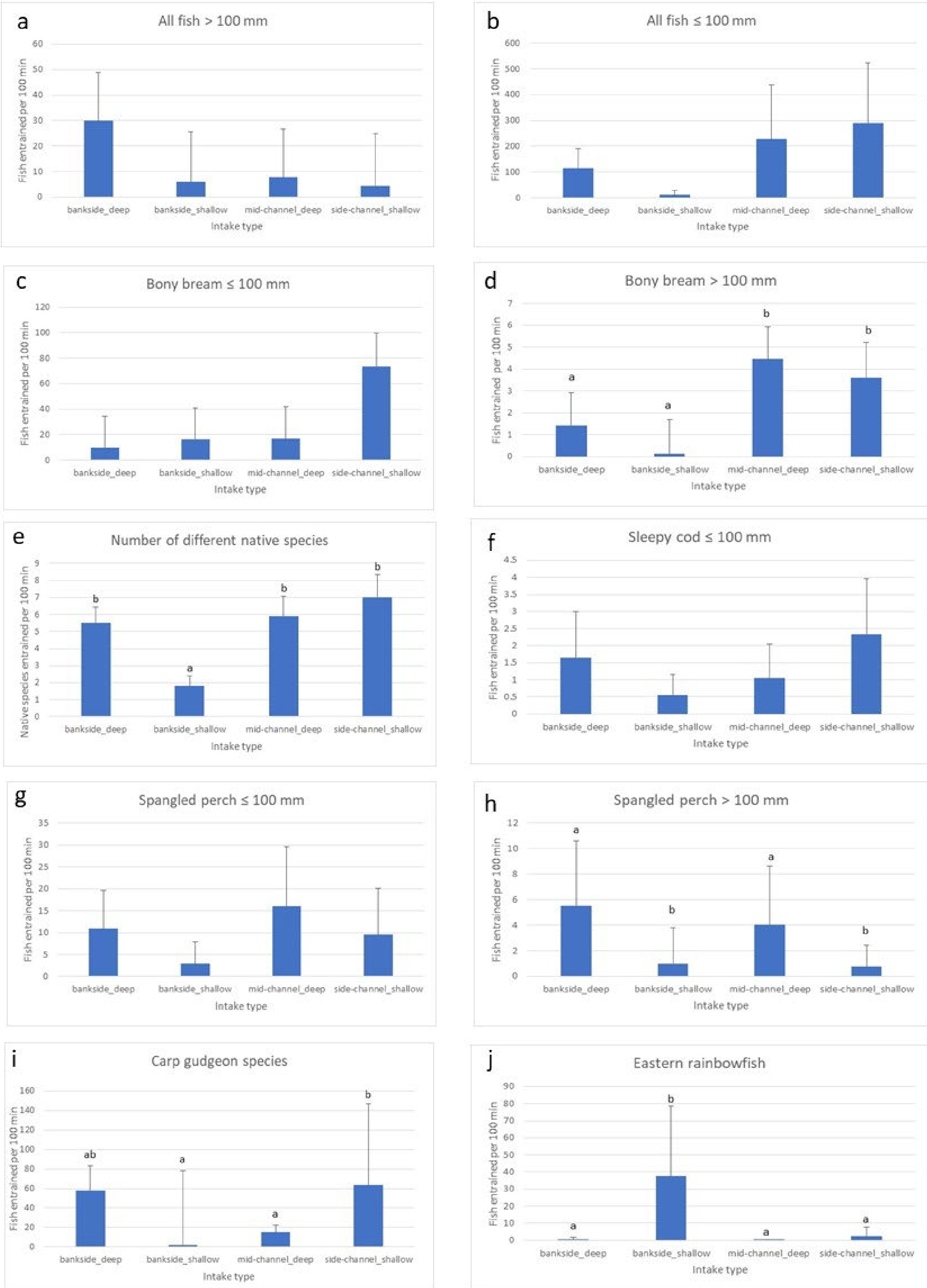


Figure 13: Adjusted mean entrainment per 100 min by intake location and depth for various fish species and size classes. Categories not sharing the same letter are significantly different (p<0.05)

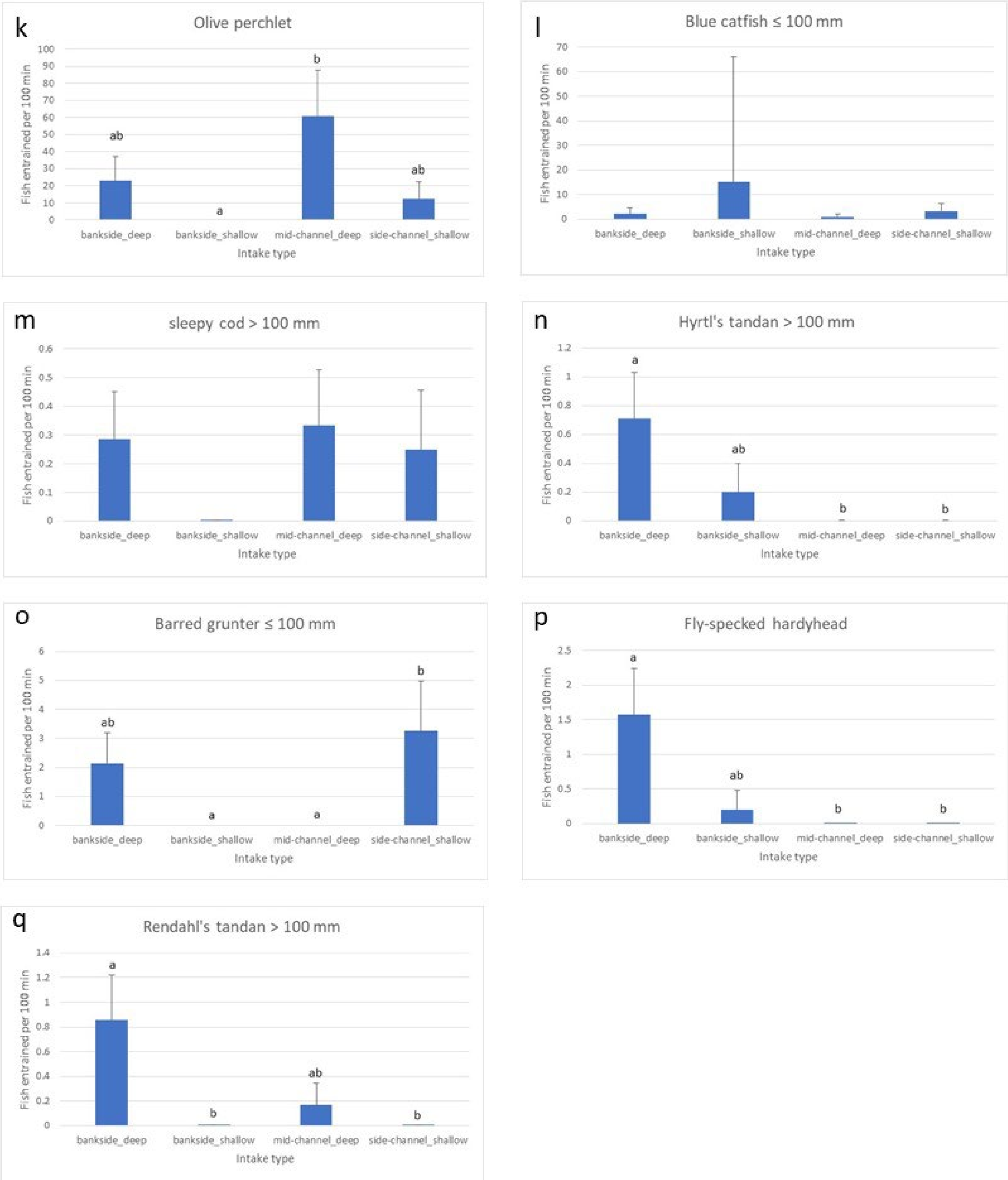


Figure 13 (continued): Adjusted mean entrainment per 100 min by intake location and depth for various fish species and size classes. Categories not sharing the same letter are significantly different ($p<0.05$). Plots in which there are no letters were not statistically significant. Error bars show one standard error of the mean. Note the vertical scale is different for different species and size classes on both this page and the previous page.

The other intake types were not consistent as to which had the highest adjusted mean entrainment rates. Across several species and size classes they were not significantly different to each other. Overall, the trend was for mid-river channel and side-channel intakes to entrain more small fish (≤100 mm) (Figure 13b) and bankside deep intakes tended to entrain more fish >100mm (Figure 13a). Olive perchlet (Figure 13k) were most susceptible to entrainment from mid-river channel intakes ($p<0.05$), although for many other species mid-river channel intakes seemed relatively benign. Bony bream ≤100 mm (Figure 13c were most susceptible to entrainment from side channel intakes ($p<0.05$), whereas bony bream >100 mm (Figure 13 d) were more susceptible to entrainment in both side-channel and mid-river channel intakes ($p<0.05$). Barred grunter ≤100 mm (Figure 13o) and carp gudgeons (Figure 13b) were quite susceptible to being entrained through side-channel intakes, but less susceptible to mid-river channel intakes ($p<0.05$).

Flow type

The most consistent pattern observed for flow type was pumps operating during overbank flows (flood flows that breach the regular riverbank or cover the bench) tended to entrain very few fish compared to allocated flows or natural flows that remain within the riverbanks (Figure 14). For most species and size classes the differences were not statistically significant. Although entrainment rates were consistently low on overbank flows across most species, there was considerable variability within the other flow types leading to quite large standard errors of the mean relative to the mean catch rate. This prevented the low catches in the overbank flows from being significantly different. For most species and size classes there was no significant difference in entrainment rates between allocated flows and natural within bank flows, but there were some species for which one was tending towards higher entrainment rates than the other. For blue catfish ≤100 mm, natural in bank flows had significantly higher entrainment rates than other flow types (Figure 14l). There was a tendency for fish >100 mm to be entrained more on natural in-bank flows (Figure 14a) with bony bream and spangled perch over 100 mm being part of this group (Figures 14d, 14h). In contrast olive perchlet tended to be entrained in greater numbers on allocated flows.

Other variables

For most species, although the catch of fish in river reference sites was generally positively related to entrainment rates in adjacent pumps, it was usually not statistically significant. However, it was significant for spangled perch >100 mm ($p<0.001$) and for olive perchlet ($p=0.025$). Season was run as a covariate in the GLMs for some species. Season was not found to be significant, but the general trend was for fewer fish to be entrained in the cool season than the warm season. However, variance was much larger in the warm season, and this accounts for lack of a significant difference between the adjusted means. Figure 15 shows an example (all fish ≤100 mm) of cool season and warm season entrainment rates. Note the large standard error of the mean for entrainment rates in the warm season.

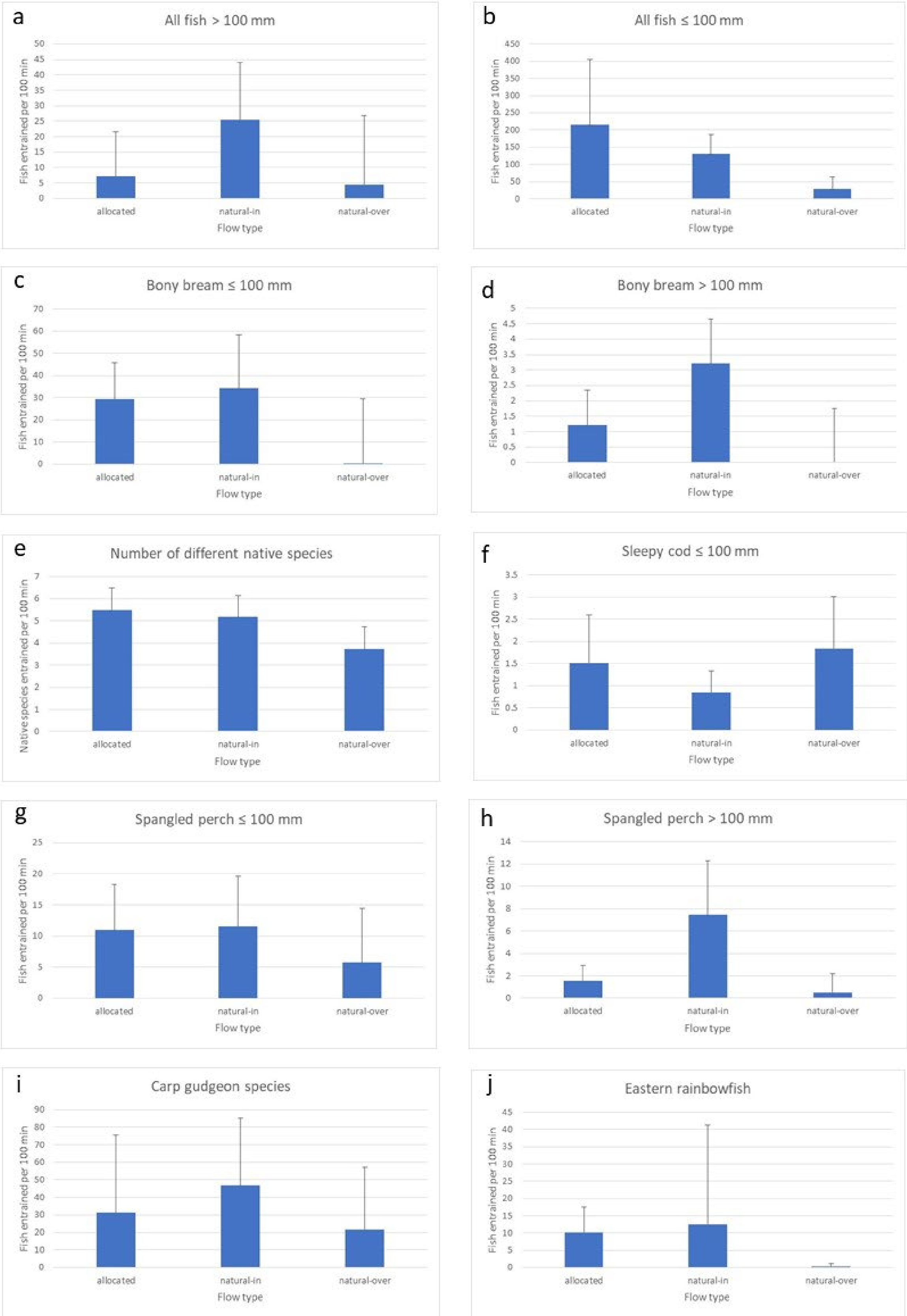
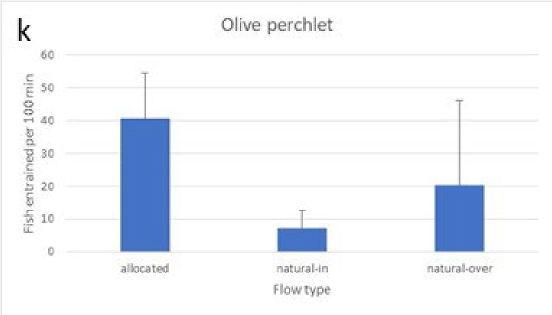


Figure 14: Entrainment rates per 100 min by flow type. Error bars show one standard error of the mean



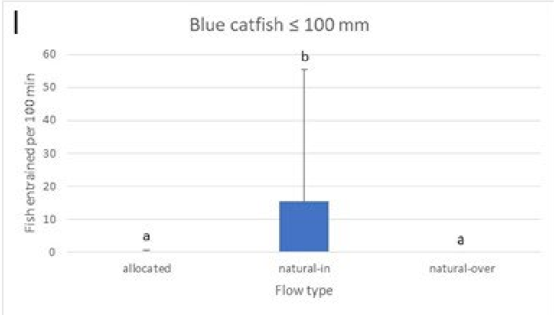


Figure 14 (continued): Entrainment rates per 100 min by flow type. Error bars show one standard error of the mean. Letters not shared between flow types indicate significant differences (p<0.05). If there are no letters on a bar graph, then all categories are not significantly different.

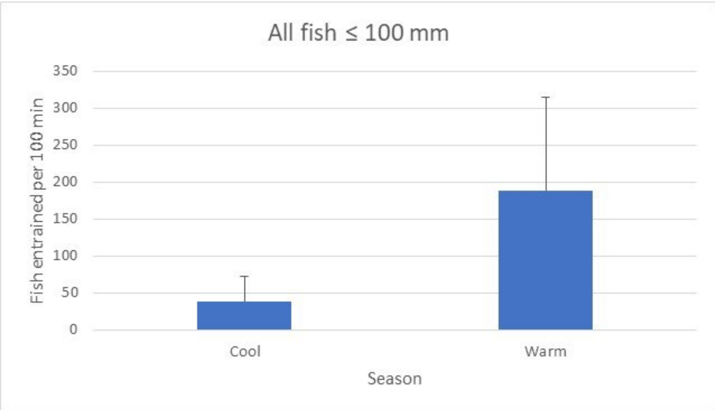


Figure 15: Adjusted mean entrainment rate (per 100min) of all fish ≤100 mm by season. Error bars show one standard error of the mean.

Larval fish and fish egg entrainment through riverine pumps

There were very few species of larvae captured frequently enough to run statistical analyses. The only larvae for which GLMs could be run were unidentified larvae, carp gudgeon larvae and golden perch larvae. All larvae combined was also run as another category and enabled inclusion of some of the less frequently encountered larvae such as bony bream and terapon perches. Eggs were encountered too infrequently to include in GLM models. Models were run that both included and excluded pump rate as a factor. Pump rate was not significant in any model, although there was a general trend for increased entrainment with increasing pump rate. Overbank flows were excluded from the analyses for simplicity, as no larvae were recorded entrained during any overbank flow. The patterns generated using models with and without pump rate included, produced similar outcomes and patterns for the other factors in the models. The adjusted mean values presented for riverine larval entrainment rates are based on those predicted by the simpler models. The transient nature of larval stages means there was considerable variation in catch rates between flow events and this has led to high standard errors of the mean in most cases.

Intake location and depth

Intake location and depth was not statistically significant (p=0.075) for golden perch larvae, but there was a tendency for more larvae to be entrained through side-channel intakes than the other intake types. However, there was high variability in larval catches between flow events.

Intake type and depth was not statistically significant for carp gudgeon larvae (p=0.963). Intake type and depth was also not significant for unidentified larvae or for combined catch of all larvae.

Flow type

Golden perch larvae were only entrained during in-bank natural flow events (*i.e*. none were recorded from any allocated flow events). Despite this clear trend, there was no significant difference between allocated and natural flows (p=0.064) and this was related to the highly variable larval catch ranging from zero to many on the natural flow events.

Flow type was not significant for entrainment of carp gudgeon larvae (p=0.270), but there was a tendency for carp gudgeon larvae to be entrained more often on allocated flows. Flow type was not significant for all larvae combined (p=0.835) or for unidentified larvae (p=0.684).

Season

There was a tendency for more larvae to be entrained in the warm season than the cool season. Season was significant in the GLMs for unidentified larvae (p=0.026) and golden perch larvae (p=0.037), although in post hoc pairwise testing using Fishers least significant difference test, golden perch larvae fell just short of the 0.05 significance level for season. Figure 16 shows adjusted mean daily entrainment rates for golden perch larvae by intake type in the cool and warm seasons, noting that this species was only entrained during natural flow events.

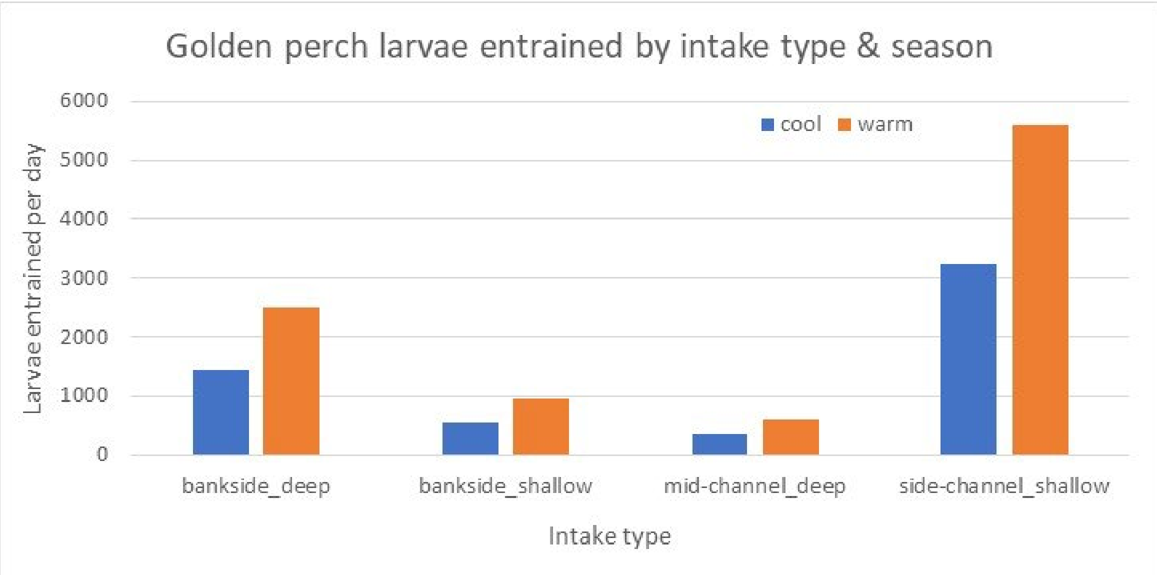


Figure 16: Adjusted mean entrainment rates of golden perch larvae through pumped riverine intakes, by intake type and depth and season.

Differences in length frequencies between entrained fish and fish in references sites

A total of 73 Kolmogorov-Smirnov comparisons were conducted initially, covering eleven different species. Most of these comparisons were significant (68.5%), including 31 tests that were significant with p<0.001, (42.5%), and 19 tests that were significant with p<0.05 (26%). Many species occurred commonly in the reference sites whilst occurring infrequently in the pump outlet sites. This included sleepy cod, blue catfish, leathery grunter, and golden perch. The lack of data for these species limited the opportunities to conduct K-S tests. Seventeen additional comparisons were made possible by combining the data from multiple sampling events on one flow type at one site. Most of these additional tests were also significant (64.7%), including eight tests with a significance level of p<0.001, (47%), and three tests with a significance level of p<0.05 (17.7%). Bony bream and carp gudgeon were generally the most abundant species at pump outlets and reference sites, enabling many K-S comparisons for these species.

Larval measurements were initially included in all K-S tests, although these measurements were infrequent and made only a small contribution to the dataset. Consequently, their omission resulted in only minor changes to K-S probabilities. Carp gudgeon were the only exception, with one comparison gaining significance and one comparison losing significance on the omission of larval measurements. The significance status of comparisons for all other species was unaffected by the omission of larval measurements. K-S probabilities for each species are presented in Appendix IV, both with and without larval measurements.

Significant differences between pump outlets and reference sites occurred on all flow types, including natural, allocated, and diversion channel flows. Species with the strongest prevalence of significant results included bony bream, spangled perch, golden perch, and flat-headed gudgeon. All K-S probabilities for flat-headed gudgeon are presented in Table 7.

Table 7: K-S probabilities for flat-headed gudgeon on discrete sampling events and combined events. Yellow shading indicates significance (p<0.05), while orange shading indicates significant values (p<0.001).

Flat-headed gudgeon	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022	Fairbairn Dam Combined Data
Weemah Channel	0.003	<0.001	<0.001
Selma Channel	<0.001	<0.001	<0.001

When K-S probabilities are viewed in conjunction with the histograms, it becomes apparent that significant differences often arise where entrained fish are much smaller than fish in the associated reference site. A good example of this is presented in Figure 17, where the distribution of entrained golden perch is clearly smaller than the distribution in the associated reference site. Observations of this nature were consistent for barred grunter, sleepy cod, golden perch (excluding larvae), blue catfish and leathery grunter. Further length frequency histograms may be found in Appendix III.

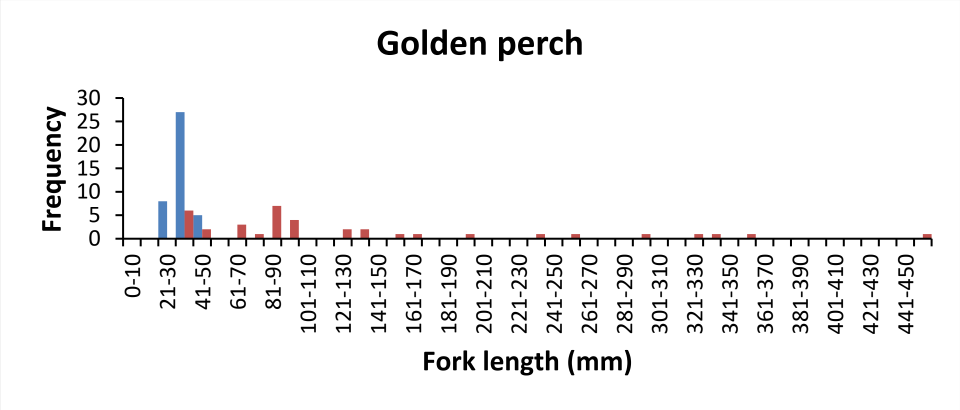


Figure 17: Histogram showing differences between length-frequency distribution of golden perch entrained into the Weemah channel (blue) and in Fairbairn Dam (red) on 24 January 2022. The K-S test revealed that the difference between these two distributions was highly significant (p<0.001).

For golden perch, fish entrained into the diversion channels were always smaller than fish in the associated reference site at Fairbairn Dam, with four out of five tests being significant and both combined data also being significant (p<0.001). The significance values for all K-S tests for golden perch (excluding larvae) are shown in Table 8**.**

Table 8: K-S probabilities for golden perch on discrete sampling events and combined events. Yellow shading indicates significance p<0.05, while orange shading indicates significance p<0.001.

Golden perch	Fairbairn Dam 17/06/2021	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022	Fairbairn Dam (Combined)
Weemah Channel		<0.001	0.041	<0.001
Selma Channel	<0.001	<0.001	0.201	<0.001

For some species, analysis of K-S probabilities in conjunction with the histograms showed that entrained fish were sometimes significantly larger than those in the associated reference site. This was especially true for glassfish (3 instances), spangled perch (2 instances), carp gudgeons (9 instances), rainbowfish (1 instance), and bony bream (5 instances). A good example of this is shown in Figure 18, where the distribution of entrained spangled perch on a natural flow at Pump Outlet 1 is clearly larger than the distribution of spangled perch at the adjacent reference site. The K-S test revealed that the difference between these sites was significant (p<0.001). The K-S probabilities for all spangled perch comparisons are shown in Table 9.

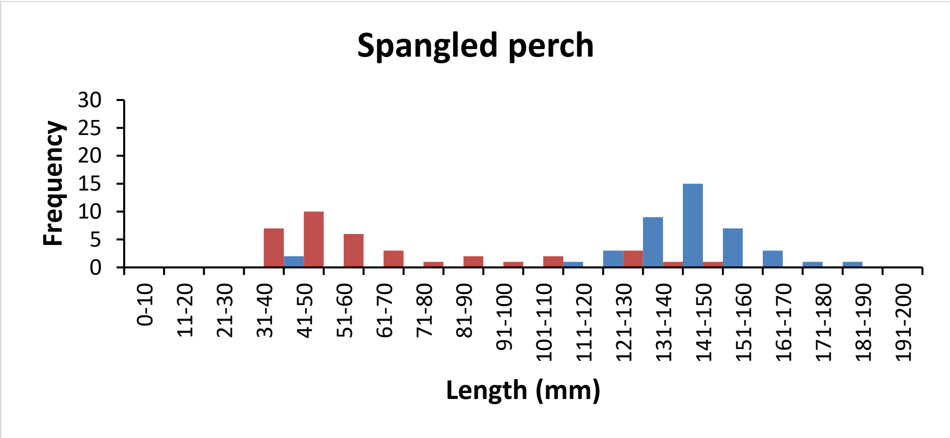


Figure 18: Histogram showing differences between length-frequency distribution of entrained spangled perch (SP) at pump outlet 1 (blue) and SP sampled in the adjacent reference site (red). The K-S test revealed that the difference between these two distributions was highly significant (p<0.001).

Table 9: K-S probabilities for spangled perch on discrete sampling events. Yellow shading indicates significance (p<0.05), while orange shading indicates significant values (p<0.001). Asterisk * denotes situations where entrained fish were evidently larger than those captured in the associated reference site.

Spangled perch	Reference Site 2 13/01/2021	Reference Site 6 19/03/2021	Reference site 14 23/02/2022
Pump Outlet 1 13/01/2021	<0.001*		
Pump Outlet 7 20/03/2021		0.088	
Pump Outlet 8 21/03/2021		0.004	
Pump Outlet 4 22/02/2022			0.073
Pump Outlet 3 22/02/2022			0.045*

The K-S comparison for glassfish also demonstrated several occasions where entrained fish were larger than those in the associated reference site, and the probability values for this species are presented in Table 10. Glassfish were not encountered in Fairbairn Dam or the two diversion channels, so K-S probabilities were only possible at riverine pump outlet sites for this species.

Table 10: K-S probabilities for olive perchlet on discrete sampling events. Yellow shading indicates significance (p<0.05), while orange shading indicates significant values (p<0.001). Asterisk * denotes situations where entrained fish were evidently larger than those captured in the associated reference site.

Olive perchlet	Reference Site 2 13/01/2021	Reference Site 6 19/03/21	Reference Site 14 23/02/2022	Reference Site 6 (Combined)
Pump Outlet 1 13/01/2021	0.415			
Pump Outlet 8 21/03/2021		0.008*		
Pump Outlet 4 22/02/2022			0.319	
Pump Outlet 3 22/02/2022			0.024*	
Pump outlet 13 (Combined)				<0.001*

Larval golden perch were captured in larval net samples during the months of November, December, January, and March. On some sampling occasions, enough larval golden perch were captured at both the entrainment site and the reference site to enable K-S comparisons, and these tests invariably showed that there were no significant differences between larval size distributions at pump outlets and associated reference sites (Table 11).

Table 11: K-S probabilities for entrained golden perch larvae on discrete sampling events at pump outlets and associated reference sites.

Golden perch	Reference Site 5 15/01/2021	Reference Site 2 16/11/2021
Pump Outlet 3 14/01/2021	0.319	
Pump Outlet 16 16/11/2021		0.066
Pump Outlet 1 16/11/2021		0.192

Where K-S comparisons tested fish size distributions in the two diversion channels against fish size distribution in Fairbairn Dam, there were many occasions where one diversion channel was significantly different from Fairbairn Dam, while the other was not. An example of this is shown in Table 12, where carp gudgeon entrained into the Weemah channel are shown to be significantly different from the Fairbairn Dam population, while carp gudgeon entrained into the Selma channel are not significantly different from the Fairbairn Dam population. The channel with more significant results alternated between species, and there was no clear trend as to which channel had the most significant results overall. There were only a few species where both channels were consistently significantly different from Fairbairn Dam, and these included golden perch and flat-headed gudgeon.

Table 12: K-S probabilities for carp gudgeon on discrete sampling events in diversion channels and Fairbairn Dam. Yellow shading indicates significance ($p<0.05$), while orange shading indicates significance ($p<0.001$). Asterisk * denotes situations where entrained fish were evidently larger than those captured in the associated reference site.

Carp gudgeon	Fairbairn Dam 17/06/2021	Fairbairn Dam 30/09/2021	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022
Selma Channel	0.105	0.121	0.252	0.153
Weemah Channel	0.276	0.015	<0.001 *	<0.001

Bony bream had the most significant results of any species, with fourteen out of twenty tests (70%) being significant where $p<0.001$, and a further three tests (15%) being significant where $p<0.05$. The histograms demonstrate that - where significant differences exist - entrained bony bream tend to be smaller than those in the associated reference site, although entrained fish were larger than reference site fish on five separate occasions.

There were various species that were encountered only in low numbers at reference sites during sampling, and never or rarely in pump outlet sites. K-S comparisons were not possible for these species, which included fish of recreational significance, such as freshwater longtom, barramundi, saratoga and Murray cod.

Susceptibility indices

Adult and juvenile fish

Analysis by one way ANOVA showed that there were significant differences in the susceptibility of different species and size classes to entrainment through riverine pumps ($p<0.001$) (Table 13).

Table 13: Summary of one-way ANOVA for susceptibility indices scores for different species and size classes entrained through riverine pumps.

Source of variation	**Degrees of freedom**	**Sum of squares**	**Mean squares**	**Variance ratio**	**F pr.**
Species and size class	20	287.257	14.363	3.19	<0.001
Residual	319	1437.409	4.506		
Total	339	1724.666			

Table 14: Mean susceptibility index scores, with standard errors of the mean (SEM) and N values for frequency of encounters, for different native fish and size classes at riverine pump locations and adjacent river reference sites. Scores are ranked from lowest to highest. Greyed out species and size classes were not encountered frequently enough for statistical analyses so their rankings should be considered with caution. Mean scores for species or size classes sharing the same letter are not significantly different. Mean scores for species not sharing the same letter are significantly different (p<0.05)

Species	Size class	N value	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	
Hyrtl's tandan	≤100 mm	2	**0**	0	
Barred grunter	>100 mm	13	**0**	0	a
Freshwater catfish	>100 mm	6	**0**	0	a
Golden perch	≤100 mm	6	**0**	0	a
Golden perch	>100 mm	18	**0**	0	a
Leathery grunter	>100 mm	13	**0**	0	a
Saratoga	>100 mm	14	**0**	0	a
Blue catfish	>100 mm	18	**0.0004**	0.0004	ab
Sleepy cod	>100 mm	22	**0.0035**	0.001	ab
Hyrtl's tandan	>100 mm	15	**0.0114**	0.007	ab
Bony bream	>100 mm	19	**0.0153**	0.008	ab
Sleepy cod	≤100 mm	21	**0.0304**	0.013	ab
Bony bream	≤100 mm	21	**0.0552**	0.019	ab
Eastern rainbowfish		21	**0.0914**	0.058	ab
Purple spotted gudgeon		1	**0.144**		
Flat-headed gudgeon		3	**0.1880**	0.108	
Fly-specked hardyhead		17	**0.1884**	0.152	ab
Barred grunter	≤100 mm	19	**0.2843**	0.210	ab
Blue catfish	≤100 mm	16	**0.2852**	0.148	ab
Rendahl's tandan	≤100 mm	1	**0.3260**		
Carp gudgeon spp		22	**0.3928**	0.221	ab
Rendahl's tandan	>100 mm	3	**0.6847**	0.245	
Spangled perch	≤100 mm	15	**1.8179**	0.874	bc
Spangled perch	>100 mm	11	**2.3896**	1.316	cd
Olive perchlet		19	**3.4852**	0.222	d
Leathery grunter	≤100 mm	2	**3.602**	3.602	

Table 14 shows the ranking of mean susceptibility indices scores of different species and size classes from least susceptible to entrainment to most susceptible to entrainment through riverine pumps. Mean scores for groups recorded on less than five occasions are shown but have not been included in statistical analyses for significant differences. The most susceptible species to entrainment through riverine pumps appears to be olive perchlet, followed by the two size classes of spangled perch. Leathery grunter ≤100 mm may also be highly susceptible to entrainment, but these were encountered too infrequently to be confident of this. There are several species and size classes that were never entrained through riverine pumps during this study with mean scores of zero. Other species fall between the two extremes. A lower susceptibility score for species with a score above zero does not necessarily mean those fish are not commonly entrained, but they are entrained at a rate proportional to their sampled population size in the river that is lower than species with higher scores.

Some size classes such as freshwater catfish ≤100 mm, saratoga ≤100 mm and Murray cod ≤100 mm were never encountered during surveys of the river, although they must exist in the river at certain times. Their vulnerability to entrainment therefore remains an open question.

Analysis by one way ANOVA also showed that there were significant differences in the susceptibility of different species and size classes to entrainment through irrigation diversion channels branching from Fairbairn Dam ($p<0.001$) (Table 15). Given the low number of samples, the mean susceptibility indices represent pooled data from both channels. The tendency was for most species and size classes to be more susceptible to entrainment through the gravity fed Weemah Channel, but more replicates would have been required to examine this between channel difference statistically.

Table 16 shows the mean susceptibility scores for the different species and size classes entrained through the irrigation diversion channels. For those species and size classes encountered often enough for statistical comparisons, the least susceptible was barramundi >100 mm. Sleepy cod >100 mm were also one of the least susceptible groups. Compared to the riverine pumps, spangled perch did not rank as highly, and appear to be less susceptible to entrainment from an impoundment than they are in a riverine setting. The most susceptible species to entrainment from an impounded water body appear to be carp gudgeons, flat-headed gudgeons, bony bream ≤100 mm and golden perch ≤100 mm. Susceptibility of some size classes could not be assessed (for example, barramundi fingerlings ≤100 mm) because they were not present in Fairbairn Dam at the time of sampling.

Table 15: Summary of one-way ANOVA for susceptibility indices scores for different species and size classes entrained in diversion channels originating from Fairbairn Dam.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Species and size class	15	0.352388	0.023493	2.96	<0.001
Residual	107	0.849925	0.007943		
Total	122	1.202313			

Table 16: Mean susceptibility index scores, with standard errors of the mean (SEM) and N values for frequency of encounters, for different native fish and size classes at Fairbairn Dam irrigation diversion channels and the adjacent dam reference site. Scores are ranked from lowest to highest. Greyed out species and size classes were not encountered frequently enough for statistical analyses so their rankings should be considered with caution. Mean scores for species or size classes sharing the same letter are not significantly different. Mean scores for species not sharing the same letter are significantly different (p<0.05)

Species	**Size class**	**N value**	**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	
Barramundi	>100 mm	6	**0**	0	a
Sleepy cod	>100 mm	8	**0.0002**	0.0002	a
Spangled perch	≤100 mm	8	**0.0008**	0.0008	a
Sleepy cod	>100 mm	8	**0.0010**	0.0006	a
Golden perch	>100 mm	8	**0.0016**	0.0016	a
Eastern rainbowfish		8	**0.0060**	0.0038	a
Barred grunter	>100 mm	8	**0.0115**	0.0045	a
Fly specked hardyhead		8	**0.0118**	0.0068	a
Barred grunter	≤100 mm	8	**0.0127**	0.0056	ab
Spangled perch	>100 mm	8	**0.0151**	0.0110	ab
Bony bream	>100 mm	8	**0.0304**	0.0203	abc
Leathery Grunter	>100 mm	4	**0.0425**	0.0425	
Dwarf Flat-headed gudgeon		2	**0.0575**	0.0575	
Leathery grunter	≤100 mm	5	**0.0724**	0.0558	abc
Golden perch	≤100 mm	8	**0.1004**	0.044	bcd
Bony bream	≤100 mm	8	**0.1105**	0.0688	cd
Flat-headed gudgeon	≤100 mm	8	**0.1109**	0.0511	cd
Carp gudgeon spp		8	**0.1750**	0.0643	d
Rendahl's tandan	>100 mm	3	**0.21**	0.051	

Larval fish

For fish larvae and eggs that were encountered frequently enough for statistical analyses of susceptibility to entrainment through riverine pump there was no significant difference found (p <0.099). The summary of the one-way ANOVA is in Table 17. The mean susceptibility scores are shown in Table 18. Post hoc pairwise comparisons with the Tukey test confirmed no significant difference between the means.

Table 17: Summary of one-way ANOVA for susceptibility indices scores for different species of fish larvae and fish eggs entrained through riverine pumps.

Source of variation	Degrees of freedom	Sum of squares	Mean squares	Variance ratio	F pr.
Species and size class	5	453.37	90.67	1.99	<0.099
Residual	42	1909.23	45.46		
Total	47	2362.61			

Table 18: 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 value	Mean susceptibility score	S.E.M	Significance (p<0.05)
Fly-specked hardyhead larvae	3	**0**	0	
Sleepy cod larvae	1	**0**	0	
Bony bream larvae	8	**0.2822**	0.1990	a
Golden perch larvae	8	**0.4036**	0.2943	a
Terapontidae (Terapon perches) larvae	7	**0.9302**	0.8988	a
Fish eggs	8	**4.0221**	1.6982	a
Carp gudgeon spp larvae	10	**5.7923**	3.3473	a
Unidentified larvae	9	**8.2269**	3.1536	a
Unidentified yolk sac larvae	2	**50.1215**	43.3365	

Larvae and fish eggs were detected too infrequently in Fairbairn Dam and the adjacent irrigation diversion channels for any meaningful analyses of susceptibilities to entrainment.

Discussion

General observations

Several studies have looked at 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). The current study is the first to quantify entrainment rates through multiple irrigation intake types to enable direct comparisons of impacts to be made. 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 3293 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 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 ranging from 0.614 fish/ML to 137.233/ML or from 43 to 5794 fish per day through pumped riverine diversions and from 7.114 fish/ML to 10.748 fish/ML (806 to 3686 fish per day) through a pumped diversion from an impoundment. It is worth noting that the impoundment diversion pumped at a considerably higher maximum rate than any of the riverine pumps examined. In the current study the highest entrainment rates were recorded in the gravity fed Weemah irrigation channel. Entrainment rates ranged from 30.932 fish/ML to 626.950 fish/ML. On a per day basis extrapolated entrainment rates ranged from 3866 to 17377 fish per day. O'Connor *et al*. (2008) also looked at a gravity fed diversion but did not quantify entrainment rates per unit time. Instead, they sampled 30 sites in the irrigation diversion by electrofishing, finding more than 10,000 native fish from ten species and almost 4000 introduced fish from five species, giving an indication of the scale of fish lost to the river system. The results of the current study suggest that gravity fed diversions most likely entrain more fish than pumped diversions. Gravity fed diversions can therefore be considered a high priority for screening. It is then a matter of prioritising which of the pumped diversions should receive attention for mitigation. The role of diversion type and the differences between the various pumped diversions are discussed in more detail below.

The role of diversion type, pump size, flow and intake position and depth

Diversion type

The direct comparison between 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. Most of the significant differences were for fish species and sizes classes ≤100 mm in length. Entrainment rates of larger fish were much lower, suggesting these fish may be better at avoiding entrainment. 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 also a highly productive area for sampling fish by electrofishing, 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. It is also possible that pump noise might have assisted in deterring some fish from approaching the intake too closely, whereas the gravity fed diversion would only have natural sounds related to flow, more like that of a natural entrance to an anabranch. 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. Although not originating from the same waterbody as the Weemah Channel, and not directly comparable, it is worth noting that the riverine pumps in this study generally had lower entrainment rates per ML compared to the Weemah Channel. This lends support to gravity fed diversions being a high priority for mitigation. However, comparative studies of other pumped and gravity fed diversions would be useful to add further support to this concept. Fish larvae were also more prevalent in the Weemah Channel than in the Selma Channel (Figures 9b and 10b), suggesting that gravity fed diversions may also be a higher risk to larval fish.

Others have also suggested that gravity fed diversions have the potential to entrain large numbers of fish (*e.g.*, Jones and Stuart 2008; O'Connor *et al*. 2008). The gravity fed diversion from a large lake like body like Fairbairn Dam is less likely to have downstream migratory cues (except perhaps during overflow events) than gravity fed diversions sites at riverine weir sites. 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. Hutchison *et al*. (2008) found downstream movements to be common for juveniles of several species of fish in the northern Murray-Darling Basin. In coastal systems there are many diadromous species (species that migrate between freshwater habitats and marine-estuarine habitats) often of economic importance, such as sea mullet, Australian bass, barramundi, mangrove jack, eels and jungle perch. These species make purposeful downstream migrations for spawning. As such they would be highly susceptible to entrainment in unscreened gravity diversions, in much the same way that downstream migrating salmon smolts in the northern hemisphere are vulnerable to gravity fed diversions (Walters et al. 2012).

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. The Weemah Channel was only sampled when dam levels were quite low, thus the intake depth was quite shallow. When water levels in Fairbairn Dam are high the intake depth of the Weemah channel would be much deeper. In summer thermoclines usually form between 4 to 6 metres below the surface. Water below the thermocline is generally low in oxygen and unlikely to contain many fish. Therefore, it is possible that during high dam water levels in summer, that entrainment rates could be low through the Weemah Channel. During high water levels, the Selma Channel would be gravity fed through a relatively shallow intake. It is probable that entrainment would be greater through the Selma Channel when it is gravity rather than pump fed. Unfortunately, prevailing conditions meant it was not possible to investigate both the effect of a thermocline on Weemah Channel entrainment rates or entrainment rates through a gravity fed Selma Channel. Gravity fed diversions from riverine weir pools are unlikely to ever sit below a thermocline, so it can be expected that gravity fed riverine diversion channels will always be highly risky for entrainment of fish while they remain unscreened.

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 also contributing to the entrainment rates of fish. Water temperature was one of the possible contributing factors, with more carp gudgeon entrained when water temperatures were warmer. Increased water temperatures can increase fish activity, which may mean they are more likely to swim into the vicinity of a pumped or gravity fed intake. Abundance of fish in the dam reference site was also a significant factor for several species. The reference site was located near to the diversion intakes. Fairbairn Dam is a very large waterbody of several thousand hectares. Thus, where fish were schooling in the lake at the time of sampling may have influenced entrainment rates to a greater level than pump rate. Inflows into the dam may have also influenced fish behaviour. Sampling was conducted in both dry periods where the dam was falling in level and shortly after small rises in water levels. This factor was not analysed in the GLMs for the diversion channels.

Riverine pumps

For riverine pumps, although not always statistically significant, entrainment rates per 100 min tended to increase with pump rate for most species and size classes. The number of species entrained per 100 min also increased with increased pump rate and this was significant. There was considerable variability in entrainment rates between flow events, which may have prevented some of the trends from being statistically significant, but with increased replication it is probable that more of the observed trends will prove to be significant. The weight of evidence for similar patterns across multiple species and size classes adds confidence to concluding that higher pump rates entrain more fish per unit time. There were some exceptions, notably spangled perch which had a much flatter relationship between entrainment rate and pump rate. Spangled perch are known to migrate laterally into floodplain lagoons (Hutchison *et al*. 2008). It is possible that spangled perch may be attracted to lateral currents and were therefore actively swimming with these lateral currents into irrigation intakes. Thus, movement into irrigation intakes may be active, rather than passive for this species and this might explain why pump rate had little effect on entrainment rates of spangled perch.

Fish larvae also showed a tendency for increased entrainment per unit time with increased pump rate, although this was not statistically significant. The sporadic nature of larval entrainment, which is linked to timing of spawning events, meant there was less statistical power to demonstrate the effect of pump rate on this life history stage. Given the poor swimming ability of larvae, especially early-stage larvae, it would be expected that larval entrainment per unit time should be correlated with pump rate.

For most species entrainment rates per ML increased only marginally with increasing pump rate. The increase was steepest as pump rates increase up to around 40-50 ML per day, after which the rate of increase flattened out. For fish >100 mm the relationship between pump rate and entrainment rate per ML was very flat and this is probably because larger fish were more effective at avoiding entrainment due to superior swimming abilities compared to smaller fish. 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 may have a greater influence on the total number of fish entrained than pump rate (see below).

Flow type

It was quite clear from the results that fish and larvae are less likely to be entrained through riverine pumps on overbank flow events. Although not statistically significant for most species, this trend for low catches on overbank flows was consistent across multiple species and size classes, providing some confidence that the effect is real. 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. In keeping with this overall trend, the tendency was also for overbank flows to have fewer species entrained per unit time than the other two flow types. Further replication would increase the likelihood of detecting statistically significant differences.

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. It is unlikely that any 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 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 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 fish could be more vulnerable to entrainment during natural within bank flows. Analyses from the current study showed little significant differences between allocated flows and natural within bank flows for entrainment rates of most juvenile and small bodied species of fish. However, there were some key patterns that stood out between the two flow types.

Olive perchlets seemed to be entrained more readily on allocated flows. This species 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). Juvenile blue catfish were more likely to be entrained on natural within bank flows than on allocated flows ($p<0.05$) and 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. The other key observation is that 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.

On balance, although there were few significant differences in entrainment rates between allocated and natural within bank flows, pumping from natural within bank flows is probably marginally more damaging because it is more likely to entrain several species of fish at breeding size and the larvae of the economically and socially important golden perch. Conversely olive perchlet are more vulnerable to entrainment on allocated flows and this species is threatened in some Murray-Darling catchments where it is still present.

Intake position and depth

The current work 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 have an influence on entrainment rates. Across most species and size classes shallow bankside intakes were consistently low in entrainment rates compared to one or more of the other intake configurations. This was statistically significant for several species and size classes. For some species further replication may be necessary to demonstrate significant differences. There were also significantly fewer species entrained per unit time through shallow bankside intakes. There was one exception to this trend, with eastern rainbowfish being significantly more likely to be entrained through shallow bankside intakes than other intakes. However, on balance, shallow bankside intakes have the lowest risk of entraining native fish. The role of intake type was less clear for larval fish, owing to the sporadic nature of their occurrence in the river system, but for golden perch larvae, the trend was for entrainment at shallow bankside intakes to be comparatively low. More replicate samples might make larval trends clearer.

The difference between the other intake types is less clear and varied between species. In some instances, there were no significant differences between the remaining intake types and there was no significant difference in the number of species entrained per 100 mins between the remaining three intake types.

For golden perch larvae, entrainment through shallow side channel intakes tended to be the highest. The same intake type also tended to entrain more carp gudgeons, juvenile bony bream and juvenile barred grunter, with entrainment rates being significantly higher ($p<0.05$) than one or more other intake types. One potential reason for side channel intakes entraining more of these fish is that these small fish may move into the short side channel to shelter from the main river current. This may lead to an aggregation of fish. The pumped incoming flow into the side channel and the river current perpendicular to it may also set up a circular or vortex type of current, which may keep fish contained in the short side channel rendering them more vulnerable to entrainment. Fish over 100 mm in length tended to be less vulnerable to entrainment through pumps positioned at the end of side channels.

Mid-river channel intakes tended to be of relatively low impact for some species such as rainbowfish, sleepy cod ≤100 mm, carp gudgeons, barred grunter ≤100 mm, fly-specked hardyhead, and blue-catfish ≤100 mm, but had significantly higher catch rates for spangled perch >100 mm, bony bream > 100 mm and olive perchlets than at least two of the other intake types.

Bankside deep intakes entrained significantly fewer bony bream >100 mm and eastern rainbowfish than two and one of the other intake types respectively, but entrained significantly more Rendahl's tandan >100 mm, Hyrtl's tandan >100 mm, flyspecked hardyhead and spangled perch >100 mm than at least two other intake types.

Most of these differences in entrainment rates of fish 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 must 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 same is probably true for Hyrtl's and Rendahl's tandans, but these two benthic species probably migrate adjacent to the riverbank as they were most prevalent in bankside deep intakes.

Fish size and Susceptibility

The prevalence of highly significant results from the Kolmogorov-Smirnov tests demonstrates that entrained fish generally have a significantly different size distribution than fish in in the associated reference site. The fact that most entrained populations were significantly smaller than reference site populations suggests that smaller fish are generally more susceptible to entrainment as predicted by Hutchison *et al*. (2020), with larger fish being better equipped to avoid entrainment. This could be the result of stronger swimming ability (Hutchison *et al*. 2020 and references therein), or the recognition of danger cues that result in avoidance behaviour. Golden perch larvae of the size commonly measured in sampling (5-7mm) are passive drifters, and have no physical mechanism to avoid entrainment, and this is demonstrated by the fact that there were no significant differences between size of larvae in the river sites and size of larvae in the entrainment sites.

The fact that the size distributions of entrained fish are occasionally larger than the distributions in reference sites may suggest that some species are willing to go with the flow, perhaps following a natural impulse to swim out of the river in search of wetland habitats. These larger fish are strong swimmers and are more likely to recognise danger cues, therefore their entrainment into pump outlets is unlikely, unless there is some sort of behavioural cue. Hutchison *et al*. (2008) documented lateral movements of spangled perch into wetland habitats, thus it is possible spangled perch may have followed lateral currents generated by pump intakes. The relatively flat graph for spangled perch entrainment rates against pump rate suggests this species may actively swim into pump intakes. Spangled perch are well known for their high mobility, frequently swimming long distances overland in search of new habitats during periods of wet weather (Lintermans 2009). Entrainment for large spangled perch was most prevalent during natural within bank flow events.

Olive perchlets are a small bodied native species that have been in general decline across the Murray-Darling Basin (Moffatt and Voller 2002; Lintermans 2009), while remaining more common in the coastal catchments of Queensland. On three occasions, histograms and the K-S test for this species showed that entrained fish were significantly larger than fish in the reference site, and these entrained fish were often mature fish. Hutchison *et al*. (2008) have documented lateral migrations of this species into wetlands for breeding. There are large knowledge gaps for this species, but it is possible that this behaviour was a response to a lateral current generated by the pump, and these larger fish may have been seeking to access a wetland habitat for breeding. The plot for glassfish entrainment rates against pump rate was not flat like that of spangled perch, but the plot for glassfish (most of which are less than 70 mm in length) was not split into juveniles and adults, so it is likely that passive entrainment of juveniles may have masked active entrainment by adults. Glassfish are now considered extirpated from most of the southern MDB (Moffatt and Voller 2002; Lintermans 2009), and it is possible that behavioural entrainment amongst other factors has contributed to this situation. More investigation is warranted to investigate the impact of water extraction on this species.

Although the susceptibility scores need to be treated with some caution, as results may be impacted by our ability to detect some species in the references sites, in general we believe they do provide an indication of the relative susceptibility of most species. The mean susceptibility scores of spangled perch >100 mm and olive perchlet were significantly higher than that of any other species or size class entrained through riverine pumps. This adds further support to the argument that these two species may actively swim into pump intakes due to some behavioural trait. Olive perchlet were not recorded in Fairbairn Dam, so their susceptibility to entrainment through a diversion channel from an impoundment could not be assessed. Spangled perch appeared less susceptible to entrainment from an impoundment. It could be that a large static waterbody such as Fairbairn Dam provides less of the migratory cues that make riverine populations of spangled perch so susceptible to entrainment.

Within Fairbairn Dam, carp gudgeons, Flat-headed gudgeons and bony bream ≤ 100 mm were among the more susceptible species to entrainment. Carp gudgeons were also one of the more susceptible species to entrainment in the riverine areas. Carp gudgeons and flat-headed gudgeons are not very powerful swimmers, so it may be expected that they would be vulnerable to entrainment. Carp gudgeons, juvenile bony bream and flat-headed gudgeons were also among the most abundant species in Fairbairn Dam, so it is possible that entrainment of these species is not having a major ecological impact. Some species although common in riverine areas (e.g., sleepy cod) were only entrained at very low rates. Sleepy cod are not powerful swimmers, but their behaviour as a slow-moving cryptic predator probably means they do not move around very much (Pusey *et al*. 2004), so they are less likely to encounter irrigation intakes than more active species like bony bream. There is little evidence for migrations by sleepy cod (Pusey *et al*. 2004) which would also make them less susceptible to entrainment

Juveniles of the socio-economically important golden perch were also among the more highly ranked species size classes for entrainment from Fairbairn Dam, especially through the gravity fed Weemah Channel. In contrast no juvenile golden perch were found entrained through any of the riverine pumps, only larval golden perch. Juvenile golden perch appear to be more abundant in Fairbairn Dam and there is evidence for good recruitment of golden perch in the Nogoa River upstream (Roberts *et al.* 2008). If juvenile golden perch were more numerous in the sites where riverine pumps were located, it could be possible that some would become entrained. Juvenile golden perch have been found entrained through pumps in the Murray-Darling Basin but at a much lower level than gudgeons and bony bream (Baumgartner *et al*. 2009; Boys *et al*. 2021a). Golden perch appear to be more prevalent in gravity fed systems (this study; O'Connor *et al*. 2008, Boys *et al*. 2021a). O'Connor *et al*. (2008) also found adult golden perch moving into gravity fed channels. We also recorded a small number of larger juveniles and sub-adults in the Weemah Channel, but at a far lower rate than for fish ≤100 mm in length.

Some life history stages and species were unable to be adequately assessed for susceptibility to entrainment in this study. This is generally because these species were not particularly abundant, or because there were few juveniles present of some species due to lack of recent recruitment or stocking in the period that we evaluated the irrigation diversion systems. For example, we were unable to evaluate the susceptibility of barramundi fingerlings to entrainment as only large individuals were present in Fairbairn Dam when we conducted sampling, as there had not been recent stocking, and growth of fingerlings is rapid in impoundments. Further sampling in the region might improve our understanding of the vulnerability of juvenile barramundi and other fish species if sampling corresponds with recent recruitment or stocking events. In riverine areas, although large saratoga, Murray cod and freshwater catfish (*T. tandanus*) were present, we did not find any juveniles of these species in the river reference sites and therefore none were entrained through irrigation pumps.

Saratoga adults although not abundant, were regularly detected in reference sites. This fish is a surface feeder and is often strongly associated with cover. Its behaviour suggests it would not regularly encounter irrigation intakes. Saratoga are mouth brooders (Allen *et al*. 2002) so early stages should be well protected from entrainment. If juveniles (post-release from the parental mouth) are also top water predators, then perhaps they will be at low risk of entrainment through pumped infrastructure. Murray cod juveniles have been recorded being entrained through pumped irrigation infrastructure in the Murray-Darling Basin, but at lower rates than more common species such as bony bream and carp gudgeons (Boys *et al*. 2021), but most reports of entrainment of Murray cod and Murray cod larvae are from gravity fed systems (King and O'Connor 2007; O'Connor *et al*. 2008). In the northern Murray-Darling Basin freshwater catfish fingerlings have been recorded being entrained through riverine pumps (Norris *et al.* 2015, Norris *et al.* 2020). In those studies, juvenile freshwater catfish were present, but not abundant in the adjacent creek system, so it seems juvenile freshwater catfish may be quite vulnerable to entrainment.

Key findings

The key findings from this work are as follows.

- Both pumped and gravity fed infrastructure can entrain significant numbers of native fish.
- There is evidence that gravity fed infrastructure entrains more fish per ML than pumped infrastructure
- For pumped infrastructure, intake position and depth can influence entrainment rates, with shallow bankside intakes tending to entrain the least number of fish.
- Pump rate has an influence on the number of fish entrained, with catch per unit time increasing as rate of pumping increases. Entrainment per ML also increases with pumping rate, but the curve is asymptotic with the rate of increase flattening as pump size increases.

- Pumping from overbank flows resulted in the lowest entrainment rates. Entrainment rates on allocated flows and natural within bank flows were similar, but pelagic larvae (*e.g*., golden perch) and fish over 100 mm in length tended to be more vulnerable to entrainment during natural within bank flows.
- Not all species and size classes of fish are vulnerable to entrainment through pumped infrastructure. Smaller species, juveniles of larger species and fish larvae are the most vulnerable to entrainment. There are some exceptions. For example, adult spangled perch can be particularly vulnerable to entrainment, especially on natural flow events.

Mitigation options

It is clear from the results of this work that gravity fed diversions and pumped diversions of river water can entrain native Australian fish. The impacts are variable, depending on diversion type, flow type, intake location and depth, and pump size or pump rate. Although not all irrigation infrastructure is high impact, those structures that do have a high impact should be considered for mitigation measures. Determining which structures are likely to be a higher priority for mitigation is outlined in the next section, which considers relative impacts, cost and feasibility. New irrigation developments should consider installing bankside shallow intakes, as these appear to be of lower impact than other intake types. If it is necessary to use a different intake depth or configuration, then fish screening should be factored in at the design stage. Screens should also be considered on new bankside shallow intakes, especially if they are large pumps with a high annual water allocation. Screening is much cheaper at the initial irrigation construction phase, than it is later when screens may be required to be retrofitted.

The good news is that there are mitigation measures available that do not result in any loss of water to the irrigator (Boys *et al*. 2021a). There are various self-cleaning screen designs available, tailored to different situations. A number of these screen designs are currently being trialled at sites in Australia, and results are being collected by the NSW Department of Primary Industries. Data is being collected on mitigation of entrainment of fish and is also being collected on how the screens affect the growers that operate them. For example, whether the screens are cost neutral, cost negative or cost beneficial to day-to-day operations. This is information many growers would be anxious to obtain before considering a screening option.

Many of the modern screens are self-cleaning (using brushes, jets of air or water, or sweeping currents) and maintain a high volume of flow, which may be better than the flow experienced through trash racks in current operation. Trash racks can clog with sticks, leaves and other debris. The large surface area of modern fish screens means the approach velocity at the screen surface is low, but the volume of water screened is high. The following link features some of the current mitigation sites around Australia and some of the screening options available https://fishscreens.org.au . There are also two useful publications available for irrigators. 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). Some of the available screening options were also reviewed in Hutchison *et al*. (2020).

Two of the designs reviewed by Hutchison *et al*. (2020) appear to be in common use at the current trial sites in Australia. They are cone screens and rotating cylinder screens. These two designs will be briefly discussed below.

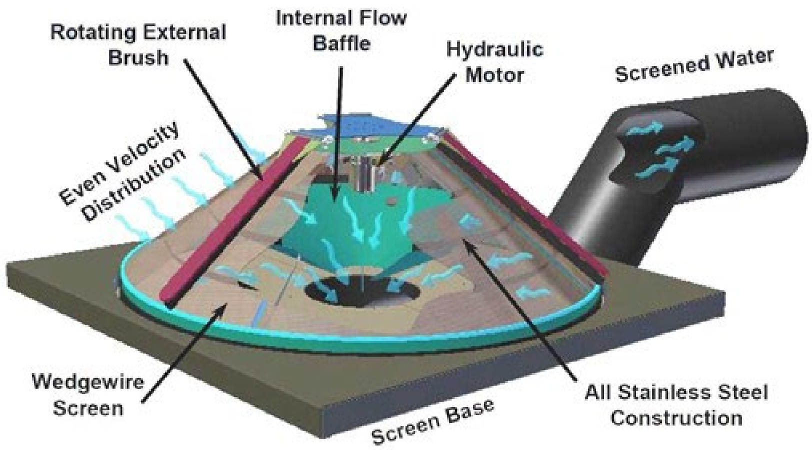


Figure 19: A diagram of a cone screen showing internal workings. Image reproduced with permission from AWMA. https://www.awmawatercontrol.com.au/products/cone-screens/

Figure 20: Installation of cone screens. Reproduced with permission from AWMA. https://www.awmawatercontrol.com.au/project/trangie-nevertire-irrigation-scheme-fish-screens

Cone screens (Figures 19 and 20) are cone shaped and come in wedge wire, perforated plate and woven wire versions (Mefford 2013). The standard application for these screens is fitted to a pump intake or a gravity diversion flow through a head wall. The cone shape offers a large surface area for a small stream depth and a small footprint (Mefford 2013). These screens can operate both fully or partially submerged. Most cone screens come with cleaning brushes. Generally, cone screens need power to operate the cleaning system, but there are some versions available with propeller drives located in the discharge pipe to operate the brush cleaning system. The head requirement for operation is low, ranging from 3-9cm. These screens are best suited to low flow (<0.15 $m.s^{-1}$) velocity environments such as backwaters and impoundments (Mefford 2013). If exposed to currents these screens can have approach velocity hotspots (Gard *et al.* 2010). A combination of internal and external baffles can be used to address current hotspots to some extent (Hanna 2013). Cone screens may be ideal for installation in perpendicular (to the river channel) side channels constructed for pump intakes. Side channel intakes are usually shallow and sheltered from the river current so meet the criteria for cone screens. Cone screens may also be suited to offtakes in impoundments and weir pools where current velocities are reduced. Cone screens have also been used to screen water for diversion channels *e.g*. at Cohuna in Australia (North Central Catchment Management Authority 2020), where brush cleaned wedge wire constructed cone screens have been used. This site has gravity fed diversion flows up to 600 ML/day (Boys *et al*. 2021). Another trial site for cone screens is the Trangie Irrigation Scheme (See Figure 20), which pumps up to 750 ML/day (Boys *et al*. 2021a).

Rotating cylinder screens are frequently used in flowing environments. Cylindrical screens are operated fully submerged and are typically used on pumped diversions within the river or weir pool where the pump intake is located. These screens can also be used on gravity fed conduits (U.S. Department of Interior 2006). Water should submerge the screen by a minimum of half the screen diameter for effective operation (Mefford 2013). As the name implies these screens are cylindrical in shape (Figure 21), and this shape provides a large surface area per unit length (Mefford 2013), which is important for helping to reduce approach flow velocities. Cylindrical screens should be placed parallel to the flow to achieve the best through screen velocity uniformity and to provide a sweeping flow from the river current. Cylindrical screens can be mounted as a single unit or end to end as a T shaped unit with an exit pipe in between (Mefford 2013).

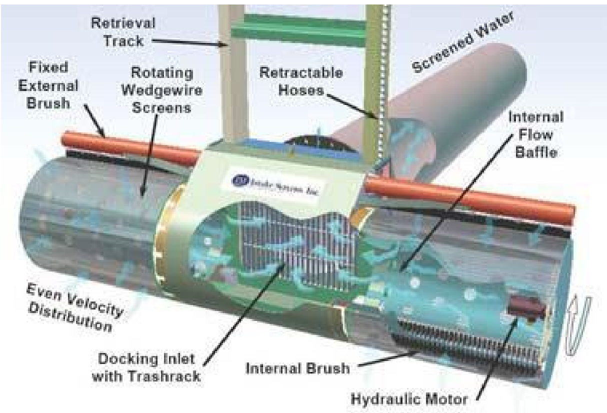


Figure 21: A diagram of a brush cleaned T style wedge-wire cylinder screen that can be raised up a retrieval track for maintenance. Internal workings are shown. Image reproduced with permission from AWMA. https://www.awmawatercontrol.com.au

Baumgartner and Boys (2012) recommended rotating cylinder screens for pump intakes. They stated water jet cleaned mesh fabric screens may be suitable for pumps with capacities less than 30ML per day, but recommended brush cleaned, wedge wire cylindrical screens for larger pumps. The brushed screens appear to be very efficient at avoiding blockages by debris.

The prices of these screens vary considerably. Good quality smaller wedge-wire screens (e.g. 12 $ML.D^{-1}$) start from around $20,000 AU. Woven mesh screens may be cheaper but less easy to clean. A wedge-wire screen for a 30 $ML.D^{-1}$ system costs around $25,000. Costs of screens for larger systems will depend on factors such as site access and retrieval systems. Installation costs will vary according to site characteristics and existing infrastructure. Costs per unit of flow can vary quite widely. Typically, costs per unit volume go down for larger structures (U.S. Department of Interior 2006).

Rotating cylinder screens generally require access to power, but some smaller models use water current driven propellor systems to rotate the screen (AWMA undated). Some cylindrical screens are static and use sweeping flows of the river current to clean them (U.S. Department of Interior 2006). However, static cylindrical screens will eventually need manual cleaning and are not suited to areas with high debris loads such as backwater areas where debris tends to accumulate. We would recommend self-cleaning screens for most situations.

Cylindrical screens have the option of being fitted to retrieval systems that can raise screens between use for maintenance (Figures 21 and 22) and lower screens back in place when required (U.S. Department of Interior 2006). Having screens raised between pumping operations should reduce the risk of biofouling and reduce maintenance costs. Screens can also be raised to avoid flood debris, then lowered for pumping when risk of heavy debris is reduced. Some cylindrical screens are bullet shaped, with the rounded end helping to deflect debris.

Figure 21: A T style retrievable wedge-wire self-cleaning cylinder screen in the raised position. Image reproduced with permission from AWMA https://www.awmawatercontrol.com.au/products/cylinder-screens-powered

To date rotating wedge wire brushed cylinder screens have mainly been fitted onto smaller pumps (4 to 10 ML/day) in Australia. Locations include Dubbo, Forbes, Narrandera, Condobolin, Cowra, Gunbower Creek, Cohuna and Orange (Boys *et al.* 2021a), but cylindrical screens can cope with much larger pumping capacities. Another 23 pumps in the northern Murray-Darling Basin in the size range of 40-150 ML/day are scheduled to be fitted with rotating wedge wire brushed cylinder screens in late 2022 and into 2023 (Craig Boys pers comm). These screens will provide useful information for irrigators on their performance.

Prioritising mitigation

The evidence suggests that gravity fed diversions have a higher impact than pumped diversions. Gravity fed diversions should be the highest priority for mitigation actions in a catchment. Depending on the size of the 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 can also have significant impacts on fish, but the impact is highly variable. Using results from the current study, we have developed an evidence-based prioritisation matrix, that can help Landcare groups, NRM groups, government agencies and irrigators prioritise pumped irrigation infrastructure within a catchment or across multiple catchments for mitigation. 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 money is used wisely so that the greatest benefit can be achieved for dollars spent. There is not much point in screening infrastructure that is currently having a minimal impact on fish or expending large amounts of money on a logistically difficult site, when the same money could have a achieved a better outcome for fish at either higher priority sites, or more logistically feasible sites. Some irrigators may opt to install fish screens on their properties out of their own pocket for reasons other than fish entrainment mitigation, such as achieving a more reliable flow of water, or for cleaner water that does not clog sprinkler or centre pivot systems.

Prioritisation matrix

The prioritisation matrix 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 landcare and NRM groups, irrigators, agricultural companies and peak bodies representing irrigator groups.

The scoring system relies on four main parameters. Three of these parameters are derived directly from this work, they are the type of flow or flows the irrigator is licensed to pump, the pump size or capacity in ML/day and the pump intake location and depth. The fourth parameter is based on 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.

The main consideration when scoring the categories flow type, pump rate and intake position and depth was 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 >100 mm, 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, but not the exact ratios observed. However, larger differences between categories are reflected where they exist. This will still lead to the same prioritisation result as using the exact ratios. For example, to mimic the trends observed in entrainment rate per ML 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 approximately equal across the three categories based on the field-derived data. However, volume allocated was given a higher maximum score than the other categories because the variations in total allocations are extreme. Very large extracted volumes will still entrain many fish, even if the rate entrained per ML is low. The final score is derived from multiplication because the way each category interacts have a multiplier effect in the field, rather than an additive effect.

The proposed scoring system is as follows.

Flow type the irrigator is licensed to harvest

Overbank natural flows only (1) Allocated flows only (2.5) Natural flows only (3) Both natural and allocated flows (2.6, 2.75 or 2.9). For predominantly allocated (supplemental) flows by volume use 2.6, predominantly natural (unsupplemented) flows by volume use 2.9, approximately equal amounts of allocated and natural flows pumped by volume use 2.75.

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. There were no statistically significant differences in entrainment rates for fish ≤100 mm between natural within bank and allocated flows or for entrainment rates of fish >100 mm for these two flow categories. Some individual species had significant differences, but the direction of these differences varied between species. The overall trend was for little difference; thus the scores reflect this minimal difference. However, there was a tendency for greater numbers of small fish to be entrained on allocated flows and greater numbers of fish >100 mm to be entrained on natural within bank flows.

The greatest difference between the two flows was that pelagic larvae (e.g., golden perch) were only ever entrained on natural within bank flows and never on allocated flows. Golden perch is an economically and socially important species, occurring widely in eastern and south-eastern Australia, including the Fitzroy, Lake Eyre, and Murray-Darling basins. Other pelagic larvae are also of socio-economic importance (e.g., silver perch) and these also occur in some major irrigation areas.

The scores of 2.5 for allocated flows and 3 for natural flows reflect the greater impact that pumping on allocated and within bank flows have in contributing to entrainment compared to overbank flows, but also reflect the small difference in impact between these two flow types. The trend for increased entrainment of fish >100 mm (some of which may be breeding fish) and entrainment of pelagic larvae only on natural within bank flows influenced the decision to score natural flows marginally higher.

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 2.6, 2.75 or 2.9 depending on the approximate proportions of allocated versus natural flows harvested by volume (see above).

Pump rate ML/day

≤ 30 ML/day (1) 31-60ML/day (1.5) 61-120ML/day (2) ≥121 ML/day (2.5)

Justification: Pump rate was found to have a positive relationship with number of fish entrained per unit time across multiple species. There was also a positive trend in fish pumped per ML, especially for fish smaller than 100 mm. However, error bars were quite large, especially for the higher pumping rates. When calculating annual impacts, the number of fish pumped per ML is more important than fish entrained per unit time if considering the total amount of water pumped. On a fish per ML basis there was also a positive relationship, but it was a much flatter asymptotic slope than for fish pumped per unit time, especially once pump volumes exceeded the 30-40ML level. There was variability in the steepness of the relationship between species and size classes, with larger size classes having generally less steep slopes. The score increases with increasing pump rate to reflect the positive trends observed, but the maximum score is relatively low, and the width between categories increases as the score rises which reflects the asymptotic curve. The relatively low maximum score reflects the lesser importance of pump rate compared to pump intake location and depth and total volume extracted.

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

Bankside shallow (1) Mid-river channel deep (3) Bankside deep (3) Side channel (3)

Justification: The bankside shallow intakes clearly had the lowest impact. The impact of the other intake types was more difficult to separate, with bankside deep intakes generally having greater impacts on larger fish, and side channel intakes having generally greater impacts on smaller fish and pelagic larval fish, whereas mid channel intakes have impacts for some larger fish and not others, high impacts on olive perchlets and virtually no impact various catfish species and on some small species like fly-specked hardyheads, eastern rainbowfish, and juvenile barred grunter. 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 remaining three categories. Perhaps with more replication the category intake position and depth can be teased out to further differentiate between the different intake types.

Annual pumping rate

≤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 figures used here 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.

Score calculations

To calculate the final score for a particular pump the score from each category needs to be cross multiplied. Referring to the score metrics for each category in Table 19 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 from overbank flows alone, then the lowest score that can be achieved using the four-step prioritisation matrix will be 2.5, and the highest possible score that can be achieved is 225. 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 (2.5) 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

2.5 x 3 x 1.5 x 1 = 11.25

A grower who uses a pump for a mixed take of natural and allocated (supplemented) flows, but mostly natural flows by volume (2.9), with a bankside shallow pump intake (1), a100 ML/day pump rate (2) and an annual allocation of 3100 ML (3) would receive a score of

2.9 x 1 x 3 x 3 = 26.1

If the grower had a side channel shallow intake, then his score would have been

2.9 x 3 x 3 x 3 = 78.3

Table 19: 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	2.5	Bankside deep	3	31-60 ML/day	1.5	1501-3000 ML/annum	2
Mixed: Mostly allocated by volume, some natural	2.6	Mid- river channel deep	3	61-120 ML/day	2	3001-4500 ML/annum	3
Mixed: Approx. equal volumes of natural and allocated flows	2.75	Side channel shallow	3	≥121 ML/day	2.5	4501-6000 ML/annum	4
Mixed: Mostly natural flows by volume, some allocated flows	2.9					6001-7500 ML/annum	5
Natural flows only: within and overbank	3					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

Other considerations

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 4000 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 1000 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

3 x 3 x 2.5 x 3 = 67.5

The score for the single pump operating on allocated flows is

2.5 x 3 x 2 x 1 = 15

Summing the two gives a score of 82.5.

If we had just considered the total allocated volume pumped (5000 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

2.9 x 3 x 2.5 x 4 = 87.

The combined score of 82.5 is smaller than the default score, which 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 pumps as the highest priority for mitigation as a first step, but the feasibility of screening those pumps identified as a high priority still needs to be considered. There are 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. Site inspections would need to 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 money available for mitigation may be better spent at two or more slightly lower priority locations where it is more cost effective install a screen to achieve a better overall outcome for the same price.

Between catchment prioritisations

The above four-part matrix is designed for prioritising within an irrigation district or within a 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 will be exposed to the same suite of species. This work was not able to produce susceptibility scores for all species likely to be exposed to entrainment in Australia, but it has identified olive perchlet as being 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 there may be recovery programs for this species, special consideration might want to be given to this species. In such cases, then perhaps a higher weighting could be given to mid-river channel irrigation intakes, that seem to entrain more of this species.

If prioritising pumps between catchments some 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, then some species may eventually be able to be weighted more highly than others for these inter catchment prioritisations. The species scores could be used as additional multipliers to the overall prioritisation model or simply be used to derive a priority score for catchments and then direct pump mitigation work 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 and thus prioritise pumps across multiple catchments.

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, 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 with confidence that pump screening will not have a significant impact on their financial position.

Acknowledgments

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Project Outputs

- **Literature review:** Susceptibility of Australian fish to entrainment through irrigation systems with a review of research and potential mitigation strategies (available on CRDC website).
- **Webinar presentation:** Presentation on the project's key results and the prioritization matrix. Presented to cotton growers, NRM groups and fisheries agencies. Video link available. https://youtu.be/_oGyejMBaHQ
- **Cotton Conference presentation:** Presentation on the prioritisation process at the Cotton Conference on the Gold Coast, August 2022.
- **Fact sheet:** A fact sheet on relative impacts of irrigation infrastructure and mitigation options. Prepared with assistance from the CRDC extension team.

Appendices

Appendix I: GLM summary tables

Please note a "." ss used to denote an interaction between variables in a model. *E.g*. pump rate.intake location indicates the interaction between pump rate and intake location.

Impoundment diversion GLMs

Adult and juvenile fish entrained per 100 min

Response variate: All fish ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of all fish ≤ 100 mm + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx. F pr.
Regression	4	11778.96	2944.74	134.52	0.001
Residual	3	65.67	21.89		
Total	7	11844.64	1629.09		
Change	-1	-5.07	5.07	0.23	0.663

Adjusted r-squared statistic (based on deviance) 0.987

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	4.723	0.318	14.87	<0.001	112.5
Pump (flow) rate	-0.002537	0.00095	-2.67	0.076	0.9975
Intake location top of dam pump	-1.592	0.608	-2.62	0.079	0.2036
Dam catch of fish ≤100 mm	0.005287	0.000398	13.29	<0.001	1.005
pump (flow) rate.div intake location top of dam pump	-0.00099	0.00203	-0.49	0.660	0.9990

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx. F pr.
+ Pump (flow) rate	1	1042.83	1042.83	47.64	0.006
+ intake location	1	4606.90	4606.90	210.45	<0.001
+ Dam catch all fish ≤100 mm	1	6124.16	6124.16	279.76	<0.001
+Pump (flow) rate.Intake location	1	5.07	5.07	0.23	0.663
Residual	3	65.67	21.89		
Total	7	11844.64	1692.09		

Response variate: All fish >100 mm

Distribution: Poisson. Link function: Log

Fitted terms: Constant+ pump (flow) rate+ intake location + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	3	7.678	2.559	1.14	0.433
Residual	4	8.947	2.237		
Total	7	16.626	2.375		
Change	-1	--0.685	0.685	0.31	0.610

Adjusted r-squared statistic (based on deviance) 0.058

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	2.475	0.864	2.86	<0.046	11.88
Pump (flow) rate	-0.00786	0.00713	-1.10	0.332	0.9975
Intake location top of dam pump	-0.72	1.17	-0.61	0.574	0.4877
pump (flow) rate.div intake location top of dam pump	0.00426	0.00802	0.53	0.623	1.004

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	6.807	6.807	3.04	0.156
+ intake location	1	0.186	0.186	0.08	0.787
+Pump (flow) rate.Intake location	1	0.685	0.685	0.31	0.610
Residual	4	8.947	2.237		
Total	7	16.626	2.375		

Response variate: All fish all sizes

Distribution: Poisson. Link function: Log

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of all fish + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	11745.34	2936.34	191.44	<0.001
Residual	3	46.01	15.34		
Total	7	11791.35	1684.48		
Change	-1	-31.94	31.94	2.08	0.245

Adjusted r-squared statistic (based on deviance) 0.991

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	4.405	0.285	15.47	<0.001	81.90
Pump (flow) rate	-0.001039	0.000828	-1.25	0.298	0.9990
Intake location top of dam pump	-1.362	0.498	-2.73	0.072	0.2562
Dam catch of all fish	0.004762	0.000299	15.90	<0.001	1.005
pump (flow) rate.div intake location top of dam pump	-0.00251	0.00171	-1.47	0.237	0.9975

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	1049.33	1049.33	68.41	0.004
+ intake location	1	4583.38	4583.38	298.83	<0.001
+ Dam catch all fish ≤100 mm	1	6080.69	6080.69	298.83	<0.001
+Pump (flow) rate.Intake location	1	31.94	31.94	2.08	0.245
Residual	3	46.01	15.34		
Total	7	11791.35	1684.48		

Response variate: Carp gudgeon

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + temperature + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	3679.86	919.97	50.16	0.004
Residual	3	55.02	18.34		
Total	7	3734.89	533.56		
Change	-1	-75.06	75.06	4.09	0.136

Adjusted r-squared statistic (based on deviance) 0.966

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	2.908	0.630	3.33	0.045	8.152
Pump (flow) rate	0.00120	0.00113	1.06	0.367	1.001
Intake location top of dam pump	-0.925	0.728	-1.27	0.293	0.3963
Temperature	0.1571	0.0206	7.64	0.005	1.170
pump (flow) rate.div intake location top of dam pump	-0.00537	0.00255	-2.11	0.125	0.9946

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	122.55	122.55	6.68	0.081
+ intake location	1	2171.40	2171.40	118.39	0.002
+Temperature	1	1310.86	1310.86	71.47	0.003
+Pump (flow) rate.Intake location	1	31.94	31.94	2.08	0.245
Residual	3	46.01	15.34		
Total	7	11791.35	1684.48		

Response variate: Eastern rainbowfish

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of rainbowfish + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	39.7899	9.9475	69.56	0.003
Residual	3	0.4290	0.1430		
Total	7	40.2189	5.7456		
Change	-1	-15.8234	15.8234	110.64	0.002

Adjusted r-squared statistic (based on deviance) 0.975

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	2.416	0.438	5.52	0.012	11.20
Pump (flow) rate	-0.1182	0.0331	-3.57	0.038	0.8885
Intake location top of dam pump	-20.51	5.31	-3.86	0.031	1.242E-09
Dam catch of rainbowfish	0.1640	0.0433	3.79	0.032	1.178
pump (flow) rate.div intake location top of dam pump	0.1473	0.0415	3.55	0.038	1.159

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	6.7976	6.7976	47.53	0.006
+ intake location	1	6.2440	6.2440	43.66	0.007
+ Dam catch rainbowfish	1	10.9249	10.9249	76.39	0.003
Pump (flow) rate.Intake location	1	15.8234	15.8234	110.64	0.002
Residual	3	0.4290	0.1430		
Total	7	40.2189	5.7456		

Response variate: Flat-headed gudgeon

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of f.h.gudgeon + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	264.45	66.11	4.89	0.111
Residual	3	40.54	13.51		
Total	7	304.99	43.57		
Change	-1	-25.31	25.31	1.87	0.265

Adjusted r-squared statistic (based on deviance) 0.690

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	2.29	1.40	1.64	0.200	9.912
Pump (flow) rate	-0.01124	0.00651	-1.73	0.183	0.9888
Intake location top of dam pump	-1.59	2.38	-0.67	0.552	0.2048
Dam catch of Flat-headed gudgeon	0.0822	0.0331	2.49	0.089	1.086
pump (flow) rate.div intake location top of dam pump	0.01133	0.00874	1.30	0.286	1.011

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	43.64	43.64	3.23	0.170
+ intake location	1	9.99	9.99	0.74	0.453
+ Dam catch Flat-headed gudgeon	1	185.51	185.51	13.73	0.034
+Pump (flow) rate.Intake location	1	25.31	25.31	1.87	0.265
Residual	3	40.54	13.51		
Total	7	304.99	43.57		

Response variate: Bony bream ≤ 100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of bony bream ≤ 100 mm + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	9351.406	2337.852	825.74	<.001
Residual	3	8.494	2.831		
Total	7	9359.900	1337.129		
Change	-1	-24.110	24.110	8.52	0.062

Adjusted r-squared statistic (based on deviance) 0.998

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	4.680	0.165	28.42	<.001	107.8
Pump (flow) rate	-0.007054	0.000656	-10.75	0.002	0.9930
Intake location top of dam pump	-3.041	0.493	-6.16	0.009	0.04781
Dam catch of b.b. ≤ 100 mm	0.005361	0.000182	29.48	<.001	1.005
pump (flow) rate.div intake location top of dam pump	0.00426	0.00154	2.76	0.070	1.004

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	1465.440	1465.440	517.60	<.001
+ intake location	1	2821.345	2821.345	996.51	<.001
+ Dam catch of b.b. ≤ 100 mm	1	5040.511	5040.511	1780.33	<.001
+Pump (flow) rate.Intake location	1	24.110	24.110	8.52	0.062
Residual	3	8.494	2.831		
Total	7	9359.900	1337.129		

Response variate: sleepy cod ≤ 100 mm

Distribution: Poisson. ink function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of sleepy cod ≤ 100 mm +pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	73.509	18.3774	22.64	0.014
Residual	3	2.435	0.8116		
Total	7	75.944	10.8492		
Change	-1	-2.054	2.0536	2.53	0.210

Adjusted r-squared statistic (based on deviance) 0.925

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	0.31	2.97	0.10	0.924	1.362
Pump (flow) rate	-0.0168	0.0287	-0.59	0.598	0.9833
Intake location top of dam pump	-4.78	4.32	-1.11	0.349	0.008430
Dam catch sleepy cod ≤100 mm	0.00698	0.00383	1.82	0.166	1.007
pump (flow) rate.div intake location top of dam pump	0.0316	0.0296	1.07	0.364	1.032

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	60.9789	60.9789	75.14	0.003
+ Intake location	1	0.0050	0.0050	0.01	0.942
+Dam catch sleepy cod ≤ 100 mm	1	10.4720	10.4720	12.90	0.037
+Pump (flow) rate.Intake location	1	2.0536	2.0536	2.53	0.210
Residual	3	2.4347	0.8116		
Total	7	75.9441	10.8492		

Response variate: sleepy cod > 100 mm

Distribution: Poisson. ink function: Log.

Fitted terms: Constant+ pump (flow) rate+pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	3	2.012	0.6707	0.67	0.570
Residual	4	2.147	0.5367		
Total	7	4.159	0.5941		
Change	-1	0.000	0.0000	0.00	0.999

Adjusted r-squared statistic (based on deviance) 0.097

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	-12	231	-0.05	0.960	8.351E-06
Pump (flow) rate	0.00	1.48	0.00	1.000	1.000
Intake location	8	232	0.04	0.972	3815.
pump (flow) rate.div intake location top of dam pump	0.01	1.48	0.00	0.996	1.007

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	1.5266	1.5266	1.53	0.217
+ Intake location	1	0.4857	0.4857	0.49	0.486
+Pump (flow) rate.Intake location	1	0.0000	0.0000	0.00	0.999
Residual	4	2.1467	0.5367		
Total	7	4.1589	0.5941		

Response variate: Barred grunter ≤ 100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of barred grunter ≤ 100 mm +pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	22.127	5.532	5.53	<.001
Residual	3	3.845	1.282		
Total	7	25.973	3.710		
Change	-1	-0.238	0.238	0.24	0.626

Adjusted r-squared statistic (based on deviance) 0.655

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	-1.56	1.61	-0.97	0.333	0.2104
Pump (flow) rate	0.00264	0.00826	0.32	0.749	1.003
Intake location top of dam pump	1.95	1.08	1.82	0.069	7.047
Dam catch barred grunter ≤100 mm	0.0500	0.0271	1.85	0.065	1.051
pump (flow) rate.div intake location top of dam pump	-0.00395	0.00762	-0.52	0.604	0.9961

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	4.196	4.196	4.20	0.041
+ Intake location	1	13.815	13.815	13.82	<.001
+Dam catch barred grunter ≤100 mm	1	3.878	3.878	3.88	0.049
+Pump (flow) rate.Intake location	1	0.238	0.238	0.24	0.626
Residual	3	3.845	1.282		
Total	7	25.973	3.710		

Response variate: Barred grunter > 100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of barred grunter > 100 mm +pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	7.1179	1.77949	1.78	0.130
Residual	3	0.2967	0.09889		
Total	7	7.4146	1.05923		
Change	-1	-1.6620	1.66198	1.66	0.197

Adjusted r-squared statistic (based on deviance) 0.907

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	-0.33	3.03	-0.11	0.913	0.7197
Pump (flow) rate	0.0008	0.0115	0.07	0.943	1.001
Intake location top of dam pump	13	386	0.03	0.972	632032
Dam catch barred grunter >100 mm	0.074	0.186	0.40	0.692	1.076
pump (flow) rate.div intake location top of dam pump	-0.19	5.14	-0.04	0.971	0.8284

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	3.09318	3.09318	3.09	0.079
+ Intake location	1	2.24904	2.24904	2.25	0.134
+Dam catch barred grunter >100 mm	1	0.11374	0.11374	0.11	0.736
+Pump (flow) rate.Intake location	1	1.66198	1.66198	1.66	0.197
Residual	3	0.29667	0.09889		
Total	7	7.41462	1.05923		

Response variate: Leathery grunter all sizes

Distribution: Poisson. Link function: Log.

Fitted terms: Constant + pump (flow) rate + intake location + temperature + pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	10.518	2.630	1.51	0.382
Residual	3	5.214	1.738		
Total	7	15.732	2.247		
Change	-1	-1.291	1.291	0.74	0.452

Adjusted r-squared statistic (based on deviance) 0.227

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	-7.91	9.09	-0.87	0.448	0.0003683
Pump (flow) rate	0.01433	0.00995	1.44	0.245	1.014
Intake location top of dam pump	2.29	6.03	0.38	0.730	9.863
Temperature	0.202	0.286	0.71	0.530	1.224
pump (flow) rate.div intake location top of dam pump	-0.0158	0.0199	-0.79	0.486	0.9843

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	2.259	2.259	1.30	0.337
+ Intake location	1	6.269	6.269	3.61	0.154
+Temperature	1	0.699	0.699	0.40	0.571
+Pump (flow) rate.Intake location	1	1.291	1.291	0.74	0.452
Residual	3	5.214	1.738		
Total	7	15.732	2.247		

Response variate: Golden perch ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of golden perch ≤ 100 mm +pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	92.544	23.136	16.83	0.021
Residual	3	4.123	1.374		
Total	7	96.667	13.810		
Change	-1	-2.679	2.679	1.95	0.257

Adjusted r-squared statistic (based on deviance) 0.900

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	0.722	0.444	1.63	0.202	2.059
Pump (flow) rate	0.00990	0.00332	2.98	0.058	1.010
Intake location top of dam pump	-0.99	1.08	-0.92	0.427	0.3722
Dam catch golden perch ≤100 mm	0.0222	0.0332	0.67	0.552	1.022
pump (flow) rate.div intake location top of dam pump	-0.00545	0.00366	-1.49	0.233	0.9946

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	9.287	9.287	6.76	0.080
+ Intake location	1	78.855	78.855	57.37	0.005
+Dam catch golden perch ≤100 mm	1	1.723	1.723	1.25	0.344
+Pump (flow) rate.Intake location	1	2.679	2.679	1.95	0.257
Residual	3	4.123	1.374		
Total	7	96.667	13.810		

Response variate: Golden perch all sizes

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location + dam catch of golden perch all sizes +pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	4	89.682	22.421	21.25	0.015
Residual	3	3.165	1.055		
Total	7	92.847	13.264		
Change	-1	-2.033	2.033	1.93	0.259

Adjusted r-squared statistic (based on deviance) 0.920

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	-0.151	0.835	-0.18	0.868	0.8601
Pump (flow) rate	0.00924	0.00264	3.50	0.039	1.009
Intake location top of dam pump	-0.860	0.919	-0.94	0.418	0.4231
Dam catch golden perch all sizes	0.0410	0.0332	1.23	0.305	1.042
pump (flow) rate.div intake location top of dam pump	-0.00510	0.00351	-1.45	0.242	0.9949

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	8.566	8.566	8.12	0.065
+ Intake location	1	73.024	73.024	69.22	0.004
+Dam catch golden perch all sizes	1	6.060	6.060	5.74	0.096
+Pump (flow) rate.Intake location	1	2.033	2.033	1.93	0.259
Residual	3	3.165	1.055		
Total	7	92.847	13.264		

Response variate: Rendahl's tandan> 100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump (flow) rate+ intake location +pump (flow) rate.diversion intake location

Summary of analysis

Source	Degrees of freedom	Deviance	Mean deviance	Deviance ratio	Approx F pr.
Regression	3	4.415	1.4717	1.47	0.220
Residual	4	1.470	0.3675		
Total	7	5.885	0.8407		
Change	-1	0.000	0.0000	0.00	0.999

Adjusted r-squared statistic (based on deviance) 0.920

Estimate of parameters

Parameter	estimate	Standard error	t (3)	t.pr.	Antilog of estimate
Constant	-0.86	1.33	-0.65	0.515	0.4215
Pump (flow) rate	0.00384	0.00740	0.52	0.604	1.004
Intake location top of dam pump	-11	213	-0.05	0.960	1.981E-05
pump (flow) rate.div intake location top of dam pump	-0.004	0.778	0.00	0.996	0.9962

Parameters are for factors compared with the reference level intake location bottom of dam gravity fed.

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Pump (flow) rate	1	0.1772	0.1772	0.18	0.674
+ Intake location	1	4.2378	4.2378	4.24	0.040
+Pump (flow) rate.Intake location	1	0.0000	0.0000	0.00	0.999
Residual	4	1.4700	0.3675		
Total	7	5.8850	0.8407		

Fish larvae

Response variate: All larvae estimated daily entrainment rate

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location + ln pump rate

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location	1	426	426	0.17	0.698
+ ln pump rate	1	10281	10281	4.07	0.100
Residual	5	12635	2527		
Total	7	23343	3335		

Response variate: Bony bream larvae estimated daily entrainment rate

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump intake location + ln pump rate

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location	1	3873.6	3873.6	11.23	0.020
+ Pump (flow) rate	1	2228.1	2228.1	6.46	0.052
Residual	5	1724.6	344.9		
Total	7	7826.3	1118.0		

Response variate: Flat-headed gudgeon larvae estimated daily entrainment rate

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump intake location

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location	1	2734.4	2734.4	5.86	0.052
Residual	6	2797.8	466.3		
Total	7	5532.3	790.3		

Response variate: All larvae entrainment rate per ML

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump intake location

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location	1	30.03	30.03	0.44	0.531
Residual	6	408.70	68.12		
Total	7	438.73	62.68		

Response variate: Bony bream larvae entrainment rate per ML

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump intake location

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location	1	30.42	30.42	2.79	0.146
Residual	6	65.34	10.89		
Total	7	95.76	13.68		

Response variate: Flat-headed gudgeon larvae entrainment rate per ML

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ pump intake location

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location	1	37.84	37.84	2.97	0.135
Residual	6	76.41	12.74		
Total	7	114.26	16.32		

Riverine pump GLMs accumulated analyses of deviance or variance

Adult and juvenile fish entrained per 100 min

Response variate: All fish ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + ln pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	891.8	297.3	1.88	0.179
+ Flow type	2	440.2	220.1	1.39	0.281
+ ln pump rate	1	191.0	191.0	1.21	0.290
+Season	1	222.3	222.3	1.41	0.255
Residual	14	2213.4	158.1		
Total	21	3958.7	188.5		

Response variate: bony bream ≤100 mm

Distribution: Normal. Link function: Identity.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Bony bream ≤ 100 mm river catch

Accumulated analysis of variance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	14530	4843	2.12	0.144
+ Flow type	2	9821	4911	2.15	0.154
+ In pump rate	1	2333	2333	1.02	0.330
+ Bony bream ≤ 100 mm river catch	1	6848	6848	3.00	0.105
Residual	14	32005	2286		
Total	21	65537	3121		

Response variate: bony bream >100 mm

Distribution: Normal. Link function: Identity.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of variance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	16.157	5.386	0.61	0.617
+ Flow type	2	8.945	4.472	0.51	0.611
+ In pump rate	1	47.558	47.558	5.43	0.035
+ Season	1	22.089	22.089	2.52	0.135
Residual	14	122.706	8.765		
Total	21	217.455	10.355		

Response variate: Sleepy cod ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	3.668	1.223	0.63	0.605
+ Flow type	2	3.758	1.879	0.98	0.401
+ In pump rate	1	0.728	0.728	0.38	0.549
+ Season	1	2.398	2.398	1.24	0.283
Residual	14	26.976	1.927		
Total	21	37.529	1.787		

Response variate: spangled perch ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Spangled perch ≤ 100 mm river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	55.67	18.56	0.51	0.680
+ Flow type	2	6.53	3.27	0.09	0.914
+ In pump rate	1	0.22	0.22	0.01	0.939
+ Spang. perch ≤100 mm river catch	1	0.20	0.20	0.01	0.942
Residual	14	507.10	36.22		
Total	21	569.72	27.13		

Response variate: spangled perch >100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Spangled perch >100 mm river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	373.75	124.58	9.98	<.001
+ Flow type	2	175.88	87.94	7.05	0.008
+ In pump rate	1	7.48	7.48	0.60	0.452
+ Spang. perch >100 mm river catch	1	228.71	228.71	18.33	<.001
Residual	14	174.70	12.48		
Total	21	960.52	45.74		

Response variate: carp gudgeon

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	1225.3	408.4	3.98	0.030
+ Flow type	2	265.0	132.5	1.29	0.306
+ In pump rate	1	19.0	19.0	0.18	0.674
+ Season	1	14.1	14.1	0.14	0.717
Residual	14	1438.2	102.7		
Total	21	2961.6	141.0		

Response variate: Olive perchlet

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Olive perchlet river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	342.56	114.19	3.43	0.047
+ Flow type	2	65.58	32.79	0.98	0.398
+ In pump rate	1	66.47	66.47	2.00	0.179
+ Olive perchlet river catch	1	209.01	209.01	6.28	0.025
Residual	14	466.07	33.29		
Total	21	1149.68	54.75		

Response variate: Eastern rainbowfish

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + Eastern rainbowfish river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	130.85	43.62	3.31	0.049
+ Flow type	2	65.41	32.70	2.48	0.117
+ Eastern rainbowfish river catch	1	20.52	20.52	1.56	0.231
Residual	15	197.78	13.19		
Total	21	414.56	19.74		

Response variate: Blue catfish ≤ 100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + Blue catfish ≤ 100 mm river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	13.862	4.621	1.74	0.202
+ Flow type	2	27.460	13.730	5.17	0.020
+ Blue catfish ≤ 100 mm river catch	1	1.965	1.965	0.74	0.403
Residual	15	39.840	2.656		
Total	21	83.127	3.958		

Response variate: Sleepy cod > 100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	2.6373	0.8791	1.30	0.305
Residual	18	12.1787	0.6766		
Total	21	14.8160	0.7055		

Response variate: barred grunter ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	40.000	13.333	3.70	0.031
Residual	18	64.780	3.599		
Total	21	104.780	4.990		

Response variate: Hyrtl's tandan >100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	9.0073	3.0024	3.06	0.055
Residual	18	17.6744	0.9819		
Total	21	26.6818	1.2706		

Response variate: Rendahl's tandan >100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	10.597	3.532	3.29	0.044
Residual	18	19.297	1.072		
Total	21	29.895	1.424		

Response variate: Fly-specked hardyhead

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	21.271	7.090	3.59	0.034
Residual	18	35.599	1.978		
Total	21	56.870	2.708		

Response variate: Number of native species

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	15.4030	5.1343	8.73	0.002
+ Flow type	2	2.9686	1.4843	2.52	0.116
+ In pump rate	1	4.0244	4.0244	6.84	0.020
+ Season	1	1.3082	1.3082	2.22	0.158
Residual	14	8.2373	0.5884		
Total	21	31.9414	1.5210		

Larval fish entrained per 100 min

Response variate: All larvae combined projected catch per day

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Season+ Intake location & depth + Flow type + In pump rate

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Season	1	53406	53406	1.63	0.229
+ Intake location & depth	3	110825	36942	1.12	0.381
+ Flow type	1	1451	1451	0.04	0.837
+ In pump rate	1	22721	22721	0.69	0.423
Residual	11	361490	32863		
Total	17	549893	32347		

Response variate: Unidentified larvae projected catch per day

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Season+ Intake location & depth + Flow type + In pump rate

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Season	1	25554.	25554.	7.27	0.021
+ Intake location & depth	3	14847.	4949.	1.41	0.292
+ Flow type	1	689	689	0.20	0.666
+ In pump rate	1	8993	8993	2.56	0.138
Residual	11	38656	3514		
Total	17	88739	5220		

Response variate: Carp gudgeon larvae projected catch per day

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Season+ Intake location & depth + Flow type + In pump rate

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Season	1	23022810	23022810	0.69	0.422
+ Intake location & depth	3	8921300	2973767	0.09	0.964
+ Flow type	1	43147455	43147455	1.30	0.278
+ In pump rate	1	22896217	22896217	0.69	0.424
Residual	11	364863327	33169393		
Total	17	462851108	27226536		

Response variate: Golden perch larvae projected catch per day

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Season+ Intake location & depth + Flow type

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Season	1	36542.	36542.	5.50	0.037
+ Intake location & depth	3	59142.	19714.	2.97	0.075
+ Flow type	1	27711.	27711.	4.17	0.064
Residual	12	79779	6648		
Total	17	203174	11951		

Selected adult and juvenile fish entrained per ML

Response variate: All fish ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	4775	1592	0.87	0.480
+ Flow type	2	2141	1071	0.59	0.570
+ In pump rate	1	149	149	0.08	0.780
+Season	1	562	562	0.31	0.588
Residual	14	25615	1830		
Total	21	33242	1583		

Response variate: All fish >100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	78.02	26.01	0.85	0.489
+ Flow type	2	50.89	25.45	0.83	0.456
+ In pump rate	1	0.07	0.07	0.00	0.963
+Season	1	12.14	12.14	0.40	0.539
Residual	14	428.37	30.60		
Total	21	569.48	27.12		

Response variate: Bony bream ≤100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Bony bream ≤100 mm river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	1459.4	486.5	2.93	0.071
+ Flow type	2	746.0	373.0	2.24	0.143
+ In pump rate	1	81.1	81.1	0.49	0.496
+ Bony bream ≤100 mm river catch	1	791.2	791.2	4.76	0.047
Residual	14	2327.5	166.2		
Total	21	5405.3	257.4		

Response variate: Bony bream >100 mm

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	1.1263	0.3754	1.17	0.357
+ Flow type	2	0.4701	0.2350	0.73	0.499
+ In pump rate	1	1.3661	1.3661	4.25	0.058
+ Season	1	0.6480	0.6480	2.02	0.178
Residual	14	4.5010	0.3215		
Total	21	8.1114	0.3863		

Response variate: Olive perchlet

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	1002.0	334.0	0.92	0.454
+ Flow type	2	300.0	150.0	0.41	0.668
+ In pump rate	1	43.6	43.6	0.12	0.733
Residual	15	5431.2	362.1		
Total	21	6776.9	322.7		

Response variate: Eastern rainbowfish

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + In pump rate + Eastern rainbowfish river catch

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	6.598	2.199	0.88	0.474
+ Flow type	2	2.899	1.450	0.58	0.572
+ In pump rate	1	6.520	6.520	2.61	0.128
+ Eastern rainbowfish river catch	1	2.431	2.431	0.97	0.340
Residual	14	34.918	2.494		
Total	21	53.365	2.541		

Larval fish entrained per ML

Response variate: All larvae combined projected catch per ML

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	136922	45641	0.37	0.775
+ flow type	1	90864	90864	0.74	0.407
+ Season	1	55031	55031	0.45	0.516
Residual	12	1475765	122980		
Total	17	1758582	103446		

Response variate: Unidentified larvae catch per ML

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	24169.	8056.	1.22	0.345
+ flow type	1	59	59	0.01	0.926
+ Season	1	10360	10360	1.57	0.234
Residual	12	79306	6609		
Total	17	113894	6700		

Response variate: Carp gudgeon larvae catch per ML

Distribution: Poisson. Link function: Log.

Fitted terms: Constant+ Intake location & depth + Flow type + Season

Accumulated analysis of deviance

Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	6673	2224	0.28	0.839
+ flow type	1	10344	10344	1.30	0.277
+ Season	1	3153	3153	0.40	0.541
Residual	12	95589	7966		
Total	17	115760	6809		

Response variate: Golden perch larvae catch per ML

Distribution: Poisson. Link function: Log.

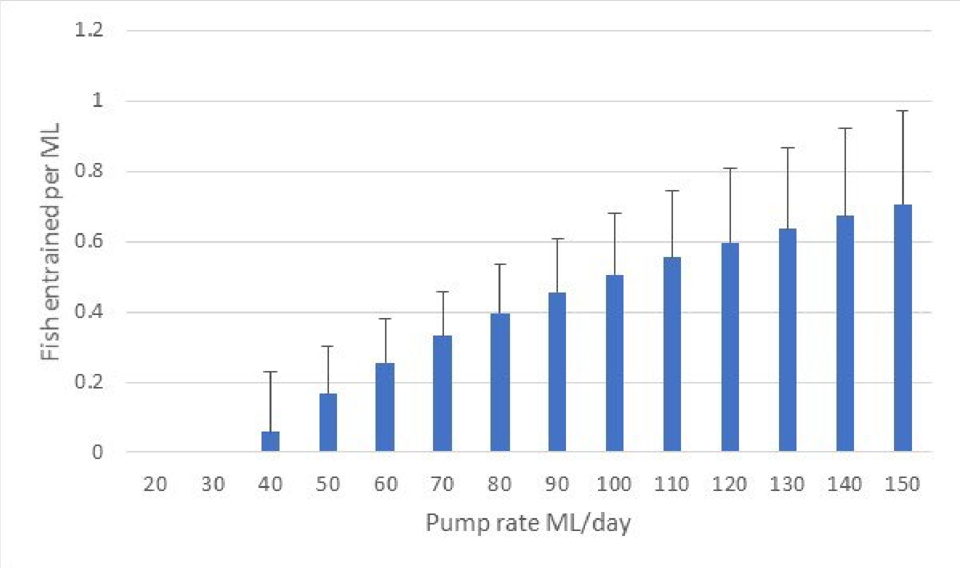
Fitted terms: Constant+ Intake location & depth + Flow type + Season

Accumulated analysis of deviance

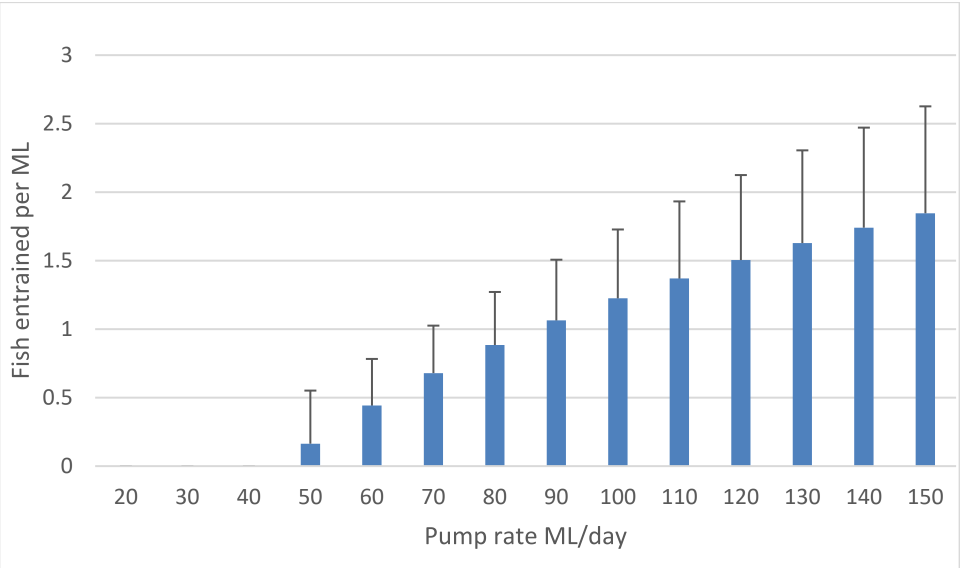
Change	d.f.	Deviance	Mean deviance	Deviance ratio	Approx F pr.
+ Intake location & depth	3	82231	27410	1.48	0.270
+ flow type	1	34936	34936	1.88	0.195
+ Season	1	3209	3209	0.17	0.685
Residual	12	222745	18562		
Total	17	343120	20184		

Appendix II: Additional plots of fish entrainment rates per ML

Bony bream >100 mm entrainment rate per ML by pump rate



Eastern rainbowfish entrainment rate per ML by pump rate

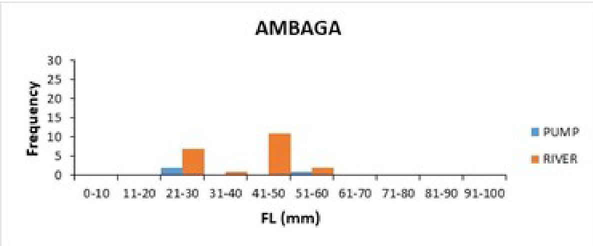


Appendix III: Length frequency histograms of entrained fish and fish in adjacent reference sites

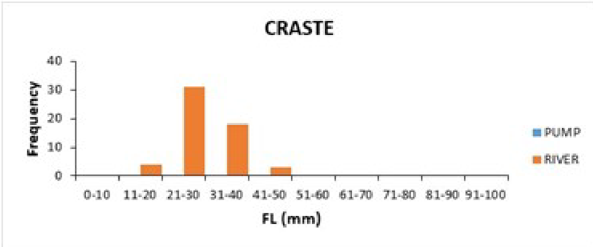
Commonly encountered fish at riverine pump or reference sites on natural flow events by site and flow event.

Pump site 3 vs Ref site 5, 14/01/21. Pump rate 49 ML/day. Side-channel intake

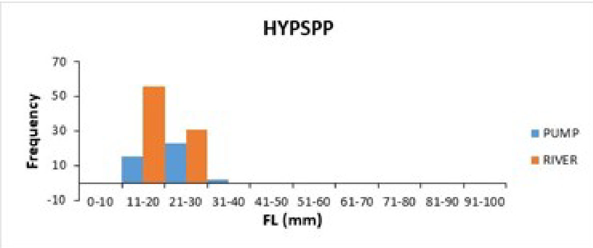
Olive perchlet



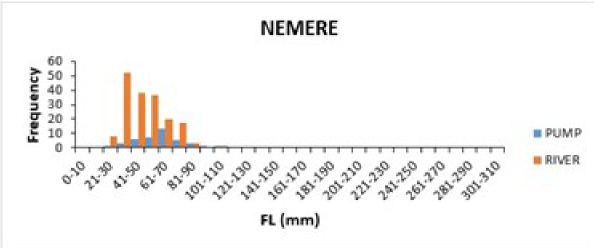
Fly-specked hardyhead



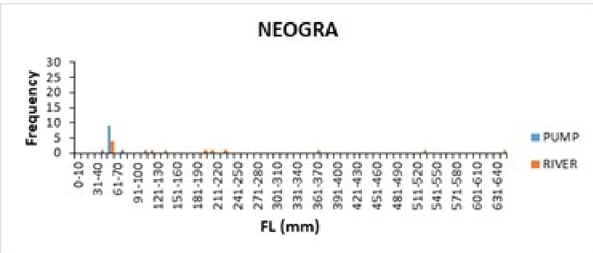
Carp gudgeon spp



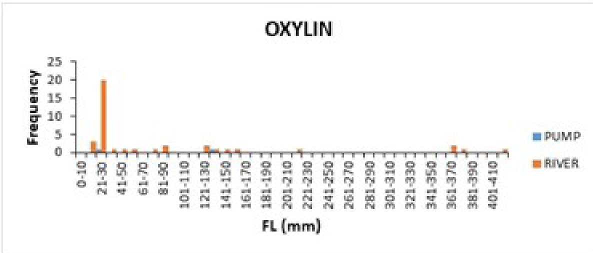
Bony bream



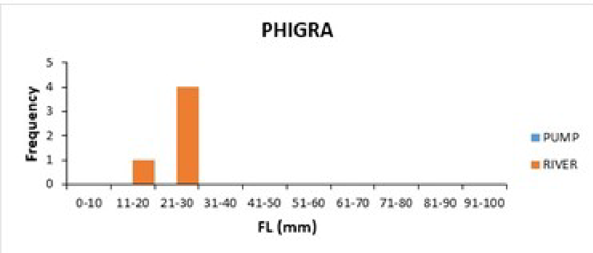
Blue catfish



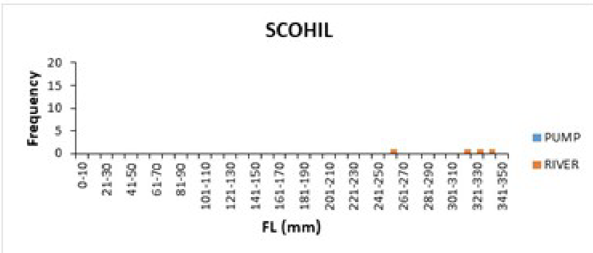
Sleepy cod



Flat-headed gudgeon

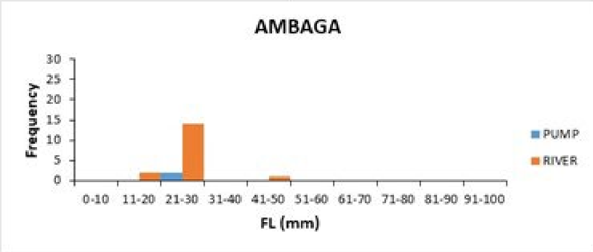


Leathery grunter

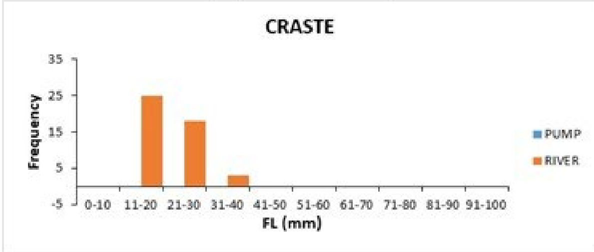


Pump site 3 vs Ref site 5, 27/11/21. Pump rate 49 ML/day. Side channel intake

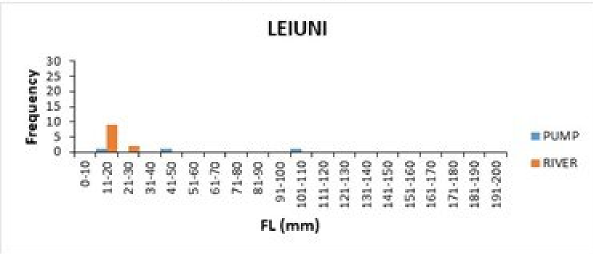
Olive perchlet



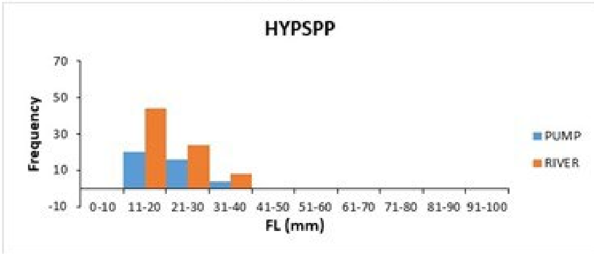
Fly-specked hardyhead



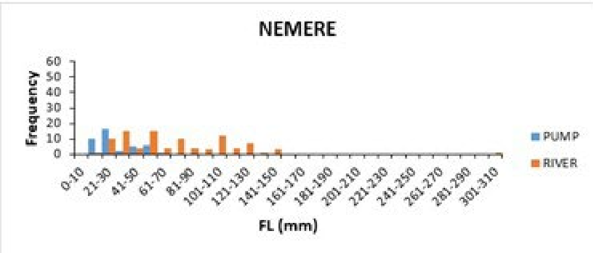
Spangled perch



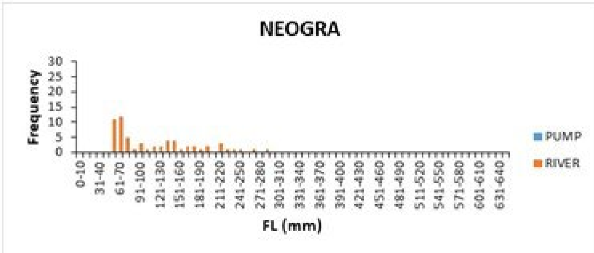
Carp gudgeon spp



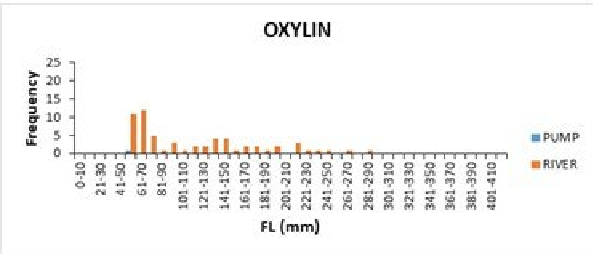
Bony bream



Blue catfish

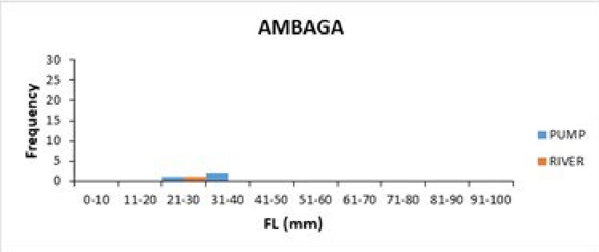


Sleepy cod

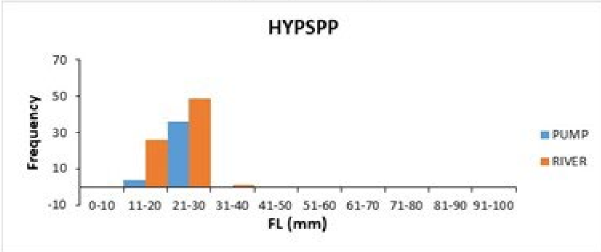


Pump site 3 vs Ref site 5, 20/03/21. Pump rate 51 ML/day. side channel intake

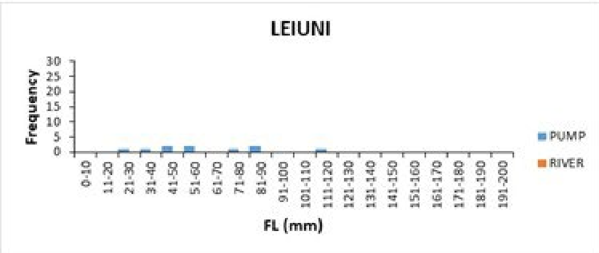
Olive perchlet



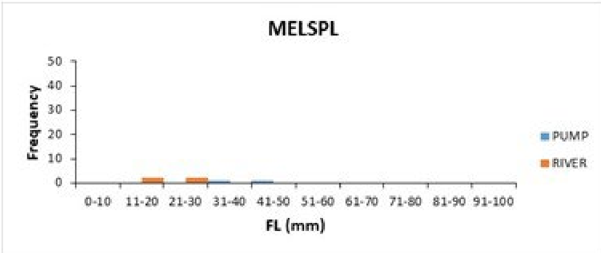
Carp gudgeon spp



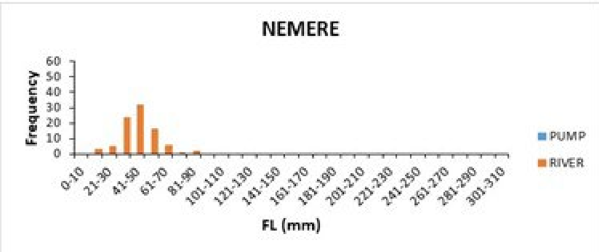
Spangled perch



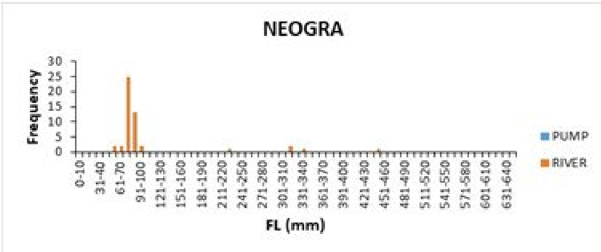
Eastern rainbowfish



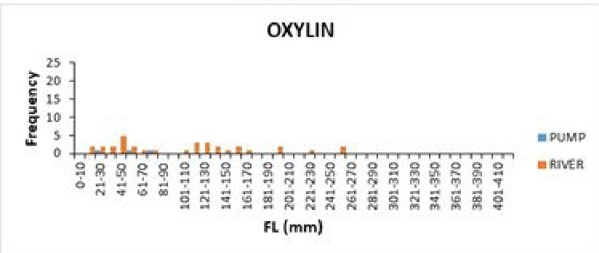
Bony bream



Blue catfish

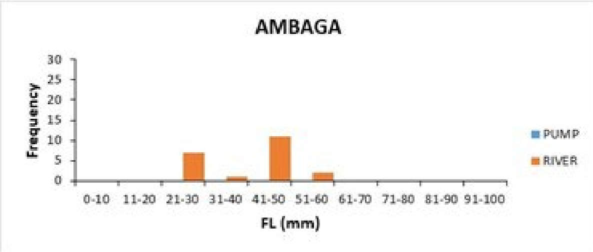


Sleepy cod

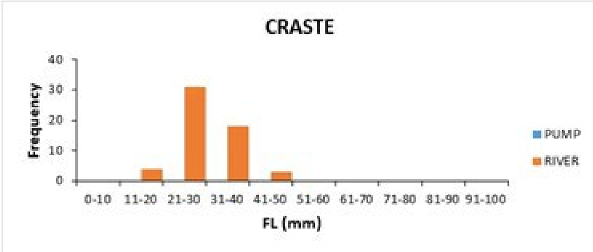


Pump site 4 vs Ref site 5, 14/01/21. Pump rate 54 ML/day. Mid-river channel intake

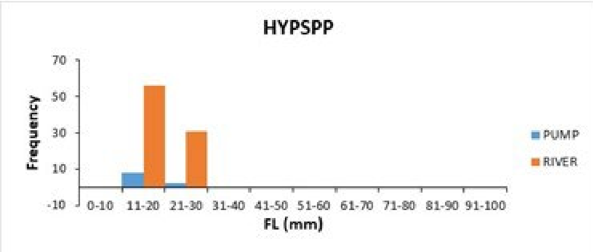
Olive perchlet



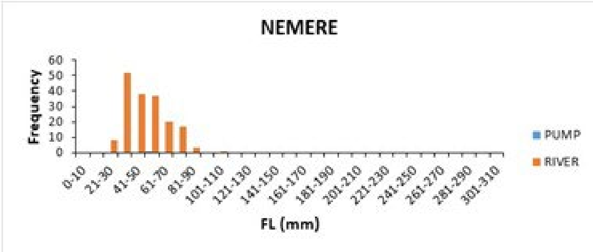
Fly-specked hardyhead



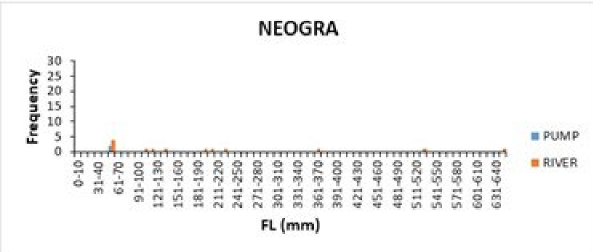
Carp gudgeon spp



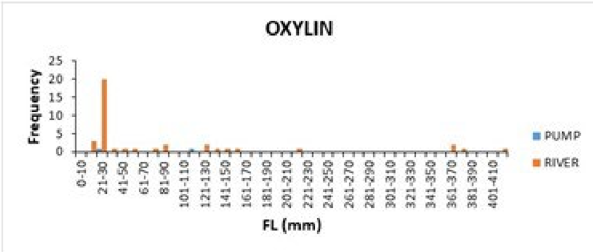
Bony bream



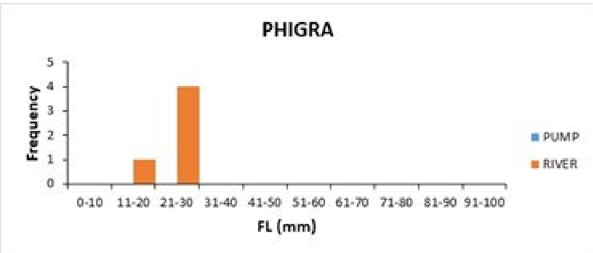
Blue catfish



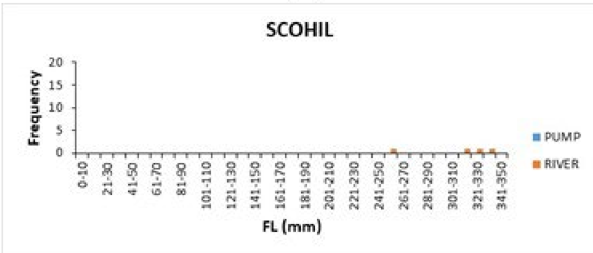
Sleepy cod



Flat-headed gudgeon

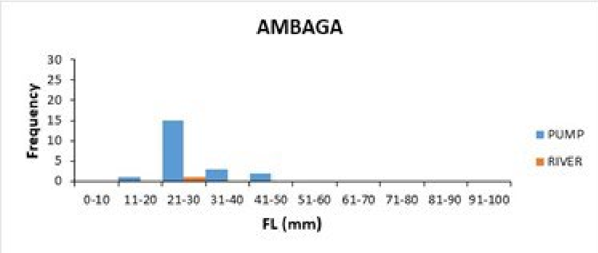


Leathery grunter

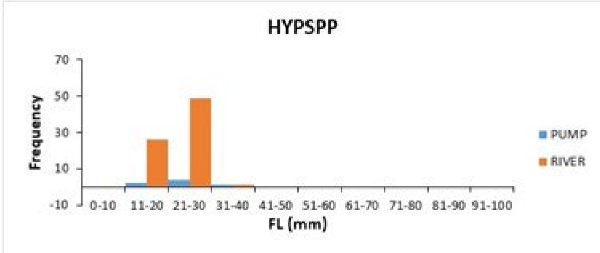


Pump site 4 vs Ref site 5, 21/03/21. Pump rate 56 ML/day. Mid-river channel intake

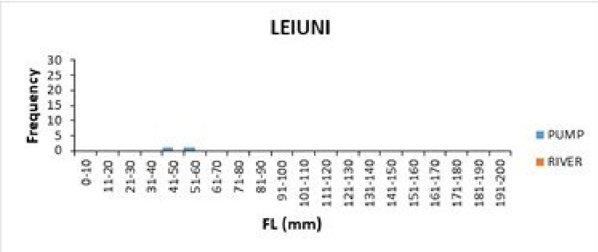
Olive perchlet



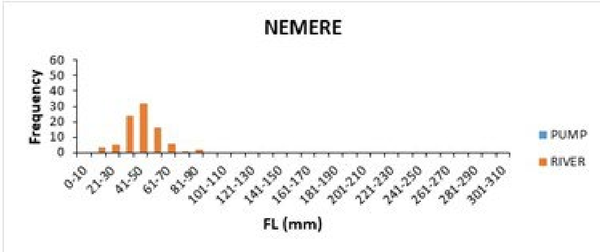
Carp gudgeon spp



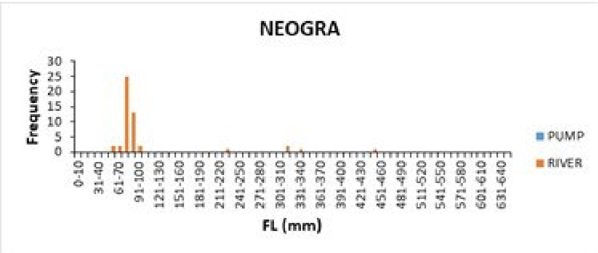
Spangled perch



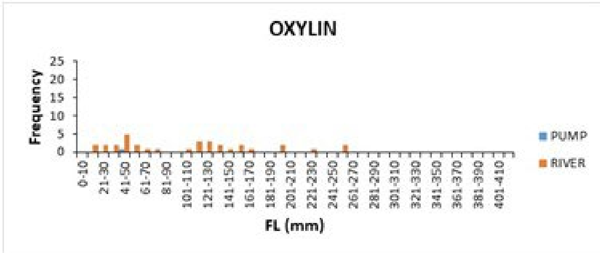
Bony bream



Blue catfish

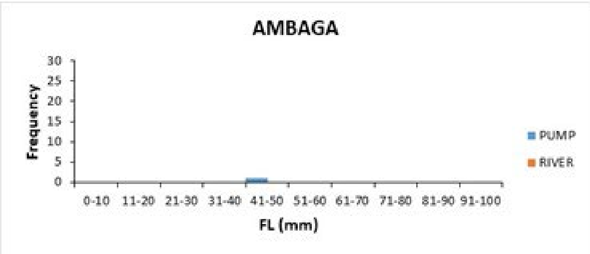


Sleepy cod

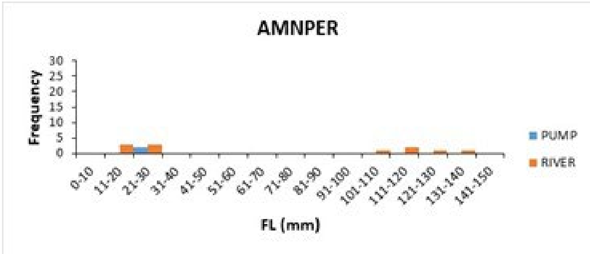


Pump site 16 vs Ref site 2, 16/11/21. Pump rate 90ML/day. Bankside deep intake.

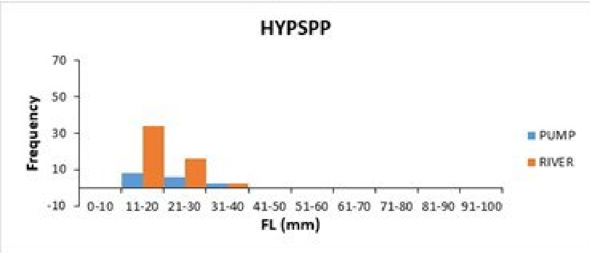
Olive perchlet



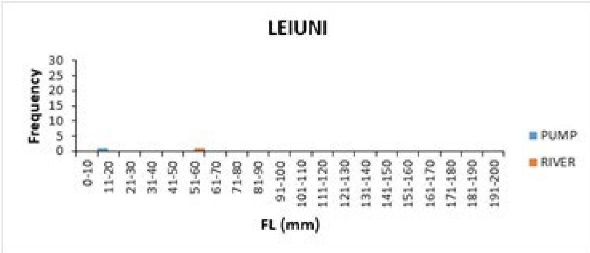
Barred grunter



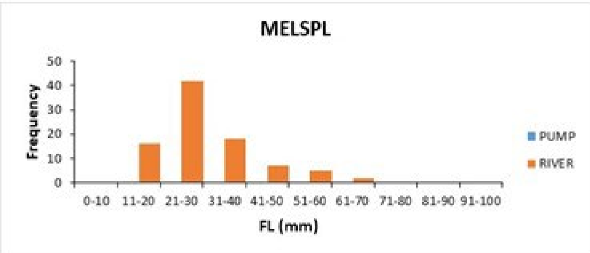
Carp gudgeon



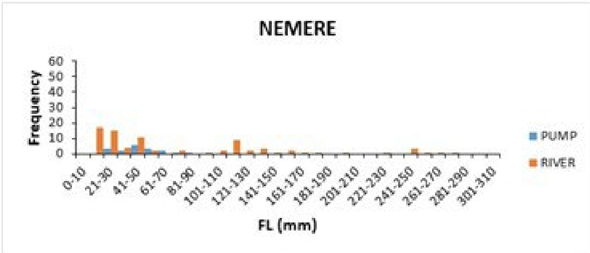
Spangled perch



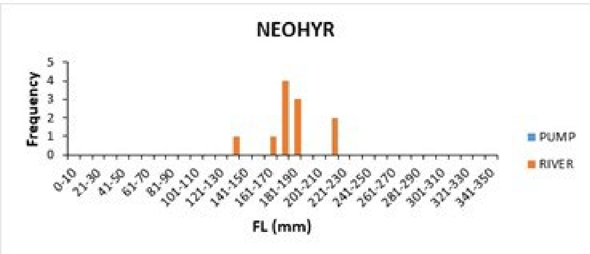
Eastern rainbowfish



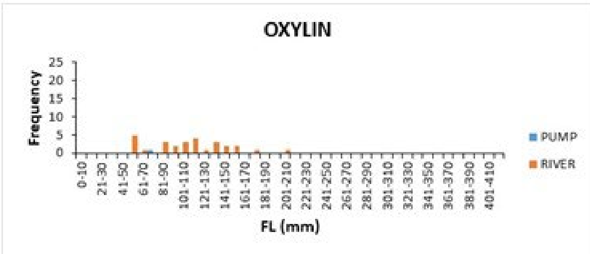
Bony bream



Hyrtl's tandan

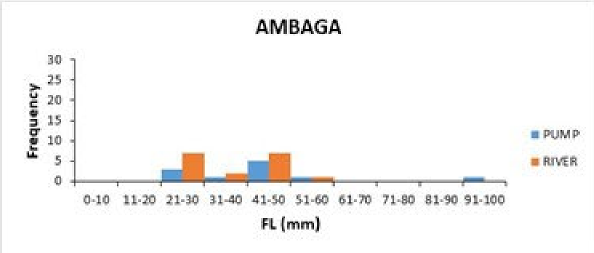


Sleepy cod

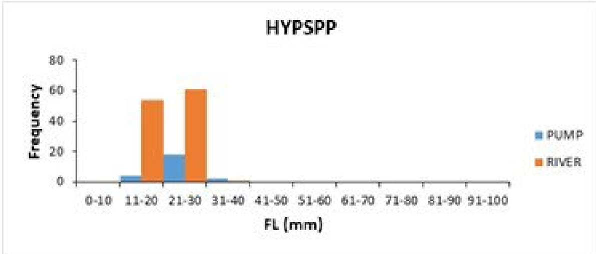


Pump site 1 vs Ref site 2, 13/01/21. Pump rate 100 ML/day. Bankside deep intake

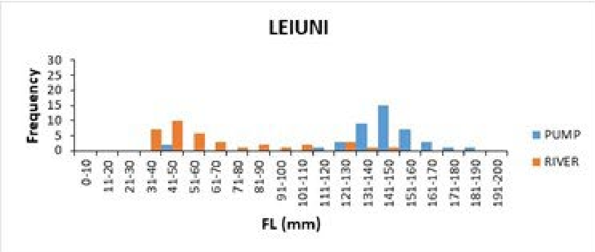
Olive perchlet



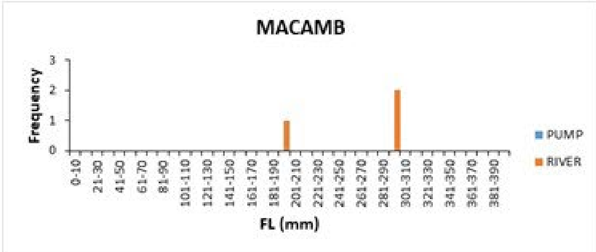
Carp gudgeon spp



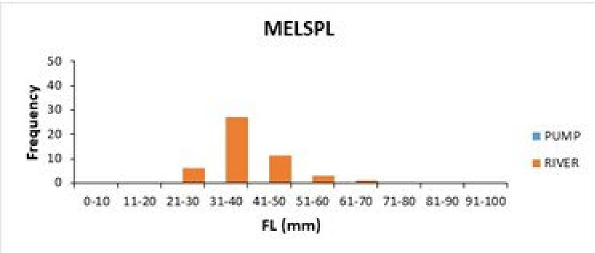
Spangled perch



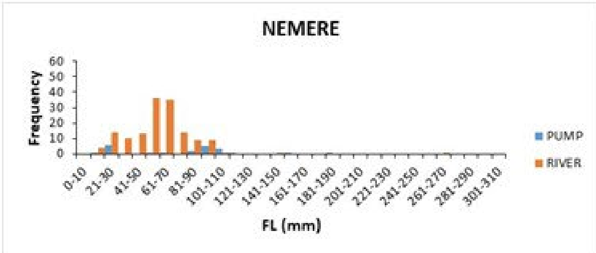
Golden perch



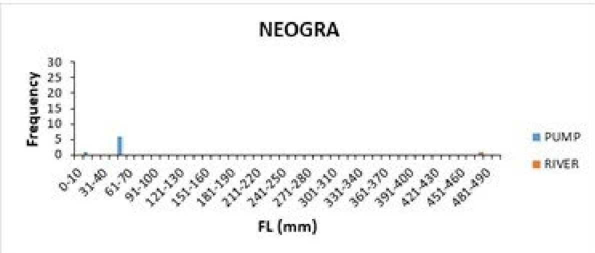
Eastern rainbowfish



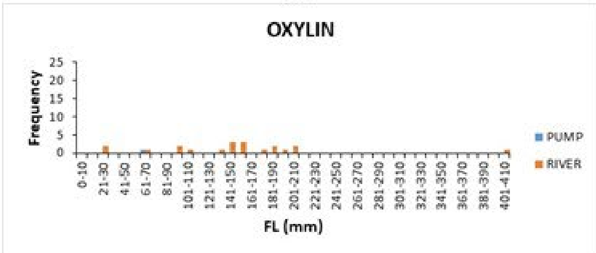
Bony bream



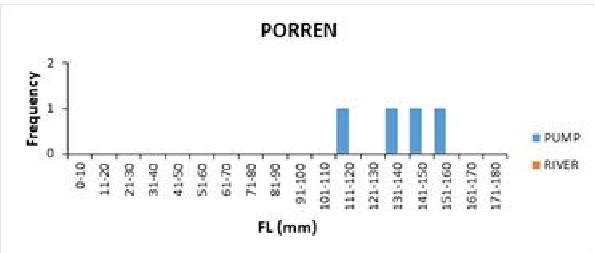
Blue catfish



Sleepy cod

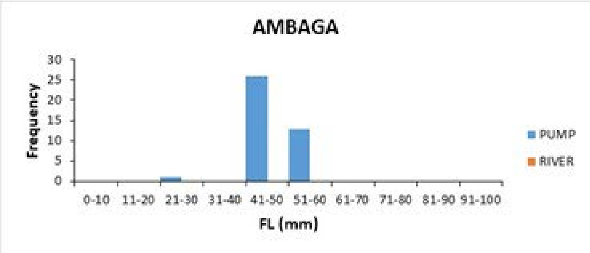


Rendahl's tandan

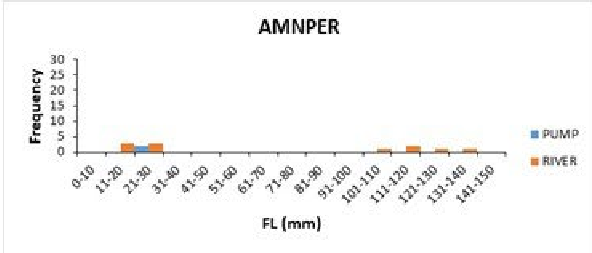


Pump site 1 vs Ref site 2, 16/11/21. Pump rate 100 mL/day. Bankside deep intake

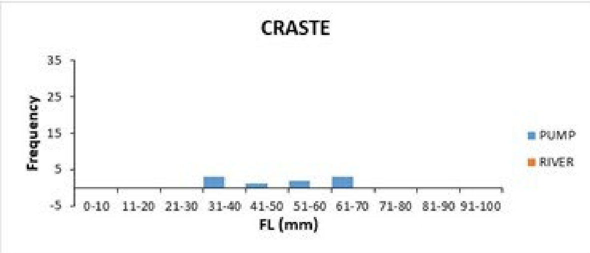
Olive perchlet



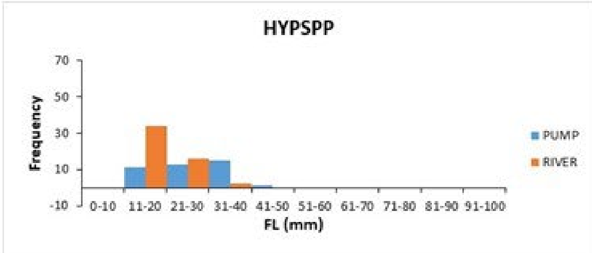
Barred grunter



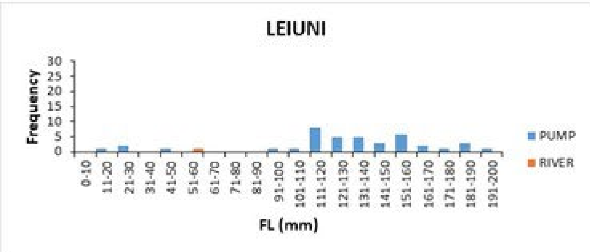
Fly-specked hardyhead



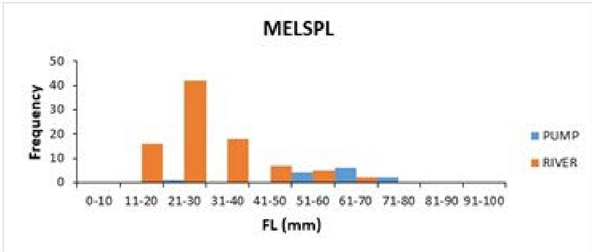
Carp gudgeon spp



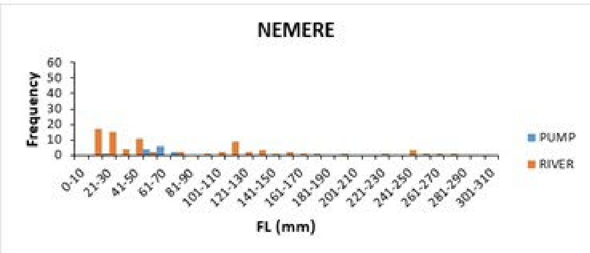
Spangled perch



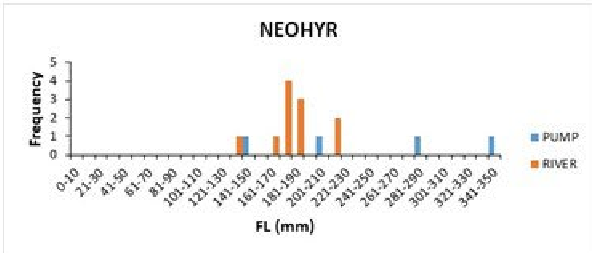
Eastern rainbowfish



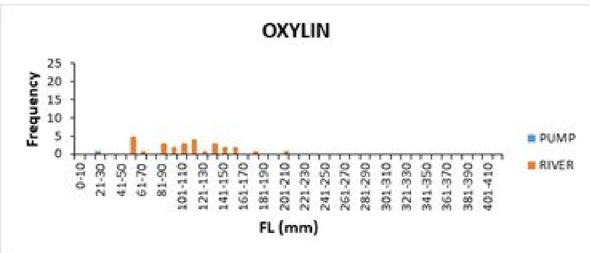
Bony bream



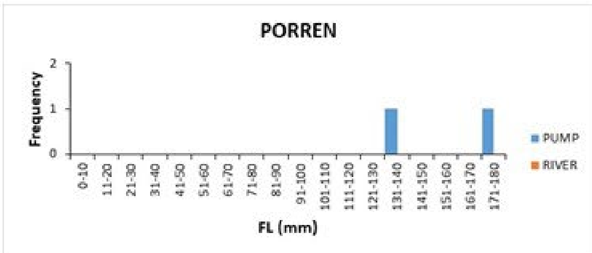
Hyrtl's tandan



Sleepy cod

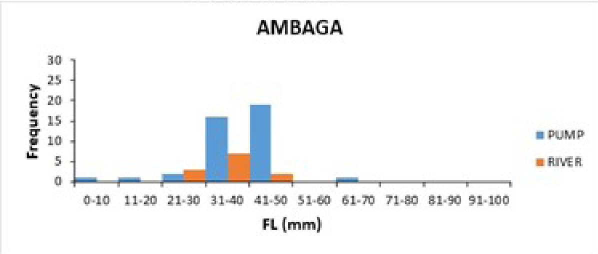


Rendahl's tandan

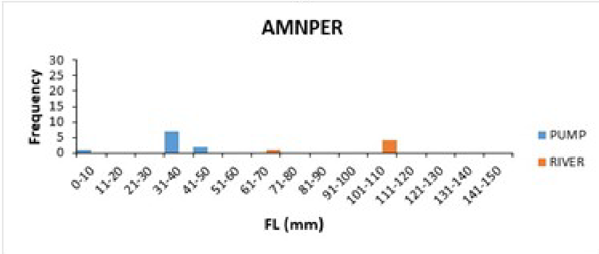


Pump site 8 vs Ref site 6, 21/03/21. Pump rate 100 ML/day Bankside deep intake

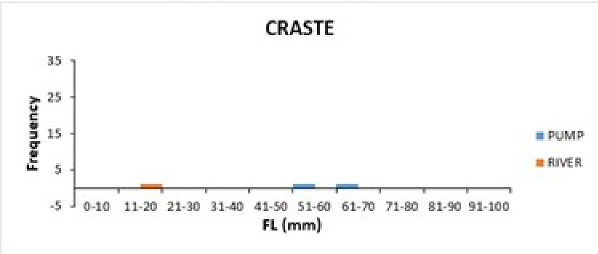
Olive perchlet



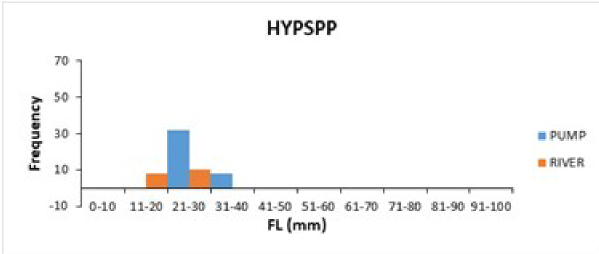
Barred grunter



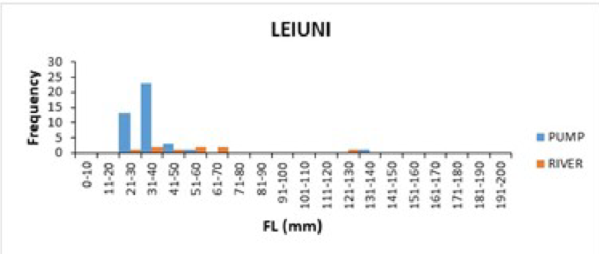
Fly-specked hardyhead



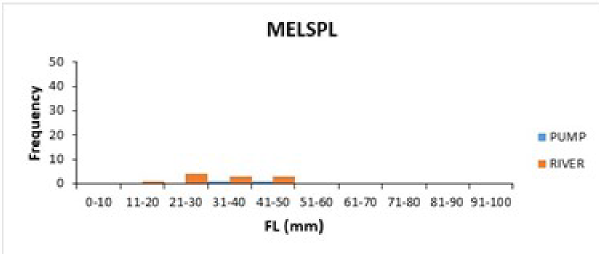
Carp gudgeon spp.



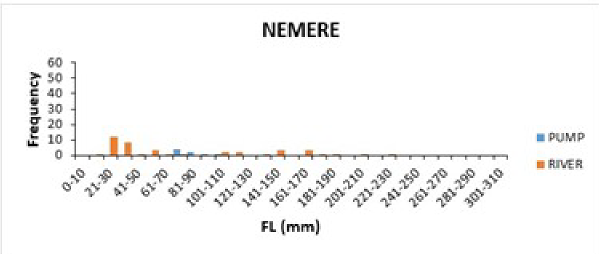
Spangled perch



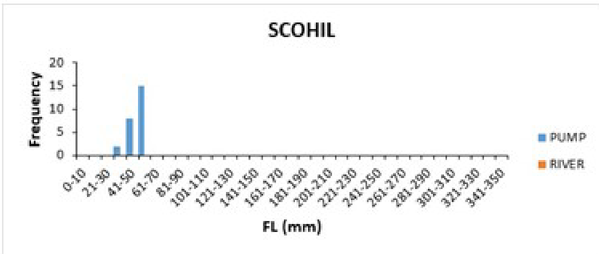
Eastern rainbowfish



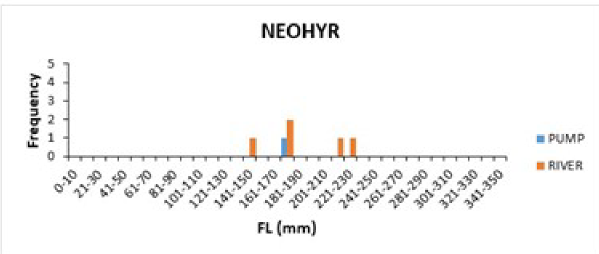
Bony bream



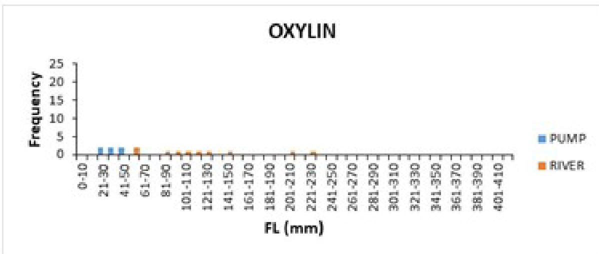
Leathery grunter



Hyrtl's tandan

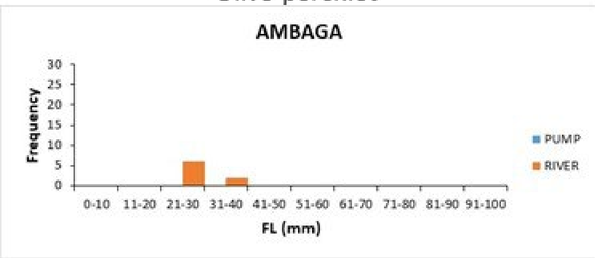


Sleepy cod

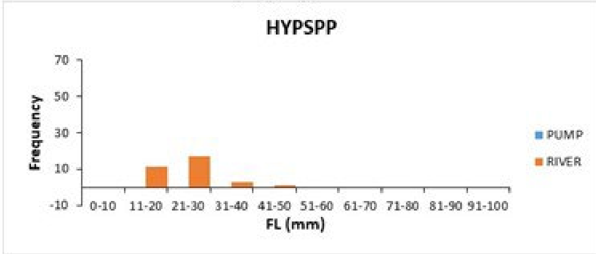


Pump site 7 vs Ref site 6, 27/11/21. Pump rate 100 ML/day. Bankside shallow intake

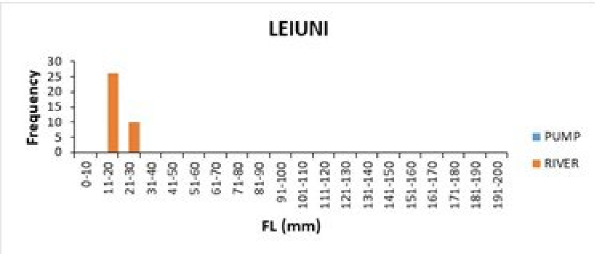
Olive perchlet



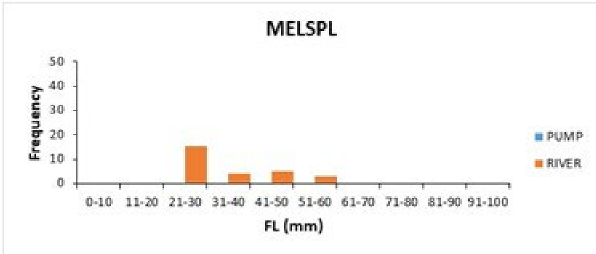
Carp gudgeon



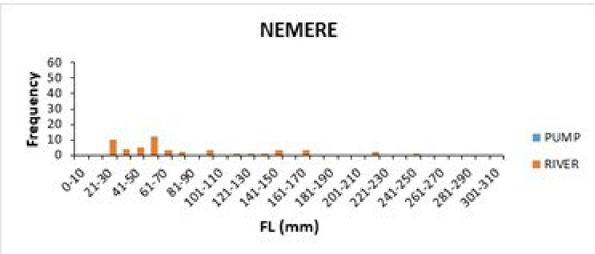
Spangled perch



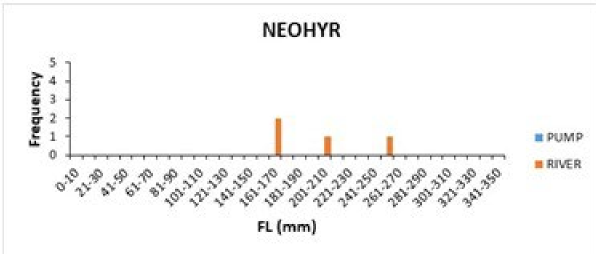
Eastern rainbowfish



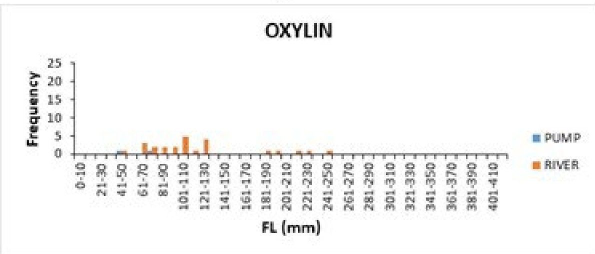
Bony bream



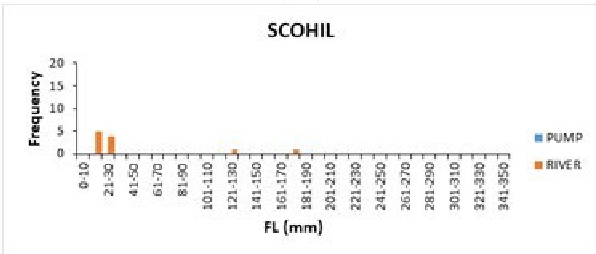
Hyrtl's tandan



Sleepy cod

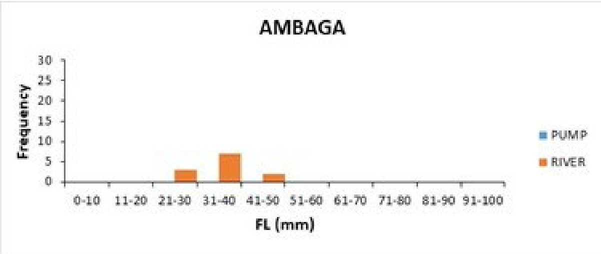


Leathery grunter

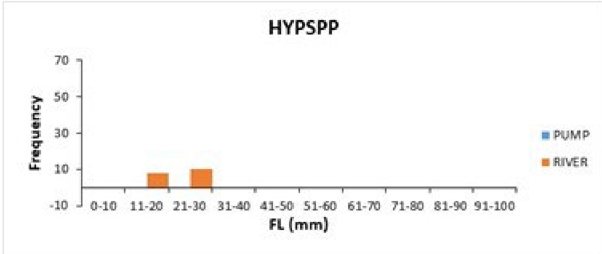


Pump site 7 vs Ref site 6, 20/03/21. Pump rate 150 ML/day bankside shallow intake

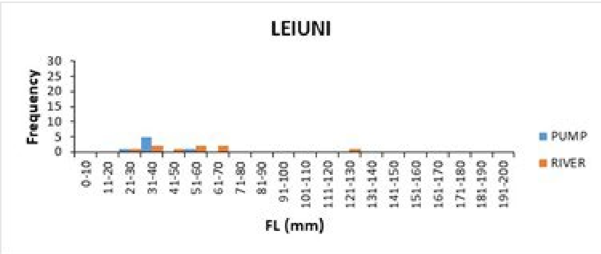
Olive perchlet



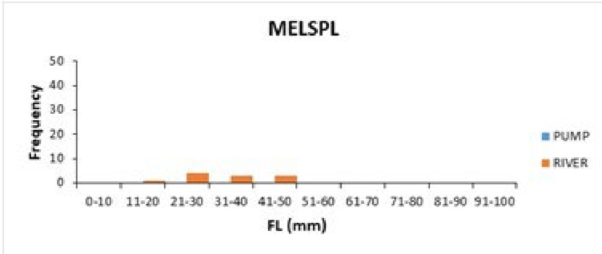
Carp gudgeon spp



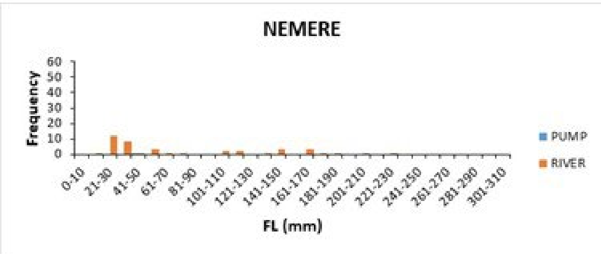
Spangled perch



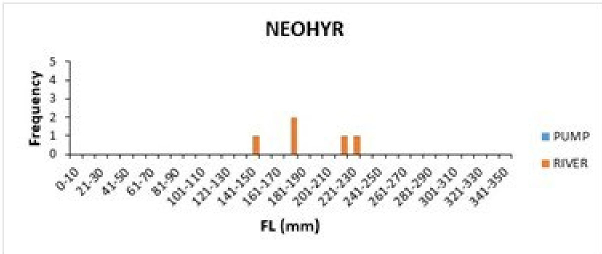
Eastern rainbowfish



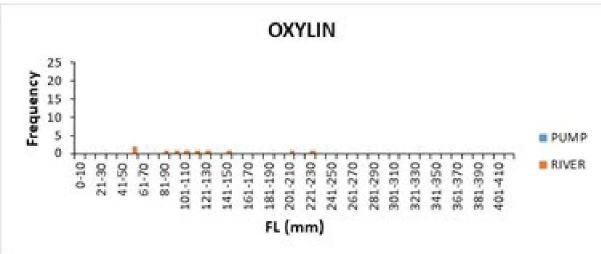
Bony bream



Hyrtl's tandan



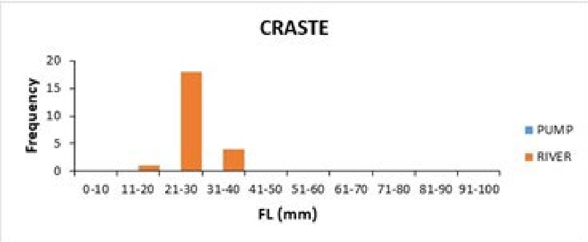
Sleepy cod



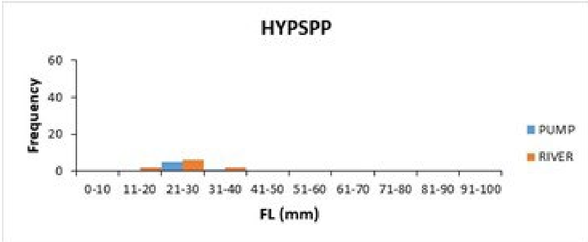
Commonly encountered fish at riverine pump or reference sites on allocated flow events by site and flow event.

Pump site 17 vs Ref site 18, 25/02/22. Pump rate 14 ML/day. Mid-river channel intake

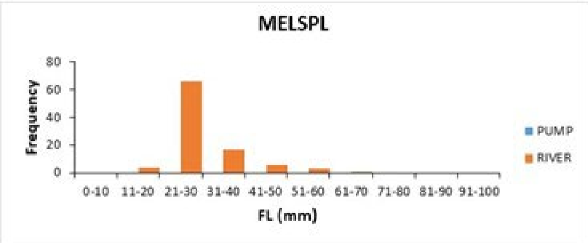
Fly specked hardyhead



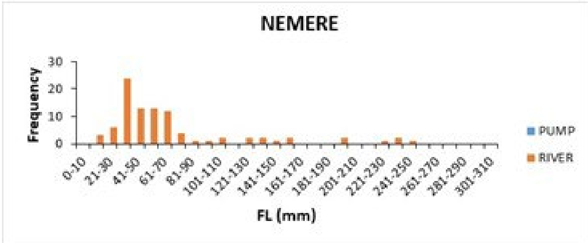
Carp gudgeon spp.



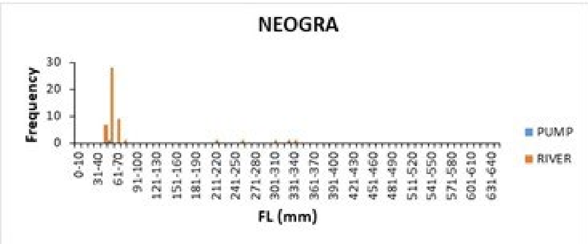
Eastern rainbowfish



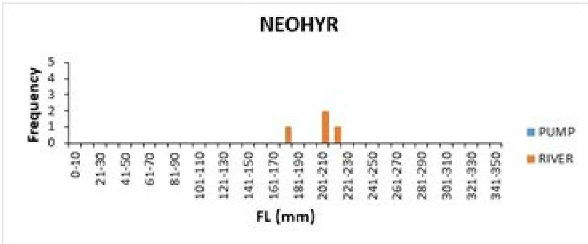
Bony bream



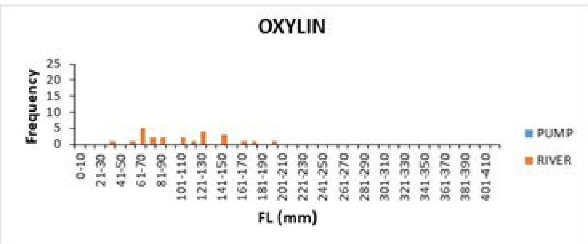
Blue catfish



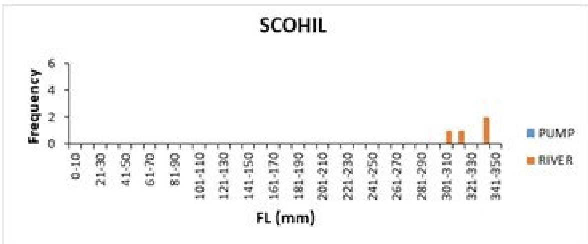
Hyrtl's tandan



Sleepy cod

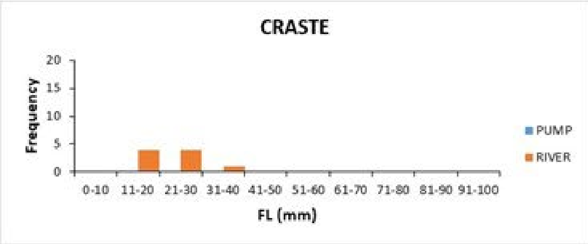


Leathery grunter

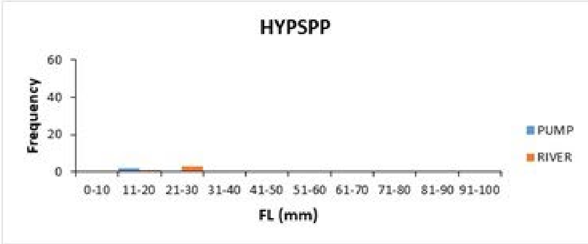


Pump site 17 vs Ref site 18, 22/01/22. Pump rate 14.5 ML/day. Mid-river channel intake

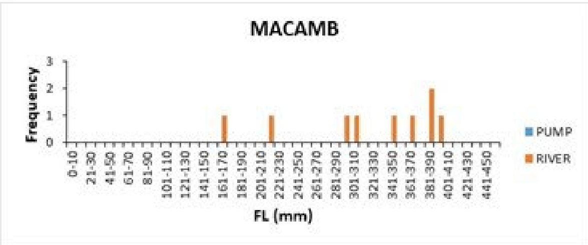
Fly specked hardyhead



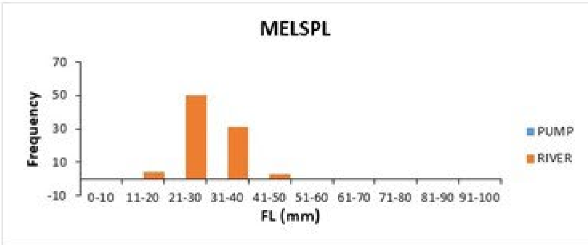
Carp gudgeon spp



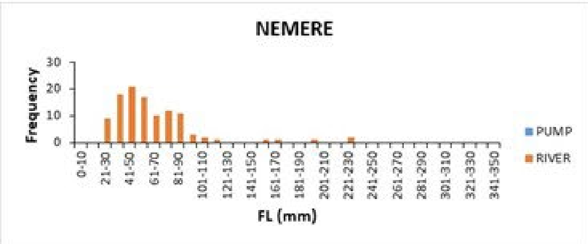
Golden perch



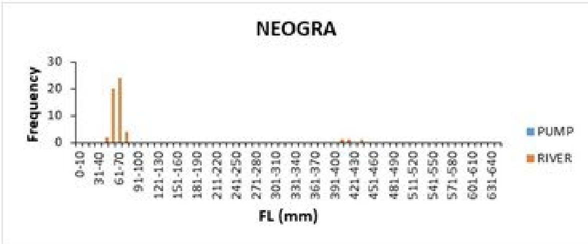
Eastern rainbowfish



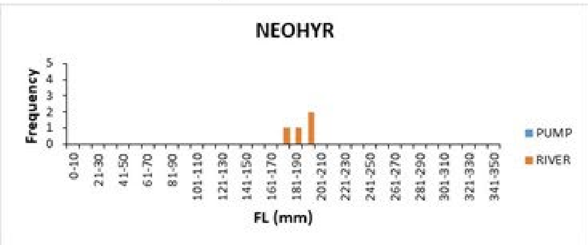
Bony bream



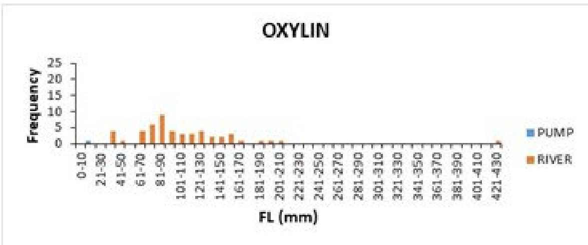
Blue catfish



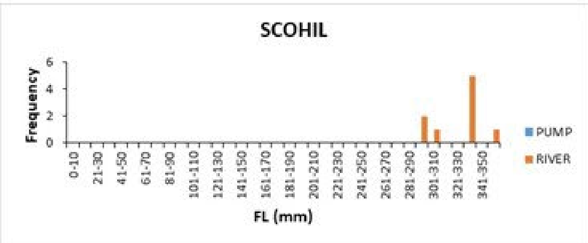
Hyrtl's tandan



Sleepy cod

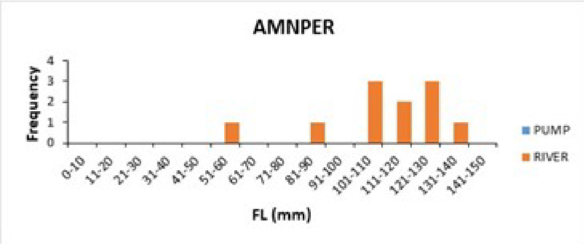


Leathery grunter

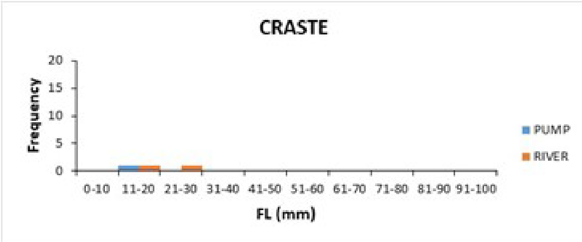


Pump site 9 vs Ref site 6, 01/06/21. Pump rate 23 ML/day. Bankside shallow intake.

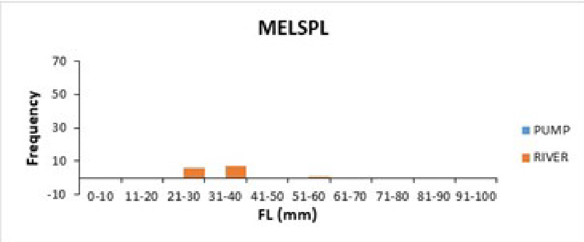
Barred grunter



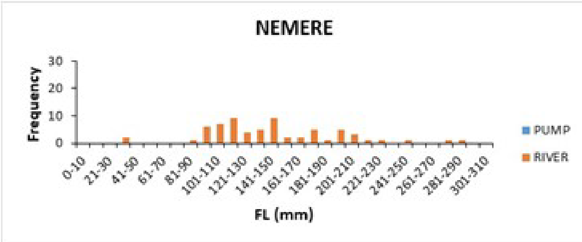
Fly-specked hardyhead



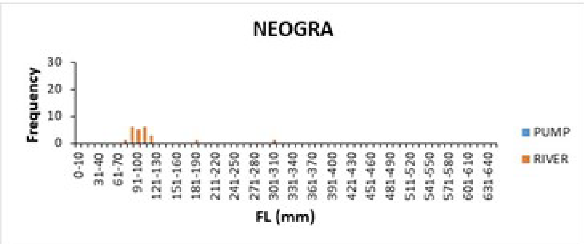
Eastern rainbowfish



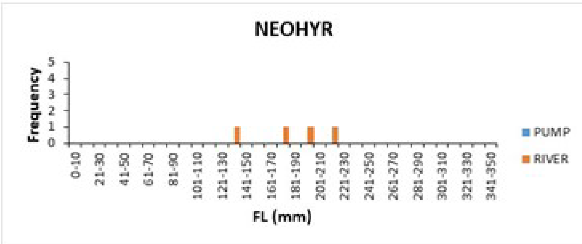
Bony bream



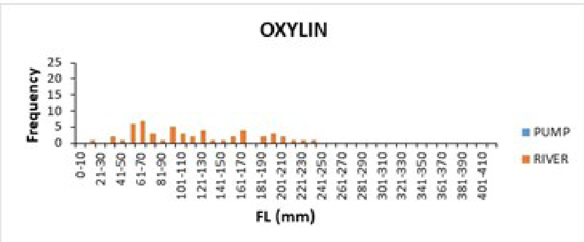
Blue catfish



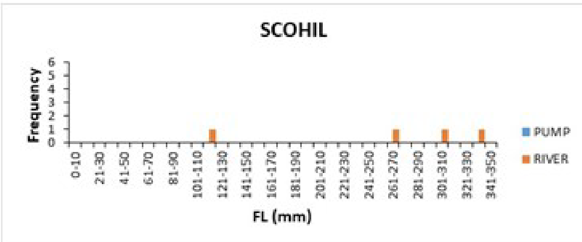
Hyrtl's tandan



Sleepy cod

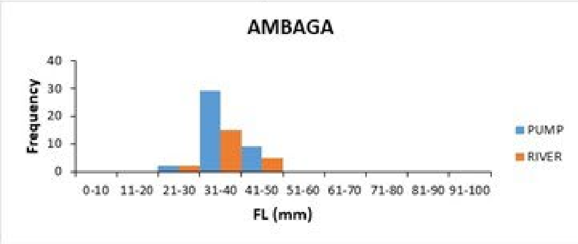


Leathery grunter

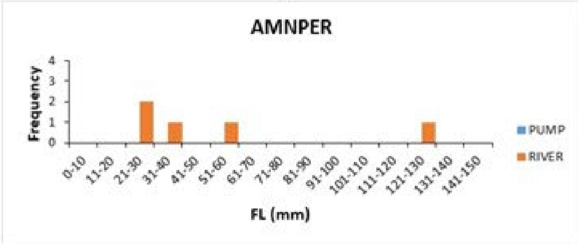


Pump site 4 vs Ref site 14, 22/02/22. Pump rate 27 ML/day. Mid-river channel intake.

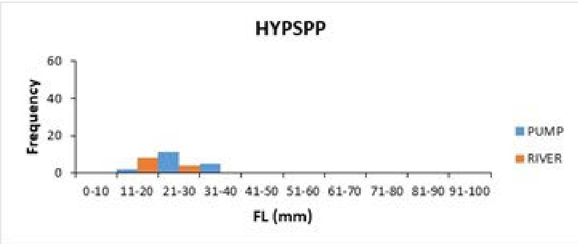
Olive perchlet



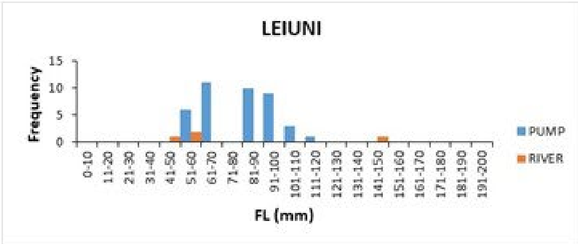
Barred grunter



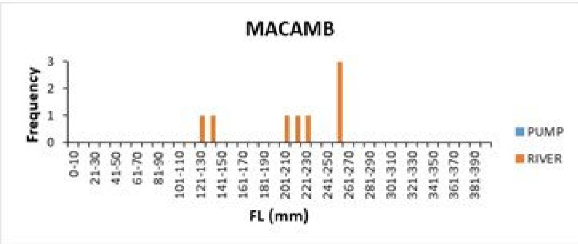
Carp gudgeon spp



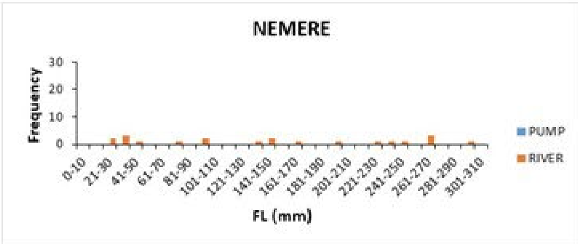
Spangled perch



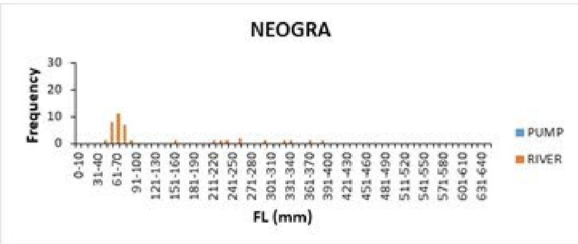
Golden perch



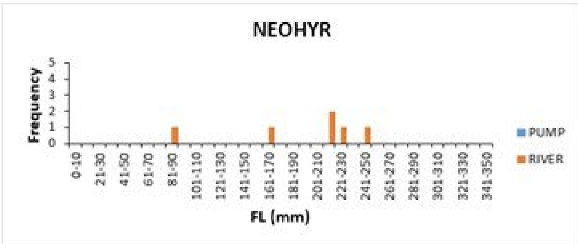
Bony bream



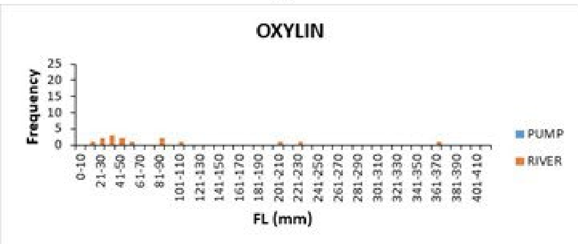
Blue catfish



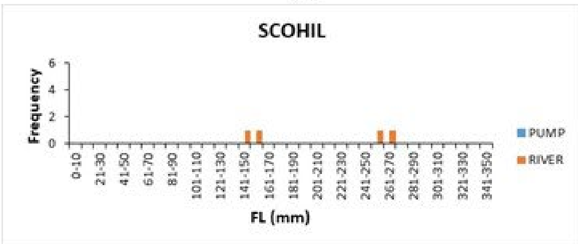
Hyrtl's catfish



Sleepy cod

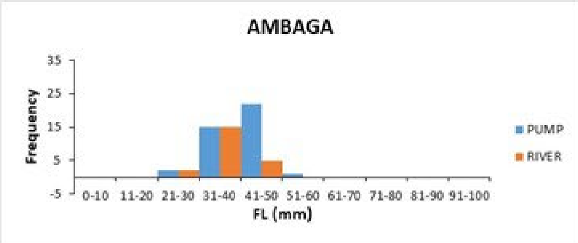


Leathery grunter

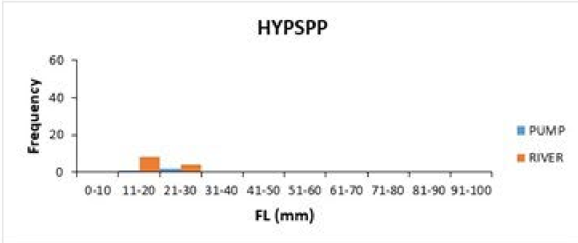


Pump site 3 vs Ref site 14, 22/02/22. Pump rate 42 ML/day. Side-channel intake.

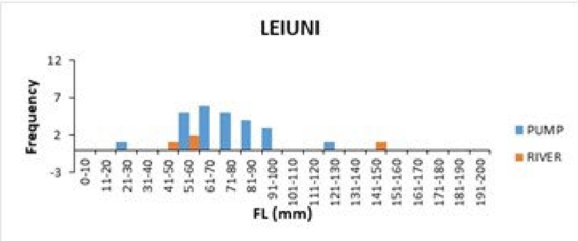
Olive perchlet



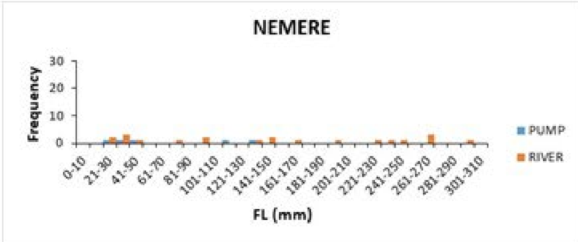
Carp gudgeon spp



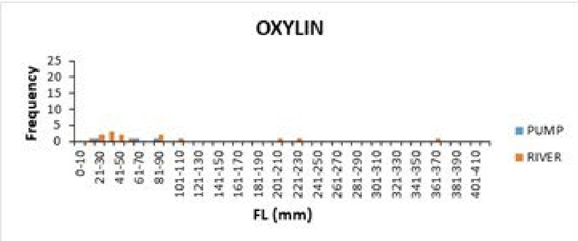
Spangled perch



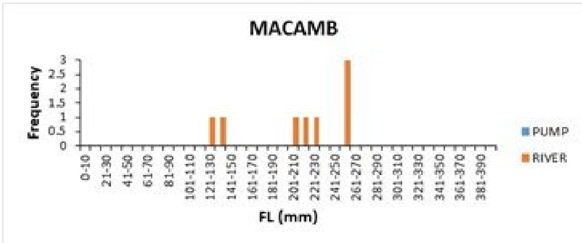
Bony bream



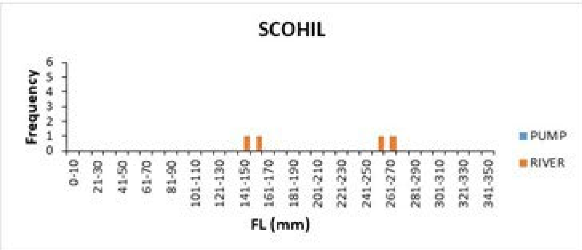
Sleepy cod



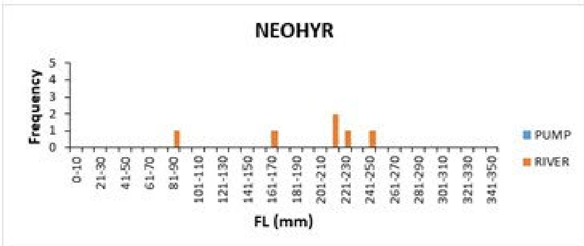
Golden perch



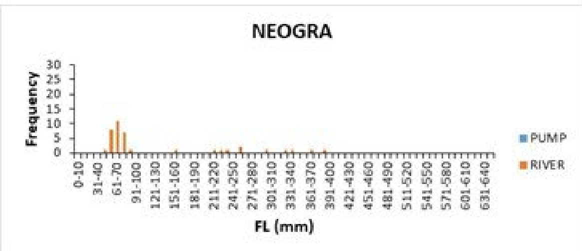
Leathery grunter



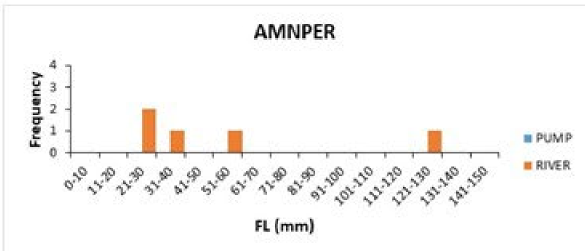
Hyrtl's tandan



Blue catfish

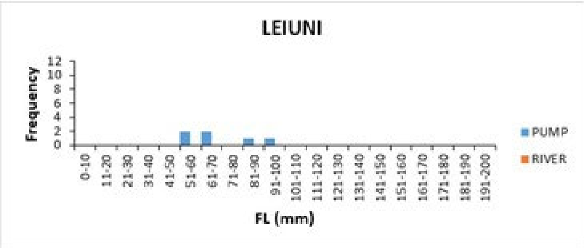


Barred grunter

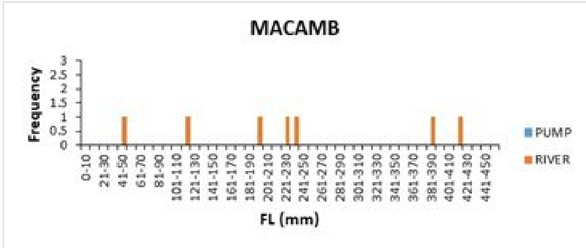


Pump site 7 vs Ref site 6, 26/02/22. Pump rate 50 ML/day. Bankside shallow intake.

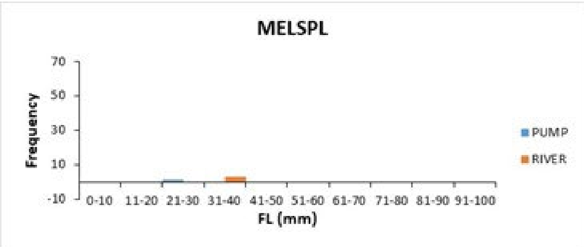
Spangled perch



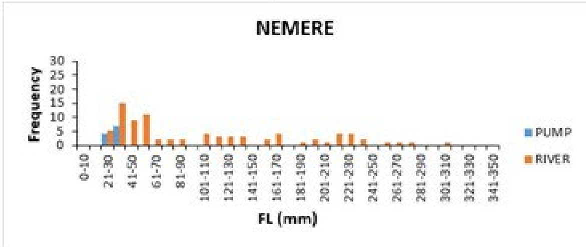
Golden perch



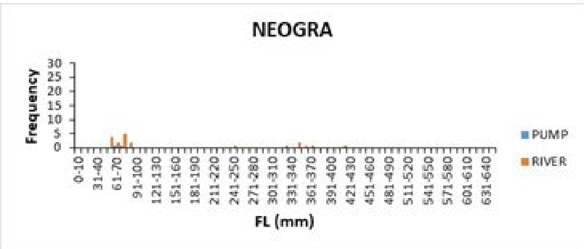
Eastern rainbowfish



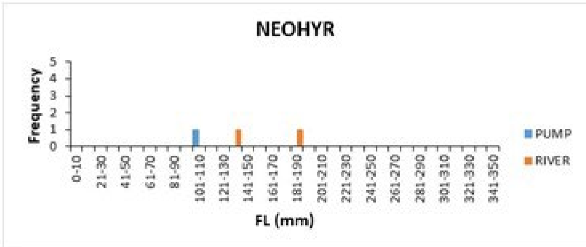
Bony bream



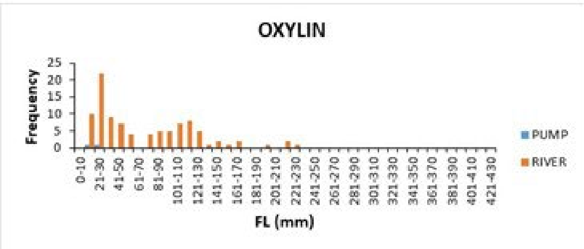
Blue catfish



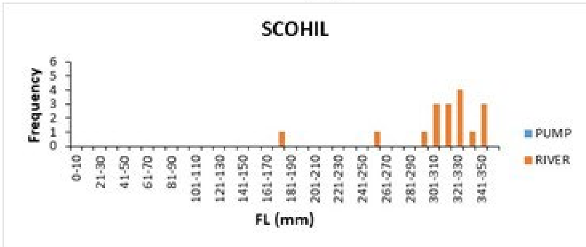
Hyrtl's tandan



Sleepy cod

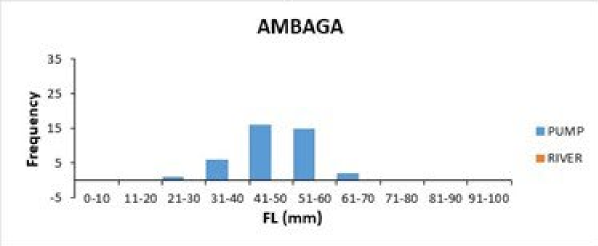


Leathery grunter

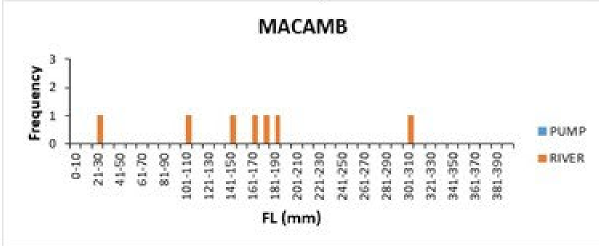


Pump site 13 vs Ref site 6, 19/06/21. Pump rate 88.5 ML/day. Mid-river channel intake

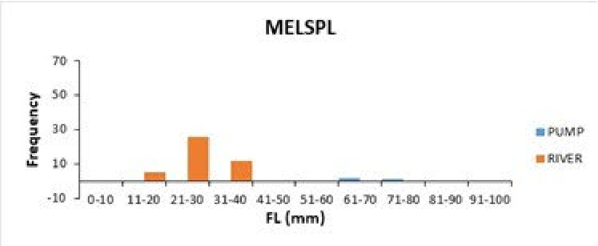
Olive perchlet



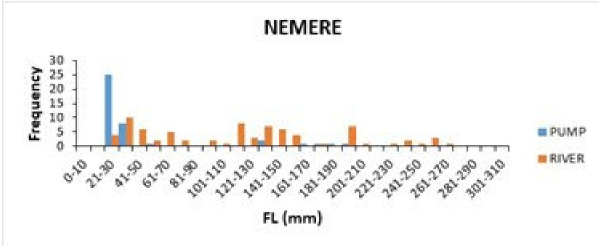
Golden perch



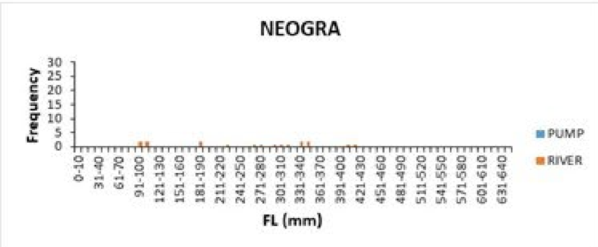
Eastern rainbowfish



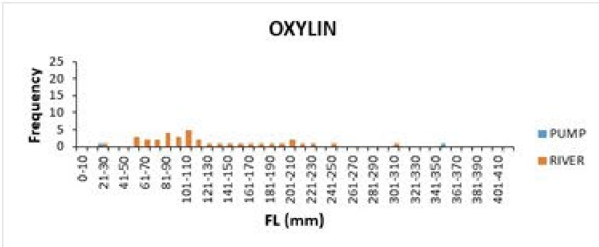
Bony bream



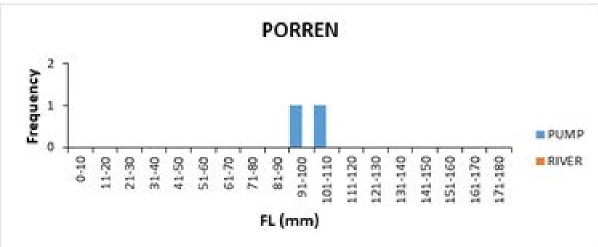
Blue catfish



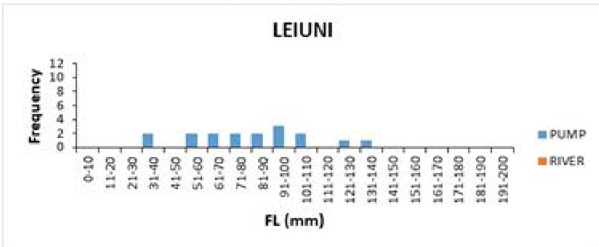
Sleepy cod



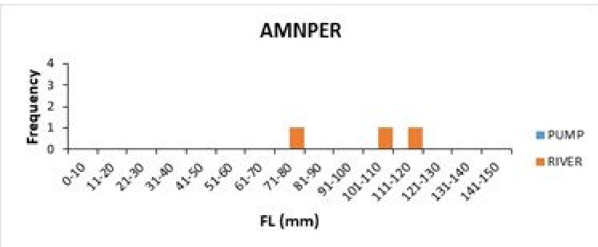
Rendahl's tandan



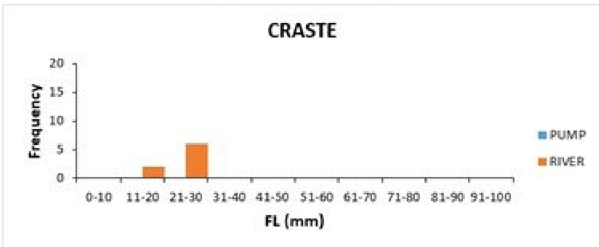
Spangled perch



Barred grunter

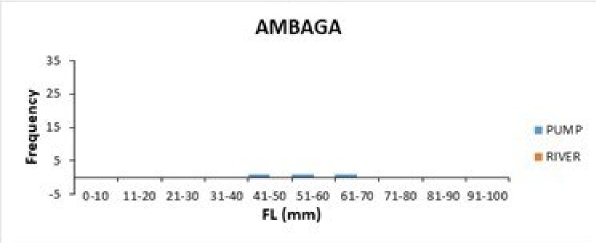


Fly-specked hardyhead

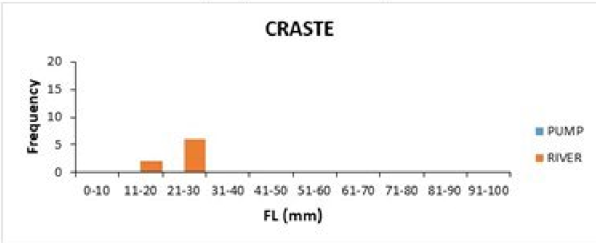


Pump site 8 vs Ref site 6, 20/06/21. Pump rate 100 ML/day. Bankside deep intake.

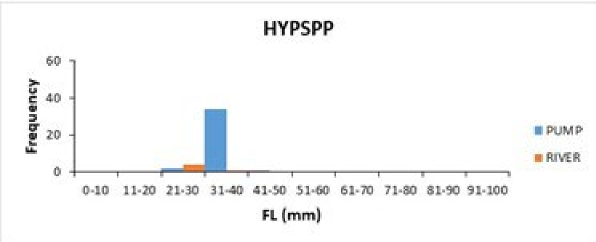
Olive perchlet



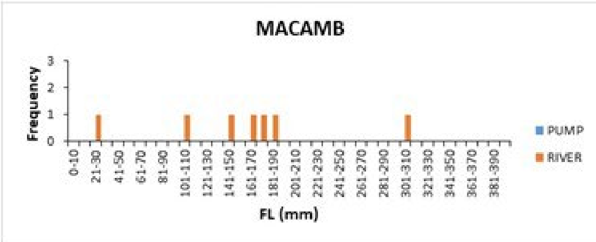
Fly-specked hardyhead



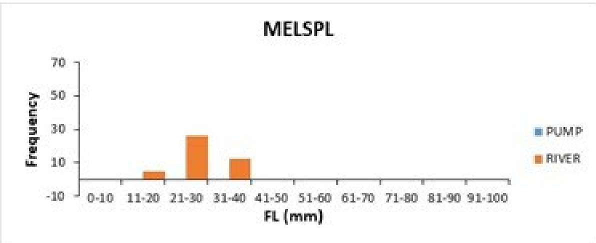
Carp gudgeon



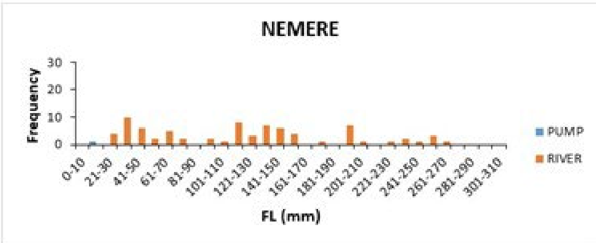
Golden perch



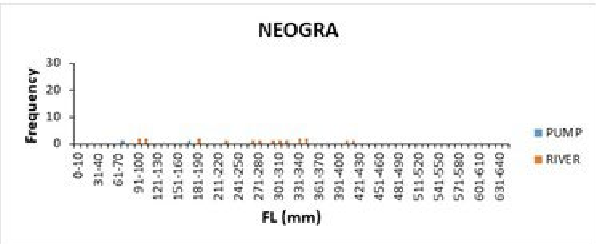
Eastern rainbowfish



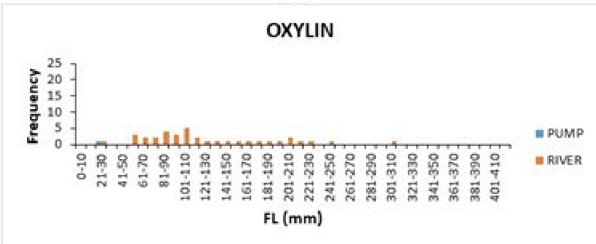
Bony bream



Blue catfish

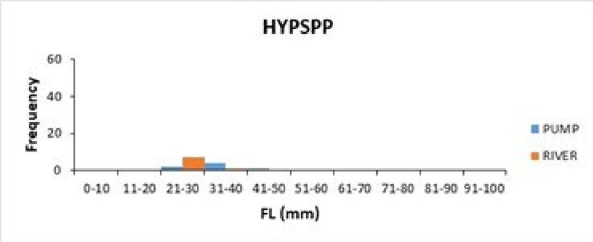


Sleepy cod

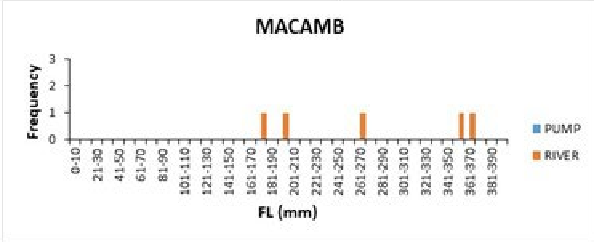


Pump site 8 vs Ref site 6, 18/09/21. Pump rate 100 ML/day. Bankside deep intake

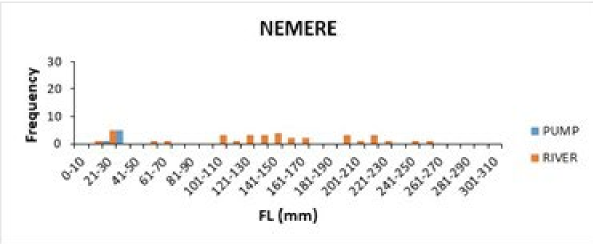
Carp gudgeon spp



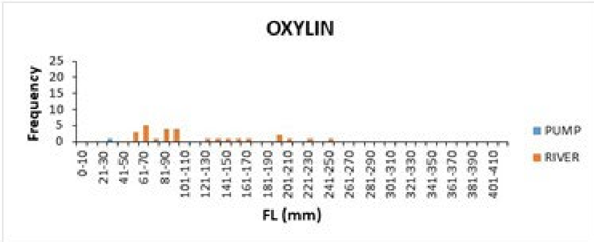
Golden perch



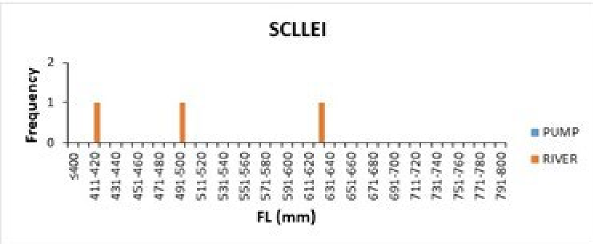
Bony bream



Sleepy cod

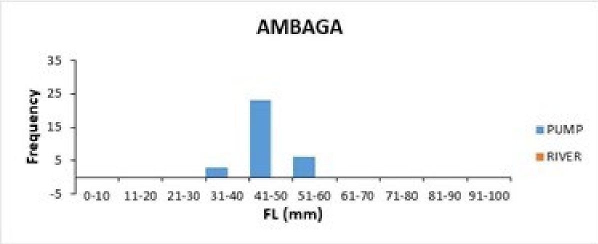


Saratoga

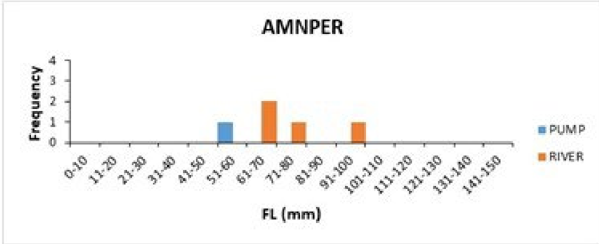


Pump site 1 vs Ref site 2, 28/09/21. Pump rate 100 ML/day. Bankside deep intake

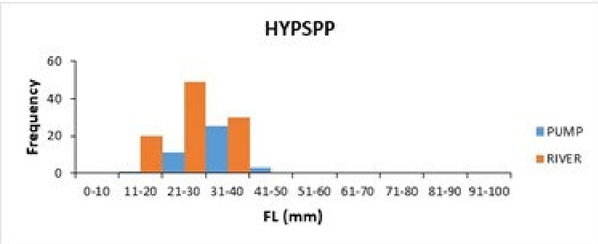
Olive perchlet



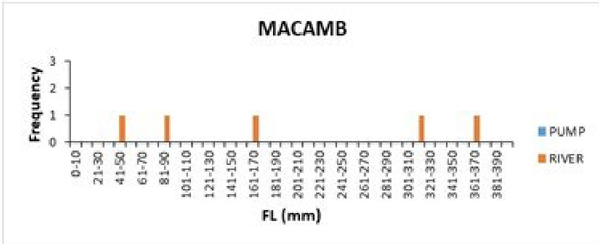
Barred grunter



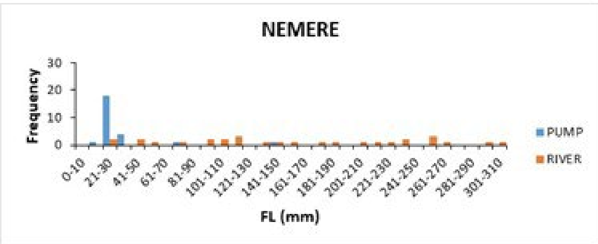
Carp gudgeon spp



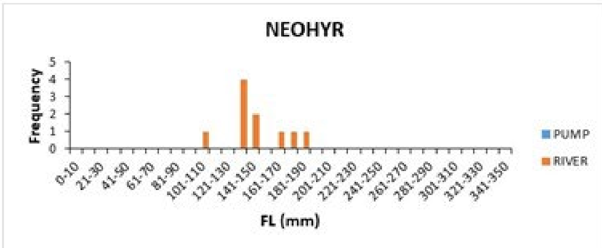
Golden perch



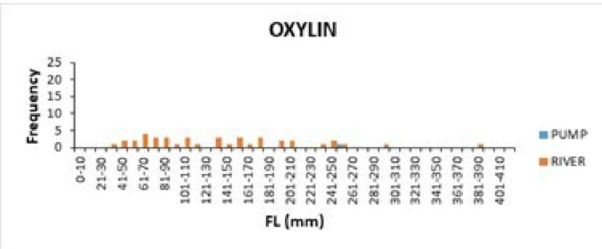
Bony bream



Hyrtl's tandan

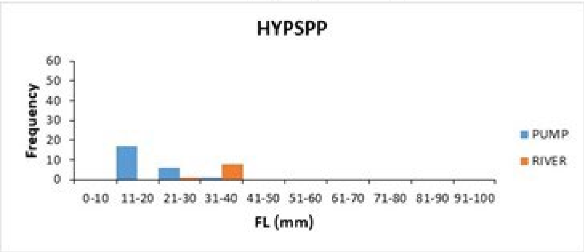


Sleepy cod

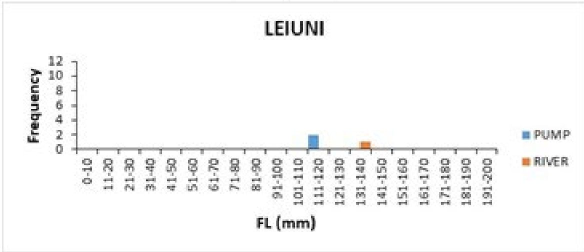


Pump site 15 vs Ref site 6, 02/11/21. Pump rate 140 ML/day. Bankside shallow intake.

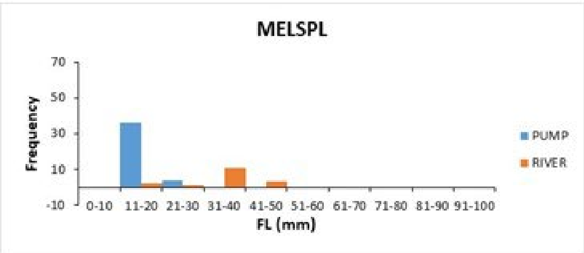
Carp gudgeon spp



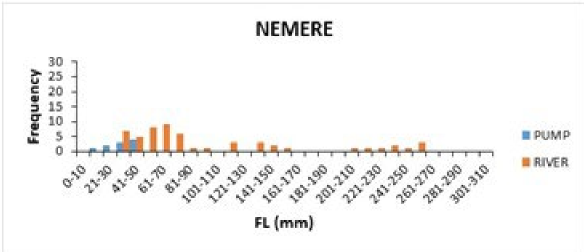
Spangled perch



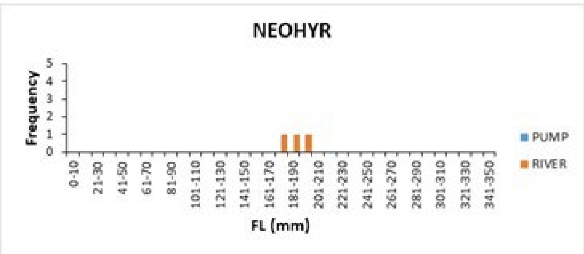
Eastern rainbowfish



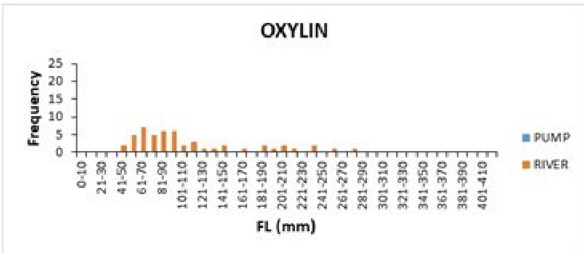
Bony bream



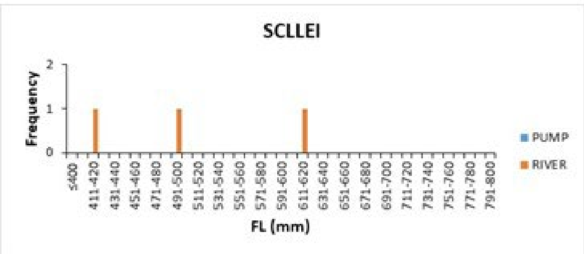
Hyrtl's tandan



Sleepy cod



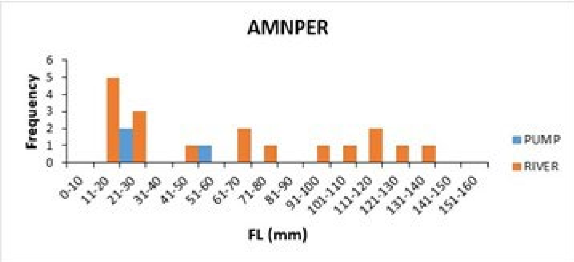
Saratoga



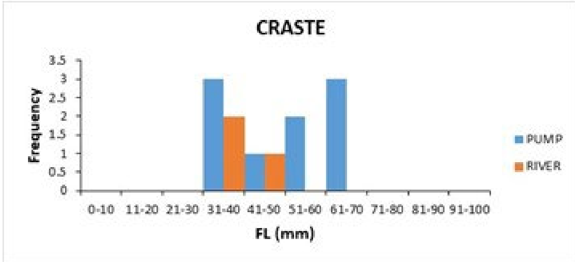
Examples of combination histogram plots from combined flow events, including some less commonly encountered fish at riverine pump or reference sites

Pump site 1 and reference site combined length frequency histogram plots. Bankside deep intake.

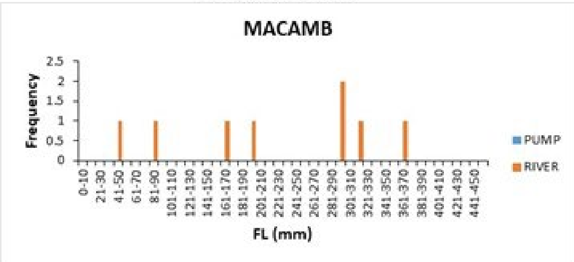
Barred grunter



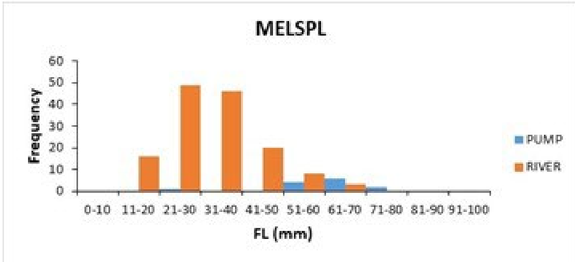
Fly-specked hardyhead



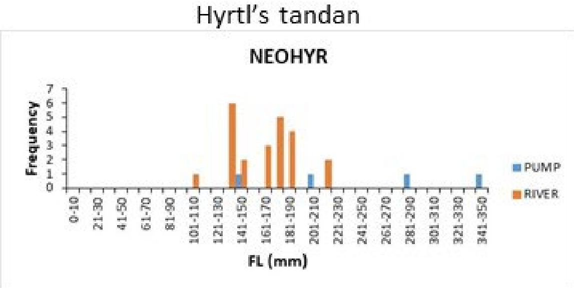
Golden perch



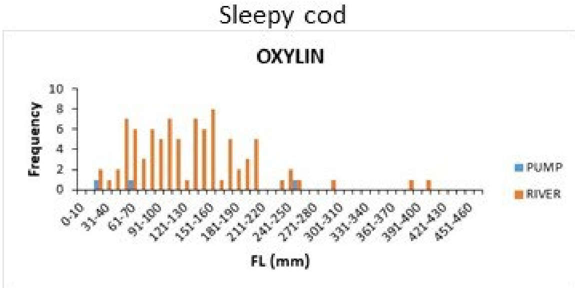
Eastern rainbowfish



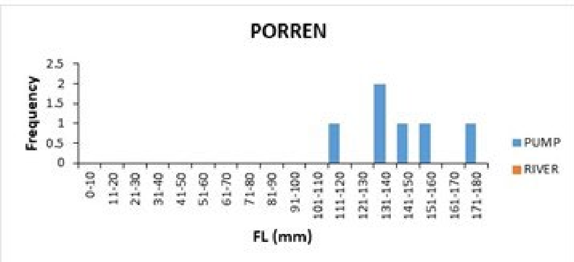
Hyrtl's tandan



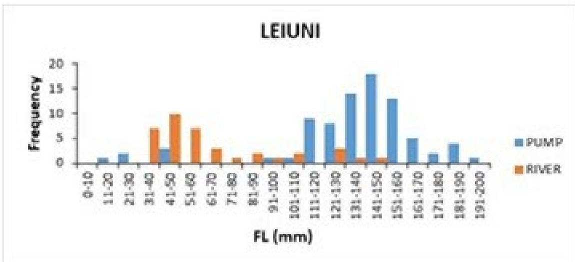
Sleepy cod



Rendahl's tandan

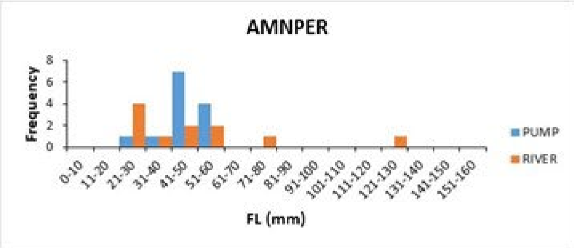


Spangled perch

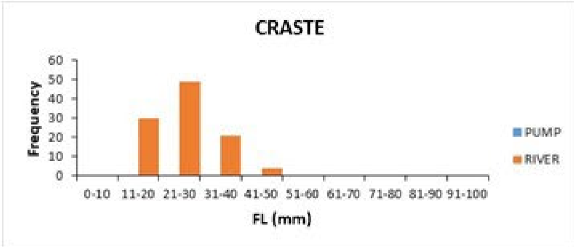


Pump site 3 and reference sites combined length frequency histogram plots. Side-channel intake.

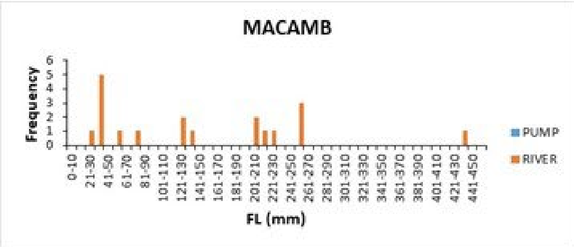
Barred grunter



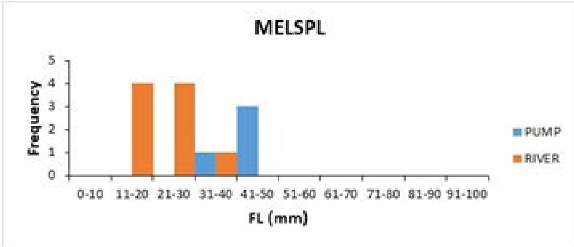
Fly-specked hardyhead



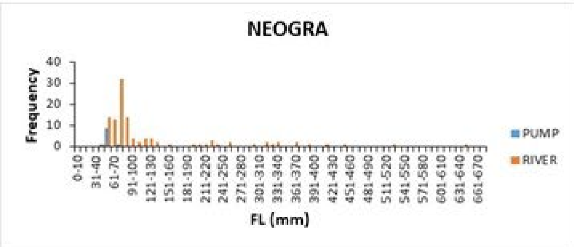
Golden perch



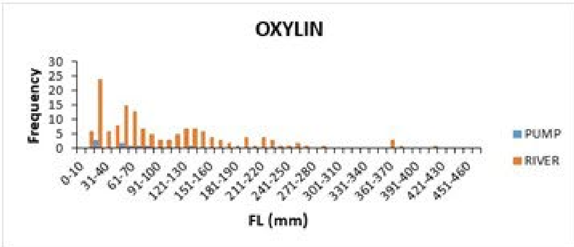
Eastern rainbowfish



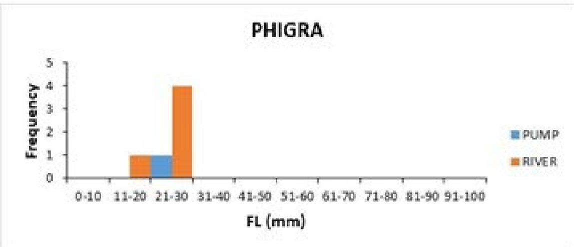
Blue catfish



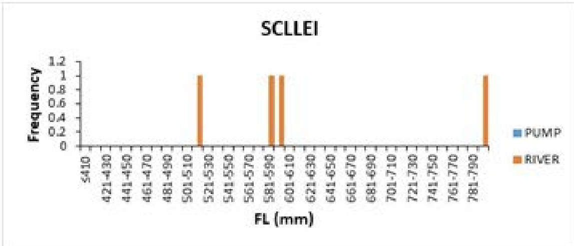
Sleepy cod



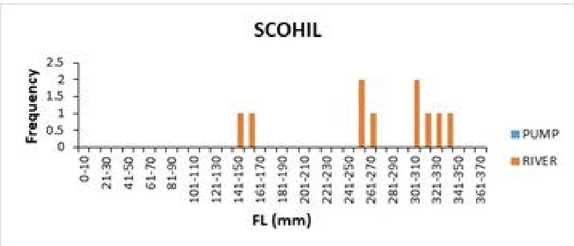
Flat-headed gudgeon



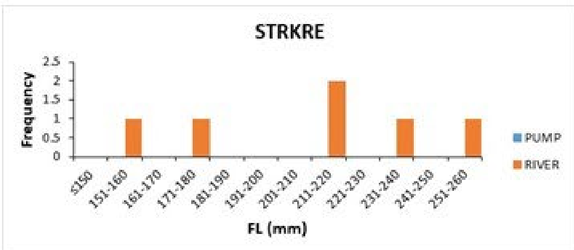
Saratoga



Leathery grunter

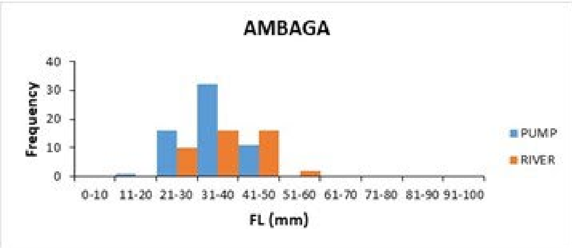


Freshwater longtom

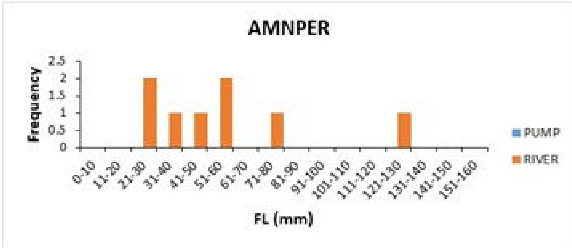


Pump site 4 and reference sites combined length frequency histogram plots. Mid-river channel intake.

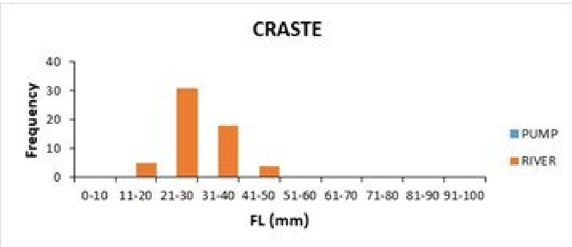
Olive perchlet



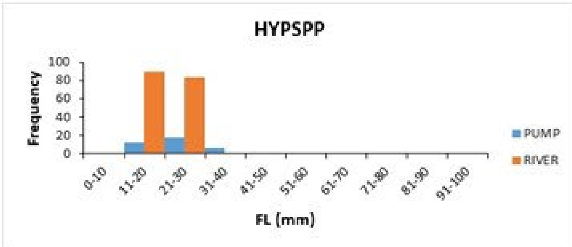
Barred grunter



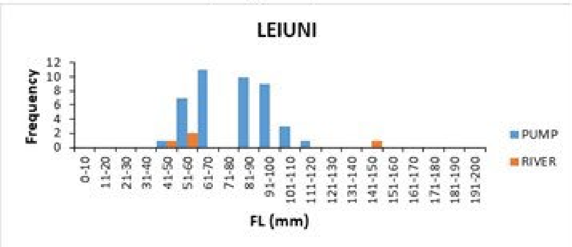
Fly-specked hardyhead



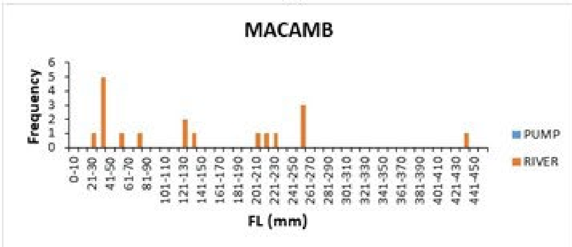
Carp gudgeon spp



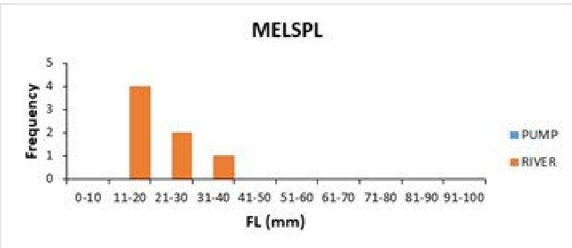
Spangled perch



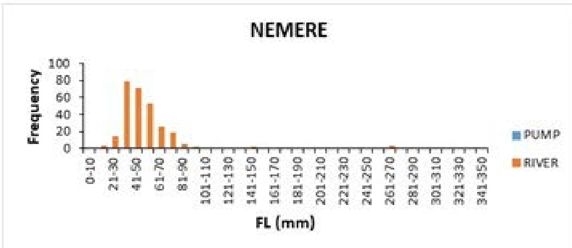
Golden perch



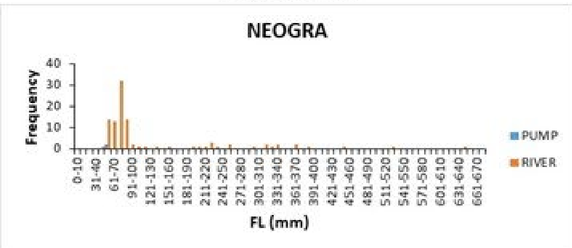
Eastern rainbowfish



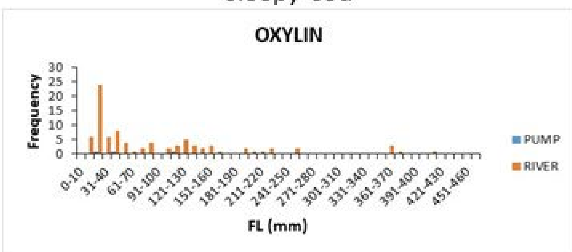
Bony bream



Blue catfish

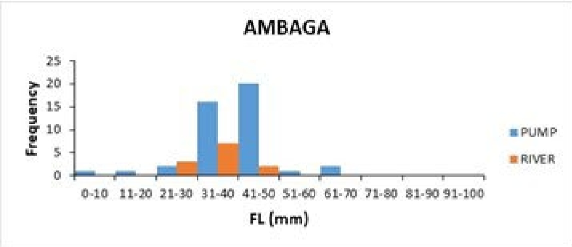


Sleepy cod

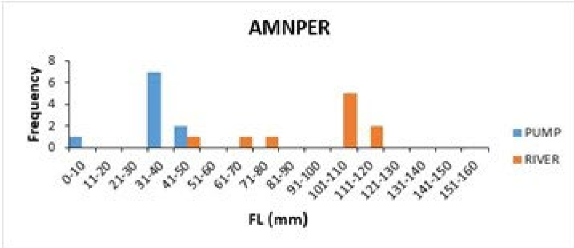


Pump site 8 and reference site combined length frequency histogram plots. Bankside deep intake.

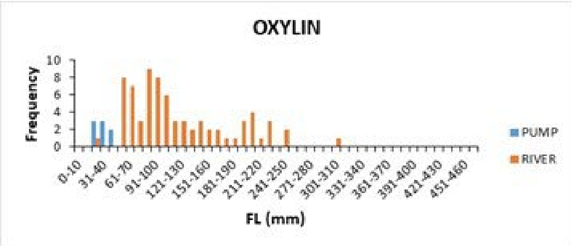
Olive perchlet



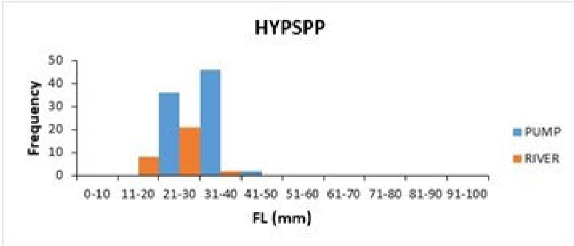
Barred grunter



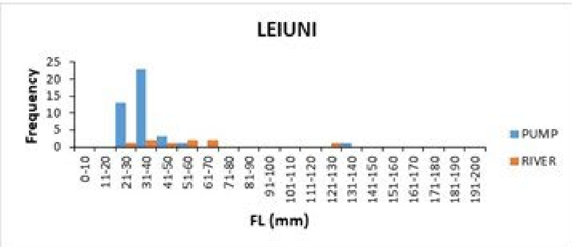
Sleepy cod



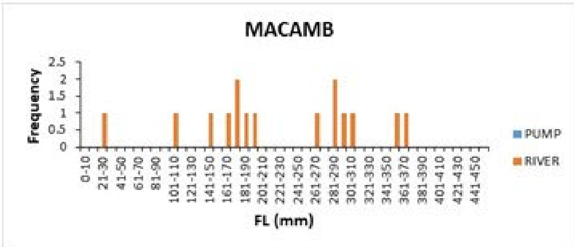
Carp gudgeon spp



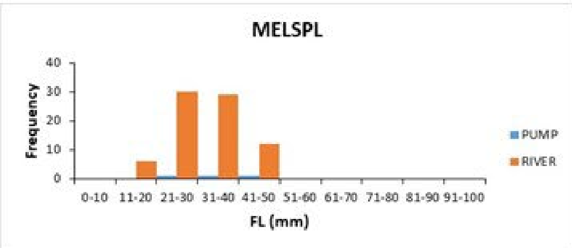
Spangled perch



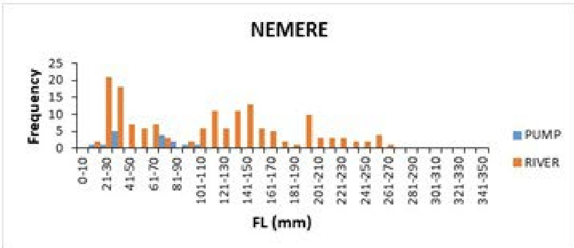
Golden perch



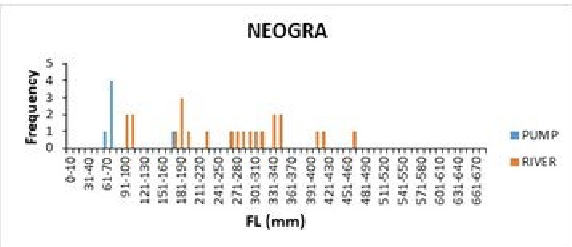
Eastern rainbowfish



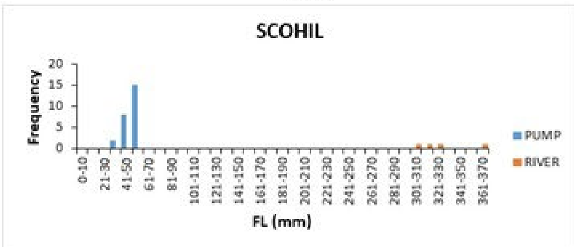
Bony bream



Blue catfish

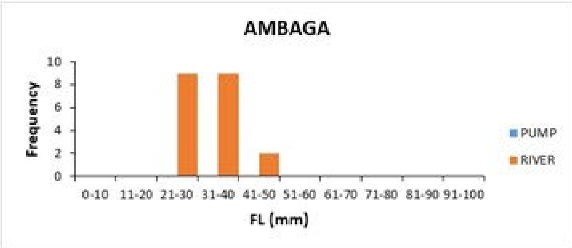


Leathery grunter

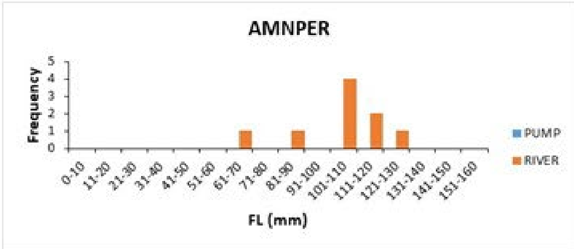


Pump site 7 and reference site combined length frequency histogram plots. Bankside shallow intake.

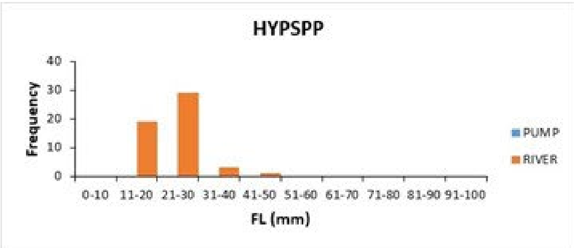
Olive perchlet



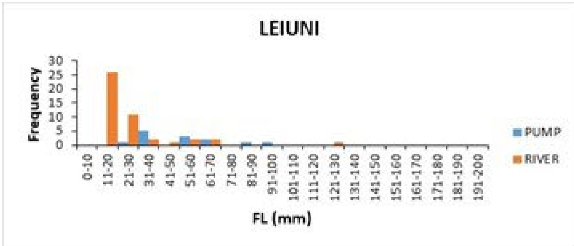
Barred grunter



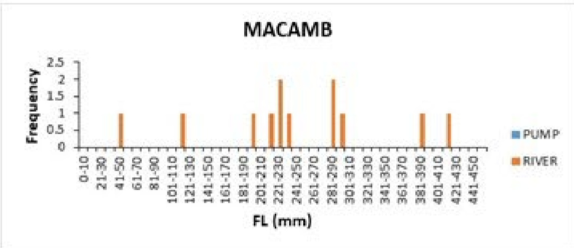
Carp gudgeon spp



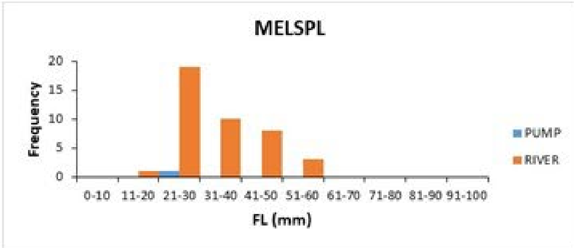
Spangled perch



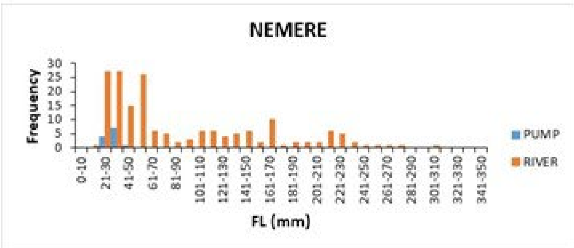
Golden perch



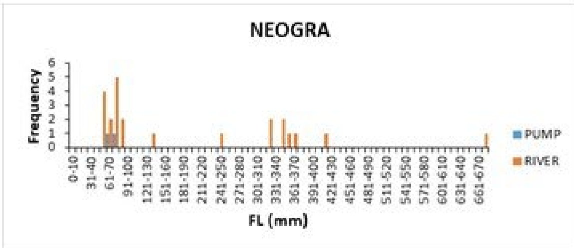
Eastern rainbowfish



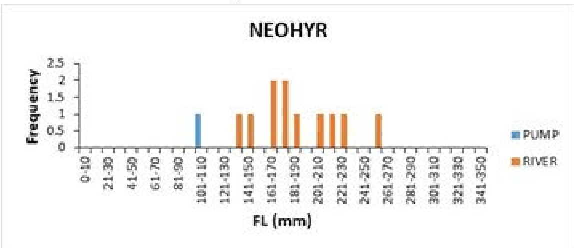
Bony bream



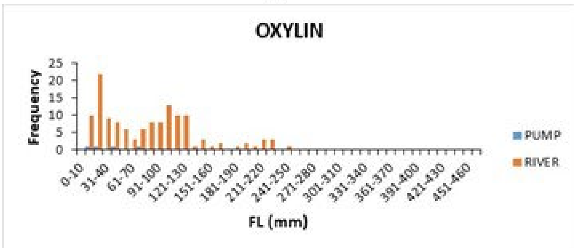
Blue catfish



Hyrtl's tandan



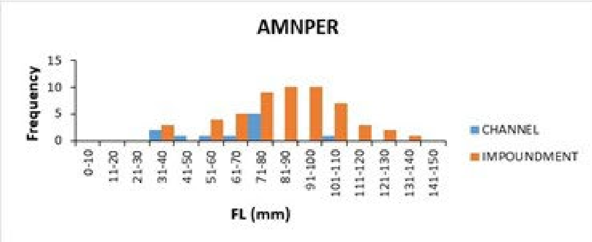
Sleepy cod



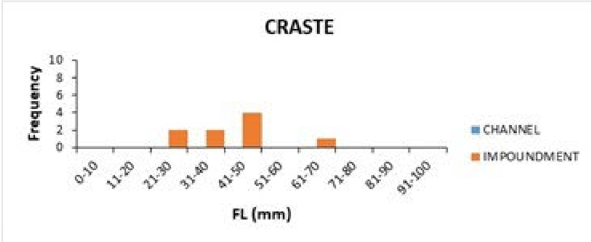
Commonly encountered fish in the Weemah or Selma diversion channels, or in the adjacent Fairbairn Dam reference site

Length frequencies in Selma Channel and Fairbairn Dam 29/09/2021. Pumped intake, 75 ML/day.

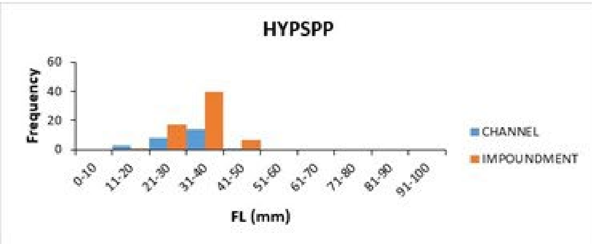
Barred grunter



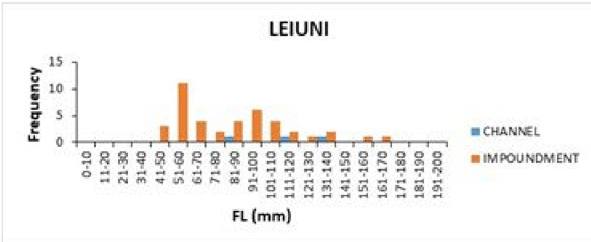
Fly-specked hardyhead



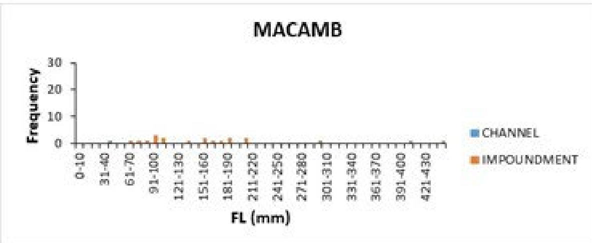
Carp gudgeon spp



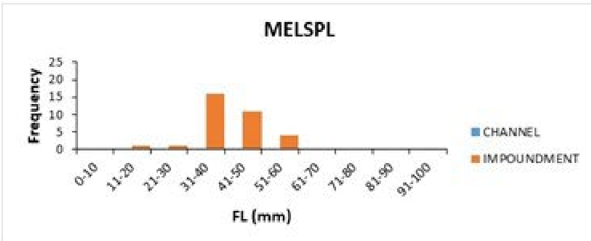
Spangled perch



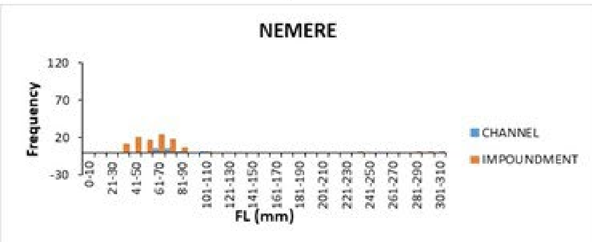
Golden perch



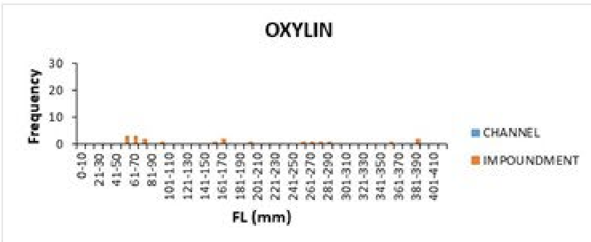
Eastern rainbowfish



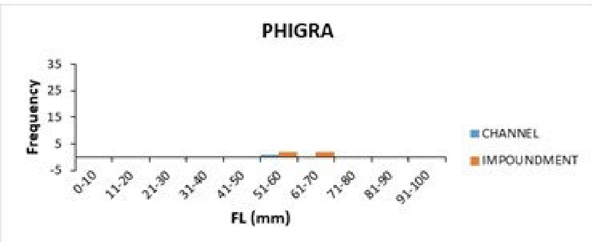
Bony bream



Sleepy cod

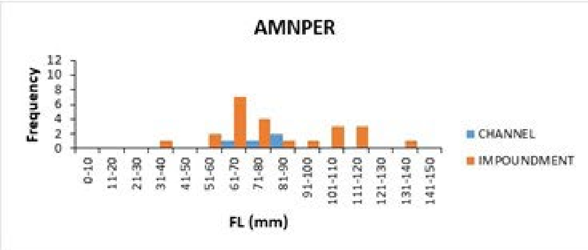


Flat-headed gudgeon

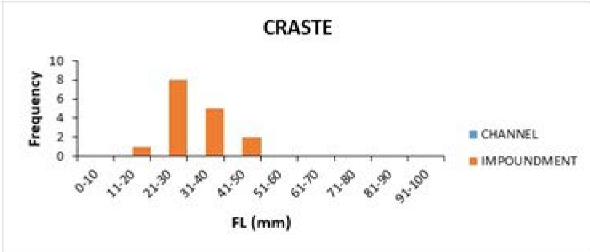


Length frequencies in Selma Channel and Fairbairn Dam 18/06/2021. Pumped intake, 140 ML/day.

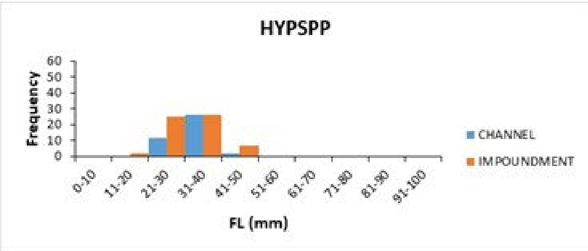
Barred grunter



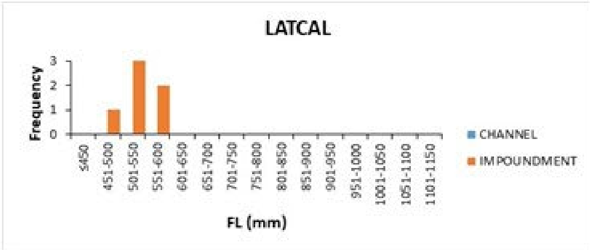
Fly-specked hardyhead



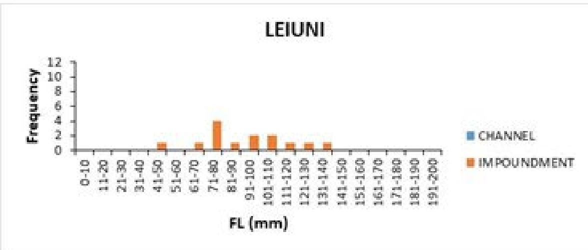
Carp gudgeon spp



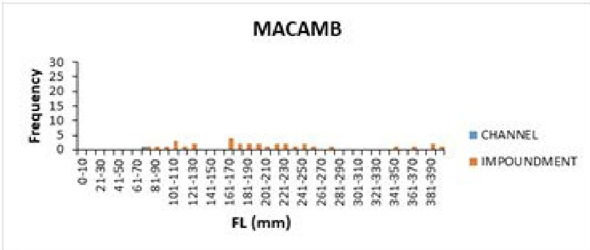
Barramundi



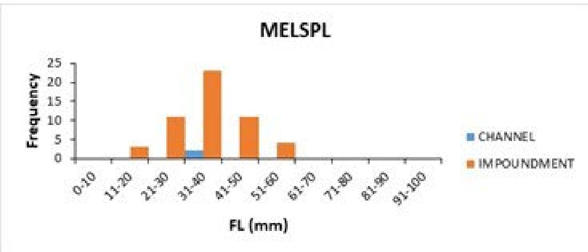
Spangled perch



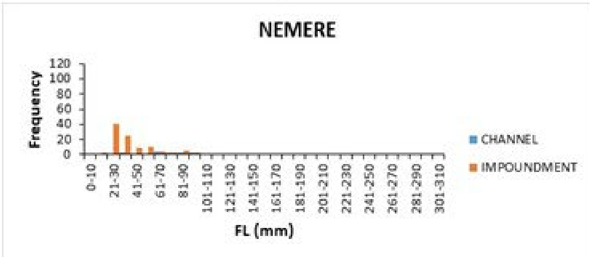
Golden perch



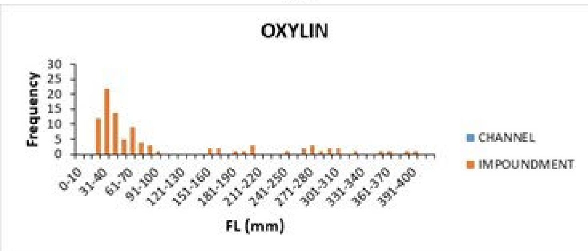
Eastern rainbowfish



Bony bream

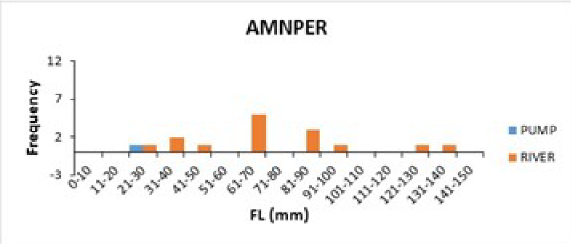


Sleepy cod

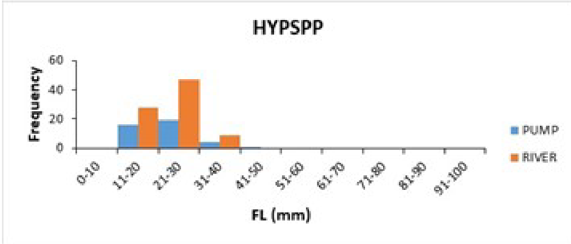


Length frequencies in Selma Channel and Fairbairn Dam 24/01/2022. Pumped intake, 340 ML/day.

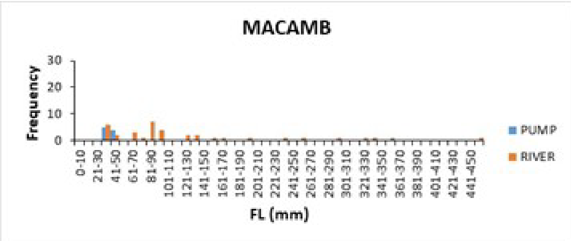
Barred grunter



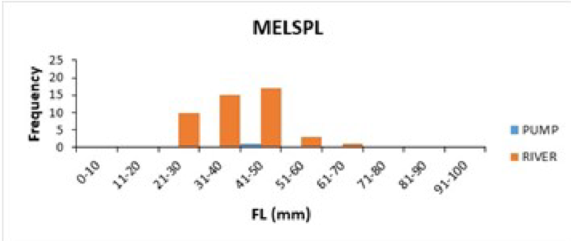
Carp gudgeon spp



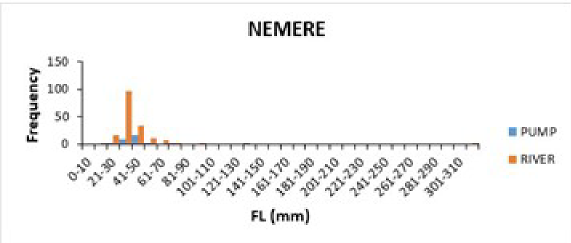
Golden perch



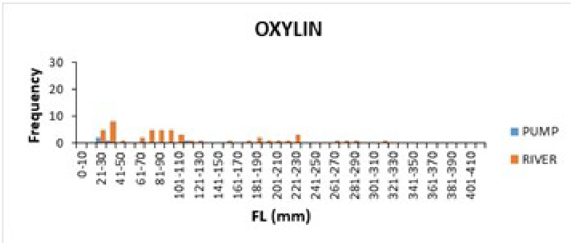
Rainbowfish



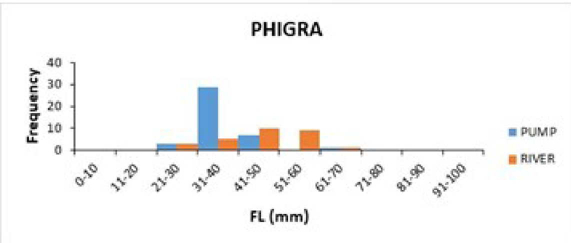
Bony bream



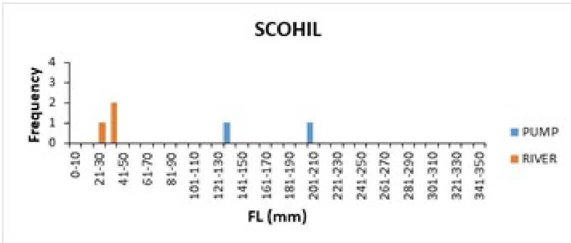
Sleepy cod



Flat-headed gudgeon

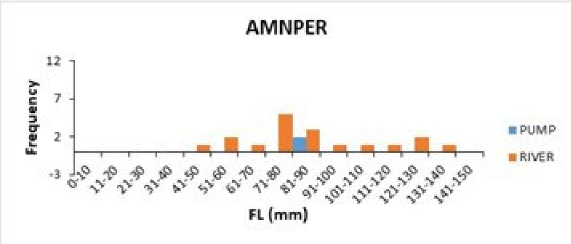


Leathery grunter

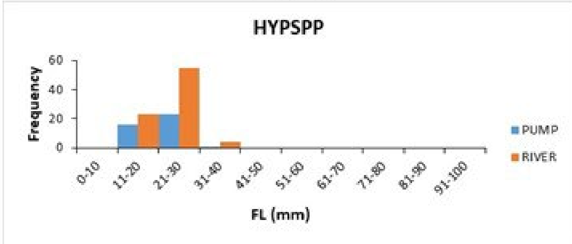


Length frequencies in Selma Channel and Fairbairn Dam 24/02/2022. Pumped intake, 400 ML/day.

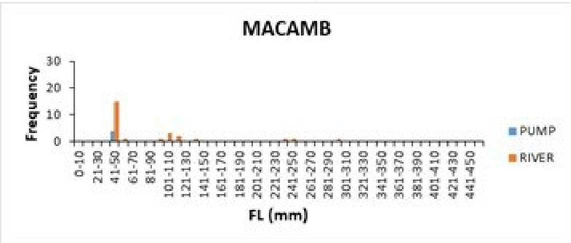
Barred grunter



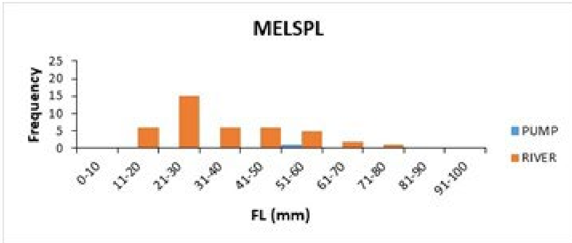
Carp gudgeon



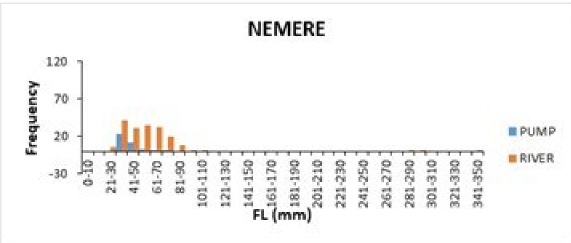
Golden perch



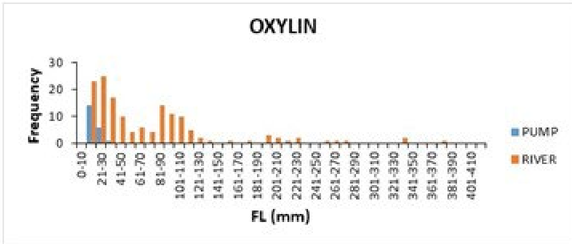
Eastern rainbowfish



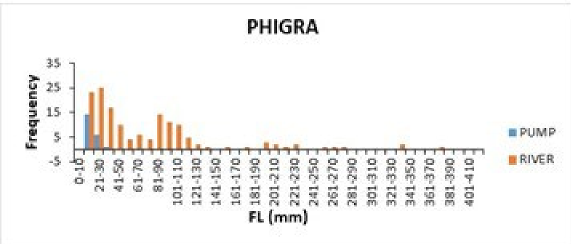
Bony bream



Sleepy cod

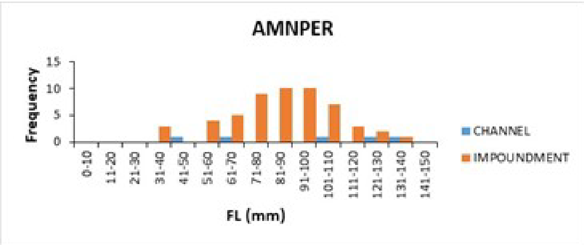


Flat-headed gudgeon

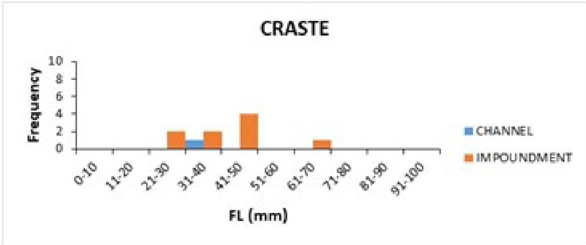


Length frequencies in Weemah Channel and Fairbairn Dam 30/09/2021. Gravity fed intake, 75 ML/day.

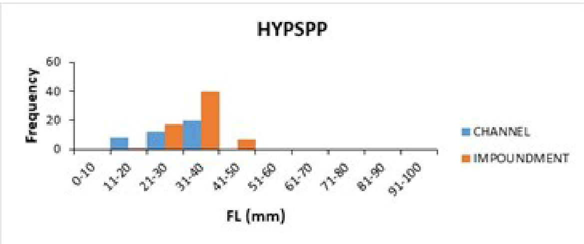
Barred grunter



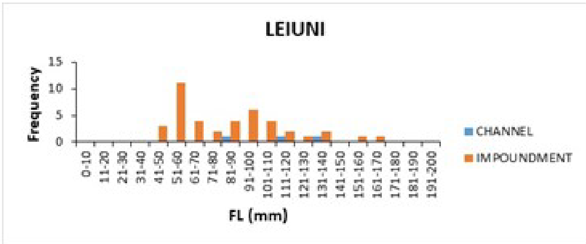
Fly-specked hardyhead



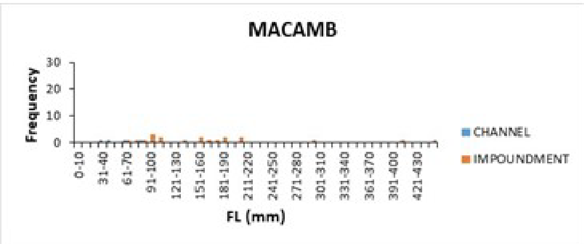
Carp gudgeon spp



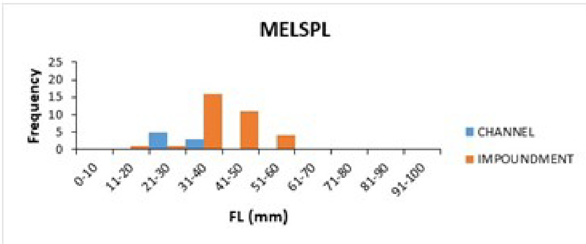
Spangled perch



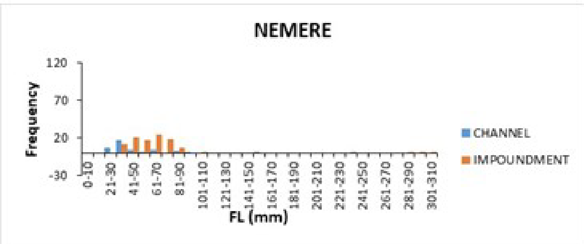
Golden perch



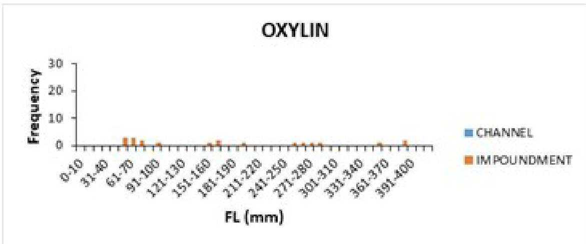
Eastern rainbowfish



Bony bream

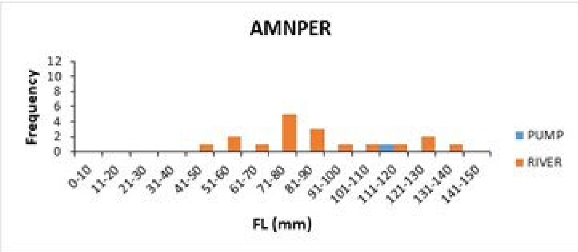


Sleepy cod

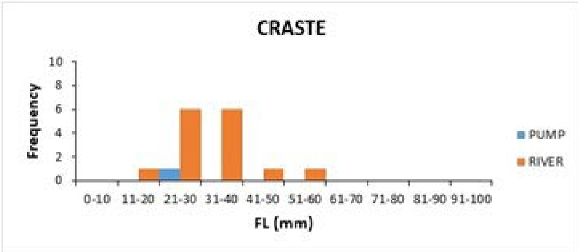


Length frequencies in Weemah Channel and Fairbairn Dam 23/02/2022. Gravity fed intake, 100 ML/day.

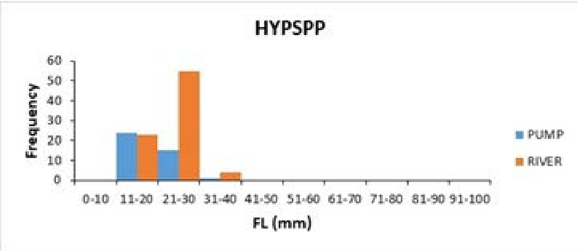
Barred grunter



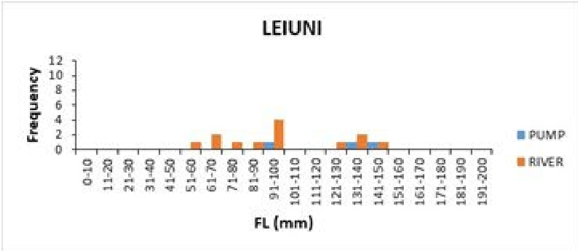
Fly-specked hardyhead



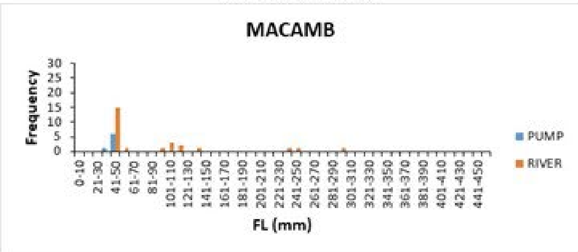
Carp gudgeon spp



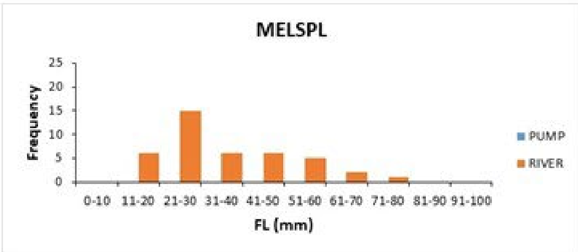
Spangled perch



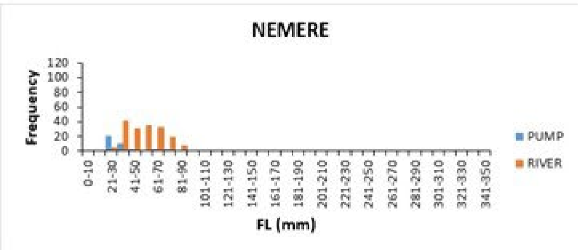
Golden perch



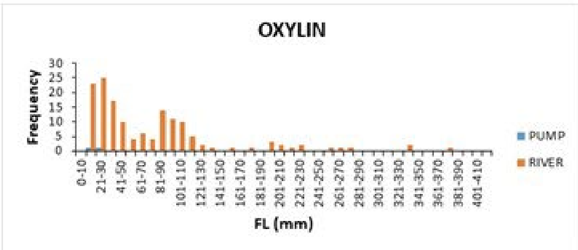
Eastern rainbowfish



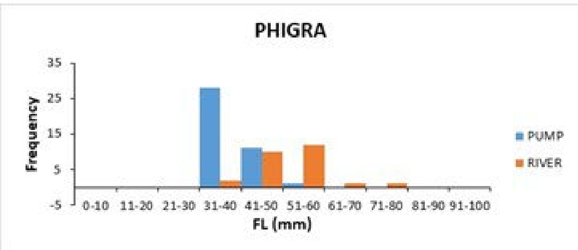
Bony bream



Sleepy cod

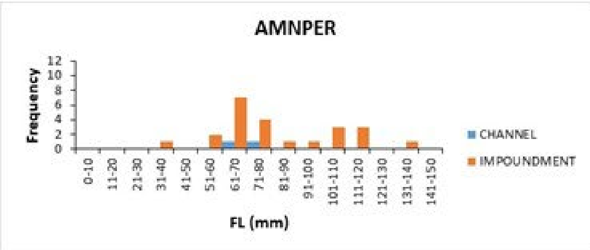


Flat-headed gudgeon

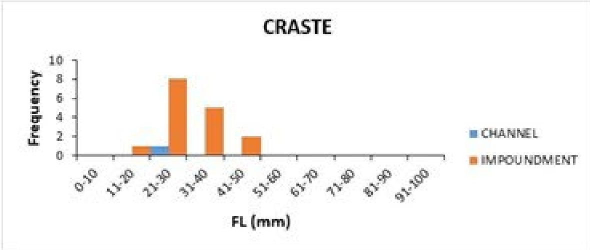


Length frequencies in Weemah Channel and Fairbairn Dam 19/06/2021. Gravity fed intake, 120 ML/day.

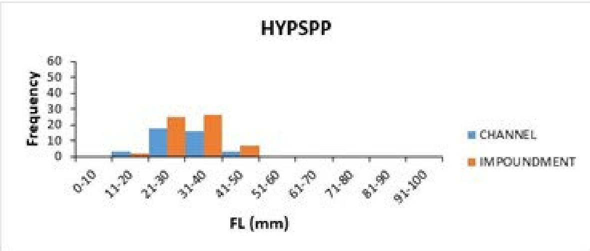
Barred grunter



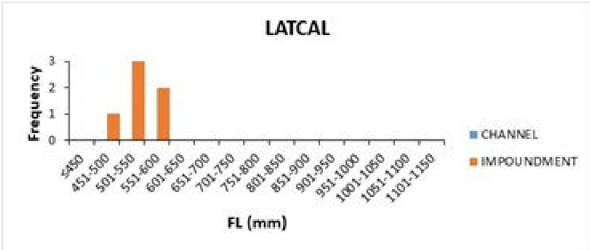
Fly-specked hardyhead



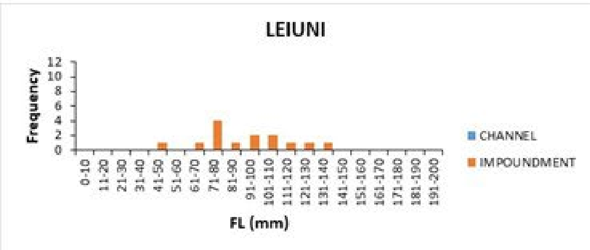
Carp gudgeon spp



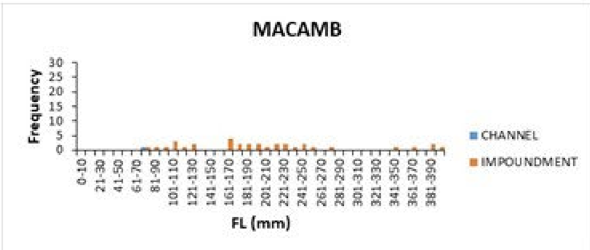
Barramundi



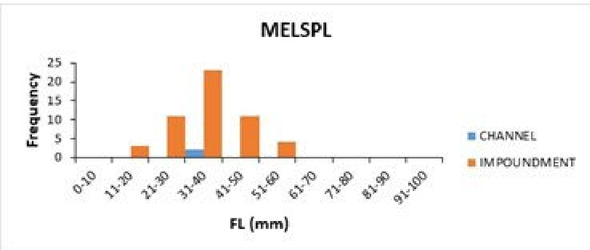
Spangled perch



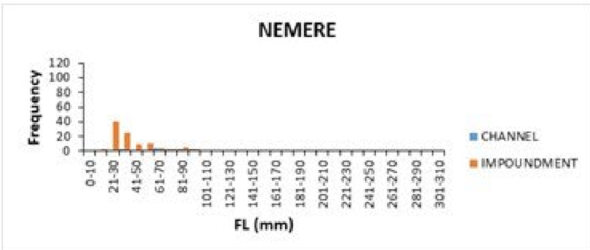
Golden perch



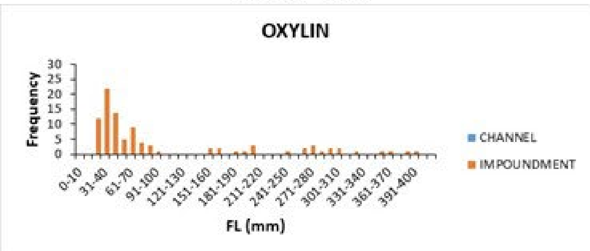
Eastern rainbowfish



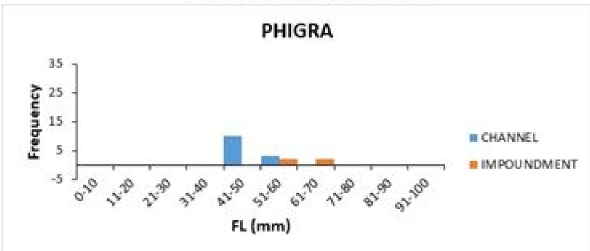
Bony bream



Sleepy cod

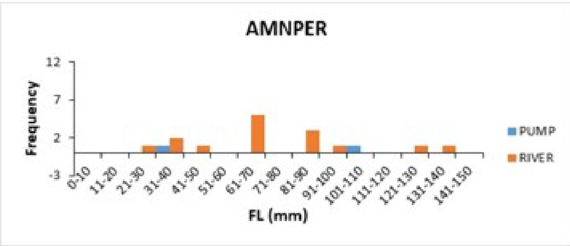


Flat-headed gudgeon

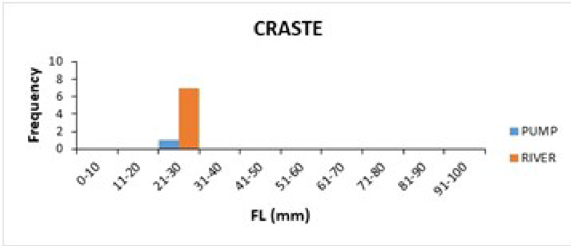


Length frequencies in Weemah Channel and Fairbairn Dam 24/01/2022. Gravity fed intake, 259 ML/day.

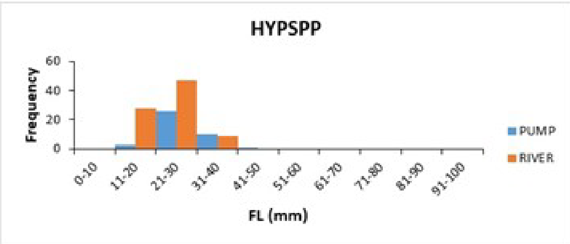
Barred grunter



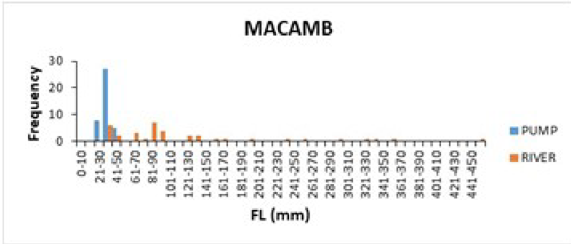
Fly-specked hardyhead



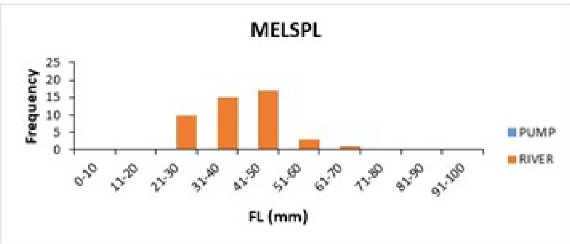
Carp gudgeons



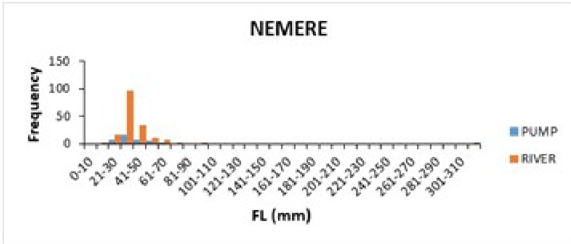
Golden perch



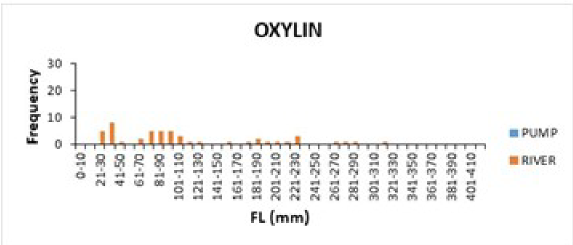
Eastern rainbowfish



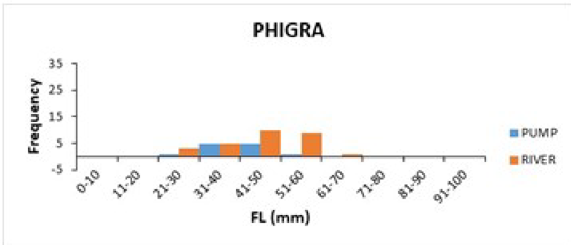
Bony bream



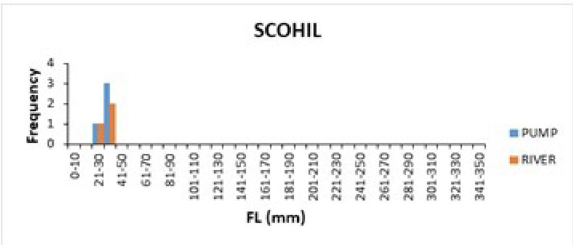
Sleepy cod



Flat-headed gudgeon

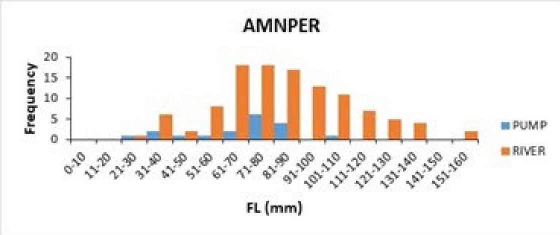


Leathery grunter

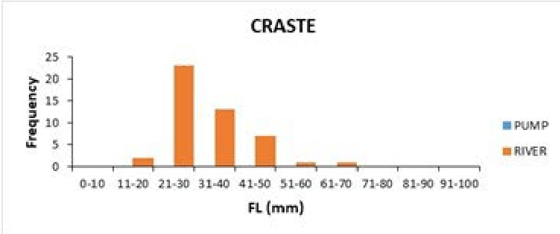


Combined length frequencies in Selma Channel and Fairbairn Dam. Pumped intake

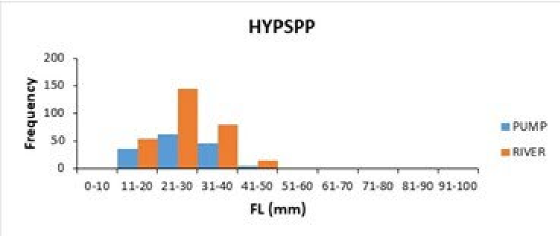
Barred grunter



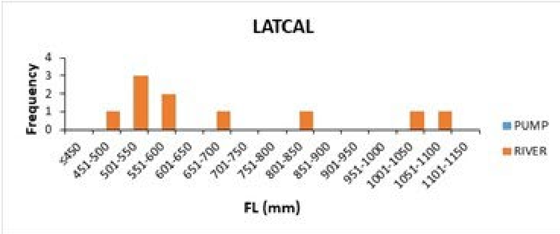
Fly-specked hardyhead



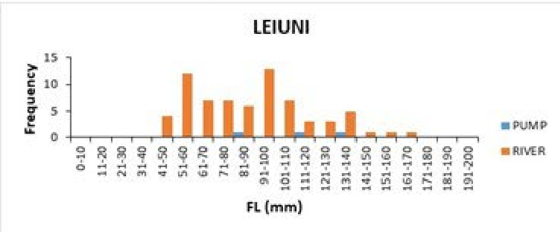
Carp gudgeon spp



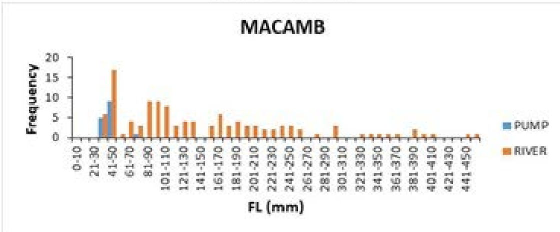
Barramundi



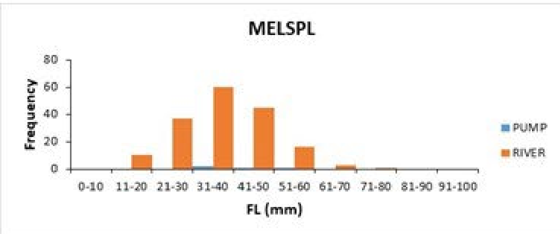
Spangled perch



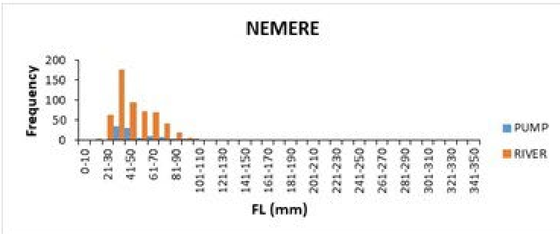
Golden perch



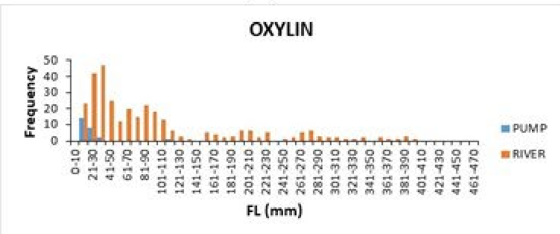
Eastern rainbowfish



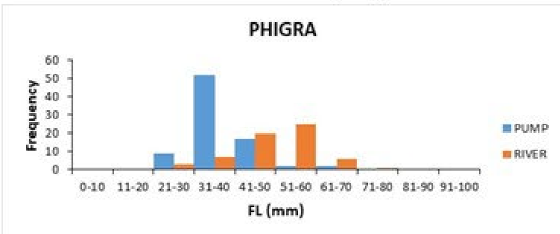
Bony bream



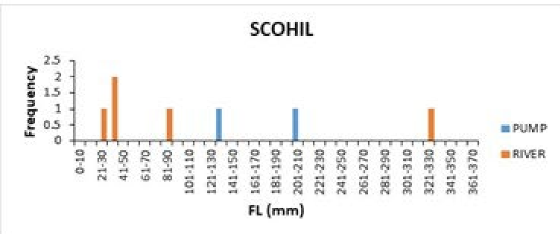
Sleepy cod



Flat-headed gudgeon

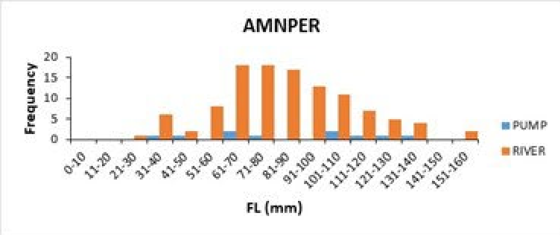


Leathery grunter

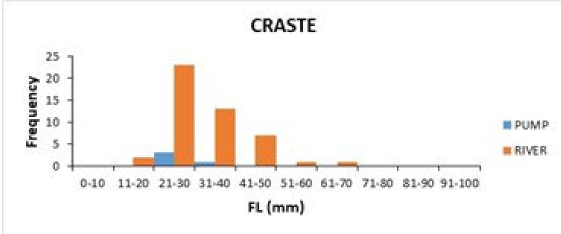


Combined length frequencies in Weemah Channel and Fairbairn Dam. Gravity fed intake

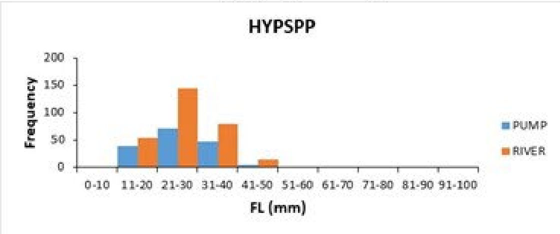
Barred grunter



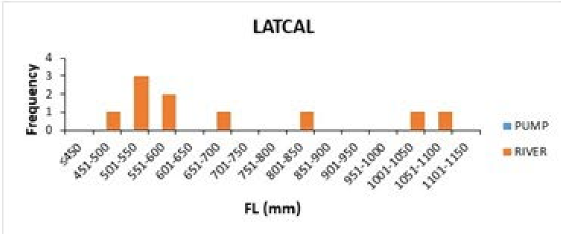
Fly-specked hardyhead



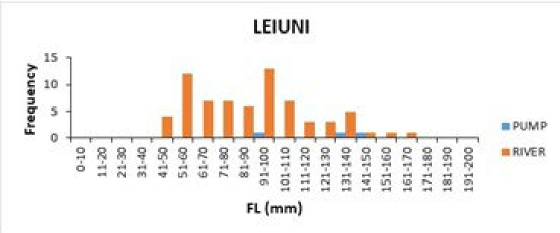
Carp gudgeon spp



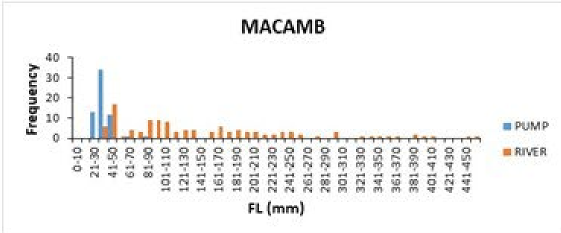
Barramundi



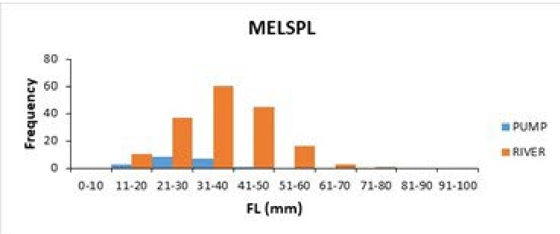
Spangled perch



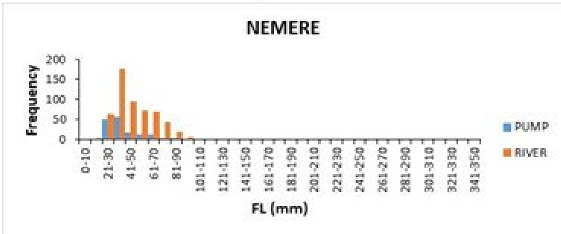
Golden perch



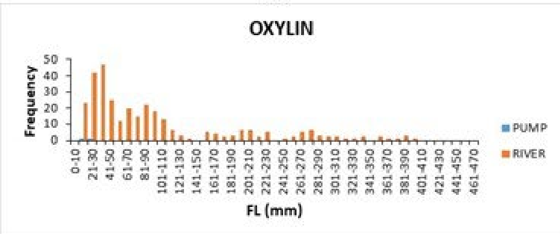
Eastern rainbowfish



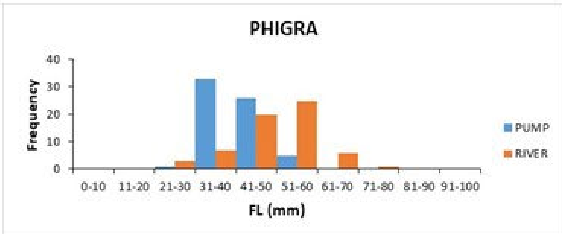
Bony bream



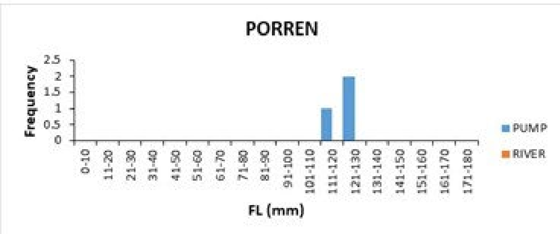
Sleepy cod



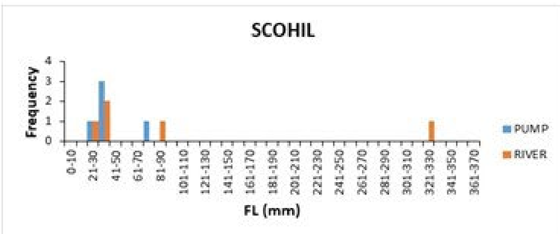
Flatheaded gudgeon



Rendahl's tandan



Leathery grunter



Appendix IV: Kolmogorov-Smirnov tables

Orange shading indicates significant values (p<0.001)
Yellow shading indicates significant values (p<0.05)

Glassfish *Ambassis agassizii* (AMBAGA)

Kolmogorov-Smirnov values for Glassfish			
AMBAGA	Reference Site 2 13/01/2021	Reference Site 6 19/03/21	Reference Site 14 23/02/2022
Outlet 1 13/01/2021	0.415		
Outlet 8 21/03/2021		0.008*	
Outlet 4 22/02/2022			0.319
Outlet 3 22/02/2022			0.024*

* denotes situations where entrained fish are apparently larger than those captured in the associated reference site.

Natural Flows (Combined)

AMBAGA	Reference Site 5 (Combined)
Outlet 4 (Combined)	0.088
Outlet 3 (Combined)	0.382

Allocated Flows (Combined)

AMBAGA	Reference Site 6 (Combined)
Outlet 13 (Combined)	<0.001*

* denotes situations where entrained fish are apparently larger than those captured in the associated reference site.

Barred grunter *Amniataba percoides* (AMNPER)

AMNPER	Fairbairn Dam 30/09/2021
Selma Channel 29/09/2021	0.007
Weemah Channel 29/09/2021	0.207

Allocated Flows (Combined)	
AMNPER	Fairbairn Dam (Combined)
Selma Channel (Combined)	0.042
Weemah Channel (Combined)	0.344

Natural Flows (Combined)	
AMNPER	Reference Site 5 (Combined)
Outlet 3 (Combined)	0.026

Carp gudgeon species *Hypseleotris* spp. (HYPSPP)

Carp gudgeon Kolmogorov-Smirnov values (dataset including larval measurements)					
HYPSPP	Reference Site 2		Reference Site 6	Reference Site 14	Fairbairn Dam
Outlet 1 13/01/2021	0.016 *				
Outlet 1 28/09/2021	0.002 *				
Outlet 1 16/11/2021	<0.001 *				
Outlet 16 16/11/2021	0.009 *				
Outlet 8 21/03/2021		<0.001 *			
Outlet 15 2/11/2021		0.038			
Outlet 3 14/01/2021			0.005 *		
Outlet 4 14/01/2021			0.547		
Outlet 3 20/03/2021			0.006 *		
Outlet 4 21/03/2021			0.607		
Outlet 3 27/11/2021			0.007 *		
Outlet 3 22/02/2022				0.687	
Outlet 4 22/2/2022				0.169	
Selma 18/09/2021					0.105
Weemah 19/09/2021					0.276
Selma 29/09/2021					0.121
Weemah 29/09/2021					0.015
Selma 24/01/2022					0.252
Weemah 24/01/2022					<0.001 *
Selma 24/02/2022					0.153
Weemah 23/02/2022					<0.001

* denotes situations where entrained fish are apparently larger than those captured in the river.

Carp gudgeon Kolmogorov-Smirnov values (dataset with larval measurements omitted)

HYPSPP	Reference Site 2	Reference Site 6	Reference Site 5	Reference Site 14	Fairbairn Dam
Outlet 1 13/01/2021	0.016 *				
Outlet 1 28/09/2021	→ <0.001 *				
Outlet 1 16/11/2021	→ <0.001 *				
Outlet 16 16/11/2021	→ 0.045 *				
Outlet 8 21/03/2021		<0.001 *			
Outlet 15 2/11/2021		→ <0.001			
Outlet 3 14/01/2021			→ 0.010 *		
Outlet 4 14/01/2021			→ 0.468		
Outlet 3 20/03/2021			0.006 *		
Outlet 4 21/03/2021			0.607		
Outlet 3 27/11/2021			→ 0.274 ##		
Outlet 3 22/02/2022				→ 0.435	
Outlet 4 22/2/2022				→ 0.012 ^^	
Selma 18/09/2021					0.105
Weemah 19/09/2021					→ 0.788
Selma 29/09/2021					0.121
Weemah 29/09/2021					0.015
Selma 24/01/2022					0.252
Weemah 24/01/2022					<0.001 *
Selma 24/02/2022					0.153
Weemah 23/02/2022					→ 0.005

* denotes situations where entrained fish are apparently larger than those at associated reference sites.

→ indicates significance values affected by omission of larval measurements

Indicates situation where relationship has lost significance on omission of larval measurements

^^ indicates situation where relationship has gained significance on omission of larval measurements

Allocated Flows (Combined)

HYPSPP	Reference Site 6 (Combined)	Reference Site 18 (Combined)
Outlet 8 (Combined)	<0.001 *	
Outlet 17 (Combined)		0.549

Spangled perch *Leiopotherapon unicolor* (LEIUNI)

LEIUNI	Reference Site 2 13/01/2021	Reference Site 6 19/03/2021	Reference Site 14 23/02/2022
Outlet 1 13/01/2021	<0.001*		
Outlet 7 20/03/2021		0.088	
Outlet 8 21/03/2021		0.004	
Outlet 4 22/02/2022			0.073
Outlet 3 22/02/2022			0.045*

* denotes situations where entrained fish are apparently larger than those captured in the associated reference site.

Allocated Flows (Combined)

LEIUNI	Reference Site 5 (Combined)
Outlet 3 (Combined)	<0.001*

* denotes situations where entrained fish are apparently larger than those captured in the associated reference site.

Golden perch *Macquaria ambigua oriens* (MACAMB)

MACAMB	Reference Site 5 15/01/2021	Fairbairn Dam 17/06/2021	Reference Site 2 16/11/2021	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022
Outlet 3 14/01/2021	0.319[L]				
Weemah 19/06/2021		<0.001[N]			
Outlet 16 16/11/2021			0.066[L]		
Outlet 1 16/11/2021			0.192[L]		
Weemah 24/01/2022				<0.001[N]	
Selma 24/01/2022				<0.001[N]	
Weemah 23/02/2022					0.041[N]
Selma 24/02/2022					0.201[N]

[L] indicates a comparison of sites where **only** larval fish were caught.

[N] indicates a comparison of sites where **no** larval fish were caught.

Allocated Flows (Combined)

MACAMB	Fairbairn Dam (Combined)
Weemah (Combined)	<0.001
Selma (Combined)	<0.001

Eastern rainbowfish *Melanotaenia splendida splendida* (MELSPL)

Rainbowfish Kolmogorov-Smirnov values (including larval measurements)

MELSPL	Fairbairn Dam 17/06/2021	Fairbairn Dam 30/09/2021	Reference Site 6 2/11/2021	Reference Site 2 16/11/2021
Weemah 19/09/2021	0.056			
Weemah 29/09/2021		0.010		
Outlet 15 2/11/2021			<0.001	
Outlet 1 16/11/2021				<0.001*

* indicates situations where entrained fish are apparently larger than fish in associated reference sites.

Rainbowfish Kolmogorov-Smirnov values (with larval measurements omitted)

MELSPL	Fairbairn Dam 17/06/2021	Fairbairn Dam 30/09/2021	Reference Site 6 2/11/2021	Reference Site 2 16/11/2021
Weemah 19/09/2021	→0.124			
Weemah 29/09/2021		0.010		
Outlet 15 2/11/2021			<0.001	
Outlet 1 16/11/2021				<0.001*

* indicates situations where entrained fish are apparently larger than fish in associated reference sites.

→ indicates significance values affected by omission of larval measurements

Allocated Flows (Combined)

MELSPL	Fairbairn Dam (Combined)
Weemah (Combined)	0.022
Selma (Combined)	0.554

Bony bream *Nematalosa erebi* (NEMERE)

Bony bream Kolmogorov-Smirnov values (dataset including larval measurements)

NEMERE	Reference Site 2 13/01/2021	Reference Site 5 15/01/2021	Reference Site 6 19/03/21	Reference Site 14 23/02/2022	Fairbairn Dam 17/06/2021
Outlet 1 13/01/2021	<0.001*				
Outlet 1 28/09/2021	<0.001				
Outlet 16 16/11/2021	<0.001				
Outlet 1 16/11/2021	0.014				
Outlet 3 14/01/2021		<0.001*			
Outlet 3 27/11/2021		<0.001			
Outlet 8 21/03/2021			0.004		
Outlet 13 19/06/2021			<0.001		
Outlet 8 18/09/2021			<0.001		
Outlet 15 2/11/2021			<0.001		
Outlet 7 26/02/2022			<0.001		
Outlet 3 22/02/2022				0.126	
Weemah 19/06/2021					0.576
Selma 18/06/2021					<0.001*
Weemah 29/09/2021					<0.001
Selma 29/09/2021					0.004*
Weemah 24/01/2022					0.497
Selma 24/01/2022					<0.001*
Weemah 23/02/2022					<0.001
Selma 24/02/2022					<0.001

* denotes situations where entrained fish are apparently larger than those captured in the associated reference site.

Bony bream Kolmogorov-Smirnov values (with larval measurements omitted)

NEMERE	Reference Site 2 13/01/2021	Reference Site 5 15/01/2021	Reference Site 6 19/03/21	Reference Site 14 23/02/2022	Fairbairn Dam 17/06/2021
Outlet 1 13/01/2021	<0.001*				
Outlet 1 28/09/2021	→ <0.001				
Outlet 16 16/11/2021	→ <0.001				
Outlet 1 16/11/2021	0.014				
Outlet 3 14/01/2021		<0.001*			
Outlet 3 27/11/2021		<0.001			
Outlet 8 21/03/2021			0.004		
Outlet 13 19/06/2021			<0.001		
Outlet 8 18/09/2021			<0.001		
Outlet 15 2/11/2021			→ <0.001		
Outlet 7 26/02/2022			<0.001		
Outlet 3 22/02/2022				0.126	
Weemah 19/06/2021					0.576
Selma 18/06/2021					<0.001*
Weemah 29/09/2021					<0.001
Selma 29/09/2021					0.004*
Weemah 24/01/2022					→ 0.409
Selma 24/01/2022					<0.001*
Weemah 23/02/2022					<0.001
Selma 24/02/2022					<0.001

* denotes situations where entrained fish are apparently larger than those captured in the associated reference site.

→ indicates significance values affected by omission of larval measurements

Blue catfish *Neoarius graeffei* (NEOGRA)

Kolmogorov-Smirnov value for blue catfish (combined)

NEOGRA	Reference Site 5 (Combined)
Outlet 3 (Combined)	<0.001

Sleepy cod Oxyeleotris lineolatus (OXYLIN)

Sleepy cod Kolmogorov-Smirnov values (including larval measurements)

OXYLIN	Reference Site 6 19/03/21	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022
Outlet 8 21/03/2021	<0.001		
Selma Channel 24/01/2022		0.146	
Selma Channel 24/02/2022			<0.001

Sleepy cod Kolmogorov-Smirnov values (Larval measurements omitted)

OXYLIN	Reference Site 6 19/03/21	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022
Outlet 8 21/03/2021	<0.001		
Selma Channel 24/01/2022		0.146	
Selma Channel 24/02/2022			→ <0.001

→ indicates values affected by omission of larval measurements

Flat-headed gudgeon *Philypnodon grandiceps* (PHIGRA)

Kolmogorov-Smirnov values for flathead gudgeon

PHIGRA	Fairbairn Dam 23/01/2022	Fairbairn Dam 24/02/2022
Weemah Channel 24/01/2022	0.003	
Selma Channel 24/01/2022	<0.001	
Weemah Channel 23/02/2022		<0.001
Selma Channel 23/02/2022		<0.001

Allocated Flows (Combined Data)	
PHIGRA	Fairbairn Dam (Combined)
Weemah Channel (Combined)	<0.001
Selma Channel (Combined)	<0.001

Leathery grunter Scortum hillii (SCOHIL)

Kolmogorov-Smirnov value, natural flows (Combined)	
SCOHIL	Reference Site 6 (Combined)
Outlet 8 (Combined)	<0.001