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Final report

Small research and development activity

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2 Executive summary

2.1 Background

River infrastructures such as dams, weirs, regulators and hydropower facilities are constructed to secure water, food and energy supplies. But their prevalence globally has contributed to vast declines in the quality of freshwater ecosystems and led to a significant reduction in the value of fisheries. The Lower Mekong Basin (LMB) sustains the largest freshwater fishery in the world and more than 80% of rural households are involved in capture fisheries. But as much as 70% of species in the fishery are at threat from the expansion of river infrastructure, largely because the health of their populations is reliant on individuals migrating freely either within rivers and/or between rivers and floodplain wetlands.

Irrigation structures can be used to regulate floodplain river flows, protecting crops from river flooding during wet seasons and retaining water during dry seasons. Many would also have the capacity to generate electricity if coupled with mini-hydropower facilities. But infrastructures need to be managed to protect the fishery, by ensuring safe fish passage is provided. Fish need to move both upstream into wetlands, but many also require return passage from the wetland to the river. Unfortunately research from the Murray-Darling Basin (MDB) suggests that significant numbers of fish may be injured and killed as they pass downstream through irrigation structures.

A holistic approach to fish passage is required in the LMB and MDB, addressing both upstream and downstream fish passage. Such an approach is hampered by an absence of available information with which to manage downstream fish passage effectively. The aim of this small research and development activity (SRA) was to progress our understanding on the protection of fish migrating downstream through irrigation structures. In doing so we sought to build upon the capacity gained from associated ACIAR fish passage activities that have been working towards improving upstream fish passage at wetland regulator structures in Lao P.D.R. (FIS/2006/183 and FIS/2009/041).

2.2 Project activities

We sought to determine the potential for injury and mortality when fish pass downstream through irrigation infrastructure in the LMB and to explore what hydraulic stressors may be responsible for fish welfare issues. More specifically, laboratory-based experiments were used to answer the following three research questions:

1. What are the mortality rates of different LMB species when they pass through river infrastructure?
2. What are the hydraulic conditions likely to be responsible for this mortality? And,
3. What are the hydraulic thresholds required for safe passage of LMB and MDB species?

The first research question involved constructing an experimental weir where we could lift or lower drop-boards to configure the weir as either ‘overshot’ or ‘undershot. Fish were passed downstream through the weir in three replicated treatments (overshot, undershot and a control) and relative mortality and/or injury rates were quantified. The larvae and juveniles of a variety of species were tested.

At the same time that live fish were passed, hydraulic sensors (Sensorfish) were released which collected high resolution data on change in pressure, acceleration and rotation. The Sensorfish enabled us to identify which hydraulic conditions may contribute to injury and mortality, thus addressing research question 2.

Finally, we used specially design hypo/hyperbaric chambers to simulate differing degrees of rapid decompression which may be experienced by fish moving through a variety of river infrastructure types. Murray cod (*Maccullochella peelii*, a MDB species) and common carp (*Cyprinus carpio*, found in both the MDB and LMB) were exposed to rapid decompression and a variety of barotrauma injuries quantified over a range of ratio of pressure changes. Logistic modelling of injury rates combined with multivariate techniques were used to determine thresholds for injury, thus addressing research question 3.

The experimental work was combined with some targeted training and dissemination activities. Lao P.D.R. and Australian researchers completed a barotrauma training course in Port Stephens, Australia. The course was run in collaboration with experts from the United States and covered the theory and practice of hydraulic Sensorfish research, barotrauma research and fish necropsy. The final workshop in Lao P.D.R. was used to disseminate the project findings to fisheries and water managers and provoke discussion of follow-up activities.

2.3 Achievements and new knowledge

We have provided the first evidence that fish in the LMB may be injured or killed during downstream passage through irrigation infrastructure. Furthermore we have been able to progress our understanding of what hydraulic conditions may be responsible for the injury or both larval and juvenile fish during infrastructure passage in both the LMB and MDB. Although not initially anticipated, some of the findings generated may also be applicable to understanding the fisheries impacts of a large range of river infrastructures, including mainstem hydropower dams.

The training activities developed new skills in both Lao and Australian researchers. These skills were not only applied throughout this SRA, but have also enabled the Lao scientists to access grant money to begin their own barotrauma and Sensorfish experiments. The findings arising from the SRA have been disseminated both regionally and internationally, facilitated by the final workshop which was run in conjunction with the International Energy Agencies Fish and Hydropower Annexe. We have been successful in having Lao P.D.R. accepted as a member country on this international Annexe, greatly improving the capacity of Lao scientists to contribute to international debate on how best to manage the fisheries risks associated with river infrastructure developments.

2.4 Conclusions and recommendations

There is evidence that fish in the LMB may be injured or killed during downstream passage through irrigation infrastructure. It is also evident that the impact is not only species and life stage specific, but can also vary between different weir designs. Larval fish of some species appear more susceptible than juveniles to mortality, with mortality rates as high as 95% being found. Although mortality was less common in juveniles, injury resulting from weir passage was reported in up to a third of juveniles for some species. These findings are of significant concern to fisheries in the LMB, where there are thousands of low-level weirs and regulators which have great potential to harm downstream migrating fish.

By simulating decompression during infrastructure passage using hypo/hyperbaric chambers we determined that larval Murray cod were very resistant to barotrauma injury. Collectively, the hydraulic measurement taken at the weir and investigations using the chambers indicate that rapid decompression may not be the primary cause of larval fish mortality during undershot weir passage. Instead, shear may also be responsible.

When compared to larval Murray cod, juvenile fish (in this instance carp) appeared highly susceptible to barotrauma and we have identified clear thresholds in decompression, which if exceeded lead to significant injury. More than 90% of fish suffered swim bladder rupture when exposed to extreme cases of decompression (above a ratio of pressure change (RPC) of 12). Even at low levels tested (RPC~2) 20 % of fish had ruptured swim bladders and at mid-range levels (i.e. RPC > 4) rupture was being seen in upward of 80% of fish, with over a third also showing signs of haemorrhage and/or emboli in the heart, gills, mouth, fins, eyes and kidneys.

Sensorfish tests showed that decompression is unlikely to reach these levels at low-level weir structures, but other studies show that RPCs above 10 can occur at large dam hydropower turbines and currently we do not know whether mini-hydropower facilities on low-head structures have the potential to exceed the low to mid-range levels of decompression shown in this study to cause injury to juvenile fish.

From the research findings and feedback received from Lao fisheries and water managers as part of our final workshop, the following recommendations can be made:

- There is potential to improve downstream fish passage survival rates at wetland regulators through design and operational modifications. Different designs should now be tested in the field, on actual regulator gates, thus validating these laboratory results for wild fish.
- Further investigation is warranted into ‘overshot’ weir designs as potentially more ‘fish-friendly’ alternatives to ‘undershot’ designs’, although the complete range of available technologies should be scoped and tested.
- More understanding is required as to what species are undertaking downstream passage from wetlands and the biomass of these movements. Such data will allow better modelling of the economic impacts associated with wetland regulator upgrades.
- More work is required to understand the risk associated with both small-scale (or mini) and large dam hydropower facilities on downstream migrating fish. Initial results from our pilot barotrauma experiments indicate that >90% of small fish passing through turbines on high-head dams may suffer mortal injuries. This is vastly different to the estimates of 2-15% that have been used in modelling the impacts of dams on the Mekong mainstem. The consequences of the higher level of mortality for viability of fish populations are likely to be severe and needs to be better understood and acknowledged.
- Future injury and mortality trials should focus on shear and turbulence when concerning larvae and barotrauma when concerning juvenile and adult fish. The barometric chamber experiments used here have proven to have great potential for determining critical thresholds of decompression associated with both low-head and large dam hydropower in the LMB. Future studies should look at establishing the link between barotrauma injuries and subsequent death in a larger number of species.
- Sensorfish technology should be employed at a larger range of river infrastructure types throughout the LMB and MDB to better understand fish welfare issues throughout their migratory range. Of particular need is the testing of mini-hydropower technologies, which have yet to be investigated or applied at a large scale in Lao P.D.R.
- Future ACIAR investments into fish passage in the LMB region would benefit from presenting upstream and downstream fish passage as a coordinated ‘whole’, rather than as two distinct issues. It is important that water managers, donor bodies and other investing in future infrastructure upgrades appreciate the need for both upstream and downstream passage. Ideally opportunities should be explored to adopt both upstream and downstream fishway technologies at the same site, thus maximising the potential environmental benefits from both fish passage investments.

3 Introduction

3.1 The impact of river infrastructure on fisheries

Healthy and productive fisheries are immensely important throughout the lower Mekong basin (the LMB, which is the Mekong drainage within Lao P.D.R., Thailand, Cambodia and Vietnam). The region sustains the largest freshwater fishery in the world, with an annual yield in excess of two million tonnes and being six to seven times the size of the combined freshwater and marine fishery sector in Australia [1]. More than 80% of rural households in the LMB are involved in capture fisheries and fish and other aquatic animals provide on average 48% and 79% of the animal protein intake in Lao P.D.R. and Cambodia, respectively [2]. Having an adequate supply of fish is fundamental for the operation of Lao society and its future development, being linked with economic and social well-being, including early childhood development [3].

In many parts of the world fisheries are under significant threat by river infrastructure developments (e.g. dams, irrigation weirs and hydropower facilities) [4, 5]. Irrigation development in the LMB has led to the proliferation of low-level (generally less than 6 m) water regulation devices which limit the movement of migratory fish. As much as 70% of fish species in this region are considered migratory, and require connectivity among river reaches to access feeding areas, spawning grounds and refuge habitats. The fishery of the LMB is therefore extremely vulnerable to population collapses when river infrastructure developments interrupt important life-cycle stages and this can have social and economic consequences. As an example, it has been estimated that planned mainstream dam developments could cost the fishery 0.7-1.6 million tonnes (or between $1.4 and $3 million USD in first-sale value) per year [1]. Impacts are also being documented in south-eastern Australia, where the impact of river infrastructure and the regulation of flows are thought to be a major contributing cause of a 90% decline in fish populations within the Murray-Darling Basin (MDB).

In both the LMB and MDB there is a requirement to respond to increasing food needs and the challenge of climate change by improving water efficiency and transitioning to ‘greener’ forms of power generation [6]. The Lao P.D.R. government plans to have 10% of the county’s energy generated from renewable sources by 2020, with Australian targets set at 20%. Across the wider-LMB the village off-grid promotion project seeks to have 1,000 villages powered via mini-hydro power within the next decade. Likewise, significant water reform currently underway in the MDB is prompting some irrigation agencies to explore the use of existing irrigation networks for the generation of mini-hydropower. All this will undoubtedly require an expansion and upgrade in irrigation infrastructure and the adoption of new technologies. Whilst such developments are important in facilitating economic growth in Lao P.D.R. and water reform of the MDB irrigation industry, it is essential that the economic, social and environmental benefits associated with healthy fisheries are not compromised.

3.2 Improving fish passage at river infrastructure

When functioning in their natural state, floodplain wetlands adjoining large rivers are among the most productive freshwater ecosystems [7] and provide important feeding, spawning and nursery habitats for fish [8-15]. In the LMB, a “grey fish” guild is composed of species having the need to migrate between floodplains and tributaries. A “black fish” guild also utilise floodplain wetlands for spawning. The sustainability of these guilds of fish is therefore reliant on good connectivity and free fish passage between wetlands and the adjacent river.

Wetlands in the LMB (as in the MDB) fulfil a dual economic and social purpose, providing important fish habitat and supporting capture fisheries, but also providing a secure supply of regulated irrigation water for farming communities. Flood control devices installed between the Mekong and its tributaries and adjacent wetlands are necessary to regulate wetland levels independent of flows in the Mekong River. But although they facilitate irrigated cropping, they also interrupt the natural passage of fish into and out of wetlands. In doing so, irrigation infrastructure sometimes puts the needs of agriculture and fisheries at odds with each other, and as such, the fishery implications of irrigation infrastructure design and operation should be considered.

A recent ACIAR investment (FIS/2009/041) has demonstrated the substantial progress can be made in restoring upstream fish movements past irrigation regulators into floodplain wetlands. However, to date the focus on restoring *upstream passage* has been associated with little or no focus on protecting fish during critical *downstream migrations* on their return to the Mekong River. Similarly in the MDB, the provision of safe downstream fish passage has been identified as a fisheries management problem that is both poorly understood and yet to be sufficiently addressed [16].

Concern over the welfare of downstream migrating fish is growing internationally, leading to research and development aimed at developing more fish-friendly infrastructure designs. Much of the research has focussed on the downstream passage of juvenile salmon at large hydropower dams and shows that fish are subjected to sudden changes in hydraulic conditions when they pass turbines (e.g. decompression, impact and shear forces) which can result in injury or death [17, 18]. Research from Australia has shown that significant injury and mortality can even occur at much smaller irrigation structures [19, 20].

Understanding the tolerances of fish to different hydraulic stressors during downstream passage is an important first step to ensuring that infrastructure can be designed and operated in a way that maximises fish survival. Unfortunately, there is currently insufficient data on the injury and survival of LMB fish as they pass river infrastructure and it is not desirable to base recommendations on a small number of studies on North American species. In the MDB, whilst studies have shown that significant numbers of fish may be injured when passing through weirs, there is still uncertainty regarding the mechanism for this injury [19, 20].

3.3 Objective and research questions

We sought to determine the potential for injury and mortality when fish pass downstream through irrigation infrastructure in the LMB and to explore what hydraulic stressors may be responsible for fish welfare issues. Laboratory-based experiments were used to answer the following three research questions:

1. What are the mortality rates of different LMB species when they pass through river infrastructure?
2. What are the hydraulic conditions likely to be responsible for this mortality? And,
3. What are the hydraulic thresholds required for safe passage of LMB and MDB species?

4 Overview of methods

4.1 What are the mortality rates of different LMB species when they pass through river infrastructure?

Experiments were conducted between October and November 2012 to quantify injury and mortality rates of fish passing downstream through different configurations of irrigation weir. These experiments involved constructing a temporary 1.5 m drop-board weir in an earthen channel at the Nong Teng Fish Hatchery in Lao P.D.R. (Figure 1). Lifting or lowering the drop-boards allowed the weir to be configured as either 'overshot' or 'undershot'[1]. For an undershot operation the drop-boards were lifted 50 mm to direct all flow under the weir. During overshot operation, the drop-boards were lowered so that all flow was directed over the weir crest. Flow was supplied to the experimental weir from a header pond.

Fish were released through a 3 m long, 50 mm diameter pipe directly upstream of the weir to ensure they passed immediately through the weir via either the 'overshot' or 'undershot' route (Appendix 1: Figure 3). Following passage the fish were collected downstream of the weir in a 500 µm net (Figure 1). In addition, a 'no-weir control was used, where fish were released immediately downstream of the overshot weir where they were not exposed to the hydraulic conditions associated with passage before being collected in the net (Appendix 1: Figure 3). By doing this we were able to determine whether any observed injury or mortality could be attributed to fish deployment and collection methods.

Six unique species and life-stage combinations were used for the experiments (Table 1), with all fish obtained from the Nong Teng hatchery or local aquaculture suppliers. Five replicates were used for each weir treatment for juveniles (10 fish per replicate) and larvae (20 fish per replicate). After the experiment, all dead and surviving larvae were immediately counted. Juveniles were housed in 5 L buckets of river water and kept in rearing troughs at the hatchery site for 24 hours. After this time any further dead fish were counted and all fish were examined to identify any injuries sustained during the experiment. The injuries quantified included fin, scale, head and eye damage, haemorrhage and decapitation. The rate of injury and mortality for each replicate was analysed as a percentage of the total number of fish recovered in the downstream net. Mean injury or mortality rates were plotted and one-way ANOVA used to test for significant differences in injury and mortality rates between the three treatments (undershot, overshot and control).

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[1] *Overshot weirs discharge water over the top of a crest, whereas undershot structures discharge water underneath a gate.*

Table 1. Species and life stages of fish used for weir mortality experiments. All fish were sourced from the Nong teng hatchery facility

Life stage	Scientific name	Common Name
Larvae	*Cyprinus carpio*	Common carp
	Clarius sp.	Pa Douk Catfish
Juvenile	*Clarius sp.*	Pa Douk Catfish
	Pangasius hypophthalmus	Shark catfish
	Oreochromis nilotica	Tilapia
	Hypsibarbus sp.	Pa Pak

4.2 What are the hydraulic conditions likely to be responsible for this mortality?

At the same time that live fish were passed through the experimental weir at Nong Teng, autonomous hydraulic sensors (Sensorfish) were also passed (Figure 1). These sensors measure linear acceleration in three directions (up-down, forward-back, and side-to-side) angular velocity in three angles (pitch, roll and yaw), and absolute pressure [21]. Analysis of these data allowed us to identify whether fish are exposed to hydraulic or physical stressors which may explain injury or death, such as rapid decompression, collisions, strike, shear[2] and turbulence. Five sensors were released per treatment, using the same method of deployment as mentioned previously for the fish. The data was then uploaded and pressure and acceleration profiles plotted for comparison.

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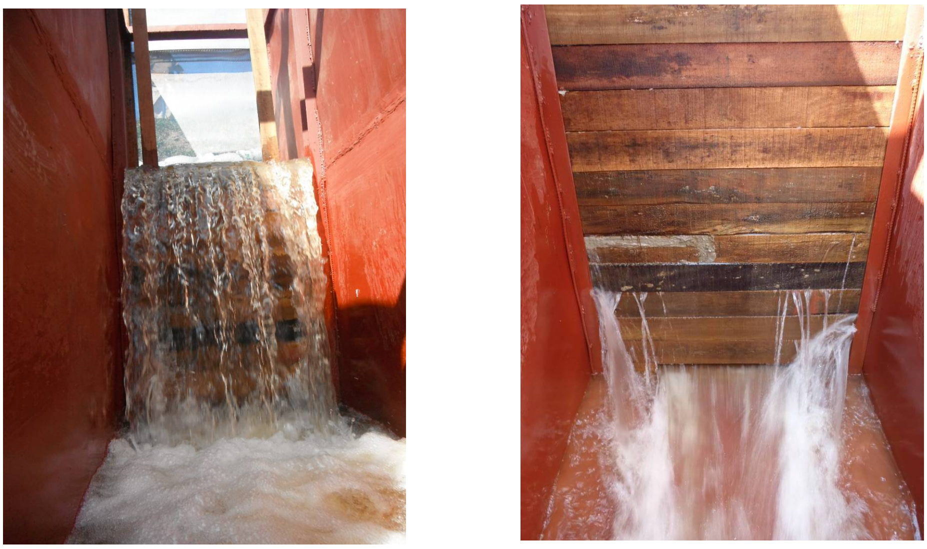
[2] *Shear is the force applied at the point where two bodies of water of differing mass and velocity intersect. Fish moving through a point of elevated shear may encounter physical injury [22] Neitzel, D. A., Dauble, D. D., Čada, G., Richmond, M. C., Guensch, G. R., Mueller, R. P., Abernethy, C. S. and Amidan, B. (2004). Survival estimates for juvenile fish subjected to a laboratory-generated shear environment. Transactions of the American Fisheries Society* ***133****: 447-454.*

Experimental drop-board weir structure constructed at Nong Teng Fish Hatchery

Collecting fish downstream of experimental weir



'Overshot' configuration

'Undershot' configuration

Quantifying mortality rates in larval fish after experimentation

Autonomous sensor (Sensorfish) used to determine hydraulic conditions during weir passage

Figure 1. Experiments were used to quantify injury and mortality rates for fish passing downstream through different weir designs.

4.3 What are the hydraulic thresholds required for safe passage of LMB and MDB species?

Rapid decompression is one possible cause of fish injury and death during river infrastructure passage [18]. When hydraulic pressure is rapidly decreased from a level at which a fish is acclimated or migrating at, the fish is at risk from suffering barotrauma [23]. A reduction in pressure causes a reciprocal increase in gas volume (i.e. for every halving of pressure, gas volume doubles: Boyle's Law) which results in expansion of the swim bladder. Since fluids (including blood) can hold greater amounts of gas in solution when under pressure (Henry's Law), when fish are decompressed gas may be forced out of solution causing bubbles to form in vasculature and organs. The injuries which typically result from the occurrence these phenomena can include rupture of the swim bladder; the formation of bubbles (embolism) in the body cavity, eyes, skin and fins; dislocation of the eyes (exophthalmia); and haemorrhage (bleeding) associated with ruptured vasculature and damage to organs such as the brain, gills and heart [24, 25, 23, 26]. These injuries have been associated with eventual death of fish [27], but they have yet to be studied in fish of the LMB or MDB.

In order to develop safe downstream fish passage criteria for river infrastructure, it is essential to know what levels of decompression fish can tolerate before injury and mortality occurs. In this experiment we sought to determine upper thresholds of rapid decompression that could be tolerated by a juvenile LMB species (Common carp, *Cyprinus carpio*) and a MDB species (larval Murray cod, *Maccullochella peelli*).

Hypo/hyperbaric chambers [28] were used at the Port Stephens and Narrandera Fisheries Centres to simulate rapid decompression as experienced by fish during downstream passage through river infrastructure (Figure 2). The severity of decompression was expressed as the ratio of pressure change (RPC) between the migrating or acclimation pressure and the lowest exposure pressure. Test groups of fish were exposed to a range of RPC from 1 (no decompression) up to a maximum of ~20 (for juvenile carp) or ~10 (for larval Murray cod). This simulated the severity of decompression that would be expected across a range of infrastructure types, including irrigation weirs and small and large-scale hydropower facilities.

After simulated infrastructure passage, larval Murray cod were kept for 24 hours to quantify delayed mortality. At this time they were examined under a microscope for signs of injury, including swim bladder rupture or internal haemorrhaging or emboli. Juvenile carp were immediately euthanased following experimentation and necropsy performed to quantify internal and external barotrauma injuries. Logistic regressions were performed to generate injury and mortality models over a range of RPC's for both the larval and juvenile fish. Because a large variety of injuries were quantified for juvenile carp, multivariate analysis was used to identify which of these injuries most contributed to a statistical significant increase in the overall rate of injury.

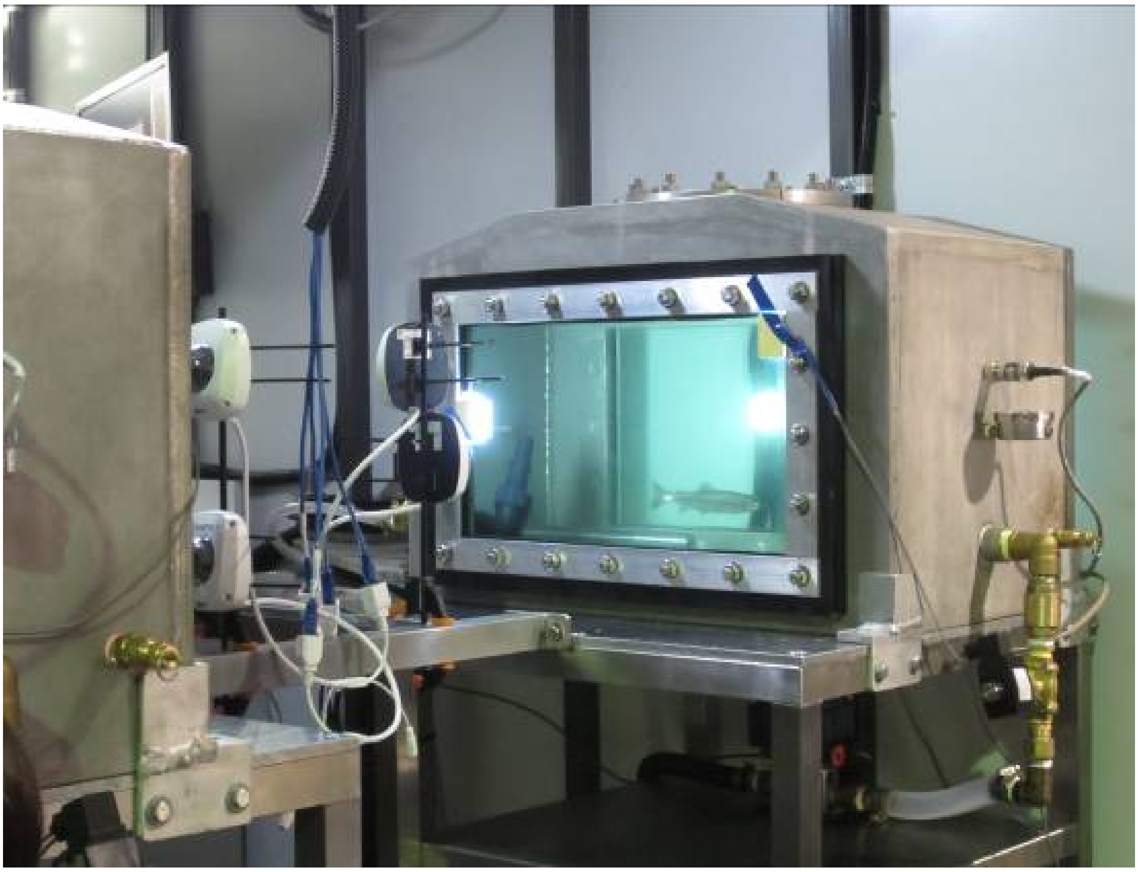


Figure 2. Hypo/hyperbaric chambers used to simulate rapid decompression during fish passage through river infrastructure

5 Overview of key results

5.1 What are the mortality rates of different LMB species when they pass through river infrastructure?

Larval fish suffered significant rates of mortality when passing downstream through an experimental weir, but the rate of mortality varied between species and different weir configurations (Appendix 1: Figure 4). On average, ~85-90% of Pa Douk catfish larvae died when passing either overshot or undershot weirs, compared to only 50% in the ‘no weir’ control. No difference was observed between the overshot and undershot configurations. In comparison, ~75% of larval carp died during undershot weir passage, which was significantly higher than the 50% mortality rate observed in the ‘no weir’ and overshot treatments.

Juvenile fish appeared less likely to die than larval fish when passing the experimental weir. Pa Douk catfish, shark catfish, Pa Pak and tilapia did not suffer significantly more mortality during weir passage when compared to the ‘no weir’ control (Appendix 1: Figure 5). Injuries were commonly reported for some species following weir passage, but only tilapia showed a significantly higher rate of injury during weir passage (~25 and 33% mortality for overshot and undershot respectively), when compared to the ‘no weir’ control (~3% injury). Scale loss was the most commonly observed injury, followed by fin, head and eye damage, with proportionally more fish being injured during undershot passage when compared to overshot passage (Appendix 1: Figure 6).

5.2 What are the hydraulic conditions likely to be responsible for this mortality?

Data obtained by Sensorfish (Appendix 1: Figure 7) identified three possible mechanisms for fish injury during weir passage, with these differing based on weir design. When passing an undershot weir, fish experience rapid decompression (in a fraction of a second), as they move from a higher hydrostatic pressure at depth upstream of a weir and are ‘shot’ into surface waters at atmospheric pressure. The ratio of pressure change (RPC) experienced would be greater for a fish migrating at depth when compared to a surface orientated fish. Rapid acceleration and rotation was measured as the sensor passed under the gate, identifying either an area of elevated fluid shear, or potential contact with the bottom of the undershot gate.

The hydraulic conditions observed during overshot weir passage were noticeably different to undershot passage (Appendix 1: Figure 7). Typically during passage pressure remained at atmospheric as the sensor remained on the surface. The only deviation from this was as the sensor plunged over the weir. A sharp spike in pressure during this time suggests that the sensor collided with the floor of the channel downstream of the weir (and this was observed to occur by staff running the experiments. Turbulence and elevated shear was also observed downstream of the weir.

5.3 What are the hydraulic thresholds required for safe passage of LMB and MDB species?

Larval Murray cod (22 and 25 day post hatch, DPH) showed little mortality when exposed to rapid decompression and there was no relationship between mortality and severity of decompression (ratio of pressure change, RPC) (Appendix 1: Figure 8).

The incidence of barotrauma injury in juvenile carp (Appendix 1: Figure 9, Figure 10 and Table 2) was in stark contrast to that observed in larval Murray cod. Below a RPC of 2.5

there was little evidence of barotrauma injury. At mid-ranged RPCs (between 2.5 and 4), there was a significant increase in the probability of various injuries, including swim bladder rupture (~48% of fish), internal haemorrhaging (~29%) and the presence of emboli in the viscera (34%), mouth (30%) and the membrane separating the gills from the body cavity (pharyngo-cliethral membrane) (65%). These emboli were likely related to gas being trapped internally following swim bladder rupture. Once RPC increased above ~4, more injuries were observed, at significantly higher rates. Swim bladder rupture was present in ~80% of fish and over a third of the fish showed signs of other injuries, including haemorrhage and/or emboli in the heart, gills, mouth, fins, eyes, kidneys and pharyngo-cliethral membrane.

5.4 Scientific impacts

The SRA will result in two journal papers: one concerning the weir experiments and the other concerning the chamber work. We have provided the first evidence that fish in the LMB may be injured or killed during downstream passage through irrigation infrastructure. Furthermore we have been able to progress our understanding surrounding what hydraulic conditions may be responsible for the injury or both larval and juvenile fish during infrastructure passage. The key findings summarised in the conclusion of this report demonstrate how our understanding of downstream mortality has been progressed not only the LMB, but also in the MDB, where the cause of downstream mortality at irrigation structures had not previously been investigated. Although not initially anticipated, some of the findings generated are applicable to understanding the fisheries impacts of a large range of river infrastructures, including mainstem hydropower dams (see section 6.1).

5.5 Capacity impacts

The SRA has substantially improved the capacity of both Lao and Australian scientists to undertake research specific to downstream fish passage. A barotrauma training course completed in Port Stephens and attended by both Lao and Australian researchers covered the theory and practice of hydraulic Sensorfish research, barotrauma research and fish necropsy. Not only were these skills applied during the experimental work in the current SRA, but the Lao researchers have subsequently obtained a grant from CGIAR under the Challenge Program on Water and Food to construct their own barotrauma chambers and begin follow-up experiments, as well as procure and begin using Sensorfish technology. This adds significant value to the current ACIAR investment as it will allow for the testing of a larger range of LMB fish species than would ever be possible in Australian facilities. None of this would have been possible without the training provided as part of this SRA. These new skills and resources will greatly enhance the ability of local researchers to better establish fishery impacts associated with current and future river infrastructure developments, including irrigation structures and both mini and large dam hydropower.

5.6 Community impacts

The SRA involved some lab-based work and workshop training. As such, it was never anticipated that any economic, social or environmental impacts would result directly from the SRA itself. It has, however, provided the proof-of-concept regarding the potential for downstream mortality at irrigation structures. When this proof-of-concept was presented at the final workshop in Vientiane in August 2013, there was overall consensus among Lao P.D.R. fisheries and water managers that the research should progress to field-based trials. Should field-based trials of different regulator designs be undertaken, it may be expected that immediate improvements in fish survival out of wetlands could result. Improved survival could translate into improved yields and social and economic benefits over the next 10 years. But many untested assumptions regarding downstream passage of fish from wetlands will need to be answered, and any follow-up field trials should include a specific component aimed at using the fish passage and survival data gathered to model the economic impacts associated with irrigation infrastructure upgrades.

6 Conclusions and recommendations

6.1 Conclusions

There is evidence that fish in the LMB may be injured or killed during downstream passage through irrigation infrastructure. It is also evident that the impact is not only species and life stage specific, but can also vary between different weir designs. Larval fish of some species appear more susceptible than juveniles to mortality, with mortality rates as high as 95% being found. Although mortality was less common in juveniles, injury resulting from weir passage was reported in up to a third of juveniles for some species. These findings are of significant concern to fisheries in the LMB, where there are thousands of low-level weirs and regulators which have great potential to harm downstream migrating fish.

By simulating decompression during infrastructure passage using hypo/hyperbaric chambers we determined that larval Murray cod were very resistant to barotrauma injury. Collectively, the hydraulic measurement taken at the weir and investigations using the barotrauma chambers indicate that rapid decompression may not be the primary cause of larval fish mortality during undershot weir passage. Instead, turbulence and shear may play a large role. Such a finding has significant progressed our understanding of downstream mortality not only in the LMB, but also in the MDB, where the mechanism responsible for downstream mortality of larvae at irrigation structures had not previously been investigated.

When compared to larval Murray cod, juvenile fish (in this instance carp) appeared highly susceptible to barotrauma and we have identified clear thresholds in decompression, which if exceeded lead to significant injury. One injury which was strongly positively related to the severity of decompression was swim bladder rupture. Under extreme cases of decompression (above a ratio of pressure change (RPC) of 12), more than 90% of fish suffered swim bladder rupture (an injury which has been shown to lead to eventual death in some species [27]). But decompression did not need to be this extreme to pose a concern for fish welfare. Even at low levels tested (RPC~2) 20 % of fish had ruptured swim bladders and at mid-range levels (i.e. RPC > 4) rupture was being seen in upward of 80% of fish, with over a third also showing signs of haemorrhage and/or emboli in the heart, gills, mouth, fins, eyes and kidneys.

Our Sensorfish experiments indicate that decompression of the magnitude discussed above is unlikely at wetland irrigation structures, explaining why barotrauma injuries were not observed during our experimental weir experiments. But RPCs above 10 have been shown to occur at large dam hydropower turbines [29]. Furthermore, we do not currently know whether mini-hydropower facilities on low-head structures have the potential to exceed the mid-range levels of decompression (RPC~4) shown in this study to cause significant injury to juvenile fish.

6.2 Recommendations

From the research findings and feedback received from Lao fisheries and water managers as part of our final workshop, the following recommendations can be made:

- There is potential to improve downstream fish passage survival rates at wetland regulators through design and operational modifications. Different designs should now be tested in the field, on actual regulator gates, thus validating these laboratory results for wild fish.

- Further investigation is warranted into ‘overshot’ weir designs as potentially more ‘fish-friendly’ alternatives to ‘undershot’ designs’, although the complete range of available technologies should be scoped and tested.
- Future field based trials should incorporate greater replication (to improve statistical power) and focus more on native and commercially important fish species (to increase stakeholder uptake of recommendations) when compared to the experiments undertaken in this SRA.
- There is a need to better understand which species are undertaking downstream passage from wetlands and the biomass of these movements. Such data will allow better modelling of the economic impacts associated with wetland regulator upgrades.
- More work is required to understand the risk associated with both small-scale (or mini) and large dam hydropower facilities on downstream migrating fish. Initial results from our pilot barotrauma experiments indicate that >90% of small fish passing through turbines on high-head dams may suffer mortal injuries. This is vastly different to the estimates of 2-15% that have been used in modelling the impacts of dams on the Mekong mainstem [30]. The consequences of the higher level of mortality for viability of fish populations are likely to be severe and needs to be better understood and acknowledged.
- Future injury and mortality trials should focus on shear and turbulence when concerning larvae and barotrauma when concerning juvenile and adult fish. The barometric chamber experiments developed in this study should be expanded to many more species in the LMB. They have great potential for determining critical thresholds of decompression associated with both low-head and large dam hydropower.
- Sensorfish technology should be employed at a larger range of river infrastructure types throughout the LMB and MDB to better understand fish welfare issues throughout their migratory range. Of particular need is the testing of mini-hydropower technologies, which have yet to be investigated or applied at a large scale in Lao P.D.R.
- Future ACIAR investments into fish passage in the LMB region would benefit from presenting upstream and downstream fish passage as a coordinated ‘whole’, rather than as two distinct issues. It is important that water managers, donor bodies and other investing in future infrastructure upgrades appreciate the need for both upstream and downstream passage. A more holistic approach would be achieved by presenting both upstream and downstream fish passage content together in future workshops whilst recognising that to achieve both, you need very different engineering solutions. Ideally opportunities should be explored to adopt both upstream and downstream fishway technologies at the same site, allowing stakeholders to more easily make the connection, as well as maximising the potential environmental benefits from both fish passage investments.

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7.2 List of publications produced by project

The SRA will result in two journal papers: one concerning the weir experiments and the other concerning the chamber work. Preparation of these two papers will begin shortly.

8 Appendixes

8.1 Appendix 1: Supplementary tables and figures

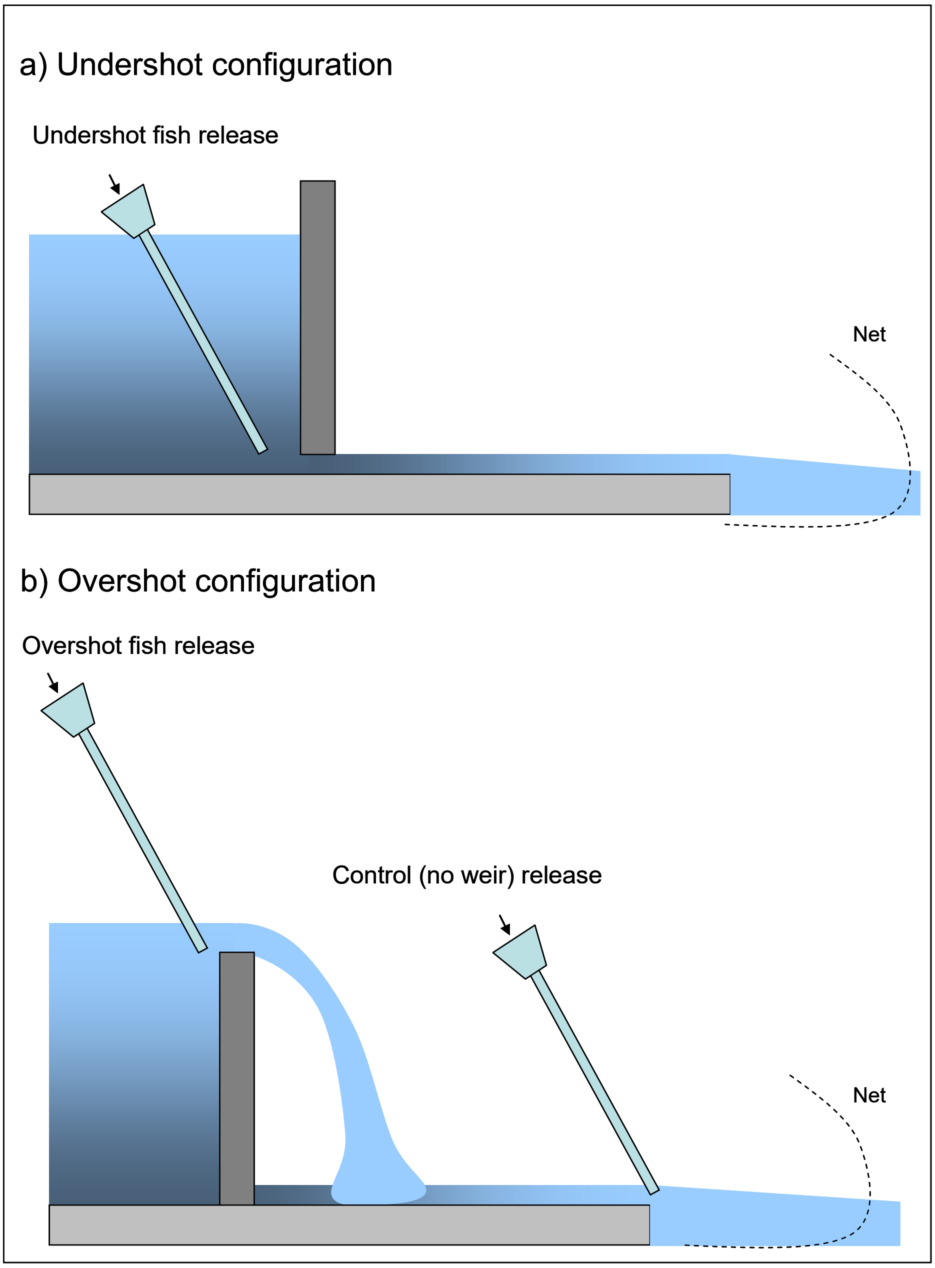
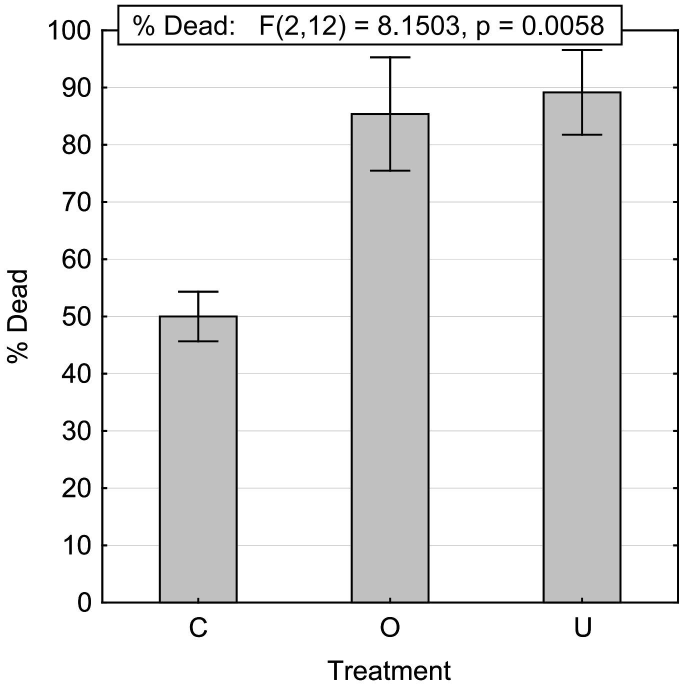


Figure 3. Fish deployment and collection locations for the three treatments during the weir experiments.

a) Catfish larvae (Pa Douk)



b) Carp larvae

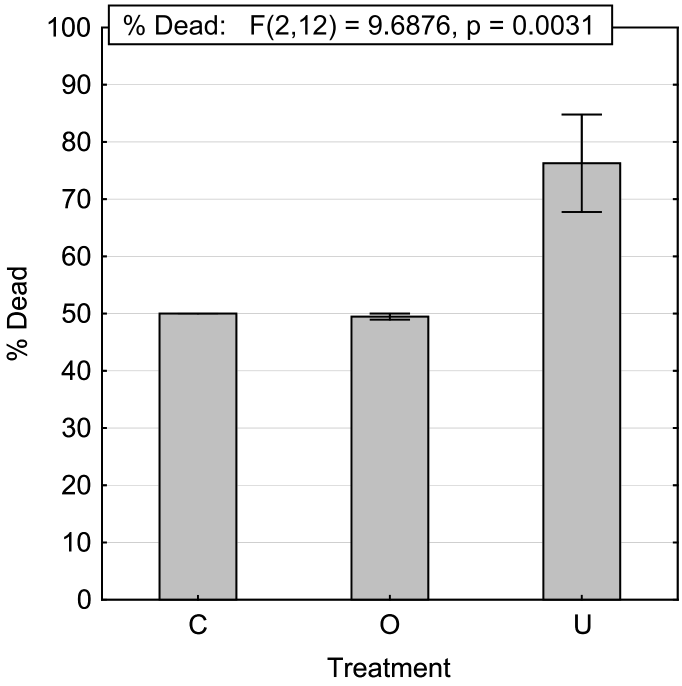
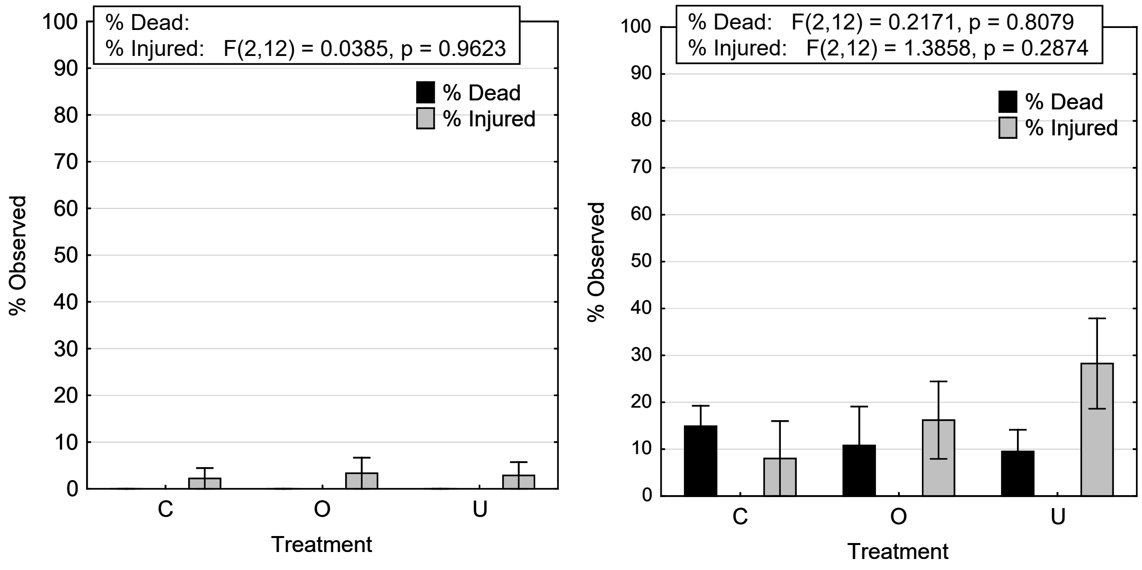


Figure 4. Mean (±S.E.) mortality rates for larval catfish (a) and carp (b) during downstream passage through an overshot (O) and undershot (U) weir, compared to the 'no weir' control (C). On average catfish larvae were significantly more likely to die when passing a weir structure when compared to the control, with mortality in larval carp particularly associated with undershot weir passage.

a) Juvenile Pa Douk catfish

b) Juvenile shark catfish



c) Juvenile Pa Pak

d) Juvenile tilapia

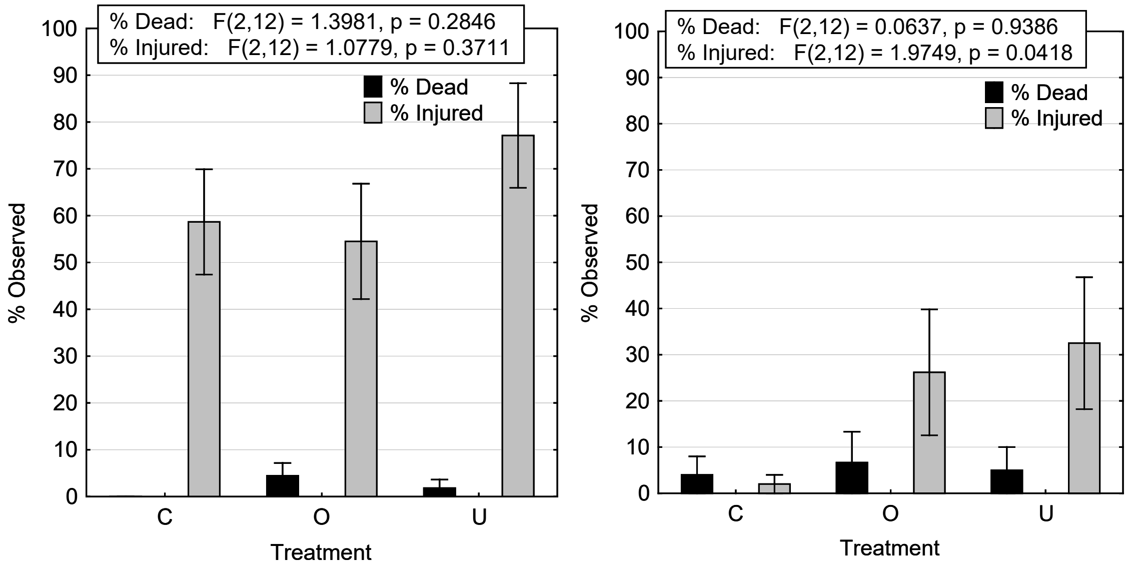


Figure 5. Mean (±S.E.) mortality (black) and injury (grey) rates for juvenile Paa Dug catfish (a), shark catfish (b), silver barb (c) and tilapia (d) during downstream passage through an overshot (O) and undershot (U) weir, compared to the 'no weir' control (C). There was no significant difference in mortality between controls and the two weir treatments for all species tested. Only Tilapia were the only species where weir passage lead to significantly higher rates of injury than the control.

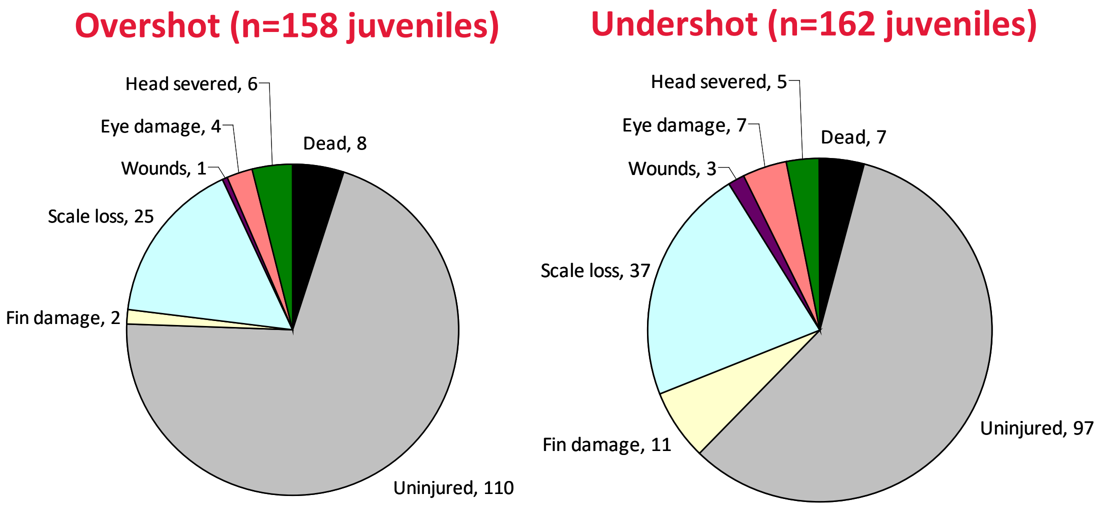
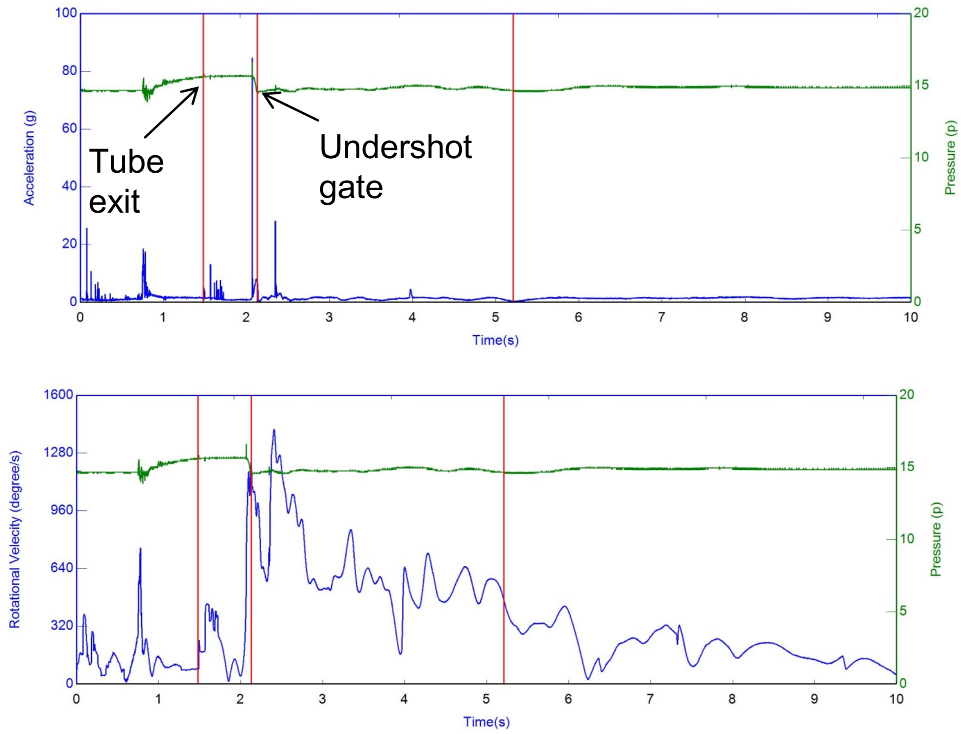


Figure 6. Proportion of total juvenile fish recovered that were dead, uninjured or displaying various injuries following overshot (left) and undershot (right) weir passage. Proportionately more juvenile fish were injured during undershot weir passage than overshot.

a) Undershot weir release



b) Overshot weir release

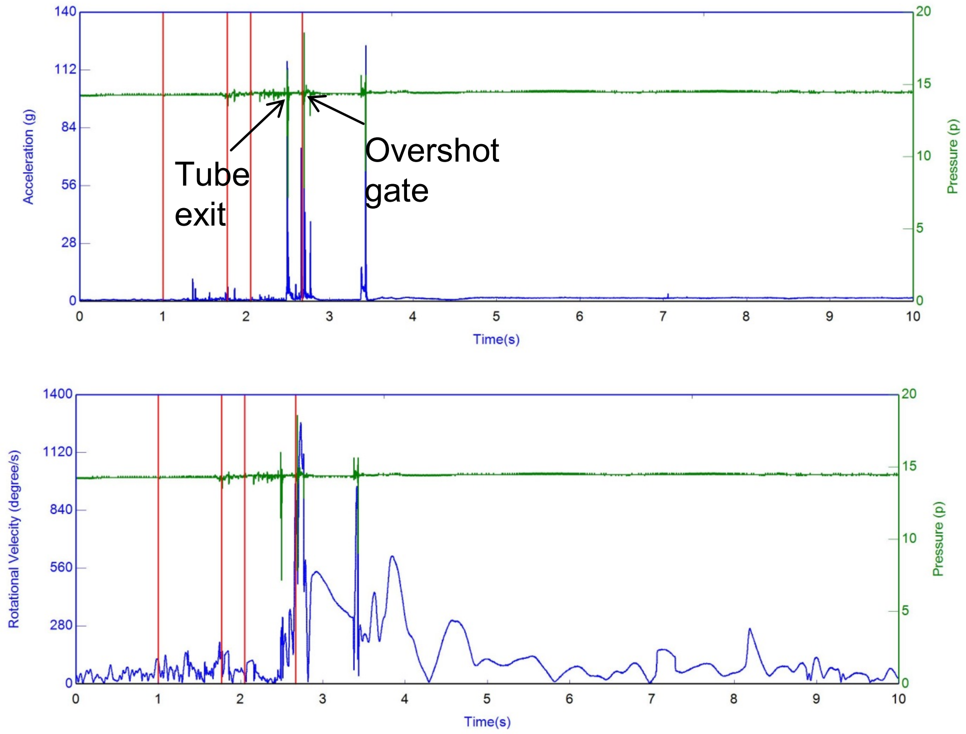


Figure 7. Typical plot of hydraulic data obtained from Sensorfish showing the pressure (green), acceleration and rotational velocity (blue) profiles experienced during undershot (a) and overshot (b) weir passage.

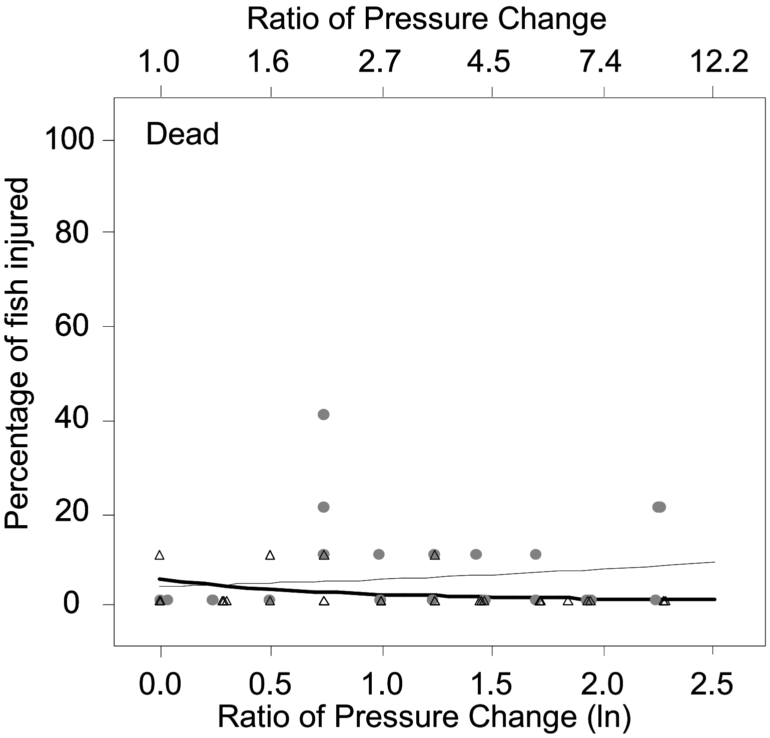


Figure 8. The relationship between the natural log ratio of pressure change and the probability of death (+ 24 hours) of larval Murray cod that had been exposed to simulated infrastructure passage. Each point represents the proportion of that test group (10 fish) affected and the lines represent the modelled mortality rate. Circles are 22 day post hatch larvae and triangles are 25 day post hatch larvae. There was little relationship between larval mortality and the severity of decompression (ratio of pressure change).

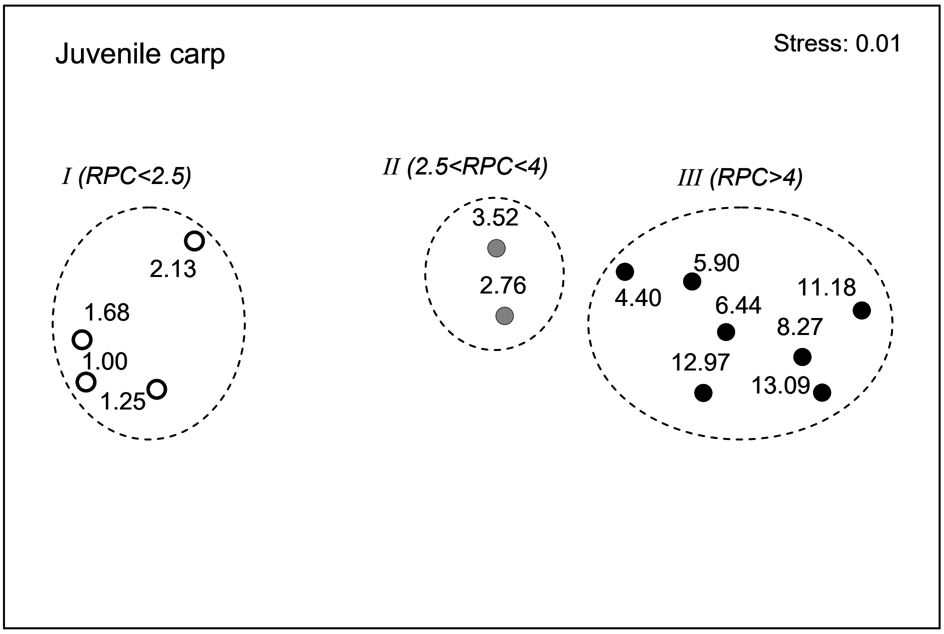


Figure 9. nMDS showing the similarity (Bray-Curtis) between different decompression scenarios based on the proportions of all injuries present in juvenile carp. Each point represents a centroid of three test groups for each scenario tested and the label gives the mean ratio of pressure change (RPC) for that centroid group. Centroids which are circled are not significantly different from each other (identified using CLUSTER and SIMPROF analysis) with respect to the type of injury and the proportion of fish affected by it within a test group. Approximate RPC ranges are given for each injury group. Significant RPC thresholds were found at ~2.5 and 4.

Table 2. SIMPER results showing which combination of injury types best explained the significant increase in overall injury rate in juvenile carp, that occurred as RPC increased above ~2.5 and ~4. The injury groupings relate to the SIMPROF groups identified in Figure 9. The proportion of fish displaying that injury per test group is given as an average across all test groups within a particular SIMPROF group. The Sim/SD value gives a measure of the consistency of that injury in explaining the average similarity within that SIMPROF group, with injuries with a Sim/SD>1 considered to have contributed consistently across all points in the SIMPROF group.

Injury Group I (RPC<2.5) Average similarity: 43.34	Av. Probability of injury	Av.Sim	Sim/SD	Contrib%	Cum.%
Fins - Haemorrhage	0.25	32.82	1.94	75.72	75.72
Swim Bladder - Ruptured	0.09	4.33	0.8	9.99	85.7
Eyes - Haemorrhage	0.04	3.58	0.88	8.26	93.97

Injury Group II (2.5<RPC<4) Average similarity: 75.79	Av. Probability of injury	Av.Sim	Sim/SD	Contrib%	Cum.%
Pharyngo-cliethral membrane - Emboli	0.65	24.77	4.14	32.68	32.68
Viscera - Mesentary emboli	0.34	11.92	3.26	15.72	48.4
Swim Bladder - Ruptured	0.48	11.36	12.75	14.99	63.39
Viscera - Haemorrhage	0.29	9.12	7.52	12.04	75.43
Mouth - Emboli	0.3	7.82	6.13	10.32	85.75
Eyes - Haemorrhage	0.16	3.72	9.21	4.91	90.66

Injury Group III (RPC>4) Average similarity: 75.90	Av. Probability of injury	Av.Sim	Sim/SD	Contrib%	Cum.%
Pharyngo-cliethral membrane - Emboli	0.89	14.94	7.58	19.68	19.68
Swim Bladder - Ruptured	0.8	12.27	7.65	16.16	35.84
Mouth - Emboli	0.54	7.97	4.14	10.5	46.34
Fins - Emboli	0.54	7.66	4.32	10.09	56.43
Kidney - Haemorrhage	0.36	5.33	9.37	7.03	63.46
Heart - Emboli	0.34	4.97	3.59	6.55	70
Viscera - Mesentary emboli	0.32	4.09	2.98	5.4	75.4
Eyes - Haemorrhage	0.28	3.79	2.7	4.99	80.39
Viscera - Haemorrhage	0.24	3.29	2.29	4.33	84.73
Gills - Haemorrhage	0.32	2.8	1.06	3.69	88.41
Eyes - Emboli	0.17	2.17	3.25	2.87	91.28

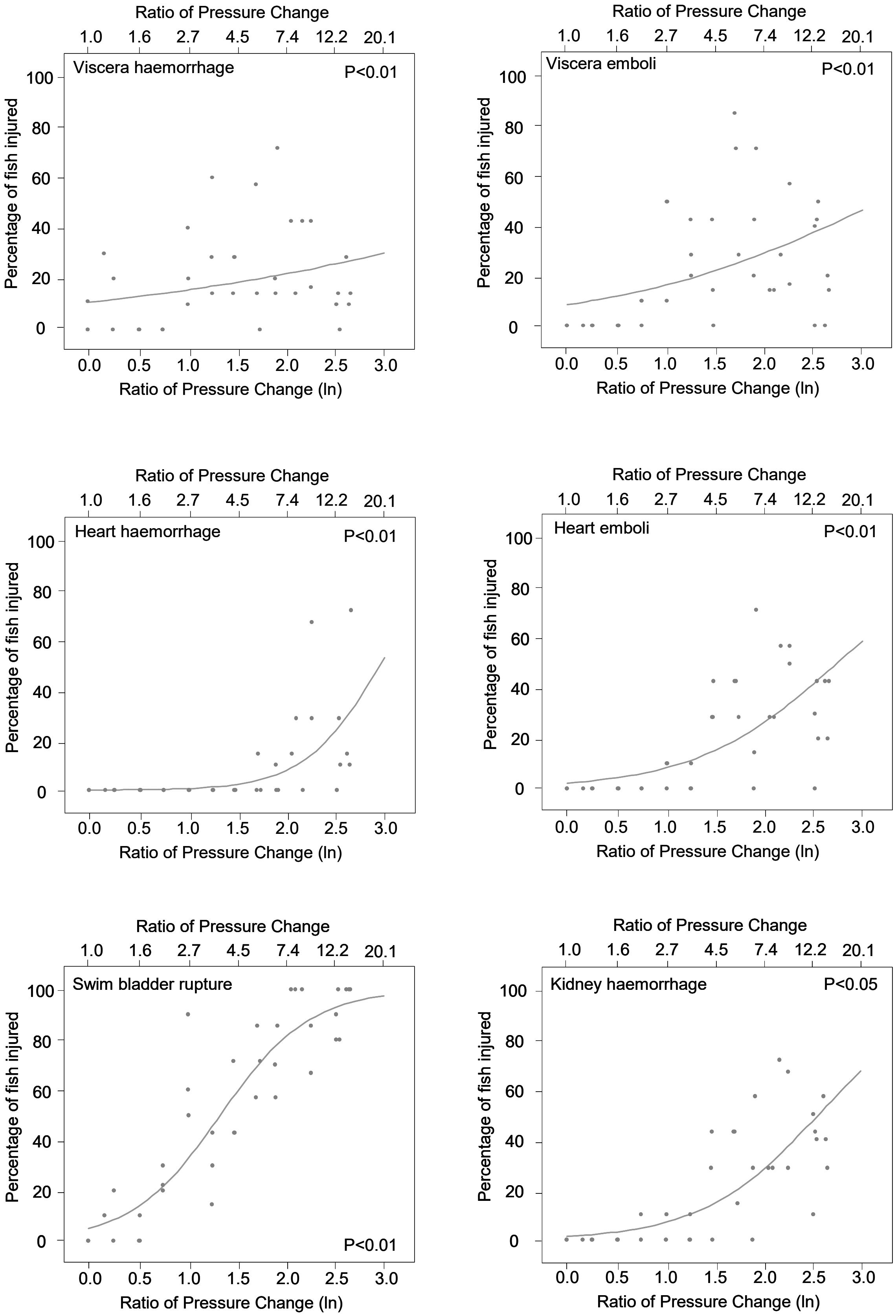


Figure 10. Several types of barotrauma injuries significantly increased as the severity of decompression (ratio of pressure change) was increased during simulated infrastructure passage in the hypo/hyperbaric chambers.