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2 Executive summary

2.1 Background and scope of the project

Agriculture is a major contributor to economic development and food security in both the Lower Mekong Basin (LMB) and the Murray-Darling Basin (MDB). Over the last century, the expansion of irrigation networks in both basins has enabled agriculture to spread into more arable areas. Expansion and intensification of irrigation has involved the construction of many levees, diversion canals and water-control structures (such as weirs, sluices and water gates) that enable rainfall and river flows to be captured and delivered more effectively. This expansion is only going to continue, as governments invest heavily in modernising ageing infrastructure and constructing more dams, weirs and regulators to achieve greater water efficiency and to "drought proof" regional and rural communities.

Unfortunately, the spread of irrigation structures has contributed to severe declines in fish populations and declines in the value of fisheries. Water-control structures create barriers to fish migrations and fragment important fish habitats. Both large-scale in-channel and small-scale lateral movements of fish have become blocked and fish are now far more constrained in their ability to move between habitats, greatly impacting their ability to reproduce, feed, seek new territories and avoid predators. One form of small-scale migration that has been particularly impacted in large floodplain river systems is the movement of fish between the main river channel and the floodplain. Such movements are extremely important for fish to access nursery habitat or for feeding.

Encouragingly, great progress has been made in recent years in the design and implementation of fish ladders at low-head (<6m) irrigation structures. These fish ladders assist fish to migrate upstream past barriers and thanks to the work of other ACIAR-funded projects (including project FIS/2006/183 and FIS/2009/041) fish ladders are increasingly acknowledged as best practice when planning irrigation projects.

However, the focus on restoring upstream passage has been associated with little or no focus on protecting fish during critical downstream migrations. Current practices of capturing and storing water rely on less-than-optimal technologies that are well behind current best practice for fish passage. A recent small ACIAR-funded pilot (SRA FIS/2011/072) undertaken in Lao PDR raised significant concerns over the potential injury and mortality that may be suffered by fish (up to 90% in some cases) on their downstream passage through water-control structures. This work corroborates findings of other studies undertaken internationally. High mortality during downstream passage is very concerning because most species and life stages of fish in large floodplain river systems like the LMB and MDB need to undertake downstream migrations. Without safe downstream migration (either as eggs, larvae, juveniles or adults), fish have access to fewer habitats, more fish die and some species cannot complete their life cycles. Therefore, if safe downstream passage is not allowed, any improvements in fish populations achieved by allowing fish greater access to upstream habitats will be compromised.

What is needed is a more holistic approach to fish passage, one that addresses both upstream and downstream fish passage simultaneously. However, while this sounds logical in theory, much more guidance needs to be offered to the agricultural sector about how to achieve it. Firstly, there is a need to better understand what design and operational features of water-control structures can make them "fish-friendlier" for downstream passage, and once this is determined, the information needs to be presented in a way that can be best understood and adopted by both a technical and nontechnical audience. This is ultimately what was achieved during this project (FIS2012/100), through a combination of desktop review and analysis, as well as hydraulic and biological field studies conducted at a refurbished water-control structure at Pak Peung Wetland (Bolikhamxay Province Lao PDR), as well as at existing irrigation structures at Colligen Creek and Yarrawonga Weirs in the Murray River system of Australia.

The overall aim of the project was to assist water management authorities to adapt irrigation structures in ways that increase the value of the associated fisheries. We tried to achieve this by meeting three objectives:

1. To better understand the impact of irrigation infrastructure on the downstream passage of fish between wetlands and rivers.

2. To assess the effectiveness of different regulator designs for improving the survival of fish exiting wetland habitats.

3. To quantify to what extent improved fish passage survival at irrigation water-control structures can return an economic benefit through improved capture fisheries.

2.2 Key research findings and recommendations

Our main conclusions and recommendations were as follows:

Downstream movement of fish from wetlands is considerable and needs to be protected.

The project was the first ever to quantify the number and species of fish passing downstream through a water-control structure from a floodplain wetland back into the Mekong River. By trapping fish moving out of the Pak Peung Wetland, we were able to show that the downstream movement of fish from wetlands to the main channel involve a significant number of individuals and different species. In the downstream trapping experiment, we observed downstream passage rates as high as 169 fish per hour, and counted 114 different fish species. The vast majority were from the 'grey fish' guild, which is known to undertake short migrations between the floodplain and main channel. When this is viewed alongside upstream movement data collected from the adjacent fishway, it demonstrates the importance of cyclical lateral fish movements in floodplain wetlands like Pak Peung. That is, movements both upstream into wetlands and downstream into the main river channel. From a fish passage remediation perspective, we suggest that restoring upstream fish passage alone at wetland water-control structures will be insufficient to protect the fishery if safe return passage is not also provided. Most of the fish captured undertaking downstream passage were small bodied, a size class that has been shown to be particularly vulnerable to injury and death when passing weirs and regulators. This emphasises the need to ensure structures are designed and operated in a way that promote greatest fish survival. Additionally, our results show the need to consider the passage of a diverse range of species, not just one or two. From the perspective of quantifying the economic and environmental benefits that can accrue from investing in safe downstream fish passage, due to the large number of fish passing regulators and the substantial number of these regulators throughout the LMB, it may be expected that even small improvements in fish survival through improved regulator design and operation could result in considerable benefits across the LMB.

Water-control structures can be designed and operated in a way that can promote safer downstream fish passage.

After an extensive desktop review, we identified the main types of water-control structures used in the irrigation industry to regulate flows. While there are a variety of manually or automated gate and weir structures available (including drop-board structures, radial gates, leaf gates, layflat gates and undershot sluice gates), generally the technologies can be divided into one of two main types: those that release water underneath a gate and those that release water over the top. Hereafter these will be referred to as undershot and overshot structures. A review of the literature revealed that fish survival is typically higher at overshot structures than undershot ones, however, the reason for this is poorly understood. We therefore undertook hydraulic investigations using state-of-the-art autonomous Sensor Fish at a number of structures in Lao PDR and Australia to identify how these can be designed and operated to provide conditions that are safer for fish passage. A key component of this project involved installing a layflat overshot gate at Pak Peung that could be used to release water from the wetland in lieu of the undershot sluice gates that previously existed there.

From the Sensor Fish research, we can conclude that design and operational adjustments to water-control structures should be considered to reduce hydraulic stressors which fish encounter when passing downstream. These design and operational guidelines have been produced in nontechnical form in both Lao and English languages. Overshot rather than undershot gates should be the design of choice to provide safer passage for fish and less injury and mortality because, based on their hydraulics, overshot structures create less stressful conditions for fish and this likely explains why previous studies have found less injury and mortality to small fish when passing this gate design. At low-head (<6 m) structures, strike with hard surfaces, rather than shear or rapid pressure changes appears the primary mechanism for injury. Therefore, design and operational improvements should focus on reducing strike events. While overshot structures can result in less frequent and severe strike to fish than undershot structures, their fish-friendliness will very much depend on spillway design, in particular, whether deep tailwater conditions are present. For this reason, a downstream plunge pool is an essential design requirement of overshot gates. Strike can be totally eliminated if there is a plunge pool sufficiently deep and long. Based on the available data, we recommend a plunge pool depth of at least 70% the head differential and long enough to capture the spill of the entire range of flows. With further targeted research of differing plunge pool depths this recommendation might be able to be further revised. The depth of a plunge pool can be increased by excavating a deeper hole downstream of the gate or by installing a drop-board structure downstream of the primary structure to raise the tailwater.

At some sites it may not be possible or cost-effective to change the design of a structure from an undershot to an overshot gate. If an undershot structure must be used, certain operational changes may help reduce the risk of strike and injury. For instance, increasing the gate opening of an undershot sluice gate should reduce the frequency and severity of strike. At sites with multiple gates this would simply be a matter of operating fewer gates with larger openings. Since most strike occurs downstream of the gate, having a sloping apron or operating the gate in a drowned state, where the downstream water level is above the gate opening, should help dissipate water velocities and keep fish from colliding with the bottom of the apron.

While decompression and shear may not be issues at low-head structures, they appear more problematic at higher structures. At structures greater than 6m, shear and decompression can be difficult to mitigate through operational changes and therefore the safer option would be to choose an overshot structure.

The environmental and economic costs and benefits associated with investing in downstream passage still need to be thoroughly quantified.

Due to the large number of fish passing regulators, and the substantial number of these regulators throughout the LMB, it may be expected that even small improvements in downstream fish survival may lead to considerable economic and environmental benefits. It was an objective of the project to quantify some of these benefits, however, in the end we were not able to successfully achieve it. While the investment in gate refurbishment was factored into a cost–benefit analysis, in the form of the Lower Mekong Fishway Support Tool (LMFST), the tool still poorly deals with investments in water-control structure upgrades from the perspective of downstream passage. The reason for this was the limited in the data we were able to collect to estimate the benefits and costs of investing in downstream passage.

Within the life of the project we were not able to trap fish over a sufficient range of different operating conditions to properly assess differences in injury and survival resulting from the upgrade of the Pak Peung Regulator from an undershot to an overshot structure. Mortality trials were only completed under a low-head condition, a scenario that our hydraulic measurements suggest may not cause as much injury to fish when passing underneath a sluice gate. At this low-head scenario we did not observe the same difference in mortality between an overshot and undershot structure at Pak Peung that has been observed in previous studies. This result needs to be treated with caution and more research needs to be done over higher-head conditions at which the gates are often operated.

Ultimately, due to these data deficiencies the current iteration of the LMFST does not estimate that there will be an economic return on our investment in downstream passage at Pak Peung. Using a default $100,000 USD cost of a new gate and no contribution to fish production, the analysis predicts a negative net value for the project and no prospect of the project breaking even within its lifespan. It also predicts that if investment in downstream passage is removed, a positive net benefit for the project arising solely from the upstream fishway would total $83,000 USD with a pay-off after 11 years. We believe this result to be misleading as it assumes an over-inflated cost and currently factors in zero benefit from improved gate design and operation (which may not be the case). It is clear that much more work needs to be done in collecting data relating to both the cost and benefit of downstream fish passage investment. Firstly, the LMFST should include a sliding scale for downstream investment that acknowledges that the cost of a project can differ substantially between a fully imported gate versus a locally produced one versus the neutral cost of making a smarter design choice at a green field site, or by changing the way an existing gate is being operated. Finally, as more data is collected over a greater range of operating conditions, we may be better able to acknowledge improvements in fish survival. By viewing these improvements in the context of cyclical movements of fish and therefore return passage into wetlands, the benefit of investments for fish production may be able to be revised and improved in the LMFST.

2.3 Summary of key impacts

The research conducted during this project included numerous world firsts. Firstly, it was the first study to quantify the types of species and their relative abundance exiting a wetland in the LMB. Secondly, it was the first to use Sensor Fish technology to measure the hydraulic conditions experienced by fish at different low-head irrigation structures. Previously, this technology had only been applied at hydropower dams. As a result of this research the findings expand the understanding of fish movements in the LMB and we have been able to offer recommendations of how to improve the design and operation of irrigation infrastructure in both the LMB and MDB.

To ensure impact of this science continues to grow over the next five years, the conclusions and recommendations from this research have been synthesised as nontechnical guidelines in both Lao and English languages. By improving the understanding that fisheries scientists, engineers and water authorities in both the LMB and MDB have of the need to protect downstream passage and how to achieve this through design and operational advances, it is anticipated that they will apply a more holistic approach to fish passage when developing future projects. Ultimately, this will encourage the adoption of technical advances in downstream passage alongside upstream passage. In this report we give an example of how this is already occurring with recommendations from this study being incorporated into the design of new structures in the MDB.

In the next five years it is expected that design guidelines produced by this project will be further promoted throughout the LMB, the MDB and more broadly by:

1. Increased circulation of the multilingual, nontechnical best-practice guidelines for water-control structures. This will be facilitated by continued activity of the ACIAR Fish Passage team through ongoing and associated projects in the region.
2. Continued teaching of downstream passage guidelines at fish passage design and barrier prioritisation master classes, as was recently done in Thailand (in collaboration with the US Department of Interior) and in Albury (as part of the international Fish Passage 2018 conference).
3. Incorporating downstream fish passage into the curriculum of at the National University of Laos and Charles Sturt University (this has already been done at both institutes), ensuring that the knowledge of current and future District and Provincial Agriculture and Fisheries Officers (the next users) is continually being developed at tertiary institutes in Lao PDR and Australia.
4. Continuing the use of the Pak Peung fish passage demonstration site as a valuable education tool where the holistic upstream and downstream approach to fish passage at water-control structures and the use of advanced manufacturing techniques can be demonstrated first-hand. The site will remain for the use of scientists and students to conduct further research.
5. Continuing the development and utilisation of downstream passage research and teaching tools that were initiated as part of this project and its proceeding SRA project – for example, National University of Laos Dongdok Campus hydraulic lab with barotrauma chambers and shear flume, and continued use of Sensor Fish at a wider variety of structures.

The scientific impact of this project has been illustrated by the fact that it has resulted in five peer-reviewed journal papers (with another two in preparation), two magazine articles and one PhD thesis. The research capacity of both Australian and Lao researchers has been improved throughout the project. Through this and other associated ACIAR Fish Passage projects in Lao PDR, the technical skills of local villagers in Pak Peung have continued to be improved in the disciplines of fish handling, fish identification, data collection, data management and how to follow set scientific protocols. There is clear evidence of the mentoring and development of future researchers during this project. Through this project Dr Pflugrath successfully attained his PhD, produced a first authored paper and was recognised with multiple awards. Our Lao researchers improved their skills by being exposed to many opportunities to present project work at international conferences.

As mentioned earlier, the environmental, social and economic impacts of this project cannot be properly quantified at this stage. Although the framework for doing this now exist in the form of the LMFST, much more work needs to be done to collect the data on differential survival rates across a range of designs and operational conditions to properly assess the benefit to capture fisheries which may accrue from projects like Pak Peung or other regulator upgrades. The LMFST also needs to acknowledge a sliding scale of cost when investing in the upgrade or installation of water-control structures. Therefore, while current evaluation of the Pak Peung study by the LMFST predicts a net economic loss when the investment in a new regulator gate is included, this result needs to be treated with caution until there is a better understanding of the benefits as well as the range of site-specific costs that could be encountered, including what it may cost to design and construct regulator gates locally.

The social impact that can come from empowering researchers and decision makers to drive positive policy change is hard to tangibly quantify, but is no less important. The biggest achievement of this project is that we have given the people of Lao PDR the tools to make more sustainable policy decisions around irrigation infrastructure investments. Through the project we have continued to foster an early-adopter mentality in Lao PDR. Researchers, conservation groups and water authorities have been emboldened to adopt technological advances and world best practice. The layflat gates installed a Pak Peung were a first for the region and the use of nonferrous materials in construction was initially met with reluctance but has now been proven successful and will greatly improve the lifespan of future investments. A key way that this adoption of new practice was facilitated was by fostering linkages between the Lao PDR government and Australian private industry (as exemplified by the involvement of an Australian firm, AWMA Water Control Structures, in the project). Our Lao PDR partners continue to build their reputation as world leaders in fish passage R&D, giving them greater influence to achieve positive outcomes for fish passage throughout the greater LMB region. For this they have been internationally recognised by their peers, receiving the Most Distinguished Project Award at the recent Fish Passage 2018 international conference.

2.4 Summary of key extension and dissemination activities

All the dissemination and communication activities proposed in the original project scope of works were completed, as well as additional ones. The key ways that the research outcomes were disseminated throughout the project are detailed in this report and include: in-country project workshops and meetings, production of multilingual nontechnical design and operation guideline documents, frequent field trips and public open days at the Pak Peung fish passage demonstration site, publication of scientific outputs in peer-reviewed and popular media, presentations at scientific conferences, fish passage master classes and social media posts.

The most prominent of the extension activities completed was the Lower Mekong Basin Fish Passage conference organised by the project team and held in Vientiane in November 2016. This was attended by 160 delegates from 14 different countries. The significant international prominence this conference achieved is highlighted by the fact that ACIAR's initial $30,000 AUD investment into the conference was able to leverage an additional $100,000 USD of sponsorship from international organisations

3 Background

Importance of inland fisheries in the Mekong and Murray-Darling basins

The Mekong and Murray-Darling Basins (MDB) are two of the world's major river systems. They drain similar catchment areas, are both over 4000 km in total length and support over 60 million people combined. Both systems contain unique inland fish communities which are important sources of biodiversity, food security and recreational opportunities.

For instance, in the Lower Mekong Basin (LMB) about 4.4 million tonnes of fish products are produced each year, with more than half of this (2.3 million tonnes, worth US$11 billion) coming from inland capture fisheries alone (Nam *et al.* 2015). Fishery participation is among the highest in the world. For example, in Lao PDR, 71% of households (2.9 million people) depend on fishing to some degree (Bishop *et al.* 2003). The LMB also has one of the highest rates of fish consumption in the world, with estimates of 47–80% of the animal protein consumed by its people coming from fisheries (Hortle 2007).

In comparison, the MDB has a recreational fishery with a participation rate of almost 20% (Henry and Lyle 2003) and this makes a direct contribution to the economy of up to AU$1.7 billion annually in expenditure (Ernst and Young 2011). Fish are not often considered a major food source of people living in the MDB, however, this was not always the case. Historically, native fish had significant nutritional, as well as social and cultural value for Indigenous people. After Europeans settled in Australia, native fish such as Murray cod formed important commercial fisheries (Rowland 2004). Unfortunately, declining native fish populations over the past century has meant there has been a significant decline in the economic, cultural and social value of MDB fisheries (Lynch *et al.* 2019).

Irrigation expansion and its impact on inland fisheries

Agriculture is a major contributor to economic development and food security in both the LMB and MDB. In the LMB, agriculture is the major source of livelihood for the population, with rain-fed and irrigated rice production being the most important crop. More than 10 million hectares of land is used to produce rice in the LMB, contributing more than 80% of all agricultural production across all member countries (MRC 2018). Similarly, the MDB is a major contributor to Australia's food and fibre production and most of this has only been made possible through irrigation. In fact, 32% of all agricultural production in Australia (AU$9.6 billion) comes from irrigated agriculture in the MDB (Meyer 2005)

Over the last century, the intensification and expansion of irrigation networks in both the LMB and MDB has enabled agriculture to spread into more arable areas. The expansion and intensification of irrigation has involved the construction of many levees, diversion canals and water-control structures (such as weirs, sluices and water gates) that enable rainfall and river flows to be captured and delivered more effectively. In the MDB this has opened up a significant proportion of south-eastern Australia to cropping, allowing water to be delivered throughout the entire spring/summer period. In the LMB, irrigation regulates water supply to crops in the wet season and supplements it during the dry season. Although the proportion of arable land that can be cropped in the LMB is much smaller than rain-fed cultivated areas, these areas are far more productive (MRC 2018). Advances in high-yield rice varieties have enabled crops to be grown all year round, resulting in a boom in irrigation expansion across the LMB (Hoanh *et al.* 2009). This expansion is only going to continue into the future, as LMB countries implement policies and plans for irrigation development to protect future dry season cropping in light of predictions of water scarcity (MRC 2018). Similarly, the MDB is in the midst of a river infrastructure boom, as the Australian Government invests heavily in modernising ageing infrastructure and constructing more dams, weirs and regulators to achieve greater water efficiency and to "drought proof" regional and rural communities.

The spread of water-control structures has contributed to severe declines in fish populations and declines in the value of fisheries. Water-control structures create barriers to fish migrations and fragment important fish habitats. Both large-scale in-channel and small-scale lateral movements of fish have become blocked and fish are now far more constrained in their ability to move between habitats, greatly impacting their ability to reproduce, feed, seek new territories and avoid predators. One form of small-scale migration that has been particularly impacted in large floodplain river systems like the LMB and MDB is the movement of fish between the main river channel and the floodplain. Such movements are extremely important for fish to access nursery habitat or for feeding.

Crisis or opportunity?

Current practices of capturing and storing water rely on less-than-optimal technologies that are well behind current best practice for fish passage. Therefore, one may despair at the rapid expansion and intensification of irrigation systems in the MDB and LMB and its likely impact of fisheries. However, this may actually be a once in a generation opportunity to improve irrigation practices as new water-control structures are planned and old ones modernised, so that win-win outcomes can be achieved for both agriculture and fisheries. Undoubtedly our understanding of how to incorporate state-of-the-art fishway technology into irrigation systems has improved over recent decades, driven by targeted research and development. In the MDB for instance, applied research now means that fish ladders (structures that facilitate upstream movement of fish past barriers) can be built that pass a much large range of species and size classes of fish. This research is influencing policy and practice as fish ladder construction is now more than ever intrinsically linked with irrigation modernisation through the NSW Fisheries Management Act. Most recently, a Ministerial Task Force in NSW was established to develop a 20-year NSW Fish Passage Strategy to remediate 160 priority barriers to restore fish access to over 10,000 km of rivers.

In the LMB, The ACIAR fishways program (including project FIS/2006/183 and FIS/2009/041) is demonstrating to the broader LMB region that fish ladders can help fish move upstream past low-head (<6m) water-control structures, and as a result the practice of building these ladders is expanding across all member countries. Fish ladders are now seen as best practice in irrigation expansion. All this was born from the original ACIAR-funded proof-of-concept work at Pak Peung Wetland (Bolikhamxay Province), demonstrating what can be achieved by adopting and refining international best-practice approaches to fish passage and driving uptake through targeted extension. The Pak Peung fishway project makes for a compelling education tool that is driving donor investment in fishways throughout the LMB. The cone fishway constructed there has passed over 170 fish species, and at times hundreds of kilograms of fish per day, upstream past a water-control structure that had disconnected the wetland and Mekong for over 50 years.

But what goes up must come down

However, the focus on restoring upstream passage has been associated with little or no focus on protecting fish during critical downstream migrations. A recent ACIAR SRA (FIS/2011/072) undertaken in Lao PDR raised significant concerns over the potential injury and mortality that may be suffered by fish (up to 90% in some cases) on their downstream passage through water-control structures. This work corroborates findings of research previously undertaken both internationally and in the MDB which demonstrates similarly high rates of fish mortality when passing downstream through water-control structures (Marttin and De Graaf 2002, Baumgartner *et al.* 2006, Baumgartner *et al.* 2013). This is very concerning because most species and life stages of fish in large floodplain river systems like the LMB and MDB undertake downstream migrations. Downstream migrations can either be ‘active’—when adult fish move by swimming, or ‘passive’—when eggs or larvae are transported by flowing water. Without downstream migration, fish have access to fewer habitats and some species cannot complete their life cycles. So, if safe downstream passage is not allowed, any improvements in fish populations achieved by allowing fish greater access to upstream habitats will be compromised.

What is needed is a more holistic approach to fish passage, one that addresses both upstream and downstream fish passage simultaneously. However, while this sounds logical in theory, little guidance is currently being offered to the agricultural sector about how to achieve it. There is a need to better understand what design and operational features of water-control structures can make them “fish-friendlier”, and once this is determined, the information needs to be presented in a way that can be best understood and adopted by both a technical and nontechnical audience. This was the goal of FIS2012/100, and it was achieved by working in Lao PDR and Australia.

4 Objectives

The overall aim of the project was to assist water management authorities to adapt irrigation structures in ways that increase the value of the associated fisheries. This was to be achieved through meeting three objectives:

1. To better understand the impact of irrigation infrastructure on the downstream passage of fish between wetlands and rivers.

2. To assess the effectiveness of different regulator designs for improving the survival of fish exiting wetland habitats.

3. To quantify to what extent improved fish passage survival at irrigation structures can return an economic benefit through improved capture fisheries.

5 Methodology

Six research questions were developed to meet each of the three project objectives (Figure 1). The following section outlines the key methods used to answer these research questions. They involved a combination of desktop review and analysis, as well as hydraulic and biological field studies conducted at an experimental fish passage site, Pak Peung Wetland (Bolikhamxay Province Lao PDR), and at irrigation regulators at Colligen Creek and Yarrawonga on the Murray River system of Australia.

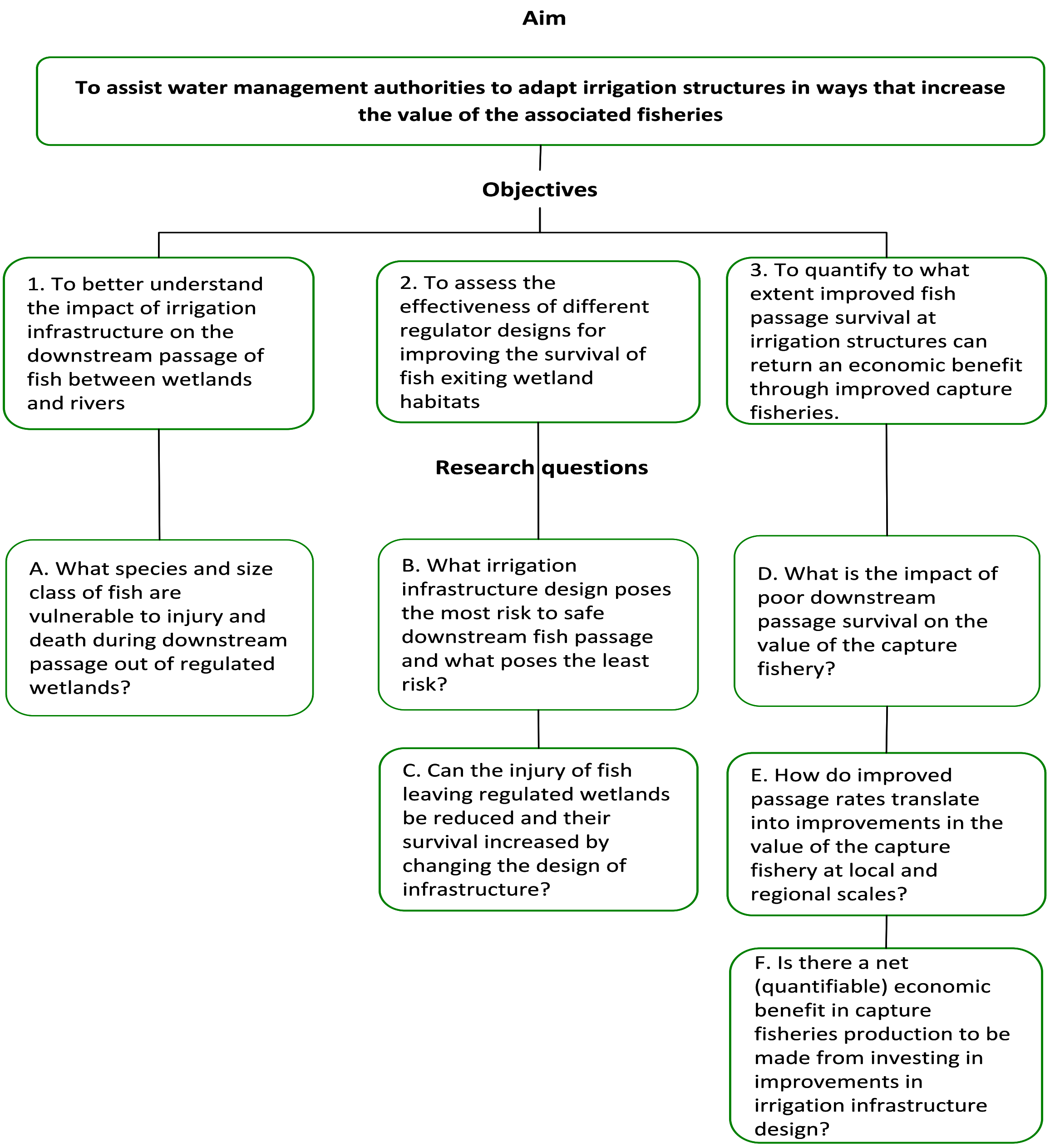


Figure 1. Flow chart showing the rationale behind project FIS2012/100, showing the research questions that were developed to meet the objectives and overall goal of the project.

5.1 What species and size class of fish are vulnerable to injury and death during downstream passage out of regulated wetlands?

To determine whether investing in the refurbishment of ageing water-control structures is warranted, we first needed to understand how many different species and how many individuals of those species are potentially being impacted. To establish this, we conducted the first ever survey of fish passing downstream water-control structure from a floodplain wetland back into the Mekong River. The location selected to do this study was Pak Peung Wetland in the Bolikhamxay Province, central Lao PDR. Pak Peung is already the site of significant ACIAR investment, with a cone fish ladder having been installed there recently as part of FIS/2009/041.

Downstream passage through the water-control structure is theoretically possible whenever the gates are discharging water. However, little is known about what species or life stages move out of the wetland, when or how frequently they do this, or in what numbers. Having an ecological understanding of fish passage needs at the site is essential if the regulators are to be designed and operated in a way that maximises fish passage and survival.

In this component of the project we endeavoured to quantify the temporal variability of downstream fish movement out of Pak Peung Wetland through a water-control structure. That is:

1. What species are moving downstream?
2. What is the typical size and life stage of fish moving?
3. What quantity of fish are moving?
4. When are they moving: day or night and when throughout wet season?
5. What is the general condition of fish caught downstream of the regulator?

5.1.1 Study site and water-control structure operation

The study was conducted at a floodplain regulator adjacent to the Mekong River at Pak Peung Wetland (Bolikhamxay Province) in central Lao PDR (Figure 2). The concrete regulator with three manually-operated ‘undershot’ steel sluice gates (Figure 3) was originally constructed in the 1960s to prevent flooding of floodplain rice crops when the Mekong River rises during the wet season, and to assist in the retention of water during the dry season. The regulator gates discharge water in an undershot fashion, through three 18.5 m long (1.5 x 1.5 m) box culverts which run underneath a road and then down a stepped tailrace before flowing a short distance into the Mekong River (Figure 4). Each gate is capable of delivering a maximum 80 ML day^{-1} (0.93 m^3 s^{-1}).

The typical operation of the gates is as follows, although this can differ from year to year depending on climatic conditions. Early in the wet season (typically between late May and early August), the gates are opened to maintain the wetland at a suitable height to prevent crop damage from localised flooding. During this time the gates are adjusted independently and fish may move downstream (from the wetland to the river) through one or more of the culverts. Once the Mekong has risen sufficiently to start inundating the culverts, the gates are closed to prevent further flooding of the wetland (typically by about August). Under these conditions, the regulator is a barrier to downstream fish movement, although upstream fish passage is still possible through the recently constructed cone fishway adjacent to the regulator (Figure 3). Once the level of the Mekong starts to fall below the culvert invert height (sometime in September-October), the regulator gates are reopened for a second time to allow the wetland level to be maintained a desirable height. After this time the gates are shut to retain water in the wetland for dry season cropping.

a)

b)

Figure 2. a) Pak Peung Wetland showing location of study site (red dashed box) which has been expanded in b) to show the location of the Pak Peung Regulator (yellow circle) relative to the upstream fishway (dashed yellow line).

a)

b)

Figure 3. Pak Peung Regulator a) viewed from the upstream direction showing the three 'undershot sluice gates,' and b) from the downstream direction at the onset of the wet season. In a typical wet season the Mekong River will rise so that the box culverts become submerged.

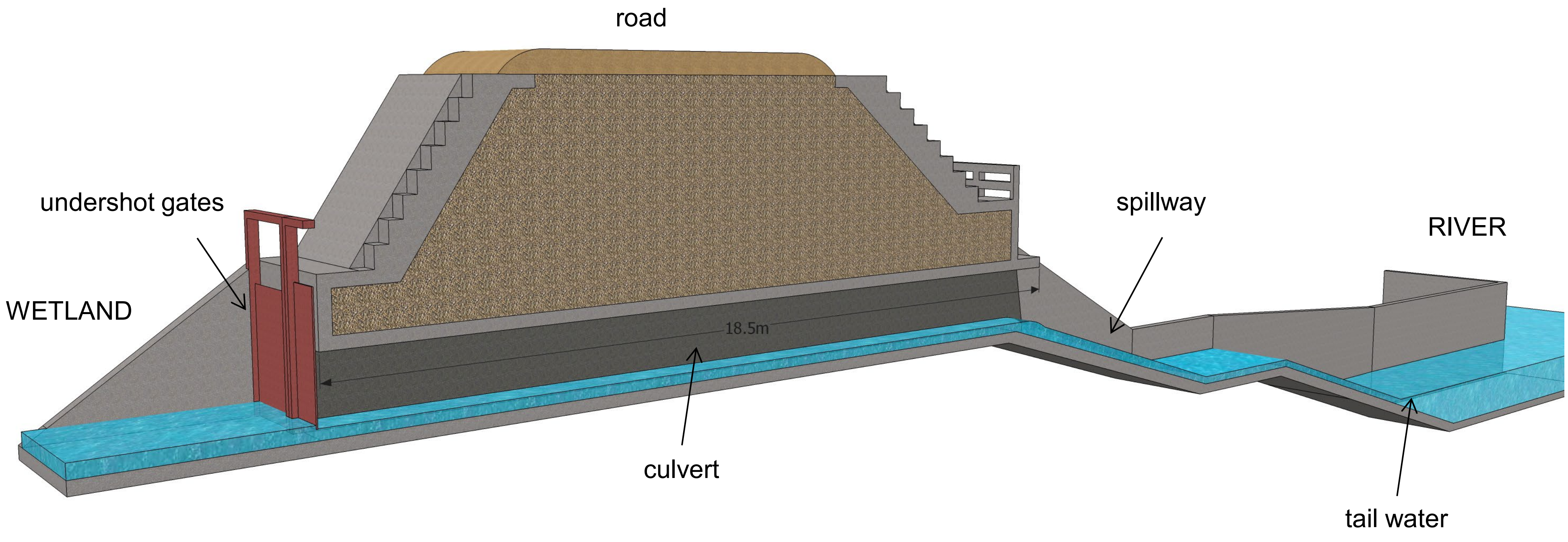


Figure 4. Scale cross-sectional drawing of the Pak Peung Regulator.

5.1.2 Fish trapping

The movement of larval and juvenile fish from the wetland to the main river at the Pak Peung Regulator was assessed using fish traps. Three 2mm fyke nets were placed downstream of each culvert to filter the majority of water release and therefore subsample most (although not all) fish passing the structure (Figure 5). In order to subsample the larval fish also passing the gates, two 500 micron mesh larval drift nets were also set upstream in the wetland, just above the gates (Figure 6). Trapping was conducted continuously while water was being released over the entire 24-hour period with the net being checked at dawn and dusk to differentiate day versus night movements. Fyke and larval nets were used on alternate days in order to keep the catches independent and a complete trapping event therefore consisted of three fyke and three larval net samples over a 48-hour period (Figure 7). Catches were sorted by species, counted, measured and weighed and any injuries or mortalities were noted.

Originally, sampling was planned for the beginning of the wet season (~May) and at the end of the wet season (~October/November) over two consecutive years (2014-2015). However, a lack of rain and therefore wetland releases prevented three of the four sampling events. To overcome this setback, the study was extended over an additional year (2016). But because of the delay, and the need to progress with gate refurbishment, the late wet season sample of 2016 only included a few days (Figure 8). Working within these constraints, the final level of sampling effort achieved over 42 24-hour trapping periods was: 140 larval samples; 174 fyke net samples; 157 day samples; 157 night samples.

Figure 5. Fyke netting downstream of the gates.

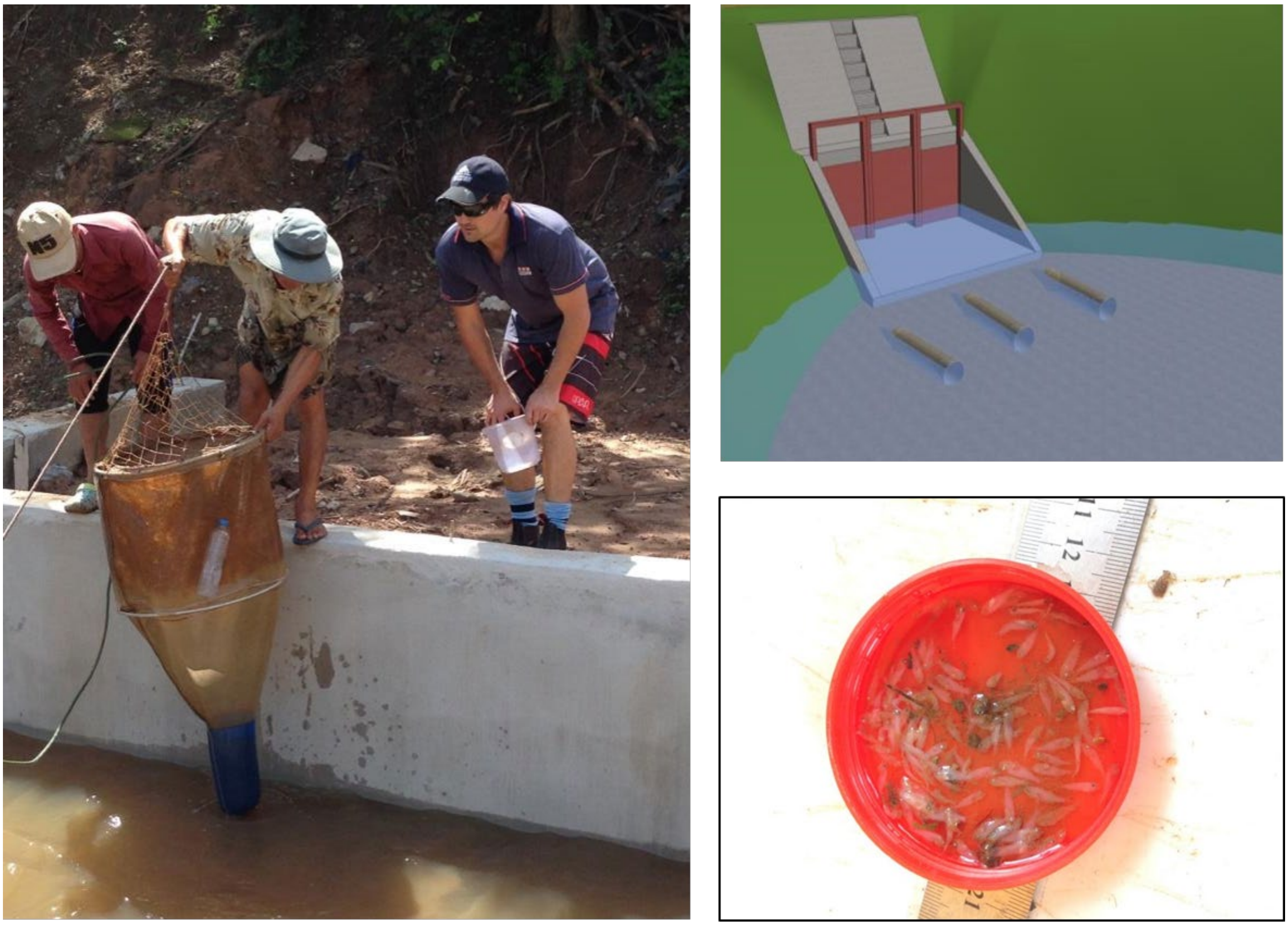


Figure 6. Larval netting upstream of the gates.

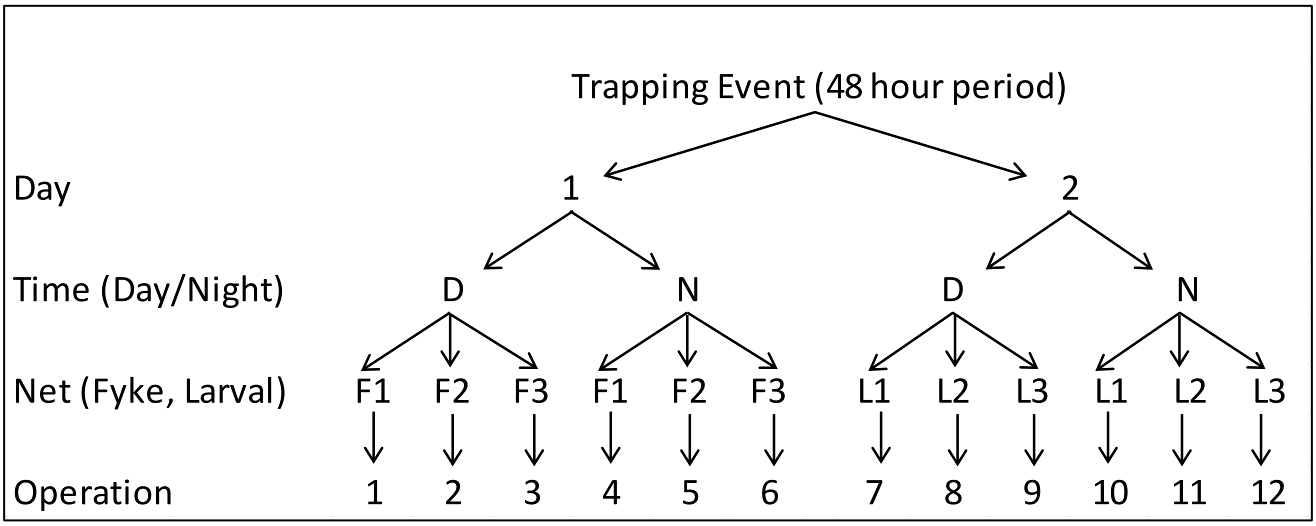


Figure 7. Trapping design of the downstream passage survey.

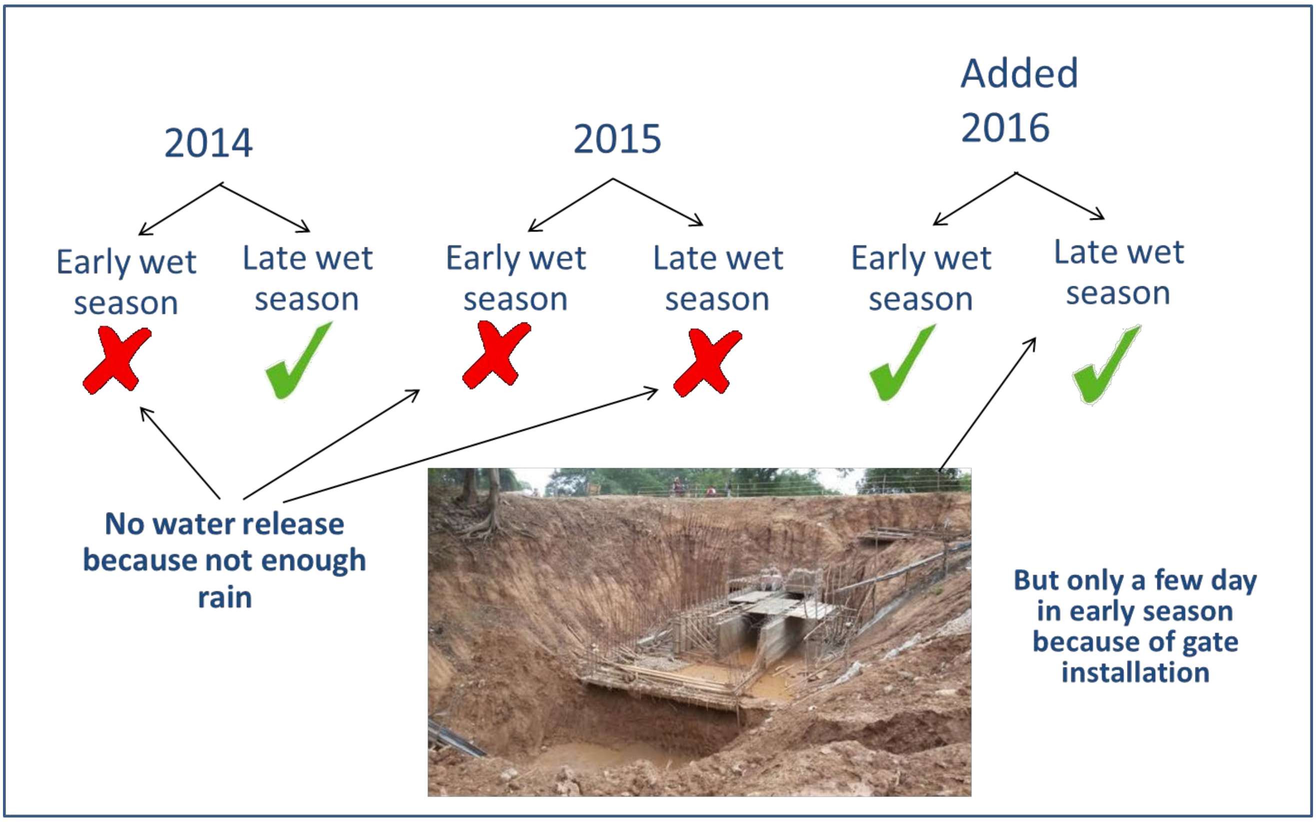


Figure 8. Years and seasons where the surveys could be conducted where constrained by a lack of rainfall and the gate refurbishment schedule.

5.2 What irrigation infrastructure designs pose the most risk to safe downstream fish passage and which pose the least risk?

Private industry was consulted (AWMA Water Control Structures) and a desktop review was conducted to identify the main types of water-control structures typically used in the irrigation industry to regulate flows. While there are a variety of manually or automated gate and weir structures available (including drop-board structures, radial gates, combination leaf gates, layflat gates and undershot sluice gates: Figure 9), generally the technologies can be divided into one of two main types: those that release water underneath a gate and those that release water over the top. Hereafter these will be referred to as undershot and overshot structures (Figure 10).

At low-head (<6 m) water-control structures, it has been shown that overshot weirs can be safer for fish passage than undershot weirs (Marttin and De Graaf 2002, Baumgartner *et al.* 2006, Baumgartner *et al.* 2013). These studies looked at direct mortality of fish captured downstream past structures and generally found considerably higher mortality rates in larval and small-bodied fish passing undershot weirs when compared to overshot weirs. Similar observations were made for some hatchery-bred fish at an experimental structure as part of a previous ACIAR SRA (FIS/2011/072). It is therefore clear that the way structures are designed and operated can have considerable influence on the survival of fish. One thing that isn't clear, however, is what it is about the hydraulics or construction of these structures that lead to differences in fish survival. Without understanding this, it is difficult to provide guidance on whether simple design or operational changes may mitigate the impacts on fish. In this project, we therefore aimed to quantify which differences in hydraulic conditions may be responsible for different survival results of fish passing overshot and undershot structures and to use this information to develop best-practice guidelines for water authorities.

Hydraulic investigations were performed in two parts:

1. In the Murray-Darling Basin - at a low-head undershot and an overshot weir (side by side) with a similar discharge at Colligen Creek Weir. These were compared to a high head (10 m) undershot structure at Yarrawonga Weir on the Murray River.
2. In Lao PDR - at an undershot and an overshot weir (side by side) with a similar discharge that was constructed at Pak Peung Wetland as part of this project.

Figure 9. Different types of water-control structures typically used in the irrigation industry to regulate flow. O = overshot, U = undershot. a) radial (O), b) undershot sluice (U), layflat (O), d) drop-board (O), e) and f) combination leaf gate (O or U). Photos courtesy of AWMA Water Control Structures.

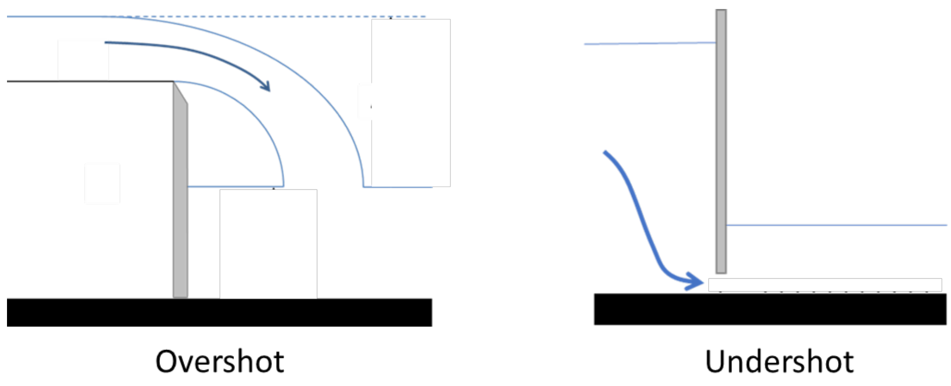


Figure 10. Most water-control structures either release water underneath a gate (undershot) or over a gate (overshot).

5.2.1 Hydraulic evaluation of Murray-Darling structures

The hydraulic conditions experienced by passing fish were quantified at three structures in the MDB: a low-head overshot and undershot (3 m) at the Colligen Creek Weir and a high-head (10 m) undershot at Yarrawonga Weir (Figure 11). This was done using autonomous Sensor Fish (Deng *et al.* 2007, Deng *et al.* 2014: Figure 12). Sensors built into Sensor Fish measure acceleration in three directions (up-down, forward-back, and side-to-side), angular velocity at three angles (pitch, roll and yaw), absolute pressure and temperature at a frequency of 2048 Hz. By releasing these Sensor Fish 1–2 m upstream of a structure, allowing them to pass, retrieving them downstream and downloading the data, the passage route and time can be determined, as can exposure to events such as decompression, collisions, fluid shear and severe turbulence, all of which are known to injure and kill fish. The method of Sensor Fish release, recapture and data analysis is outlined in more detail in Pflugrath et al. (2019), a journal paper arising from this project.

5.2.2 Design, construction and installation of Pak Peung Regulator gate

Based on a desktop evaluation, plus the results emanating from the previous evaluation of the hydraulics at Colligen Creek Weir, it was decided that an overshot layflat gate with downstream plunge pool was the best option for replacing the undershot sluice gates at Pak Peung. The design of the gate was developed by AWMA Water Control Solutions, a firm in Australia with extensive experience in irrigation modernisation programs in the MDB. AWMA staff travelled to Lao PDR to inspect the site and meet with local irrigation authorities and villagers to establish their operational needs (Figure 13). Through this process the local community had direct input into the refurbishment of the regulator and AWMA gained a better appreciation of their requirements. For example, given this was a proof-of-concept trial, the local authorities requested that the old gates remain in place downstream of the new structure to help manage their risk should the new gates not meet their needs (Figure 13). It was also a great opportunity to transfer knowledge from Australia on advanced manufacturing techniques. For example, there was initial local resistance to build the gates out of aluminium, and instead use traditional materials such as steel. Steel is seldom used in Australia for water-control structures as aluminium is much light, can be just as strong (when properly designed) and lasts far longer.

The new layflat gates were manufactured in Australia, flat packed and shipped to Lao PDR, where they were assembled at Pak Peung and installed within a day (Figure 15). Before this, significant civil works were required onsite using local contractors (Figure 14). Most of these civil works related to a road and culvert widening project that was under way on site. It was therefore imperative to coordinate the installation of the new layflat gates closely with the road works. While this created considerable challenges, it did result in great community input and engagement in the project than would otherwise have happened (Figure 16).

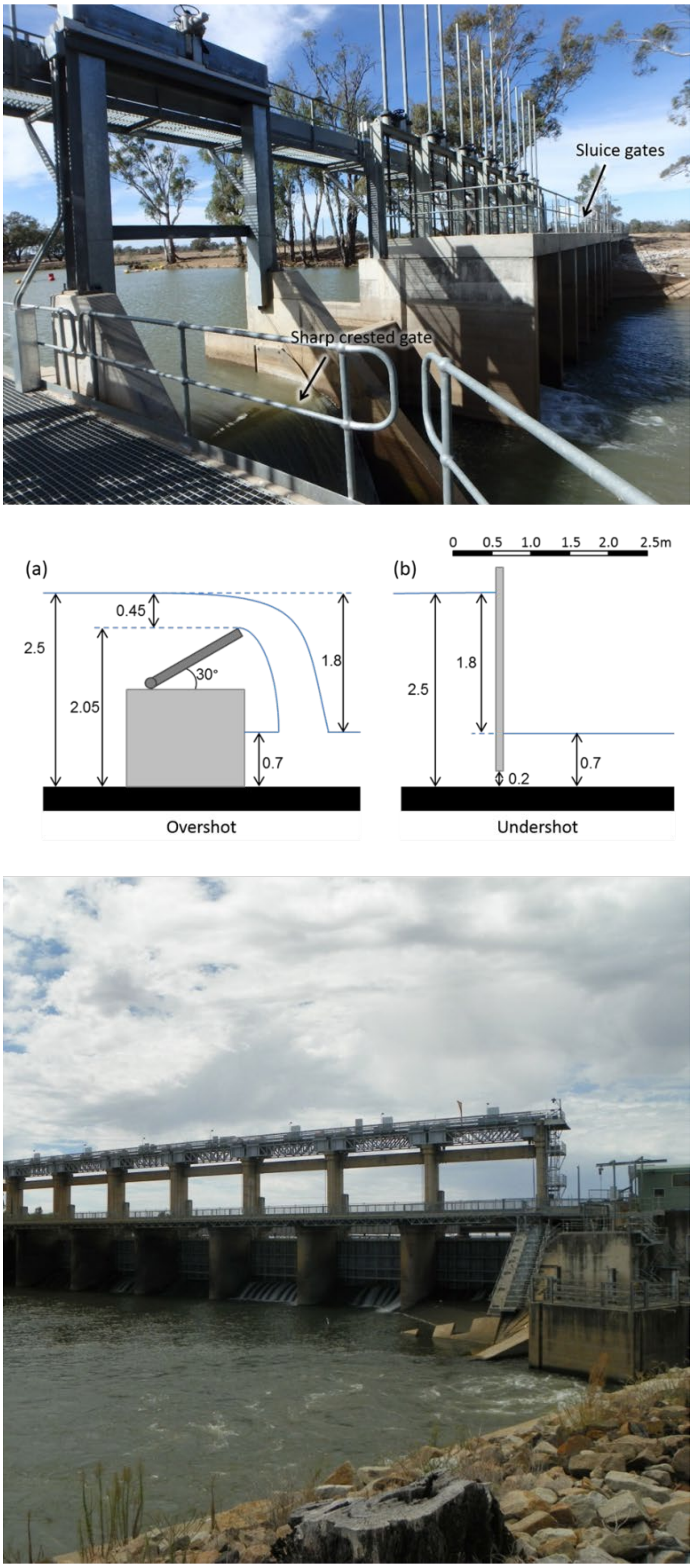


Figure 11. Top – low-head weir (3 m) at Colligen Creek where Sensor Fish was used to quantify hydraulics. The operating conditions are shown for the a) overshot and b) the undershot gate (Source Pflugrath *et al.* 2019). Bottom – Yarrawonga Weir where a high-head (10 m) undershot was investigated.

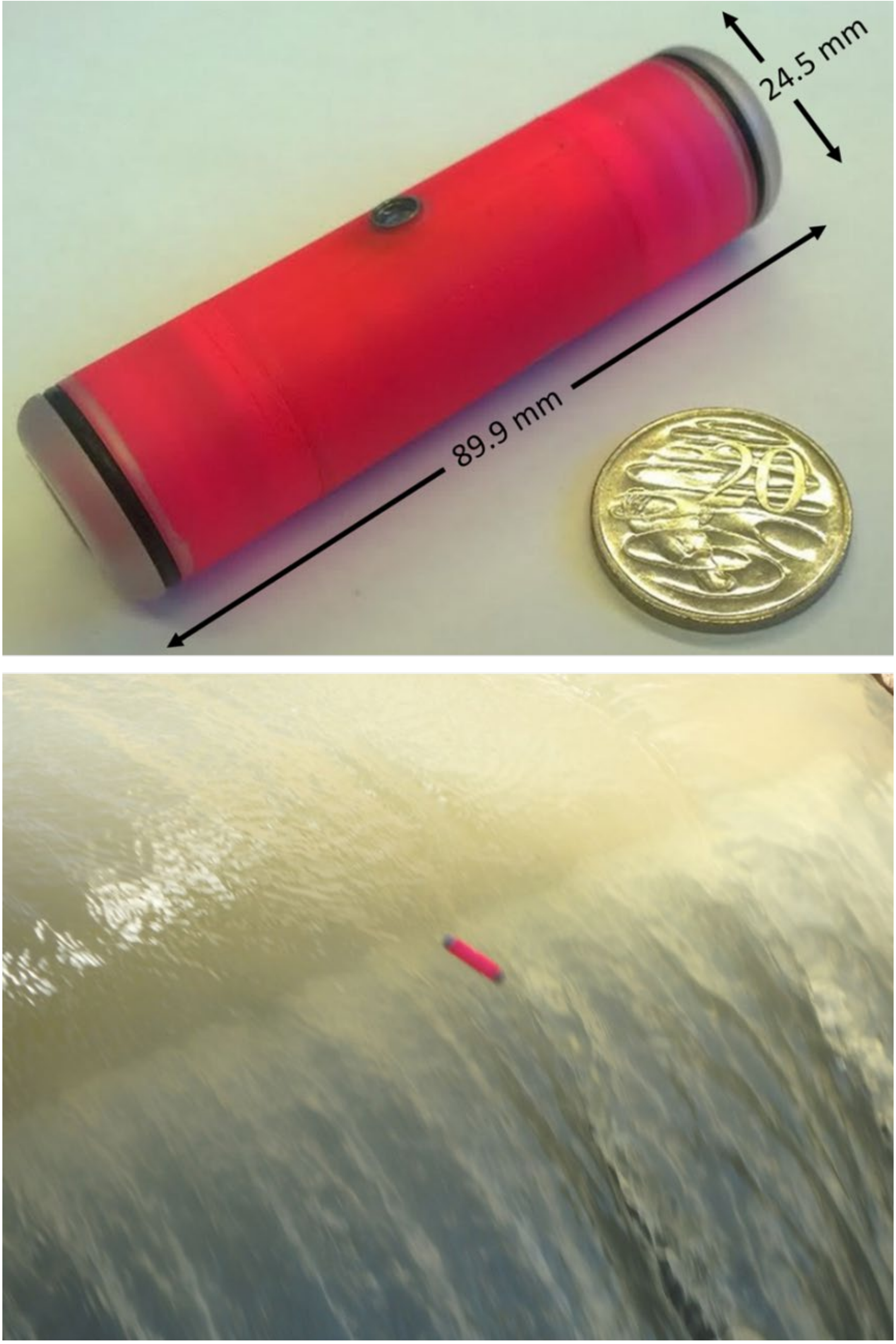


Figure 12. Top: Sensor Fish next to an Australian twenty-cent coin for scale. Sensor package includes a pressure sensor, three-axis accelerometer, three-axis gyroscope, an orientation sensor and a temperature sensor. Bottom: Sensor Fish being deployed at an overshot structure.

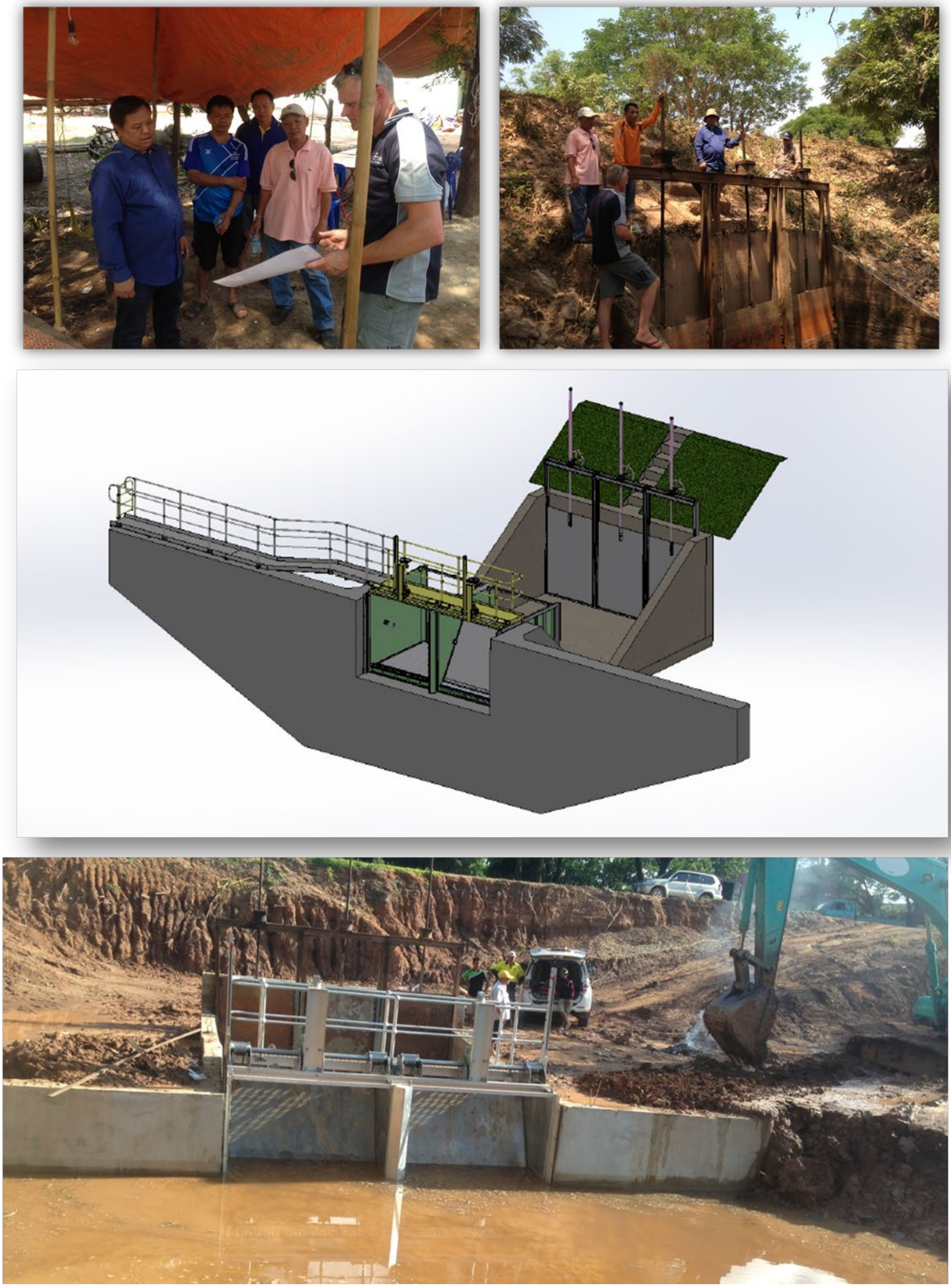


Figure 13. Private industry from Australia worked with ACIAR research partners to design the Pak Peung Regulator refurbishment. Community consultation was important to ensure the operational needs of local authorities would be met and that the villagers accepted the new technology. An important component of the refurbishment requested by the Lao authorities was the retention of the downstream undershot gates (seen in the middle drawing and the background of the bottom picture). Not only did this provide locals with peace of mind (given this was a proof-of-concept in Lao PDR), but it also was of benefit to the project because it would allow the research team to do a direct comparison of overshot and undershot gates at the same structure and would provide a lasting education and demonstration site for years to come.

Figure 14. Civil works were completed at Pak Peung in May 2016 in preparation for the new gates being delivered. The works had to be coordinated with planned road widening and culvert extension works that were under way. An important part of the design was the excavation of a plunge pool into which water from the layflat gates would be discharged (second photo from the bottom).

Figure 15. The experimental gates were installed at Pak Peung in June 2016.

Figure 16. Mr Thonglom Phommavong of National University of Laos (NUOL) (left) was instrumental in coordinating a local Laos crew to assist Mr Phil Berry of AWMA Water Control Solutions (right) install the Pak Peung overshot gates.

5.2.3 Hydraulic evaluation of Pak Peung Regulator gates

Once the new overshot layflat gates were installed at Pak Peung, Sensor Fish were used to compare pressure, shear and collision between the old undershot gates and new overshot gates (Figure 17). Because the undershot gates remained in place downstream of the new overshot gates, it was possible to operate the structure either completely as an undershot, or completely as an overshot, enabling comparisons to be made relatively easy. Details about Sensor Fish, their release and how that data is analysed has been covered in the previous section relating to Colligen Creek Weir and in Pflugrath *et al.* (2019).

Figure 17. Sensor Fish (top) were used to evaluate the hydraulics of the Pak Peung gates. They were deployed upstream of the structure by trained staff (middle) and recaptured after passing the gates using a net (bottom).

Firstly, the overshot gates were completely removed (lowered) and the undershot gates were set at three different slot heights (5 cm, 9 cm and 14 cm) (Figure 18). The undershot gates were then completely removed (raised) and the overshot gates were operated at one of three heights (Figure 19). The heights that the overshot gates were set at was determined in order to match the discharges of the undershot treatments (Table 1). The method used to calculate discharge at the undershot and overshot structures is outlined in Pflugrath *et al.* (2019). Ten Sensor Fish were released at each of the three operating conditions at each of the two weir types (total number of releases = 60). Differential head at the structures at time of testing was 2.4 m.

Table 1. Summary of operating conditions of the overshot and undershot gates during the Sensor Fish Trials.

Overshot (height of water over crest)	Undershot slot height	Discharge
20 cm	5 cm	~0.4 ML/Day
30 cm	9 cm	~0.6 ML/Day
40 cm	14 cm	~0.9 ML/Day

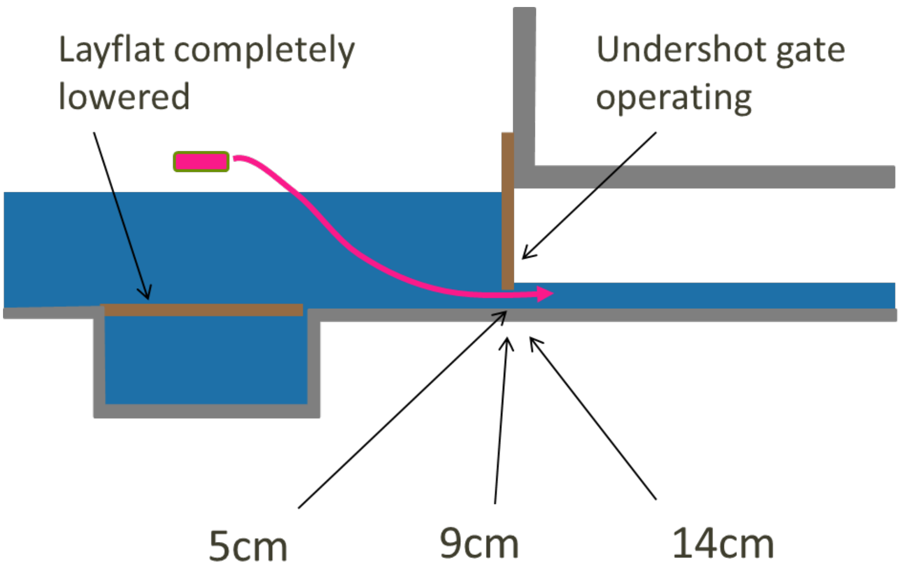


Figure 18. Hydraulics of the undershot gate at Pak Peung was evaluated by completely lowering the layflat gates and operating the undershot gates at one of three slot heights. Ten Sensor Fish releases were performed at each slot height.

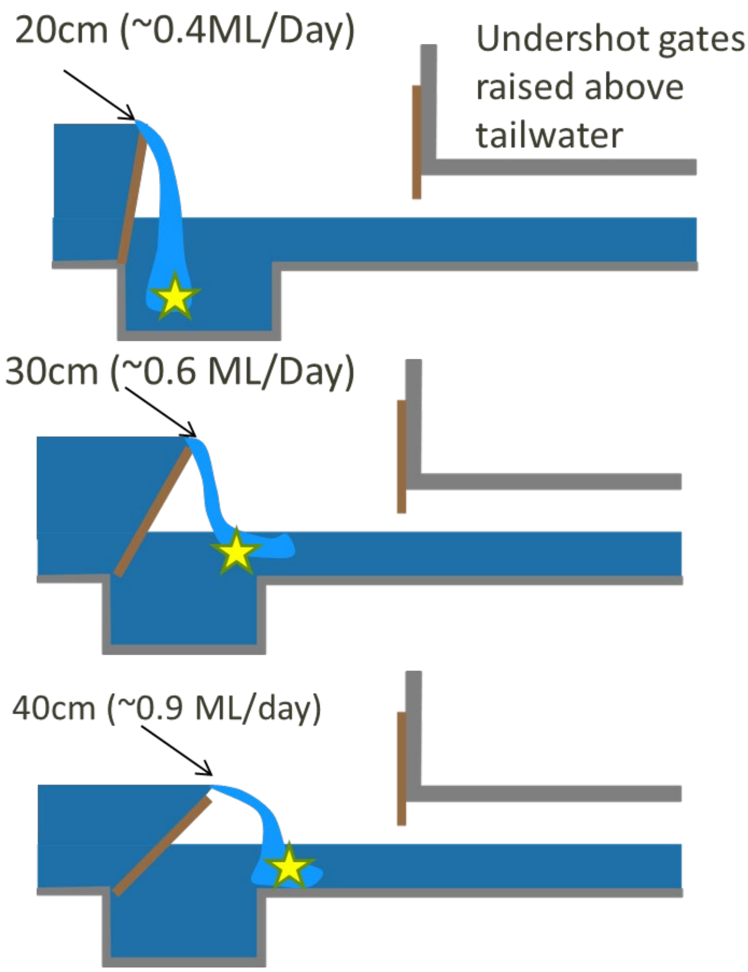


Figure 19. Hydraulics of the overshot gate at Pak Peung was evaluated by completely raising the undershot gates and operating the layflat overshot gates. Three gate heights were tested and were chosen so that they generated comparable discharges to what was evaluated in the undershot treatments. Ten Sensor Fish releases were performed at each slot height.

5.3 Can the injury of fish leaving regulated wetlands be reduced and their survival increased by changing the design of infrastructure?

Once the new overshot gates were installed and their hydraulics quantified, efforts moved onto assessing whether the injury and mortality rates of downstream moving fish had been improved when compared to passage through the old undershot gates.

Previous live fish mortality experiments like this have been done using hatchery-bred fish (e.g. Baumgartner *et al.* 2006, Baumgartner *et al.* 2013 and SRA FIS/2011/072). We therefore planned to use the same approach and ran a short pilot experiment to determine its feasibility. Juveniles of two native species, *Hypsibarbus lagleri* (n = 100) and Pa Duk catfish (n = 87), were obtained from the local markets and released at the structure. Fish were either released upstream of the overshot gate (Figure 20) and recaptured in a net set in the culvert, or they were released downstream of the overshot gate immediately upstream of the net as a control (Figure 21). Recovery of fish was relatively poor for both the overshot (19% recovered) and control (58% recovered). Considerably large numbers of the fish recaptured in the net control were dead or injured, demonstrating that using this approach would make it impossible to determine if fish were damaged due to weir passage or damaged due to net handling. Based on the poor recapture rate and net damage, we proposed a change in the experimental approach and had this change endorsed at the final project review meeting as part of a no-cost 12-month extension.

Figure 20. Lao researchers release fish upstream of the overshot gates for a pilot study to determine feasibility of release and recapture of live hatchery-bred fish.

Figure 21. Lao researcher release fish upstream of a net installed into the culvert section of the wetland's regulator. This was a control to determine feasibility of live fish release and recapture.

The revised plan for comparing the injury and mortality of fish at the overshot and undershot gates at Pak Peung involved relying on recapturing fish that were volitionally migrating downstream from the wetland, rather than using hatchery-bred fish. The trapping method was also changed. Instead of using fyke nets in the culvert or spillway (which had proven to cause considerable damage to fish), Lee traps were constructed in the spillway (Figure 22). Lee traps are a traditional way of trapping migrating fish in the LMB. They involve river flows spilling through an elongated perforated screen. As water travels along the screen, more of it falls through the mesh and therefore energy dissipates. Fish slide along the screen and out of the flow, where they can then be retrieved by hand. This approach was pilot-tested and confirmed that considerably less damage was occurring to fish. It was then implemented as part of the full trial in June 2019.

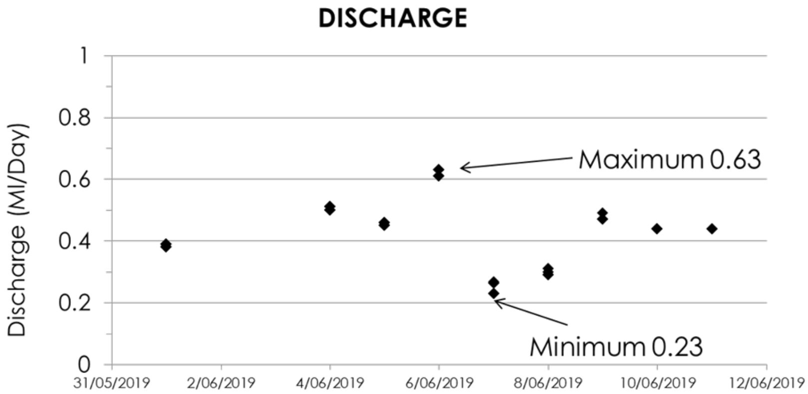
In June 2019 (early wet season) the Lee trap surveys were run. Both the overshot gates were trapped simultaneously, as were two of the three undershot gates. Trapping two gates simultaneously was critical in order to achieve enough replication while minimising the time required to run the experiments. As the experiments were being run in the early wet season, it was imperative that we did not compromise the water management plan of the Pak Peung Village. While we are experimenting on the structure, less water is being released than would otherwise be planned. Therefore, the longer the experiments run, the greater the risk that not enough water is released before the Mekong rises and the wetland regulator needs to be closed. Ultimately, this places the village in an unacceptable risk of their rice crops being flooded later in the wet season.

In order to trap two gates simultaneously, the left and right gates were kept independent by closing the middle-undershot gate and constructing a sandbag wall down the centreline to separate the gates (Figure 23). It was initially planned to totally randomise which configuration (overshot or undershot) was tested between the left and right gate at any particularly time. However, the head differential created when one gate was operated as undershot and the other as overshot caused the sandbag wall to collapse a number of times. It was therefore only possible to run both gates as either overshot or undershot at any given time. The wetland height was rising daily, effecting the discharge that could be achieved for a given gate configuration. This was not a problem because we ensured that in any given day the discharge was matched between a pair of overshot and undershot treatments, allowing it to vary throughout the experiment. The discharge for each day of trapping is shown in Figure 24, as is the differential heads and undershot slot heights. It can be seen from Figure 24 that, although the slot heights studied were relatively comparable to the earlier Sensor Fish evaluations, the head at the gates and therefore discharges examined during the mortality trials were considerably less than were experienced during the previous Sensor Fish trails. The consequences of this are discussed in further detail in the results section.

The experiments began on the 1st June 2019 and had to be ceased on the 11th June, once the Mekong had risen sufficiently to approach the bottom of the Lee traps, and the wetland had risen sufficiently to start overtopping the sandbag wall. Throughout this time, some days were lost to the Buddha day public holiday and sandbag wall collapse. In the end, nine trapping days were completed. Each trapping replicate was run for 2 hours so that multiple replicates could be run per day and to ensure fish did not stay in the bucket for too long before being sorted, counted, weighed and inspected for injury. Due to some replicates being cancelled throughout the study, the final dataset included 21 undershot replicates and 15 overshot replicates.

Figure 22. Lee traps were constructed in the Pak Peung spillway to capture fish that had passed the undershot or overshot gates. The Lee traps resulted in considerably less damage to fish than the original approach of using fyke nets. As water flows along the Lee trap it falls through the mesh, reducing the energy of flow and allowing every single fish to be captured. To further reduce the chances of net damage, the traps were constantly manned and fish removed and put in a bucket of water as soon as they were captured.

Figure 23. A sandbag wall was installed to separate the left and right gates, thus enabling two gates to be independently trapped at a time.



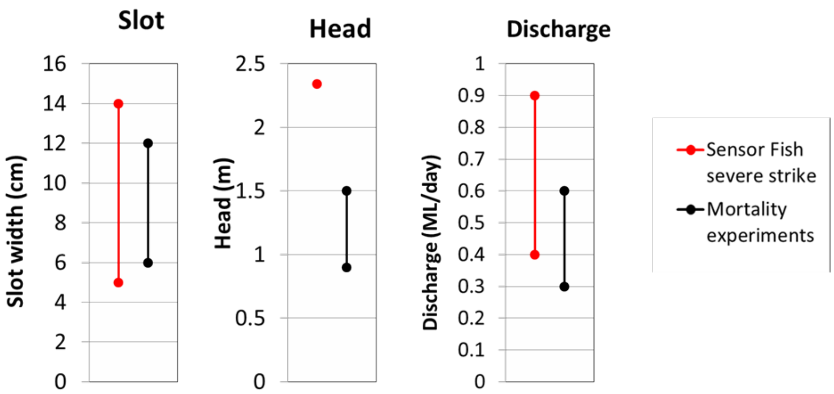


Figure 24. Discharges evaluated during the mortality trial (top) and comparison of the undershot slot height, differential head on the gate, and discharge experienced between the mortality experiment and the hydraulic evaluations with Sensor Fish (bottom).

5.4 What is the impact of poor downstream passage survival on the value of the capture fishery? How do improved passage rates translate into improvements in the value of the capture fishery at local and regional scales? Is there a net (quantifiable) economic benefit in capture fisheries production from investing in improvements in irrigation infrastructure design?

The three research questions above are all subcomponents of a larger economic analysis that planned to determine how the cost of investing in fish passage remediation at low-head irrigation structures can translate into economic returns through improvements in the capture fishery. To answer these questions, the project team worked with Dr Bethany Cooper and Lin Crase from University of South Australia who were developing a cost–benefit analysis for a related project FIS/2014/041. The resultant Lower Mekong Fishway Support Tool that was produced (LMFST: Cooper *et al.* 2019) allows decision makers to consider the cost of fish passage works against the likely economic and nutritional benefit accruing from improved upstream and downstream fish passage. The LMFST was developed using the Pak Peung fishway and regulator gate upgrade as a worked example.

The LMFST recognises that if a regulator gate needs to be upgraded to facilitate return downstream passage (as at Pak Peung), this will come at a cost, but also has the potential to return additional fish field through lower mortality of fish from the wetland (Figure 25). Therefore, to populate the model, the economists required the current project to provide costs associated with gate construction and installation and data relating to the improved survival of fish due to moving from an undershot to an overshot structure. Costs were to be determined using Pak Peung as an example, but also through consultation with AWMA Water Control Structures. Survival data was to come directly from the live fish mortality experiments undertaken at the Pak Peung Regulator gates.

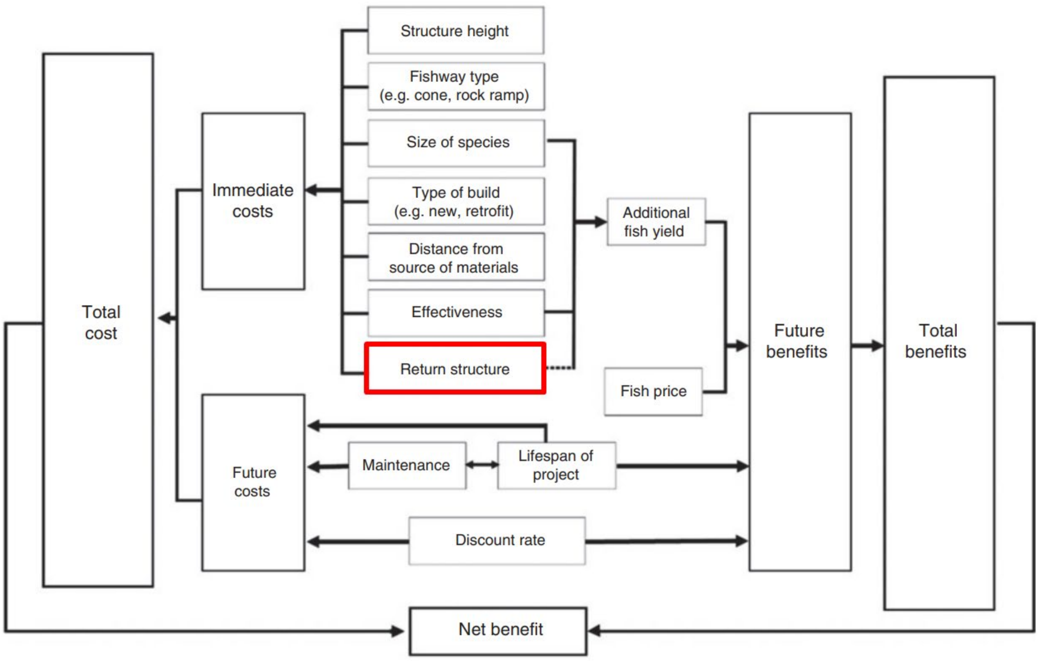


Figure 25. The conceptual framework of the Lower Mekong Fishway Support Tool (LMFST) shows the primary drivers of the costs and benefits of fish passage remediation at low-head irrigation structures and was developed through expert elicitation (source: Cooper *et al.* 2019). The red box highlights how addressing downstream passage at a regulator has implications for both the cost and benefit and therefore overall return on investment.

6 Achievements against activities and outputs/milestones

Objective 1: To better understand the impact of irrigation infrastructure on the downstream passage of fish between wetlands and rivers

no.	activity	outputs/ milestones	completion date	comments
1.1	Project inception meeting, identifying staffing and roles, workshopping experimental designs to quantify fish mortality	Workplan and methods document (PC)	Completed November 2014	An inception meeting was held with the project partners in Pak San and Vientiane in June 2014 to develop workplans, and clarify budgets. A methods paper was produced to guide the first phase of downstream fish sampling. A public project inception meeting was held on November 28 in the Pak San district with 45 delegates present from local and central Lao PDR government and irrigation agencies. The project team received support and feedback on the proposed project activities.
1.2	Pilot trial to evaluate experimental design and netting techniques to be used at regulator	Workplan and methods document (PC)	Completed June 2014	A variety of nets were tested at the Pak Peung Regulator and this was used to determine suitable trapping techniques. A full set of fyke and larval nets were designed, made in Australia and shipped to Lao PDR. A methods paper was produced to guide the downstream fish sampling.
1.3	Field sampling of fish migrating downstream through Pak Peung regulator when draining	Dataset of fish moving through Pak Peung regulator generated (PC)	Completed September 2014-October 2016	Trapping of downstream fish passing the Pak Peung Regulator began late in the wet season of 2014. A dry year meant that no water was released from Pak Peung in 2015 and no sampling was done. Sampling resumed once water began being released again in June 2016, but was ceased after a week to enable the new gates to be installed. Sampling resumed September 2016 and was completed in October. In total, 140 larval and 174 fyke net samples were collected over 42 trapping days. 157 of these samples were carried out during the day, and 157 at night. 18,434 individuals encompassing 114 species were trapped leaving the wetland.

PC = partner country, A = Australia

Objective 2: To design and assess the effectiveness of a fish-friendly regulator for improving the survival of fish exiting wetland habitats

no.	activity	outputs/ milestones	completion date	comments
2.1	Desktop review of different gate designs to scope options for testing	Shortlist of regulator gate designs produced (A)	Completed December 2014	Review complete. Three technologies identified to enable overshot release of water (layflat, leaf gate and stop board). Options presented to district officers in May 2015 (see 2.3) and based on cost and ease of operation the layflat design was selected as best solution for safe fish passage and wetland regulation at the Pak Peung site.
2.2	Procure Sensor Fish and identify hydraulic characteristics of different infrastructure designs in NSW and Lao	Sensor Fish data collected and used to produce summary statistics for various infrastructure designs (A, PC)	NSW study completed March 2015 Lao PDR study completed November 2018	Sensor Fish were procured in December 2014 and surveys of a number of weir and hydro facilities in NSW were completed in March 2015. Analysis of data confirmed overshot gates had more benign hydraulics for the protection of fish when compared to undershot sluice gates, radial undershot gates and horizontal and low-head vertical Kaplan turbines. Sensor Fish trials were also carried out at Pak Peung in November 2018. The results confirmed findings of the NSW trials that the hydraulic conditions of overshot structures were more suitable for safer fish passage than undershot structures.
2.3	Construction of regulator gates and install in dry season	Experimental gates built upstream of Pak Peung Regulator (PC)	Completed June 2016	In May 2015 Brett Kelly (AWMA) met with District Irrigation officers in Pak Peung to discuss and seek approval of the proposed gate design, materials and construction/installation process. In May 2016 National University of Laos (NUOL) coordinated civil works with local road contractors at Pak Peung to extend the culvert and build the concrete structure into which the new gates could be installed. The gates were designed and built in Australia by AWMA Water Control Solutions, shipped to Lao PDR (arriving on site June 16) and installed at Pak Peung on the 22nd of June.

no.	activity	outputs/ milestones	completion date	comments
2.4	Data analysis and presentation of results and experimental regulator at regional fish passage workshop	Regional workshop completed (PC)	Completed November 2016	This activity was delayed a number of months due to the ASEAN conference in Vientiane. In November 2016 the Lower Mekong Basin Fish Passage conference was held in Vientiane. It presented work not only from this project but showcased the complete ACIAR Fish Passage program in Lao PDR. It was hugely successful with over 160 delegates participating, including high level officials and regional policy makers, developers, researchers, local provincial and district leaders and natural resource managers. 14 countries were represented and experts from around the world shared their experiences across 25 years of fish passage research. With specific reference to the scientific outcomes of this project, Craig Boys presented a talk on developing sustainable irrigation infrastructure to protect inland fisheries, Brett Pflugrath presented a talk relating the Sensor Fish deployments at Australian infrastructure, Oudom Phoekhampeng presented about the construction of the layflat gates at Pak Peung, Brett Kelly presented on the need to incorporate fish-friendly design into irrigation gate construction, and Khampheng Homesomebath presented the results of pilot trials of fish mortality at weirs undertaken as part of a previous ACIAR SRA. As part of the conference, delegates were taken on a field trip to Pak Peung to see the facilities first-hand.
2.5	Live fish mortality trials at experimental regulator gates at Pak Peung Regulator	Completion of four experiments on four separate occasions generating dataset of numbers of fish surviving, injured and dead after passage through different designs (PC) December 2017	This original activity could not be completed but instead was replaced by activity 2.5.1 and 2.5.2 as part of a project variation	In June 2017 a pilot study was conducted to determine the feasibility of releasing and recapturing hatchery-bred fish at the Pak Peung for mortality trials. Two species: *Hypsibarbus laleri* (n = 100) and Pa Duk catfish (n = 87) were released upstream of the Pak Peung gates. Recapture rates were extremely low (19% for *H. laleri* and 58% for the catfish) and handling controls showed net damage using fyke nets would be difficult to control. The pilot study demonstrated that it is not feasible to release and recapture fish within the regulator. These difficulties were discussed at the final project review meeting and an alternative approach of sampling actively migrating fish with the use of Lee traps was agreed to. This was included as additional activities 2.5.1 and 2.5.2 as a contract variation that involved a 12 month no-cost extension.

no.	activity	outputs/ milestones	completion date	comments
2.5.1	Pilot trials of Lee Trap at Pak Peung Regulator	Completion of 2 weeks of experiments testing effectiveness of Lee trap for capturing downstream migrants	October 2018	A test Lee trap was set up and tested. When regularly monitored so that fish can be removed quickly, the Lee trap resulted in very little net damage to fish. It was therefore confirmed as the method for catching fish in 2.5.2.
2.5.2	Downstream mortality trials at Pak Peung Regulator	Completion of 4 weeks of experiments quantifying passage and injury/mortality of fish moving past the overshot and undershot structure (PC)	Completed May 2019	These experiments were run in close discussion with district officers as we could not interfere with releases for too long and therefore compromise the management of the wetland. We completed 36 trapping ours over 9 days, catching a total of 839 fish comprising 59 different species. Unfortunately, we were only able to sample when there was a small-head difference at the structure.
2.6	Calculate relative survival rates and biomass impacts over all affected species	Estimates produced of survival rates under different designs (A)	Completed August 2019	The results of this analysis were presented at the final workshop meeting in Pak San in September 2019. Unfortunately, because data was only obtained when the regulator was operating at very low head, the results do not reflect what we would expect over larger head operations (as demonstrated with the Sensor Fish).

PC = partner country, A = Australia

Objective 3: To quantify to what extent improved fish passage survival at irrigation structures can return an economic benefit through improved capture fisheries

no.	activity	outputs/ milestones	completion date	comments
3.1	Undertake cost–benefit analysis of Pak Peung Regulator upgrade and use barrier mapping data (from associated project) to model over larger regional scale	Paper outlining results of economic analysis (A, PC)	Not achieved	We were able to provide University South Australia economists with costings of gate refurbishment that have now been incorporated into published fish passage cost–benefit models for the LMB as part of project FIS-2014-041 – Quantifying biophysical and community impacts of improved fish passage in Lao PDR. That is, developers can factor in the cost of both upstream and downstream fish passage works into projects. However, we were unsuccessful in quantifying benefits to fisheries as part of this model. To do this we were relying on quantifying mortality differences between the old and new gates. Because injury and mortality data were only obtained when the regulator was operating at very low head, little injury and mortality was observed and we consider the results do not reflect what we would expect over larger head operations. To model these benefits properly it would be prudent to run more mortality experiments over the complete operational range of the gates.

no.	activity	outputs/ milestones	completion date	comments
3.2	Analyse and present data at final project workshop	Final workshop held at Pak Xan (PC)	Not achieved	For the above-mentioned reasons we were unable to conduct this analysis. At the final project workshop in Pak San on the 18th of September, options were discussed for future research that could enable this objective to be achieved.
3.3	Produce guidelines for effective regulator construction in papers, report and nontechnical form	Paper on biological performance of different regulator designs (A, PC)	To be published early 2020	On the 18th September 2019 the project team met with met with various Lao PDR government, university and community representatives (see Appendix 1) to present draft guidelines and seek feedback. Based on this advice the guidelines are being summarised into nontechnical brochures which are currently in production and due for publication early 2020.

PC = partner country, A = Australia

7 Key results and discussion

7.1 What species and size class of fish are vulnerable to injury and death during downstream passage out of regulated wetlands?

Over 42 trapping days 18,434 fish encompassing 114 species were captured moving downstream through the Pak Peung Regulator gates. The vast majority of fish captured (approximately 80%) were from three families: Cyprinidae, Ambassidae and Siluridae (

Table 2). Passage rates varied through time. On average 23 fish per hour were moving downstream, however, at times this was as high as 169 fish per hour (Figure 26). On average, there was no difference between passage rates between night and day (Figure 27). The trapping method we used captured very few larval fish, however, most of the fish captured could be classed as small juveniles or small-bodied adults. Sixty per cent of all fish captured were between 30 and 70 mm in length (Figure 28). The majority of fish recovered from the nets were either dead or in poor condition, however, we expect that much of this may be to damage suffered while in the net. Therefore, the injury and mortality data has not been presented.

The number of species that were captured moving downstream is not much less than the 170 species that have been recorded moving upstream through the adjacent cone fishway into the wetland as part of project FIS/2014/041. Considering that the fishway trapping has been going for many more years than the downstream trapping, it would be expected to see very similar numbers of species seeking return passage to the Mekong when compared to those moving upstream into the wetland. This is supported by our observation that the vast majority of species and individuals trapped passing the regulator can be classed as belonging to the ‘grey fish’ guild (Figure 29). That is, they are generally known to undertake short migrations between floodplains and the main channel. What this demonstrates is, that while wetlands like Pak Peung provide important breeding, nursery and foraging habitat for many species, the ecology of many of these species means that they seek return passage to Mekong to replenish river populations and to extend their range to other adjacent wetlands. It is a generally accepted principle in river ecology that fish movements like this are extremely important to ensuring gene flow and maintaining access to a variety of necessary habitats.

It is clear from these results that lateral movements from wetlands to the main channel involve a significant number of fish and different species. From a fish passage remediation perspective, it demonstrates that restoring upstream fish passage alone past a wetland water-control structures will be insufficient to protect the fishery if safe return passage is not also provided. Most of the fish captured undertaking downstream passage were small bodied, a size class that has been shown to be particularly vulnerable to injury and death when passing water-control structures (Marttin and De Graaf 2002, Baumgartner *et al.* 2013). This emphasises the need to ensure structures are designed and operated in a way that promote greatest fish survival. Additionally, our results show the need to consider the passage of a diverse range of species, not just one or two. From the perspective of quantifying the economic and environmental benefits that can come from ensuring safe downstream fish passage, due to the large number of fish passing regulators, and the substantial number of these regulators throughout the LMB, it may be expected that even small improvements in fish survival through improved regulator design and operation could result in considerable benefits across the LMB.

Table 2. Catch summary of the fish trapped moving downstream through the Pak Peung Regulator, categorised by family (2014 and 2016).

Number of species

Family	No of species
Cyprinidae	51
Siluridae	9
Bagridae	7
Cobitidae	7
Channidae	4
Mastacambelidae	4
Tetraodontidae	4
Osphronemidae	3
Clariidae	2
Nandidae	2
Notopteridae	2
Pangasiidae	2
Ambassidae	1
Anabantidae	1
Balitoridae	1
Belonidae	1
Cichlidae	1
Clupeidae	1
Eleotridae	1
Gobiidae	1
Schilbeidae	1
Soleidae	1
Synbranchidae	1

Number of individuals

Family	No of fish	%
Cyprinidae	6864	37
Ambassidae	6073	33
Siluridae	1938	11
Belonidae	758	4
Nandidae	689	4
Bagridae	509	3
Notopteridae	377	2
Pangasiidae	326	2
Cobitidae	191	1
Clupeidae	126	1
Osphronemidae	125	1
Clariidae	108	1
Channidae	73	<1
Mastacambelidae	73	<1
Eleotridae	51	<1
Tetraodontidae	21	<1
Anabantidae	17	<1
Balitoridae	15	<1
Cichlidae	13	<1
Synbranchidae	4	<1
Schilbeidae	3	<1
Soleidae	2	<1
Gobiidae	1	<1

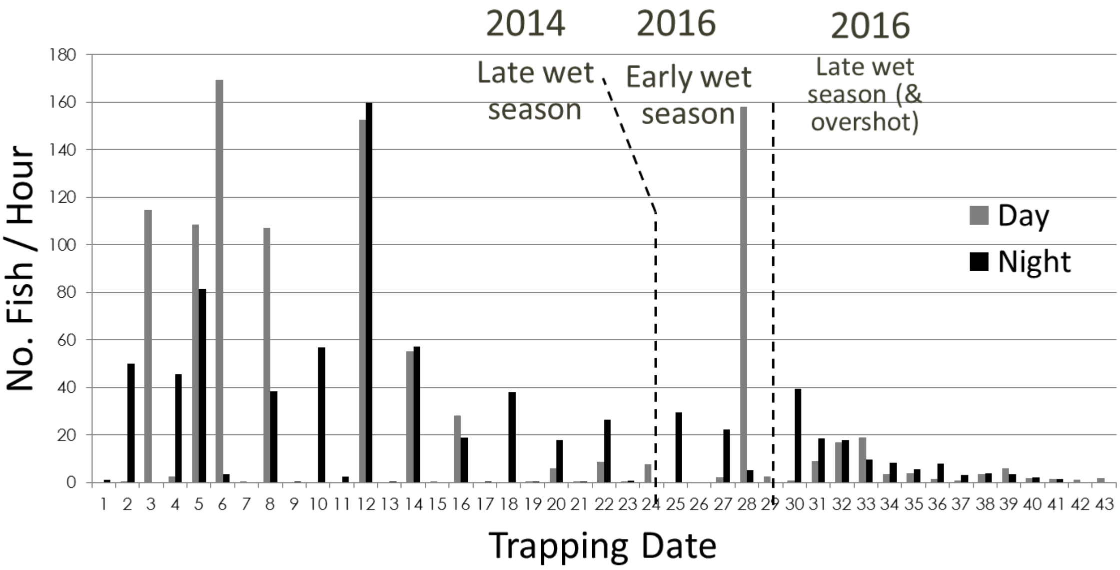


Figure 26. Downstream fish passage rates measured at Pak Peung Regulator.

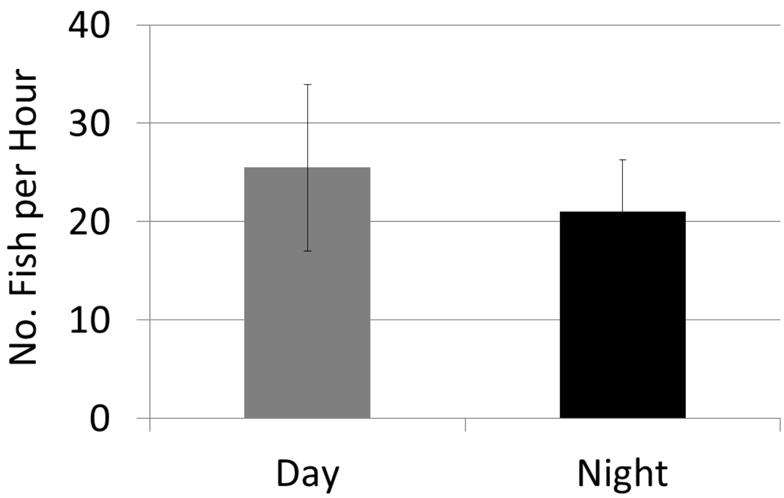


Figure 27. Average downstream passage rates at Pak Peung Regulator split between day and night.

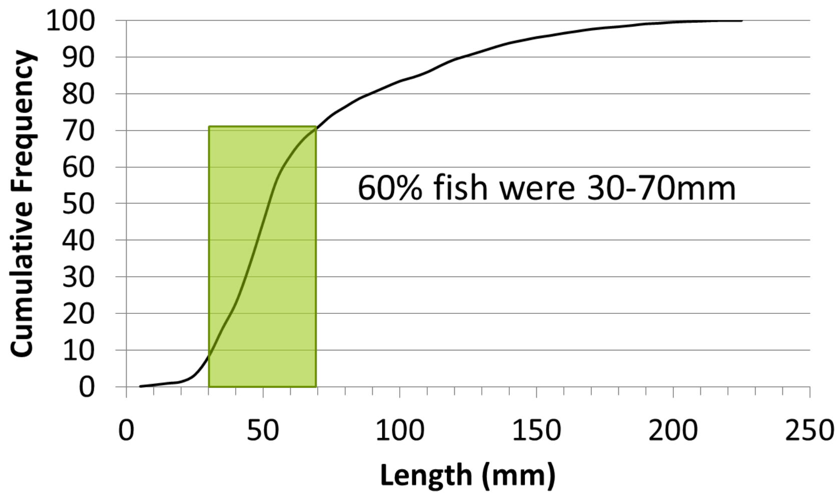


Figure 28. Size-class cumulative frequency curve for all fish trapped passing downstream through the Pak Peung Regulator.

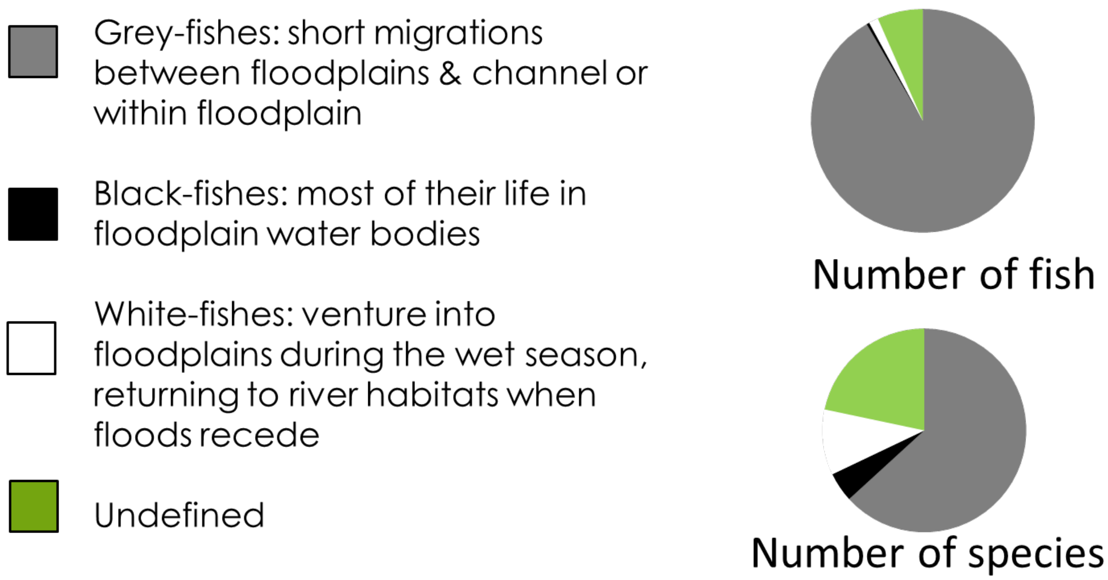


Figure 29. Proportion of all fish captured migrating downstream through Pak Peung Regulator categorised according to their ecological guild.

7.2 What irrigation infrastructure designs pose the most risk to safe downstream fish passage and which pose the least risk?

In this section the key findings of both the Australian and Lao PDR Sensor Fish work are combined and presented to give an overview of how different design and operation conditions of water-control structures can affect the main stressors for downstream migrating fish: pressure, shear and strike. Many of the findings relating to the MDB work are presented in more detail in Pflugrath (2017) and Pflugrath *et al.* (2019). This research has been used to develop nontechnical design and operation guidelines for water-control structures (see Appendix).

7.2.1 Pressure

Rapid decompression can result in barotrauma injuries like swim bladder rupture, emphysema in tissues and organs, haemorrhage and exophthalmia (Boys *et al.* 2016a, Boys *et al.* 2016b). The extent to which injury is likely depends on the ratio between the pressure at which fish are acclimated at prior to passage and the lowest (nadir) pressure they are exposed to during passage (Brown *et al.* 2014). It is therefore important to examine the pressure profile fish are exposed to in order to determine the likelihood that fish will be injured as they pass a structure. From the pressure profiles obtained from the undershot and overshot low-head (3 m) weirs at Colligen Creek and Pak Peung, as well a higher-head (10 m) undershot structure at Yarrawonga Weir characteristic pressure profiles were generated for overshot and undershot structures (Figure 30).

The pressure profile experienced by a fish is very different between an undershot and overshot structure. For an undershot sluice gate pressure increases as the fish dives and is entrained at the bottom of the gate. The pressure exerted here will be greater for higher-head structures. The fish is then exposed to rapid decompression over a fraction of a second as it passes underneath the gate. At this stage the pressure can become slightly negative (below atmospheric pressure of ~100 kPa) due to the Bernoulli Effect caused by the rapid acceleration of water. Slow pressurisation occurs as the fish enters the tailwater, with the pressure experienced depending on whether the fish remains at the surface or is plunged deeper into a pool. In comparison, when a fish passes an overshot structure it is not exposed to the rapid acceleration and rapid decompression as it passes the gate because it is travelling from surface pressure over the gate crest into the downstream tailwater where it will experience slow pressurisation as it dives deeper.

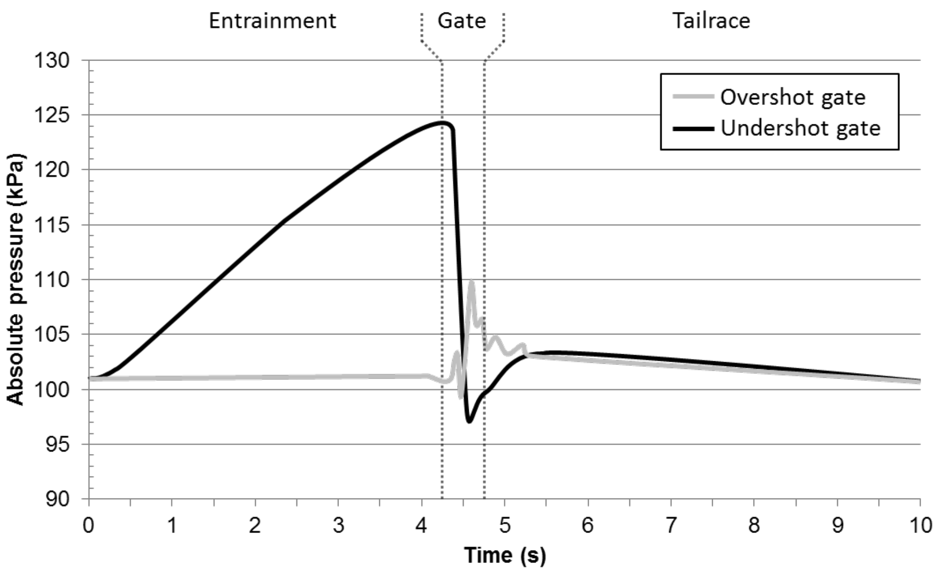


Figure 30. Generalised pressure profiles experienced by fish passing overshot and undershot structures were developed using Sensor Fish data from Colligen Creek, Pak Peung and Yarrawonga weirs (Pflugrath *et al.* 2019).

From the pressure data collected by Sensor Fish it can be inferred that decompression at low-head structures like Colligen Creek and Pak Peung (overshot or undershot) will not be of a magnitude likely to cause injuries to fish. However, the likelihood of experiencing more severe levels of decompression at undershot gates does increase at higher-head structures (>6m). For example, if a fish acclimated to the bottom of the weir pool before it passes Yarrawonga undershot gate (10 m head) could be exposed to up to a 38% decrease in pressure (Figure 31). Based on laboratory studies on susceptibility of fish to barotrauma, that magnitude of decompression may result in swim bladder rupture in 25% of Silver perch (*Bidyanus bidyanus*) (Boys *et al.* 2016a). For context, the severity of decompression that a fish may be exposed to at a high-head undershot structure is still considerably less that what may be experience when passing through a hydropower turbine (Figure 31). This is because those turbines can create significantly negative nadir pressures (Pflugrath 2017, Boys *et al.* 2018).

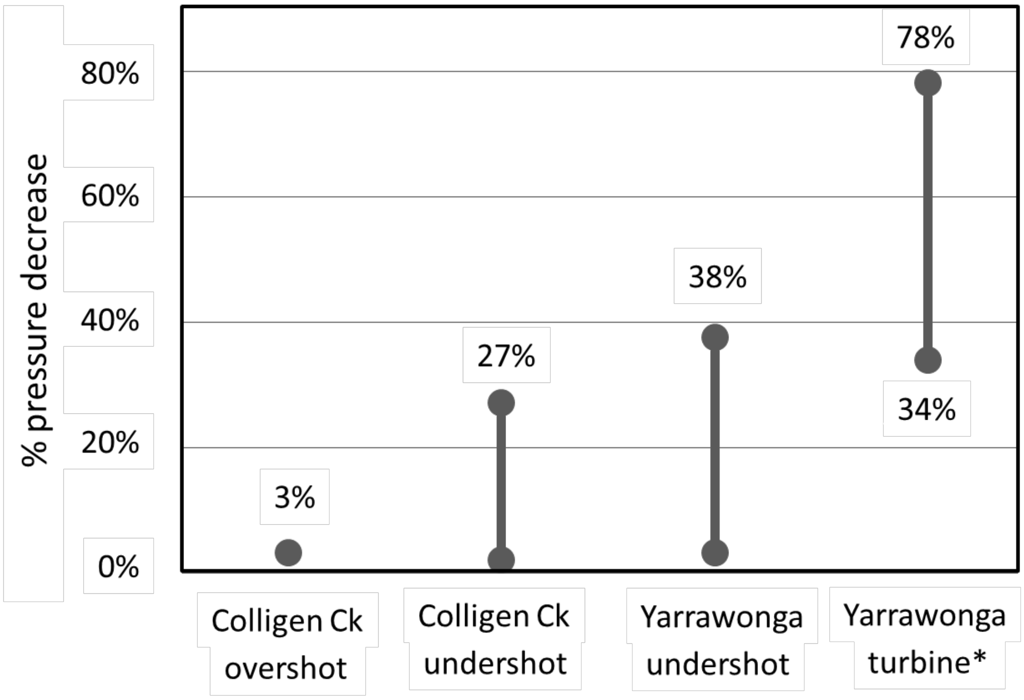


Figure 31. Decompression ranges (per cent change from starting pressure) a fish may be exposed to a different water-control structures obtained using Sensor Fish data of nadir pressure. This assumes fish are either approaching the structure at the surface (lowest per cent decrease) or on the bottom (highest per cent decrease). * Data obtained from a Kaplan hydropower turbine is shown for context (Kaplan data source Pflugrath 2017).

7.2.2 Shear

At the low-head structure at Colligen Creek, shear events were not noted at the overshot structure and were very infrequent at the undershot structure; they were only noted at the gate itself (Figure 32). Similarly, no notable shear events were recorded at the low-head overshot and undershot structure at Pak Peung. In comparison, shear events were far more frequently experienced at the high-head undershot structure at Yarrawonga Weir (Figure 32). At Yarrawonga the shear events occurred at the gate itself but also frequently in the downstream spillway as the fish were entrained in highly turbulent flows.

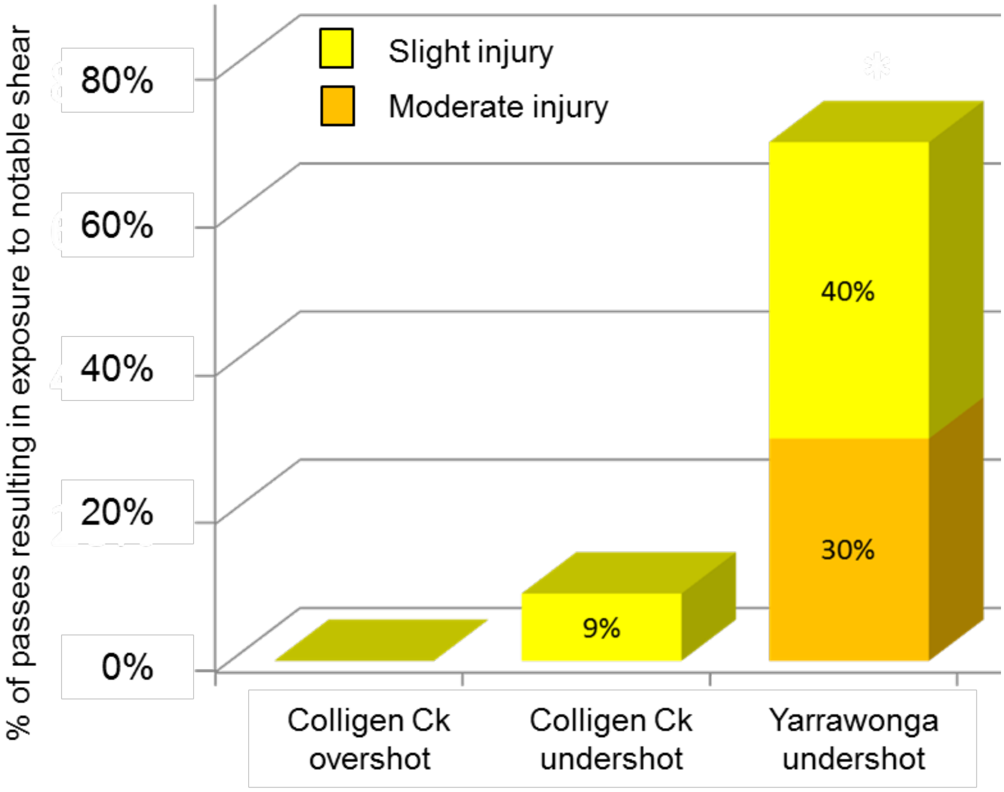


Figure 32. Likelihood of fish being exposed to shear at levels expected to cause injury for a low-head overshot and undershot structure (Colligen Creek) and a high-head undershot structure (Yarrawonga). Data obtained using Sensor Fish. For a detailed explanation of how shear values are associated with likelihood of causing injury to fish see Pflugrath *et al.* (2019).

7.2.3 Strike

Strike was found to be the most likely cause of injury and mortality to fish passing downstream through water-control structures. Although strike was frequently observed at all structures studied (Figure 33 and Figure 34), some interesting differences were noted that have provided insights into how best to design and operate structures to minimise both its occurrence and severity.

Strike can occur in two main places, when passing directly over or under the gate, and secondly in the spillway of the structure (Figure 35). While strike on the gate edge can occur when a fish passes over the crest of an overshot structure, the likelihood of this happening is far less than when passing an undershot structure. This was observed when we compared the overshot and undershot structures at Pak Peung (Figure 33a). At undershot structures, both the likelihood and severity of strike at the gate can be directly related to the gate opening or slot height. At Pak Peung undershot, strike at the gate was considerably less frequent and severe when the gate was operated at the largest slot height (Figure 33a). Pflugrath (2017) conducted a separate experiment at an undershot sluice gate in as laboratory and similarly determined that strike was far greater when sluices are operated with narrower openings. In that study, high speed video of Sensor Fish passing an undershot sluice identified that collision with the gate itself was rare. Instead, most strike occurred on the sill 0-40 cm downstream of the sluice gate.

By far the most frequent location for strike at both overshot and undershot structures is at the spillway downstream of a structure (Figure 33b and Figure 35). So, while strike can be considerably less at an overshot than an undershot structure, this is very dependent on how the spillway is designed. At Colligen Creek, the spillway was observed to be too shallow to effectively dissipate the energy of the spilling water. As such, Sensor Fish frequently collided with the spillway floor. Therefore, strike at Colligen Creek overshot occurred just as much as at the adjacent undershot and was just as likely at the 10 m head Yarrawonga Weir undershot, which had an exposed concrete spillway due to a low tailwater level (Figure 34). The tailwater depth a Colligen Creek Weir at the time of testing was 0.7 m, or 40% of the head differential. Historically, tailwater depths of 40% the total head differential have been recommended at overshot structures (Martin Mallen-Cooper pers. comm., 2017). In light of our findings, that recommendation is undoubtedly insufficient to allow safe passage. Until plunge pool depths can be further evaluated, it is recommended that tailwater be a depth of 70% of head differential (Pflugrath *et al.* 2019), an operating scenario that has been shown to result in little direct mortality to small fish (Baumgartner *et al.* 2013).

Tailwater depth can be increased downstream of an undershot structure by excavating a deeper plunge pool and this was factored into the design of Pak Peung overshot. But problems can occur if the plunge pool is not long enough, or if water is discharged at a high enough level that it ‘overshoots’ the plunge pool (Figure 35). This was observed when the Pak Peung overshot structure was operated at the highest discharge. When operated in this way, the spilling water went past the plunge pool and landed on the concrete apron in front of the culvert. As a result, 85% of Sensor Fish passing encountered severe strike downstream of the gate, far more than any of the other design and operational scenarios evaluated (Figure 33b). Spillway design is also an important consideration for undershot structures. It has been observed that strike downstream of undershot structures is considerably less when the spillway slopes away from the gate and when the spillway is completely submersed, sometimes referred to as ‘drowned’ (Pflugrath 2017).

In summary, an overshot structure can result in less frequent and severe strike to passing fish than an undershot structure and therefore should be the design of first choice. However, the fish-friendliness of an overshot will very much be dependent on the way the spillway is designed and operated. Overshot weirs require a downstream plunge pool. If the plunge pool is not deep or long enough, then strike is highly likely and can be just as severe and frequent as that which occurs at undershot structures. The depth of the plunge pool can be increased by excavating a deeper hole downstream of the weir or by installing a drop-board structure downstream of the primary structure in order to raise the tailwater. If this latter approach is used, it is important to apply the same design and operation principles to the secondary overshot as the primary one. In the case of Pak Peung Regulator, where the overshot spill was seen to go past the end of the plunge pool at higher discharges, a couple of solutions can be considered. Firstly, when possible, water should be passed over both gates instead of just one, thus reducing the discharge of each gate. Once this is no longer effective at very high discharges, it may be possible to construct a low-level drop-board structure downstream of the gate (either at the culvert entry or exit) in order to raise the tailwater.

At sites where an undershot structure must be used, there are a number of design and operational modifications that can reduce the occurrence and severity of strike and therefore make them more fish friendly. Firstly, the spillway should be designed to slope away from the gate. The sluice should also be operated in a drowned state where the downstream water level is above the gate opening. This helps to dissipate water velocities and keep fish from colliding with the bottom of the spillway. Increasing the gate opening (slot height) should further reduce the occurrence and severity of strike on the sill. At structures with multiple gates (such as Pak Peung), this can be achieved by passing water through fewer gates with greater openings, rather than through more gates opened only slightly.

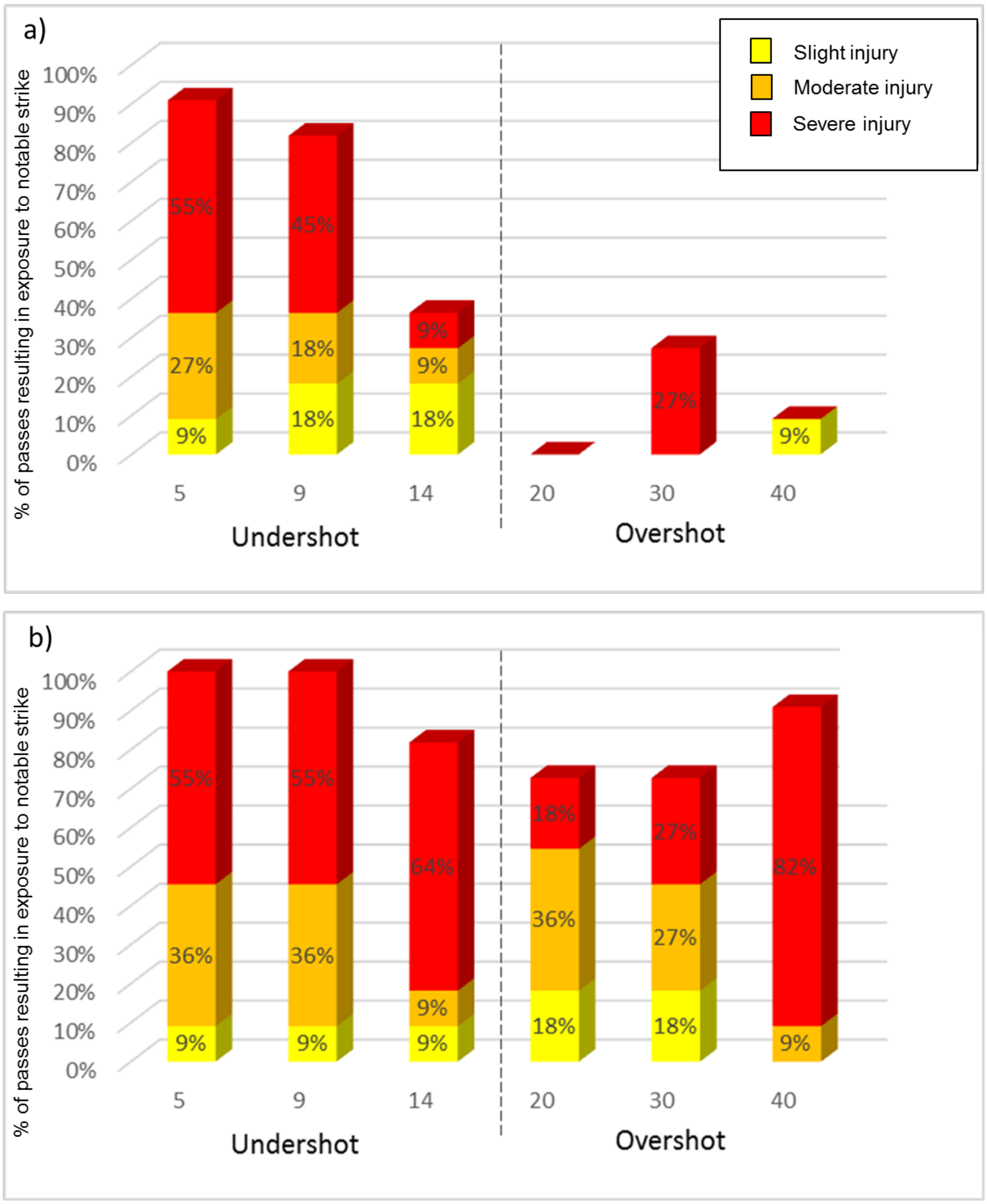


Figure 33. Likelihood of fish being exposed to strike a) at the gate and b) downstream of the gate when passing either the undershot or overshot structures at Pak Peung Regulator (as determined by Sensor Fish). Different gate openings (cm) shown for the undershot and different flows over the crest (cm) shown for the overshot. Bars are colour coded according to the severity of injury likely to come from the strike event (see Pflugrath *et al.* (2019) for a detailed explanation of how injury severity is determined from Sensor Fish data).

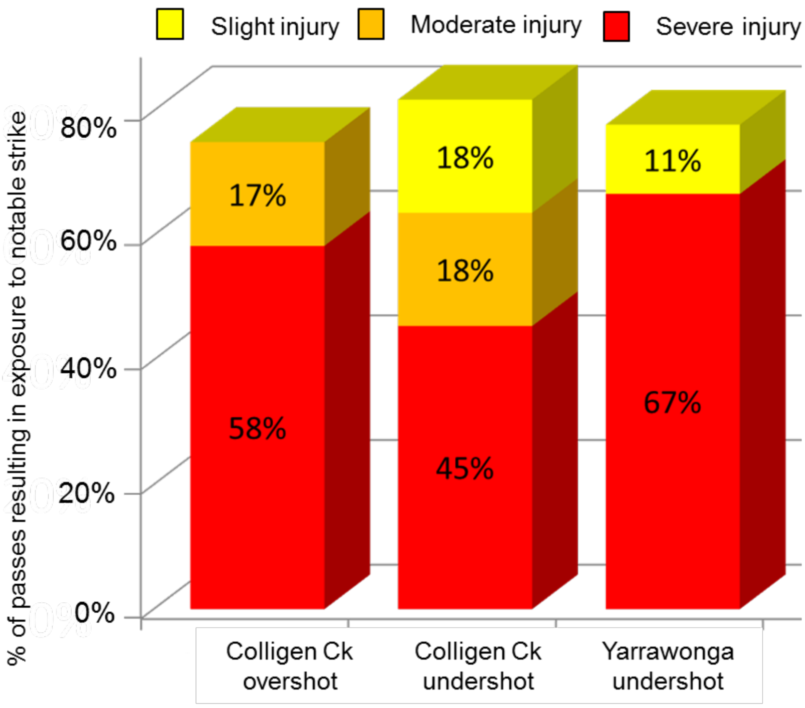


Figure 34. Likelihood of fish being exposed to strike at levels expected to cause injury for a low-head overshot and undershot structure (Colligen Creek) and a high-head undershot structure (Yarrawonga). Data obtained using Sensor Fish. For a detailed explanation of how strike values are associated with likelihood of causing injury to fish see Pflugrath *et al.* (2019).

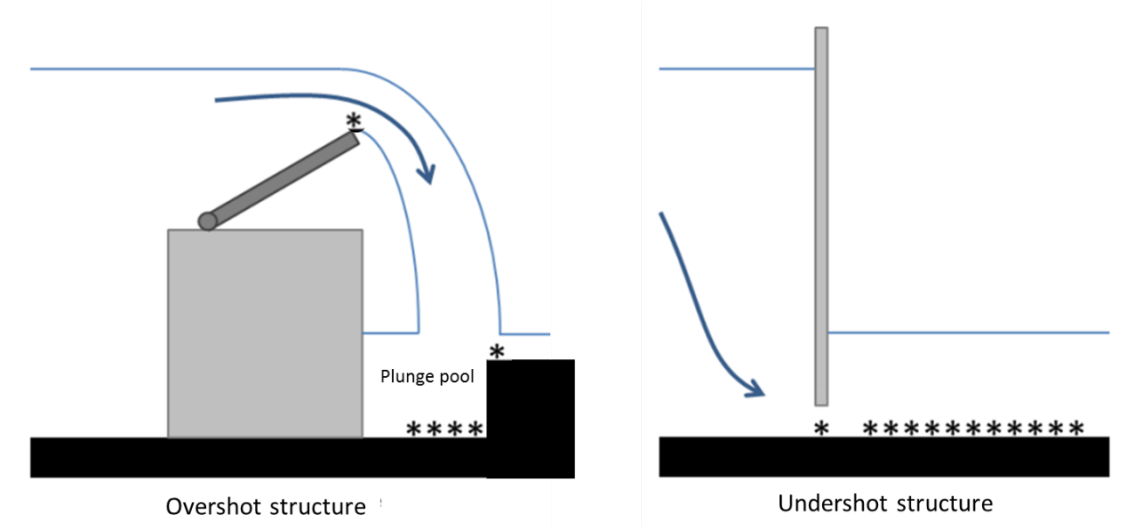


Figure 35. Summary of the most typical locations where fish will experience strike when passing overshot and undershot structures. The frequency and severity of these strikes can be reduced by applying several design and operational principles.

7.3 Can the injury of fish leaving regulated wetlands be reduced and their survival increased by changing the design of infrastructure?

A total of 839 fish comprising 59 species were caught in the Lee traps migrating downstream through the Pak Peung Regulator over 36 hours of trapping. The vast majority of fish caught (75%) were from three families: Anabantidae, Osphronemidae and Cyprinidae (Table 3). As was found with the previous downstream trapping experiments, most of the fish moving downstream were small bodied, with 70% of fish being less than 50 mm in length (Figure 36).

Table 3. Catch summary from Lee trap experiments showing families of fish caught exiting the Pak Peung Regulator (undershot and overshot combined).

Family	Number	per cent
Anabantidae	255	30.4%
Osphronemidae	221	26.3%
Cyprinidae	151	18.0%
Ambassidae	78	9.3%
Mastacembelidae	37	4.4%
Channidae	35	4.2%
Nandidae	33	3.9%
Clupeidae	6	0.7%
Cobitidae	6	0.7%
Bagridae	4	0.5%
Toxotidae	4	0.5%
Belonidae	2	0.2%
Eleotridae	2	0.2%
Cichlidae	2	0.2%
Notopteridae	1	0.1%
Datniodidae	1	0.1%
Badidae	1	0.1%
Total	**839**	

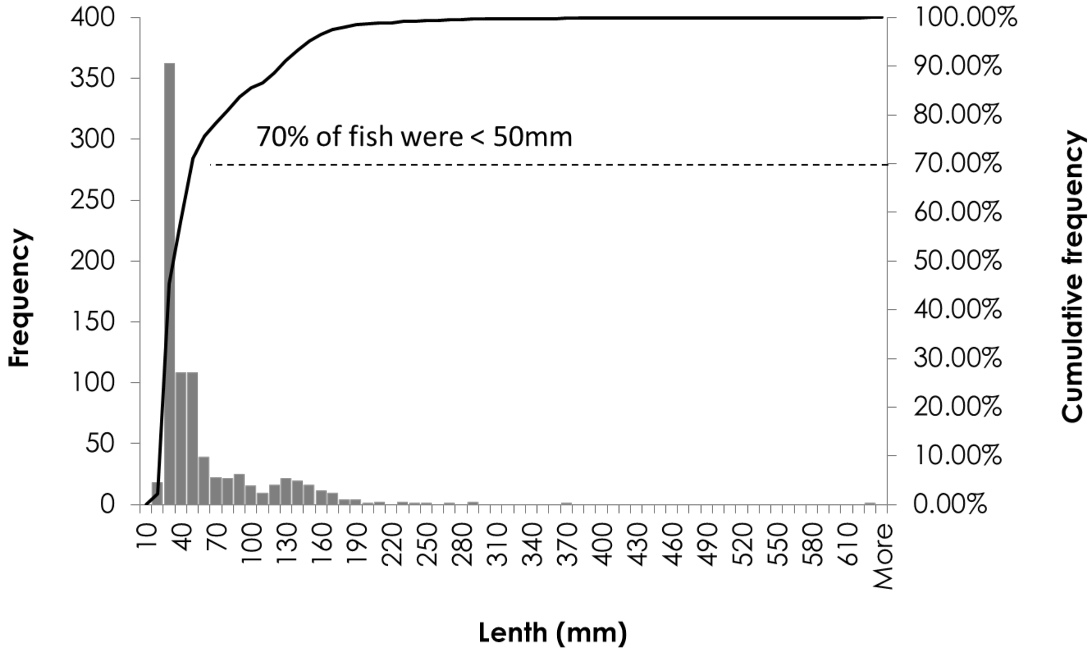


Figure 36. Size-frequency distribution of fish caught in the Lee trap experiments.

Evaluation of the hydraulic conditions at a number of overshot and undershot structures throughout this project shows that when designed and operated properly, overshot structures can produce more benign conditions for fish than undershot structures. Based on this, and the findings of past studies (Marttin and De Graaf 2002, Baumgartner *et al.* 2006, Baumgartner *et al.* 2013), one would expect that upgrading the Pak Peung Regulator gates from undershot to overshot gates would create a quantifiable reduction in the injury rate and improvement in the survival of fish passing the gates. However, we did not observe this during the Lee trap experiments. Over the 36 trapping hours we did not observe a difference in the injury rate, even at the more severe end of the spectrum (Figure 37).

These results suggest that improvements may not be seen by changing gate design over all operating conditions. At the time of the mortality testing, the head differential at the undershot structure was quite low (Figure 24), being 0.9-1.5 m. Pak Peung can operate a head differential twice as large as that, and at the time of the earlier Sensor Fish study the head differential was 2.5 m and the discharge through the structure was considerably higher (Figure 24). Therefore, caution must be exercised when interpreting the relevance of these findings. We have shown previously that different operating conditions and different scales of structures can alter the hydraulic conditions immensely. For example, strike, shear and decompression can all be higher at undershot gates with a greater water level differential across the structure. At Pak Peung, Sensor Fish suggested that strike in particular would be expected to be higher under a higher-head operating condition. So, while no difference was seen in injury rates at Pak Peung, mortality trials need to be repeated over the entire range of head differentials, because the results may be very different to what was observed under just a low-head scenario. If these experiments are to be carried out, the gates and wetland levels should be manipulated to obtain a large range of conditions. Additionally, it would be much better to use Sensor Fish at the same time as trapping live fish so that the hydraulic conditions can be more closely associated with differences in injury rates.

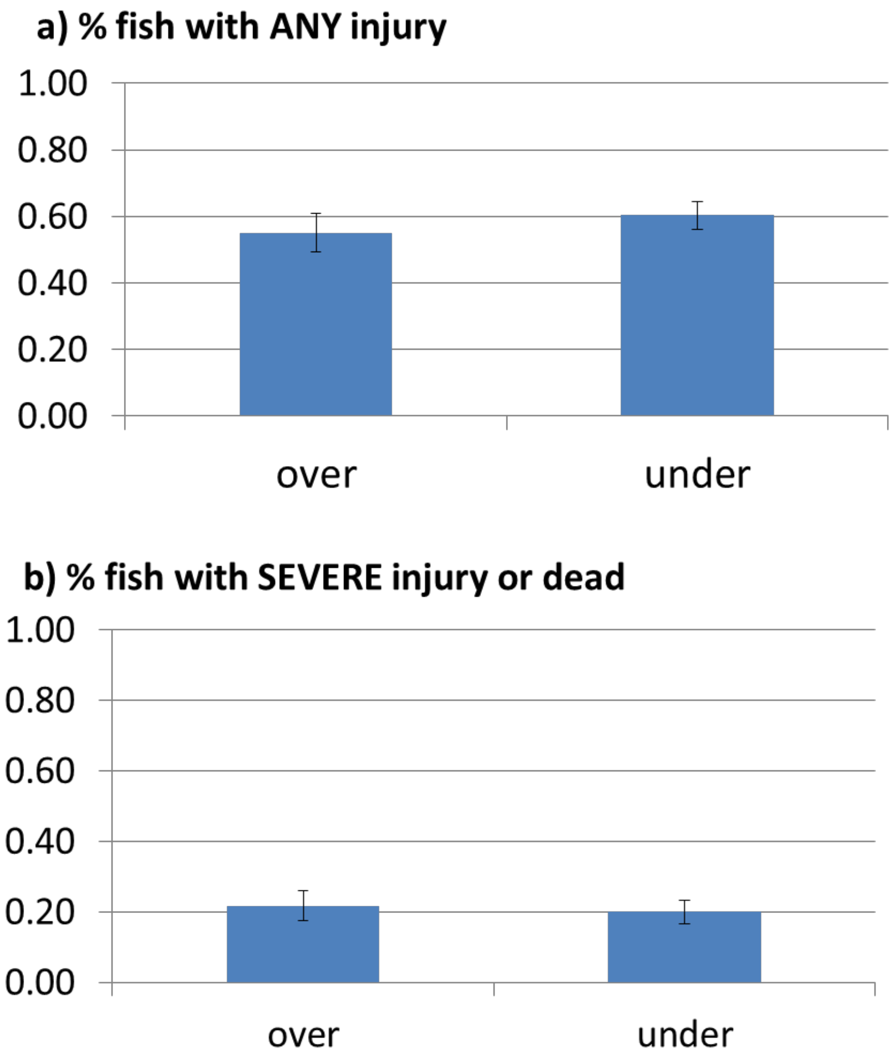


Figure 37. Percentage of fish that had any injury (a), or had a severe injury or were dead (b) when passing downstream through the Pak Peung overshot and undershot structures.

7.4 What is the impact of poor downstream passage survival on the value of the capture fishery? How do improved passage rates translate into improvements in the value of the capture fishery at local and regional scales? Is there a net (quantifiable) economic benefit in capture fisheries production from investing in improvements in irrigation infrastructure design?

This component of the project was reliant on quantifying a difference in injury and survival of fish between the old undershot gates and new overshot layflat gates at Pak Peung, and subsequently using this information to estimate improvements in the value of the capture fisheries using the LMFST cost–benefit model. As outlined in the previous section, we were unable to detect a difference in survival, however, we believe this was due to the small-head differential of the structure at the time of testing. Our hydraulic investigations suggest that testing the gate over higher-head differentials may yield measurable differences in survival between gate designs.

As a result, data could not be provided to economists to estimate environmental and economic benefit. To complete this task properly, future mortality trials will need to be conducted over the complete range of operating conditions known to exist at the Pak Peung Regulator, including high-head differentials. Further to this, the migratory behaviour of commercially important species needs to be further interrogated. It will be important to understand why fish are migrating downstream out of the wetland and whether many of these individuals return to the wetland at a later stage, when they are then captured as part of the wetland fishery. That is, does improving downstream passage provide a positive feedback loop that increases return passage through the fishway and therefore result in larger wetland fish populations? Answering this question may require using fish tagging and tracking studies.

Because we could not obtain data on differential survival at Pak Peung, the benefits to fisheries of downstream passage investment remain set at zero within the LMFST (Cooper *et al.* 2019). At the same time, the cost information used was set to a default value of $100,000 USD, the single scenario we tested at Pak Peung. This is problematic because this example is based on a gate that was manufactured in Australia and shipped to Lao PDR, a scenario likely to be at the most expensive end of the scale. Manufacturing the gates locally is expected to be far less expensive. It is also difficult to be prescriptive about the cost of making a structure more fish friendly and this may need to be considered on a project by project basis. A large proportion of the cost of gate installation does not come from the gate itself, but rather the civil works required at a site. Also, the additional cost of dealing with downstream passage at a green field site may be negligible when a regulator needs to be built anyway. In that instance, the decision may be purely about choosing one design over another, a cost-neutral decision. Or it may just involve changing how the structure is operated so that passage rates can be improved.

Ultimately, due to these data deficiencies the current iteration of the LMFST does not view the economic return on investing in downstream passage at Pak Peung favourably. Using a default $100,000 cost of a new gate and no contribution to fish production, the analysis predicts a negative net value for the project and no prospect of the project breaking even within its lifespan (Cooper *et al.* 2019). It also predicts that if investment in downstream passage is removed, a positive net benefits for the project arising solely from the upstream fishway would total US$83,000 with a pay-off after 11 years. It is clear that much more work needs to be done in collecting data relating to both the cost and benefit of downstream fish passage investment. Firstly, the LMFST should include a sliding scale for downstream investment that acknowledges that the cost of a project can differ substantially between a fully imported gate versus a locally produced one versus the neutral cost of making a smarter design choice at a green field site, or by changing the way an existing gate is being operated. Finally, as more data is collected over a greater range of operating conditions, we may be better able to acknowledge improvements in fish survival. By viewing these improvements in the context of cyclical movements of fish and therefore return passage into wetlands, the benefit of investments for fish production may be able to be revised and improved in the LMFST.

8 Impacts

8.1 Scientific impacts – now and in five years

The research conducted during this project included numerous world firsts. Firstly, we completed the first ever study quantifying the types of species and their relative abundance exiting a wetland in the LMB. From this it was determined that lateral movements from wetlands to the main channel involve a significant number of fish and different species. The majority of fish were small bodied and juveniles of larger fish. Not only does this confirm the importance of floodplain wetlands as nursery habitats, but it also suggests that these size classes may be the most frequently exposed to injury at poorly designed structures. As a result of this research it became clear that design and operational guidelines of water-control structures need to consider a diverse range of species, not just one or two. It is also apparent that due to the large number of fish passing regulators, and the substantial number of these regulators throughout the LMB, even small improvements in fish survival through improved regulator design has the potential to result in huge benefits across the LMB.

Secondly, it was the first time Sensor Fish technology has used to measure the hydraulic conditions experienced by fish at different low-head irrigation structures. Previous to this this technology had only been applied at hydropower dams. The findings expand the understanding of the hydraulic stressors present at low-head structures, and we have been able to offer recommendations of how to improve the design and operation of irrigation infrastructure. To ensure impact of this science continues to grow over the upcoming five years, the conclusions and recommendations from this research have been synthesised as nontechnical guidelines in both Lao and English languages; there is already evidence that they being applied by fisheries managers and engineers in the design and operation of future structures (see capacity impacts).

The scientific impact of this project is also illustrated by the fact that it has resulted in five peer-reviewed journal papers, two magazine articles one PhD thesis (see section 10.2). Another two journal papers are in preparation – one looking at the cyclical movement of fish into and out of a Mekong wetland (building a justification for fish passage remediation) and one combining the hydraulic and biological evaluations of the new and old Pak Peung Regulator gates.

8.2 Capacity impacts – now and in five years

By improving the understanding that fisheries scientists, engineers and water authorities in both the LMB and MDB have of the need to protect downstream passage and how to achieve it with design and operational advances, it is anticipated that they will apply a more holistic approach to fish passage when developing future projects. Ultimately, this will encourage the adoption of technical advances in downstream passage alongside upstream passage at water-control structures.

There is already evidence that this is occurring. In NSW, based on the findings of this study, fisheries managers use a guideline on new structures requiring plunge pools no shallower than 70% of the total head differential of the structure. Prior to this project, plunge pools of only 40% depth were being recommended (Martin Mallen-Cooper pers. comm., 2017). This design requirement is currently being engineered into a re-regulating structure that will soon be constructed near Gin Gin Weir on the Macquarie River. This outcome is directly due to the research undertaken during this project and our ability to disseminate this information so that behaviour of fisheries managers, water authorities and engineers can be changed.

In the next five years it is expected that design guidelines produced by this project will be further promoted throughout the LMB, the MDB and more broadly by:

1. Increasing circulation of the multilingual, nontechnical best-practice guidelines for water-control structures. This circulation will be facilitated by continued activity of the ACIAR Fish Passage team through ongoing and associated projects in the region.
2. Continued teaching of downstream passage guidelines at fish passage design and barrier prioritisation master classes, as was recently done in Thailand (in collaboration with the US Department of Interior) and in Albury (as part of the international Fish Passage 2018 conference).
3. Incorporating downstream fish passage into the curriculum of at the National University of Laos, and Charles Sturt University (this has already been done at both institutes) ensuring that the knowledge of current and future District and Provincial Agriculture and Fisheries Officers (the next users) is continually being developed at tertiary institutes in Lao PDR and Australia.
4. Continuing the use of the Pak Peung fish passage demonstration site as a valuable education tool where the holistic upstream and downstream approach to fish passage at water-control structures and the use of advanced manufacturing techniques can be demonstrated first-hand. The site also remains for the use of scientists and students to conduct further research.
5. Continuing the development and utilisation of downstream passage research and teaching tools that were initiated as part of this project and its proceeding SRA project – for example National university of Laos Dongdok Campus hydraulic lab with barotrauma chambers and shear flume; continued use of Sensor Fish at a wider variety of structures.

Through this and other associated ACIAR Fish Passage projects in Lao PDR, the technical skills of local villagers in Pak Peung have continued to be improved in the disciplines of fish handling, fish identification, data collection, data management and how to follow set scientific protocols. These skills have now reached a point where local staff can now undertake field experiments with limited supervision. Their fish identification skills are exceptional and as such they now train Australian researchers working on the projects.

There is clear evidence of the mentoring and development of future researchers during this project. Through this project Dr Pflugrath successfully attained his PhD (Pflugrath 2017), produced a first authored paper (Pflugrath *et al.* 2019) and was recognised with the NSW Department of Primary Industries John Holliday Student Award in 2015 and received best student talk award at an international conference (Pflugrath *et al.* 2016). Our Lao researchers continued to be exposed to opportunities to present project work at international conferences, including the Lower Mekong Fish Passage Conference (Vientiane), American Fisheries Society (Portland) and Fish Passage 2018 (Albury) (see section 8.4 and 10.2 for examples).

8.3 Community impacts – now and in five years

8.3.1 Economic impacts

Considerable numbers of fish pass downstream through water-control structures. Given the substantial number of these structures throughout the LMB, it may be expected that improving their design and operation to achieve even small improvements in downstream fish survival may lead to considerable economic and environmental benefits. It was an objective of the project to quantify some of these benefits. While some progress was made in this respect by factoring downstream fish passage into the LMFST, much more work remains to be done to improve the modelling of economic benefit. Due to the unavailability of adequate cost and benefit data, the LMFST did not view the economic return on investing in downstream passage at Pak Peung favourably. However, this result must be viewed with extreme caution until better data is collected. Firstly, the LMFST needs to include a sliding scale for downstream investment that acknowledges that the cost of a project can differ substantially between a fully imported gate versus a locally produced one versus the neutral cost of making a smarter design choice at a green field site, or by changing the way an existing gate is being operated. Secondly, more fish survival data is required over a greater range of operating conditions to be better able to quantify what improvements in fish survival could be expected. By viewing these improvements in the context of cyclical movements of fish and therefore return passage into wetlands, the benefit of investments for fish production may be able to be revised and improved in the LMFST.

8.3.2 Social impacts

An important contribution of the LMFST has been its capacity to predict social impacts of fish passage investments in the LMB. For example, at Pak Peung it was estimated that the impact of the fishway at Pak Peung can provide almost 2 tonne of additional edible protein annually, equivalent to the annual dietary requirements of almost 1200 children under the age of three years (Cooper *et al.* 2019). This demonstrates how investment in improving floodplain wetland fish passage can lead to significant community benefits beyond economic ones. It may be expected that better downstream passage could further improve this fish production, however, for the reasons mentioned above (and in section 9) such modelling will require better data to be collected on fish survival at water-control structures.

The social impact that can come from empowering researchers and decision makers to drive positive policy change is hard to tangibly quantify, but is no less important. Through the project we have continued to foster an early-adopter mentality in Lao PDR. Researchers, conservation groups and water authorities have been emboldened to adopt technological advances and world best practice. The layflat gates installed a Pak Peung were a first for the region and the use of nonferrous materials in construction was initially met with reluctance but has now been proven successful and will greatly improve the lifespan of future irrigation investments. One way that this adoption of new ideas has been achieved was through fostering linkages between the Lao and Australian private sectors through our collaboration with AWMA Water Control Solutions. Our Lao PDR partners continue to build their reputation as world leaders in fish passage R&D, giving them greater influence to achieve positive outcomes for fish passage throughout the greater LMB region. A fine example of this recognition was when the ACIAR LMB Fish Passage team was recognised by its peers as the most distinguished project at the recent Fish Passage 2018 international conference (Figure 38).

8.3.3 Environmental impacts

As mentioned above in section 8.3.1, due to the considerable numbers of fish we found passing downstream at Pak Peung Regulator, combined with the substantial number of these structures throughout the LMB, it may be expected that even small improvements in downstream fish survival may lead to considerable environmental benefits. Unfortunately, because we were not able to complete mortality trials over moderate to high-head operating conditions (where we would expect the most improvement in survival to come from design and operational changes), we are unable to quantify the expected environmental benefits. Therefore, it is recommended that testing of mortality continue over a larger range of operating head differentials to enable the data to be collected on environmental benefits.

Figure 38. Recognition of our Lao and Australian researchers on the world stage as leaders in fish-friendly agricultural advances continue to motivate our partners and drive changing social attitudes in the LMB, acknowledging that a balance between irrigated agriculture and fisheries production can be achieved through engineering solutions. Pictured here are team members of the ACIAR-funded Lao PDR Fish Passage program receiving the Distinguished Project Award at Fish Passage 2018.

8.4 Communication and dissemination activities

All the dissemination and communication activities proposed in the original project scope of works were completed, as well as additional ones. The key ways that the research outcomes were disseminated throughout the project included:

In-country project workshops and meetings – These have been an important way to disseminate research findings to those who will use the knowledge. The final project workshop held in Pak San in September 2019 was a prime example (Figure 39). At the workshop, presentations and posters were used to communicate the key research findings to representatives from District and Provincial Agriculture and Fisheries Offices (DAFO and PAFO), Department of Water Resources, Mekong River Commission, Ministry of Planning and Investment, National Agriculture and Fisheries Research Institute (NAFRI), Living Aquatic Resources Research Centre (LARReC), National University of Laos (NUOL), and local community members from Pak San, Pak Peung and surrounding villages. Draft downstream guidelines for the best-practice design and operation of water control were presented, discussed and feedback was given to the project team. Recommendations for future research were also provided to the research team.

Field trips to the Pak Peung fish passage demonstration site – The site of the fishway and layflat gates at Pak Peung Regulator has become far more than a research site. It has become a valuable education tool where the holistic upstream and downstream approach to fish passage at water-control structures can be demonstrated first-hand. Over the life of the project a number of field trips for local and international dignitaries, engineers, irrigation officers, fish biologists and donor agencies were run to the Pak Peung site in association with events such as the Lower Mekong Fish Passage Conference and regional workshops (Figure 40). During these visits it was clear that discussions that were had at the demonstration site helped solidify and clarify what was being taught in theory indoors. The site will continue to be a teaching tool long after this project has finished.

Published scientific outputs – This project resulted in five journal papers, two magazine articles one PhD thesis (see section 10.2) and nontechnical guidelines produced in both Lao and English languages (see Appendices). Another two journal papers are in preparation – one looking at the cyclical movement of fish into and out of a Mekong wetland (building a justification for fish passage remediation) and one combining the hydraulic and biological evaluations of the new and old Pak Peung Regulator gates.

Conference presentations – In total the project team gave 12 presentations at national and international conference (see section 10.2). These were important opportunities to share and discuss the research outcomes of the project with other scientists and managers. Many of the presentations were given by the Lao PDR research partners, which was beneficial to developing their ability to present research confidently to an international audience. Some notable conferences that the project team presented at included:

- 145th Annual Conference of the American Fisheries Society. Special session: "Sustaining Diverse Fisheries in the Mekong Basin". 16-20 August 2015. Portland, Oregon, USA.
- Lower Mekong Fish Passage Conference. 14th-18th November 2016. Lao Plaza Hotel, Vientiane, Lao PDR.
- 11th International Symposium on Ecohydraulics. Melbourne, Australia, 7-12 February 2016.
- 5th Biennial Symposium of the International Society for River Science. 15-24th November 2017. Hamilton, New Zealand.
- Annual Conference of the Australian Society of Fish Biology. Sydney, New South Wales, Australia.

The most prominent of the conferences was the Lower Mekong Basin Fish Passage conference organised by the project team and held in Vientiane in November 2016 (Figure 41). This was attended by 160 delegates from 14 different countries. The significant international prominence this conference achieved is highlighted by the fact that ACIAR's initial $30,000 AUD investment into the conference was able to leverage an additional $100,000 USD of sponsorship from international organisations.

Fish passage master classes – Dr Lee Baumgartner has coordinated a number of fish passage master classes to help disseminate practical information on fishway and infrastructure design more broadly throughout Asia. As well as covering topics such as barrier mapping, prioritisation of investment and fishway design, the master classes no incorporate a section on downstream fish passage which directly references the outcomes of this research project. This material was presented in two recent master classes, one in Thailand (in collaboration with the US Department of Interior) and one in Albury (as part of the international Fish Passage 2018 conference).

Social Media – In 2016 the Lower Mekong Fish Passage group page was established on Facebook by the ACIAR Fish Passage team. It currently has 115 members and has been a valuable way of quickly disseminating information associated with research being undertaken in country as well as publications coming from the research.

Figure 39. In-country project workshops and meetings have been an important way to disseminate research findings to those who will use the knowledge. The final project workshop held in Pak San in September 2019 was a prime example of this and involved presentations, poster displays, discussions and a site visit.

Figure 40. The ACIAR-funded Pak Peung fish passage research site, including fishway and fish-friendly regulator gates, has become a valuable education tool where the holistic upstream and downstream approach to fish passage at water-control structures can be demonstrated first-hand.

Figure 41. The Lower Mekong Basin Fish Passage conference organised by the project team and held in Vientiane in November 2016 was attended by 160 delegates from 14 different countries.

9 Conclusions and recommendations

Downstream movement of fish from wetlands is considerable and needs to be protected.

Lateral movements from wetlands to the main channel involve a significant number of fish and different species. In the downstream trapping experiment, we observed downstream passage rates as high as 169 fish per hour, and counted 114 different fish species. The vast majority were from the ‘grey fish’ guild, which is known to undertake short migrations between the floodplain and main channel. When this is viewed alongside upstream movement data collected from the adjacent fishway, it demonstrates the importance of cyclical lateral fish movements for floodplain wetlands like Pak Peung. That is, movements both upstream into wetlands and downstream into the main river channel. From a fish passage remediation perspective, we suggest that restoring upstream fish passage alone at wetland water-control structures will be insufficient to protect the fishery if safe return passage is not also provided. Most of the fish captured undertaking downstream passage were small bodied, a size class that has been shown to be particularly vulnerable to injury and death when passing weirs and regulators. This emphasises the need to ensure structures are designed and operated in a way that promote greatest fish survival. Additionally, our results show the need to consider the passage of a diverse range of species, not just one or two. From the perspective of quantifying the economic and environmental benefits that can accrue from investing in safe downstream fish passage, due to the large number of fish passing regulators and the substantial number of these regulators throughout the LMB, it may be expected that even small improvements in fish survival through improved regulator design and operation could result in considerable benefits across the LMB.

Water-control structures can be designed and operated in a way that can promote safer downstream fish passage.

Design and operational adjustments to water-control structures should be considered to reduce hydraulic stressors which fish encounter when passing downstream (Table 4). Overshot rather than undershot gates should be the design of choice to provide safer passage for fish and less injury and mortality. Based on their hydraulics, we found that overshot structures create less stressful conditions for fish and this likely explains why previous studies have found less injury and mortality to small fish when passing overshot gates, when compared to undershot gates (Marttin and De Graaf 2002, Baumgartner *et al.* 2006, Baumgartner *et al.* 2013). While we did not observe the same difference in mortality between an overshot and undershot structure at Pak Peung, we believe this was due to the low-head differential that existed at the time of testing; more research needs to be done at higher-head conditions at which the gates are often operated.

At low-head (<6m) structures, strike rather than shear or rapid decompression appears to be the primary mechanism for injury. Therefore, design and operational improvements should focus on reducing strike events. Overshot structures can result in less frequent and severe strike to fish than an undershot structure. But their fish-friendliness will very much depend on spillway design, in particular whether deep tailwater conditions are present. For this reason, a downstream plunge pool is an essential design requirement of overshot structures. Strike can be totally eliminated if there is a plunge pool sufficiently deep and long. Based on the available data, we recommend a plunge pool depth of at least 70% the head differential and long enough to capture the spill of the entire range of flows. With further targeted research of differing plunge pool depths this recommendation might be able to be further revised. The depth of a plunge pool can be increased by excavating a deeper hole downstream of the gate or by installing a drop-board structure downstream of the primary structure to raise the tailwater.

At some sites it may not be possible or cost-effective to change the design of a structure from an undershot to an overshot gate. In these instances, changing the operational settings may help reduce the risk of strike and injury at undershot gates. For instance, increasing the gate opening of a sluice gate should reduce the frequency and severity of strike. At sites with multiple gates this would simply be a matter of operating fewer gates with larger openings. Since most strike occurs downstream of the gate, having a sloping apron or operating the gate in a drowned state, where the downstream water level is above the gate opening, should help dissipate water velocities and keep fish from colliding with the bottom of the apron.

While decompression and shear may not be issues at low-head structures, they appear more problematic at higher structures. At structures greater than 6 m shear and decompression can be difficult to mitigate through operational changes and therefore the safer option would be to choose an overshot structure.

Table 4. Summary of recommendations for the design and operation of water-control structures.

Structure	Concern for fish passage	Recommendation for mitigation
Overshot	Strike	Ensure plunge pool is sufficiently deep (at least 70% head differential) and sufficiently long to capture spill over entire discharge range
Undershot	Strike	Design with a sloping downstream apron
	Strike	Operate with a low-head differential
	Strike	Operate in a drowned state (i.e. tailwater level above gate opening)
	Strike	Maximise gate opening/slot height
	Shear	Unlikely to be a concern at low-head (<6 m) structures but maybe unavoidable at higher-head (>6 m) structures. At high-head structures, opt for overshot design whenever possible
	Barotrauma	Unlikely to be a concern at low-head (<6 m) structures but maybe unavoidable at higher-head (>6 m) structures. At high-head structures, opt for overshot design whenever possible

The environmental and economic costs and benefits associated with investing in downstream passage still need to be thoroughly quantified.

Due to the large number of fish passing regulators, and the substantial number of these regulators throughout the LMB, it may be expected that even small improvements in downstream fish survival may lead to considerable economic and environmental benefits. It was an objective of the project to quantify some of these benefits, however, in the end we were not able to successfully achieve it. While we were able to factor the investment in gate refurbishment into the Lower Mekong Fishway Support Tool (LMFST), it still poorly deals with investments in water gate upgrades from the perspective of downstream passage. The reason for this was the inability to collect and include data that effectively estimates the benefits and costs of investing in downstream passage.

Within the life of the project we were not able to trap fish over a sufficient range of different operating conditions to properly access differences in injury and survival resulting from the upgrade of the Pak Peung Regulator. Mortality trials were only possible under a low-head condition, a scenario that our hydraulic measurements suggest may not be as injurious for fish when passing under a sluice gate. Therefore, data could not be provided to economists to estimate environmental and economic benefit. Future mortality trials will need to be conducted over the complete range of operating conditions, as we know that the Pak Peung Regulator like many structures is commonly releasing water under high-head conditions. Further to this, the migratory behaviour of commercially important species needs to be further interrogated. It will be important to understand why fish are migrating downstream out of the wetland and whether many of these individuals return to the wetland at a later stage, when they are then captured as part of the wetland fishery. That is, does improving downstream passage provide a positive feedback loop that increases return passage through the fishway and therefore result in larger wetland fish populations? Answering this question may require using fish tagging and tracking studies.

The cost information being used in the LMFST is also over simplistic and inadequate at this stage. Firstly, given that Pak Peung was the only example we had to work off, a default value of $100,000 USD has been placed on the cost of investing in a regulator gate upgrade. This is problematic because this example is based on a gate that was manufactured in Australia and shipped to Lao PDR. Manufacturing the gates locally is expected to be far less expensive. Secondly, the cost of a more fish-friendly gate is extremely hard to estimate and may need to be factored in on a project by project basis. A large proportion of the cost of gate installation does not come from the gate itself, but rather the civil works required at a site. Also, the cost of dealing with downstream passage at a green field site may be very different to replacing a regulator at a pre-existing site. For example, at a green field site that requires a gate to be installed, the decision to choose a more fish-friendly design over a less friendly one would not affect the overall project cost. However, if an existing ageing undershot gate is present and requires replacing, this will obviously come at additional cost. Finally, some of the operational improvements recommended in this report would cost nothing, but rather involve changing the way gates are operated so that they improve passage rates.

Ultimately, due to the unavailability of adequate cost and benefit data, the LMFST does not view the economic return on investing in downstream passage at Pak Peung favourably. Using the default $100,000 USD cost of a new gate and no contribution to fish production, the analysis predicts a negative net value for the project and no prospect of the project breaking even within its lifespan (Cooper *et al.* 2019). It also predicts that if investment in downstream passage is removed, a positive net benefits for the project arising solely from the upstream fishway would total US$83,000 with a pay-off after 11 years. It is clear that much more work needs to be done in collecting data relating to both the cost and benefit of downstream fish passage investment. Firstly, the LMFST should include a sliding scale for downstream investment that takes into account that the cost of a project can differ substantially between a fully imported gate versus a locally produced one versus the neutral cost of making a smarter design choice at a green field site, or by just changing the way an existing gate is being operated. Finally, as more data is collected over a greater range of operating conditions, we may be better able to acknowledge improvements to fish survival. By viewing these improvements in the context of cyclical movements of fish and therefore return passage into wetlands, the benefit of investments for fish production may be able to be revised and improved in the LMFST. At the final project workshop, it was suggested that the project team write a project concept note or full project proposal to the department of research under the National University of Lao for consideration.

10 References

10.1 References cited in report

Baumgartner, L., McPherson, B., Doyle, J., Cory, F., Cinotti, N. and Hutchison, J. (2013). *Quantifying and mitigating the impacts of weirs on downstream passage of native fish in the Murray-Darling Basin*. Fisheries Final Report Series No. 136. NSW Department of Primary Industries, Port Stephens Fisheries Institute, 73 pp.

Baumgartner, L. J., Reynoldson, N. and Gilligan, D. M. (2006). Mortality of larval Murray cod (*Maccullochella peelii peelii*) and golden perch (*Macquaria ambigua*) associated with passage through two types of low-head weirs. *Marine and Freshwater Research* **57**: 187–191.

Bishop, A., Veasna, B., Campbell, I., Feldkotter, C., Garsdal, G. S., Gerrinck, L., Griffiths, D., Hodgkinson, P., Hook, J., Ishihata, T., Juntopas, M., Little, M., Lund, A., Novak, S., Sokhem, P., Seager, M., Im, S. S., Sukraroek, W., Ward, K. and Young, A. (2003). *State of the Basin report: 2003 executive summary*. Mekong River Commission, Phnom Penh, Cambodia. (http://www.mrcmekong.org/assets/Publications/basin-reports/state-basin-executive-sum2003.pdf).

Boys, C. A., Robinson, W., Miller, B., Pflugrath, B., Baumgartner, L. J., Navarro, A., Brown, R. and Deng, Z. (2016a). A piecewise regression approach for determining biologically relevant hydraulic thresholds for the protection of fishes at river infrastructure. *Journal of Fish Biology* **88**: 1677–1692.

Boys, C. A., Robinson, W., Miller, B., Pflugrath, B., Baumgartner, L. J., Navarro, A., Brown, R. and Deng, Z. (2016b). How low can they go when going with the flow? Tolerance of egg and larval fishes to rapid decompression. *Biology Open*: doi: 10.1242/bio.017491.

Boys, C. A., Pflugrath, B. D., Mueller, M., Pander, J., Deng, Z. D. and Geist, J. (2018). Physical and hydraulic forces experienced by fish passing through three different low-head hydropower turbines. *Marine and Freshwater Research* **69**: 1934–1944.

Brown, R. S., Colotelo, A. H., Pflugrath, B. D., Boys, C. A., Baumgartner, L. J., Deng, Z., Silva, L. G. M., Brauner, C. J., Mallen-Cooper, M., Phonekhampeng, O., Thorncraft, G. and Singhanouvong, D. (2014). Understanding barotrauma in fish passing hydro structures: a global strategy for sustainable development of water resources. *Fisheries* **39**: 97–122.

Cooper, B., Crase, L. and Baumgartner, L. J. (2019). Estimating benefits and costs: a case of fish passages in Lao PDR and the development of the Lower Mekong Fishway Support Tool. *Marine and Freshwater Research* **70**: 1284–1294.

Deng, Z., Carlson, T. J., Duncan, J. P. and Richmond, M. C. (2007). Six-degree-of-freedom sensor fish design and instrumentation. *Sensors* **7**: 3399–3415.

Deng, Z. D., Lu, J., Myjak, M. J., Martinez, J. J., Tian, C., Morris, S. J., Carlson, T. J., Zhou, D. and Hou, H. (2014). Design and implementation of a new autonomous sensor fish to support advanced hydropower development. *Review of Scientific Instruments* **85**: 115001.

Ernst and Young (2011). *Economic contribution of recreational fishing in the Murray–Darling Basin*. Melbourne, Australia. (https://www.fishhabitatnetwork.com.au/userfiles/EconomicContributionofRecFishingintheMDBFinalReport08_08_20112.pdf).

Henry, G. W. and Lyle, J. M. (2003). *The National Recreational and Indigenous Fishing Survey*. FRDC Project Number 99/158, Canberra, Australia. (https://eprints.utas.edu.au/2526/1/Henry_Lyle_Nationalsurvey.pdf).

Hoanh, C. T., Facon, T., Thuon, T., Bastakoti, R. C., Molle, F. and Phengphaengsy, F. (2009). Irrigation in the Lower Mekong Basin countries: the beginning of a new era? In: F. Molle, T. Foran and M. Kakonen (eds.). *Contested Waterscapes in the Mekong Region: Hydropower, Livelihoods and Governance*. Earthscan, London, U.K., 143–172 pp.

Hortle, K. G. (2007). Consumption and the yield of fish and other aquatic animals from the Lower Mekong Basin. *MRC technical paper* **16**: 1–88.

Lynch, A., Baumgartner, L. J., An V, V., Boys, C. A., Conallin, J., Cowx, I., Finlayson, C. M., Franklin, P. A., Hogan, Z., Koehn, J. D., McCartney, M. P., O'Brien, G., K., P., L.G.M., S., Tob, C. A., Valbo-Jørgensen, J., Whiting, L. and Wibowo, A. (2019). Speaking the same language: Using the SDGs to talk inland fish into irrigation decisions. *Marine and Freshwater Research* **70**: 1211–1228.

Marttin, F. and De Graaf, G. J. (2002). The effect of a sluice gate and its mode of operation on mortality of drifting fish larvae in Bangladesh. *Fisheries Management and Ecology* **9**: 123–125.

Meyer, W. S. (2005). *The irrigation industry in the Murray and Murrumbidgee Basins*. Technical Report No. 03/05. (http://www.clw.csiro.au/publications/waterforahealthycountry/2005/IrrigationIndustryMurrayCRCIF.pdf).

MRC (2018). *Irrigation Database Improvement for the Lower Mekong Basin*. MRC Technical Report No. 1. The Mekong River Commission, Vientiene, 122 pp.

Nam, S., Phommakone, S., Vuthy, L., Samphawamana, T., Son, N. H., Khumsri, M., Bun, N. P., Sovanara, K., Degen, P. and Starr, P. (2015). Lower Mekong fisheries estimated to be worth around $17 billion a year. *Catch and Culture* **21**: 4–7.

Pflugrath, B. D., Boys, C. A., Deng, Z. D. and Cathers, B. (2016). Sensor Fish: using an autonomous sensor to quantify hydraulic conditions experienced by fish when passing downstream through river infrastructure. In: *Proceedings of the 11th International Symposium on Ecohydraulics*. Melbourne, Australia, 7–12 February 2016.

Pflugrath, B. D. (2017). Quantifying Stressors and Predicting Injury and Mortality in Fish Passing Downstream Through Weirs and Turbines. Doctorate of Philosophy Thesis, UNSW. 158 pp.

Pflugrath, B. D., Boys, C. A., Cathers, B. and Deng, D. Z. (2019). Over or under? Autonomous sensor fish reveals why overshot weirs may be safer than undershot weirs for fish passage. *Ecological Engineering* **132**: 41–48.

Rowland, S. J. (2004). Overview of the history, fishery, biology and aquaculture of Murray cod (Maccullochella peelii peelii). In: *Proceedings of the Management of Murray cod in the Murray-Darling Basin*. Canberra, Murray Darling Basin Commission, 3–4.

10.2 List of publications produced by project

Baumgartner, L. and Boys, C.A. (2016). Lao Ministry of Agriculture and Forestry hosts international fishway conference. *Catch and Culture* **22**: 34–37.

Baumgartner, L. J., Boys, C. A., Barlow, C. and Roy, M. (2017). Lower Mekong Fish Passage Conference: Applying innovation to secure fisheries productivity. *Ecological Management & Restoration* **18:** doi: 10.1111/emr.12272.

Baumgartner, L. J., Barlow, C., Mallen-Cooper, M., Boys, C. A., Marsden, T., Thorncraft, G., Phonekhampheng, O., Singhanouvong, D., Rice, W., Roy, M., Crase, L. and Cooper, B. (2019). Achieving fish passage outcomes at irrigation infrastructure; a case study from the Lower Mekong Basin. *Developments in Aquaculture and Fisheries Science* **Early online release (https://doi.org/10.1016/j.aaf.2018.12.008)**: 1–12.

Boys, C. A., Phonekhampeng, O., Singhanouvong, D. and Thorncarft, G. (2015). Restoring fish passage to wetland habitats of the Lower Mekong Basin: What goes up, must come down. *Paper presented at 145th Annual Conference of the American Fisheries Society. Special session: "Sustaining Diverse Fisheries in the Mekong Basin"*. 16–20 August 2015. Portland, Oregon, USA.

Boys, C. A., Singhanouvong, D., Phonekhampeng, O. and Thorncarft, G. (2015b). Opening Lao floodplains for migrating fish: not just an uphill battle. *Catch and Culture* **21**.

Boys, C. A. (2016). Fish and Rice – Developing Sustainable Infrastructure to Protect Inland Fisheries. *Paper presented at Lower Mekong Fish Passage Conference. 14th-18th November 2016*. Lao Plaza Hotel, Vientiane, Lao PDR.

Boys, C. A., Brown, R. S., Deng, Z. D., Baumgartner, L. J., Pflugrath, B. D., Silva, L. G., Phonekhampeng, O. and Thorncarft, G. (2016). Ecohydraulic research to protect downstream migrating fish at hydropower and other river infrastructure: solving a global problem through international collaboration. *In: Proceedings of the 11th International Symposium on Ecohydraulics*. Melbourne, Australia, 7–12 February 2016.

Boys, C. A. and Baumgartner, L. J. (2017). Refinement of fish-friendly criteria for hydropower and irrigation diversions. *Paper presented at Integrating Multiple Aquatic Values: The 5th Biennial Symposium of the International Society for River Science*. 15–24th November 2017. Hamilton, New Zealand.

Boys, C. A. and Baumgartner, L. J. (2017). Impacts of weirs on downstream passage of native fish in the Murray-Darling Basin. *Paper presented at Integrating Multiple Aquatic Values: The 5th Biennial Symposium of the International Society for River Science*. 15–24 November 2017. Hamilton, New Zealand.

Cooper, B., Crase, L. and Baumgartner, L. J. (2019). Estimating benefits and costs: a case of fish passages in Lao PDR and the development of the Lower Mekong Fishway Support Tool. *Marine and Freshwater Research* **70**: 1284–1294.

Homsombath, K. and Boys, C. A. (2016). Irrigation regulator design influences mortality of downstream migrating Mekong species. *Paper presented at Lower Mekong Fish Passage Conference. 14th–18th November 2016*. Lao Plaza Hotel, Vientiane, Lao PDR.

Kelly, B. (2016). Building fish friendly gates: the importance of contractor involvement. *In: Proceedings of the Lower Mekong Fish Passage Conference*. Lao Plaza Hotel, Vientiane, Lao PDR, 15th–18th November 2016.

Lynch, A., Baumgartner, L. J., An V, V., Boys, C. A., Conallin, J., Cowx, I., Finlayson, C. M., Franklin, P. A., Hogan, Z., Koehn, J. D., McCartney, M. P., O'Brien, G., K., P., L.G.M., S., Tob, C. A., Valbo-Jørgensen, J., Whiting, L. and Wibowo, A. (2019). Speaking the same language: Using the SDGs to talk inland fish into irrigation decisions. *Marine and Freshwater Research* **70**: 1211–1228.

Pflugrath, B. D. (2017). Quantifying Stressors and Predicting Injury and Mortality in Fish Passing Downstream Through Weirs and Turbines. Doctorate of Philosophy Thesis, UNSW. 158 pp.

Pflugrath, B. and Boys, A., Craig (2016). Predicting pressure-related fish passage success through irrigation infrastructure. *Paper presented at Lower Mekong Fish Passage Conference*. 14th–18th November 2016. Lao Plaza Hotel, Vientiane, Lao PDR.

Pflugrath, B. D. and Boys, C. A. (2015). Quantify Hydraulic Conditions Fish Encounter Passing Downstream Through River Infrastructure. *Paper presented at Annual Conference of the Australian Society of Fish Biology*. Sydney, New South Wales, Australia.

Pflugrath, B. D., Boys, C. A., Deng, Z. D. and Cathers, B. (2016). Sensor Fish: using an autonomous sensor to quantify hydraulic conditions experienced by fish when passing downstream through river infrastructure. *In: Proceedings of the 11th International Symposium on Ecohydraulics*. Melbourne, Australia, 7–12 February 2016.

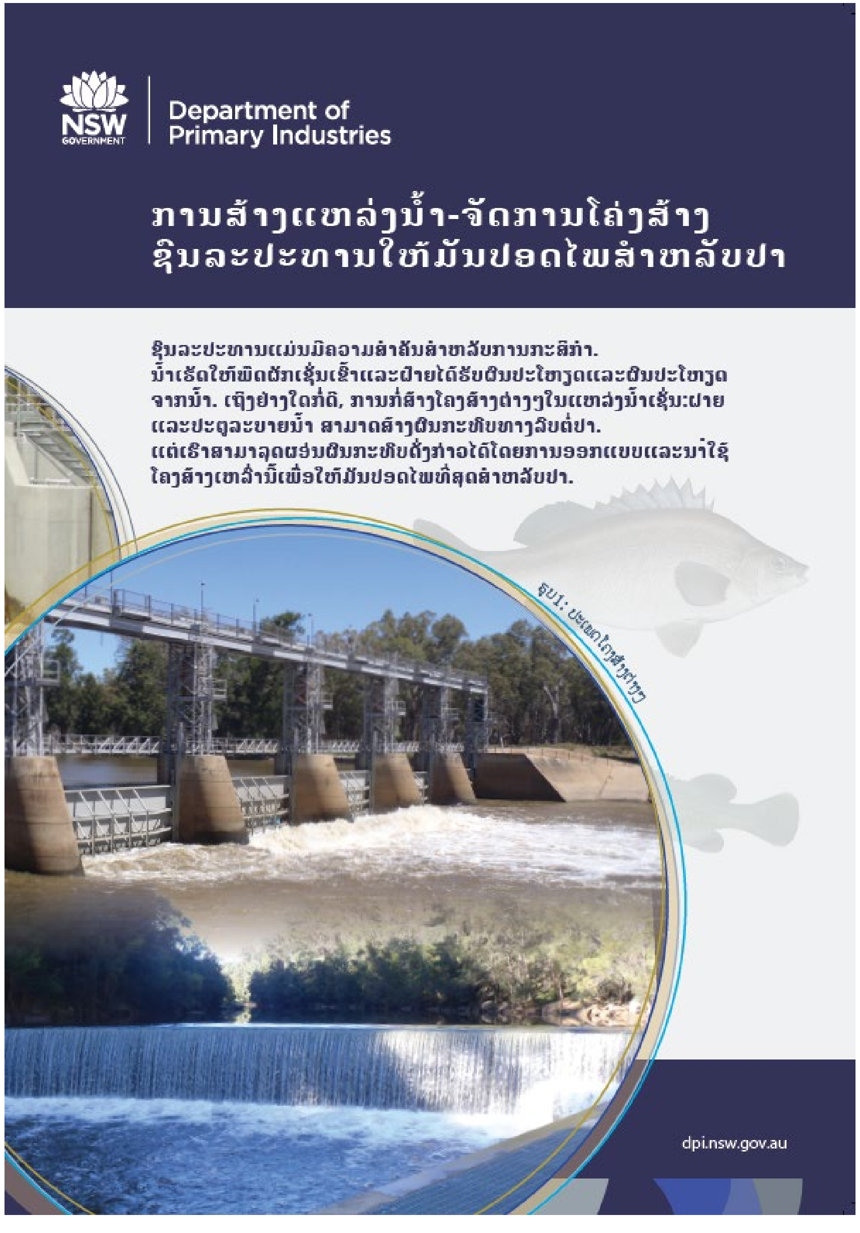
Pflugrath, B. D., Boys, C. A., Cathers, B. and Deng, D. Z. (2019). Over or under? Autonomous sensor fish reveals why overshot weirs may be safer than undershot weirs for fish passage. *Ecological Engineering* **132**: 41–48.

Phommavong, T., Phonekhampeng, O., Singhanouvong, D., Thorncarft, G. and Boys, C. A. (2015a). Fish movement through a wetland floodgate in the Lower Mekong Basin. *Paper presented at 145th Annual Conference of the American Fisheries Society*. 16–20th August 2015. Portland, Oregon, USA.

Phommavong, T., Phonekhampheng, O., Singhanouvong, D., Thorncarft, G. and Boys, A., Craig (2015b). Going with the flow: Over 100 species sampled exiting a lower Mekong wetland. *Paper presented at 145th Annual Conference of the American Fisheries Society. Special session: "Sustaining Diverse Fisheries in the Mekong Basin"*. 16–20 August 2015. Portland, Oregon, USA.

11 Appendixes

11.1 Appendix 1: Nontechnical guidelines for the best-practice design and operation of water-control structures for safe downstream fish passage (in both Lao and English language)



Water control structures impact fish

There are many types of water-control structures. They allow rainfall and river flows to be captured and delivered when and where water is needed by farmers.

There are generally two main types: 'overshot' structures send water over the top of the gate or crest, while 'undershot' structures pass water underneath the gate (Figure 1 - Front cover).

Scientists have used electronic sensors called 'Sensor Fish' (Figure 2) to measure the conditions that a real fish would experience as it moves downstream past a water control structure. The data shows that fish are exposed to stresses such as collisions, rapid drops in pressure and strong turbulence (resulting in shear forces). These stresses are rarely found in natural, flowing rivers and can damage or kill eggs, larvae, juvenile and adult fish. Common injuries include decapitation, wounds, bleeding, loss of scales and eye injuries.

Many more fish eggs and larvae are injured by undershot structures compared to overshot structures.

Impacts on individual fish lead to impacts to entire fish populations. Over time, water-control structures block natural fish movements and migrations, reducing the health and abundance of fish populations. Because fish need to move up and down rivers, and from the main river channel out onto floodplains, structures that block or kill fish ultimately stop them from completing their life cycles, finding food, breeding and recolonising key habitat after drought. This results in less fish in the river for people to catch.

Over time, water-control structures block natural fish movements and migrations, reducing the health and abundance of fish populations.

FIGURE 2: An electronic 'Sensor Fish' is a device that can collect data about the stresses that real fish experience as they travel downstream and through water control structures.

Fixing the problem

Major efforts have been made over the past few decades to help fish move upstream past water-control structures. Fishways have been installed at many sites and have delivered real fisheries benefits. Fishways work like a set of stairs that fish can swim up and over instream structural barriers (Figure 3).

Downstream fish movements are equally important as upstream movements but have received far less attention. Downstream movement through/underneath a water-control structure may only take a fraction of a second, however, even this short time can be dangerous or fatal.

Sensor Fish experiments show that the design and operation of water control structures are critical to fish safety. Structures can be made more "fish-friendly" by reducing the physical stresses that fish experience, thereby allowing them to pass safely downstream.

As irrigation systems are expanded and upgraded, there is a substantial opportunity to fix this problem. These innovations will help enhance fish populations and improve the fishing, nutrition and livelihoods of vulnerable regional communities.

As irrigation systems are expanded and upgraded, there is a substantial opportunity to fix this problem. These innovations will help enhance fish populations and improve the fishing, nutrition and livelihoods of vulnerable regional communities.

Making structures safer for downstream moving fish

There are several simple changes we can make to improve water-control structures for fish safety.

1. **Send fish over the top.** Use structures that discharge water over the top (overshot), not underneath (undershot). Undershot gates injure more fish and are especially dangerous for small fish.
2. **Create soft landings.** Create deeper water downstream of overshot structures, so fish do not hit concrete or other hard surfaces. Maintain a downstream water depth that is at least 70% of the difference between upstream and downstream water levels. Tailwater can be increased by using downstream drop-boards or by excavating a plunge pool.
3. **Upgrade undershot structures.** If the use of an undershot structure is unavoidable, fish injuries can be reduced by meeting the following conditions:

a. **Create a downstream ramp.** The downstream apron should ramp down and away from the structure, thus reducing the risk and severity of downstream collisions.

b. **Operate in a "drowned state".** Keep the downstream water level above the bottom edge of the undershot gate. This dissipates energy, which means fish are less likely to be exposed to extreme stresses.

c. **Keep it low.** As the difference between the upstream and downstream water levels (the head) increases, so too does velocity and the likelihood of fish collisions and shear stresses.

d. **Maximise "slot height".** A narrower gate opening (known as the slot height) results in a higher likelihood of a fish striking the concrete below the bottom edge of the gate. Releasing water through fewer gates will ensure maximum slot height of any one gate.

e. **Keep it closed when fish are on the move.** Avoid operating undershot structures at times when egg and larval fish are drifting downstream. This might be hard to achieve, but is the best way to protect fish from injuries.

It works!

Following these simple guidelines is already helping thousands of fish migrate safely, thus improving the productivity of fisheries in both the Mekong and Murray-Darling Basins.

In the small village of Pak Peung in Laos, the refurbishment of an undershot regulator is already delivering benefits to a wetland fishery. The Pak Peung Wetland Regulator in the Bolikhamxay Province was built in the 1960's. It stops the Mekong River flooding rice crops during the wet season and stores water for the dry season.

The concrete regulator was constructed with three manually-operated 'undershot' sluice gates. These gates disconnected the wetland from the Mekong River, preventing fish passage and removing a very productive wetland fish nursery from the river system.

A program of research funded by the Australian Centre for International Agricultural Research (ACIAR) over the past decade has restored fish passage at the regulator (Figure 3), and has become the first project in the region to demonstrate an integrated approach incorporating safe upstream and downstream fish passage simultaneously.

The first step was to fix upstream movement from the river into the wetland. A cone fishway was installed, which has allowed over 170 fish species and hundreds of kilograms of fish per day to move into the wetland.

Figure 3. Fish passage was restored both into and out of the Pak Peung wetland. A cone fishway was used to allow fish to move upstream into the wetland and fish-friendly gates were installed to facilitated downstream movement back into the river.

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The second step was to restore downstream movement, back into the river. The original undershot gates were passing 100 species and up to 170 fish per hour from moving downstream. These gates were replaced with overshot lay-flat gates with an excavated plunge pool. Subsequent research has shown that these gates are now creating safer hydraulic conditions for fish.

The gates were manufactured in Australian and then shipped to Lao PDR, where they were assembled and installed on site within a day – a fast and effective fix!

This solution is helping fish that have bred or grown in the wetland to survive the return migration to the Mekong River, thus contributing to future generations of fish for the ecosystem and capture fishery.

Many more projects like this are being undertaken in the Murray-Darling Basin, Australia. A great example is Yallakool Creek Weir near Deniliquin in southern New South Wales (Figure 4). There, 90 km of river has been opened up to native fish by installing a vertical-slot fishway for upstream passage and "fish-friendly" lay-flat gates with a deeply excavated plunge pool for downstream passage

Acknowledgements

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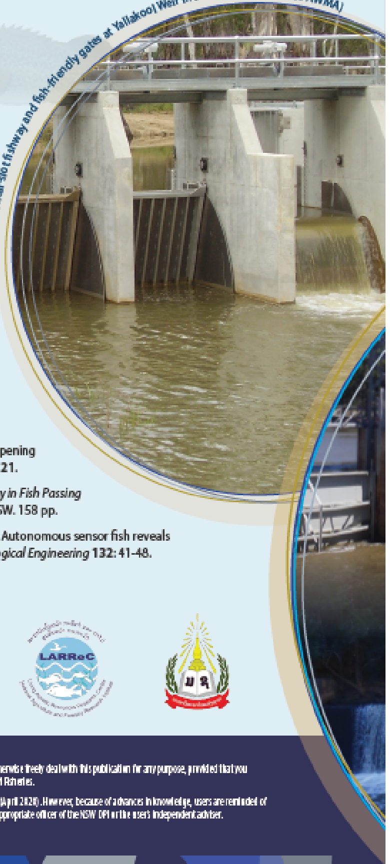

FIGURE 4. A vertical-slot fishway and fish-friendly gates at Yallakool Weir in southern NSW (photo AWMA)

Find out more

Boys, C. A., Pflugrath, B. D., Singhanouvong, D., Phonekhampeng, O., Thorncraft, G., Phommavong, T., Vorasan, P., Homsombath, K., Baumgartner, L., Fowler, T. and Kelly, B. (2020). *Improving the design of irrigation infrastructure to increase fisheries production in floodplain wetlands of the Lower Mekong and Murray-Darling Basins.* Final Report to ACIAR for project FIS/2012/100. ACIAR, Canberra, 76pp. Available for download at www.aciar.gov.au

Boys, C. A., Singhanouvong, D., Phonekhampeng, O. and Thorncraft, G. (2015). Opening Lao floodplains for migrating fish: not just an uphill battle. *Catch and Culture* **21**.

Pflugrath, B. D. (2017). *Quantifying Stressors and Predicting Injury and Mortality in Fish Passing Downstream Through Weirs and Turbines.* Doctorate of Philosophy Thesis, UNSW. 158 pp.

Pflugrath, B. D., Boys, C. A., Cathers, B. and Deng, D. Z. (2019). Over or under? Autonomous sensor fish reveals why overshot weirs may be safer than undershot weirs for fish passage. *Ecological Engineering* **132**: 41-48.

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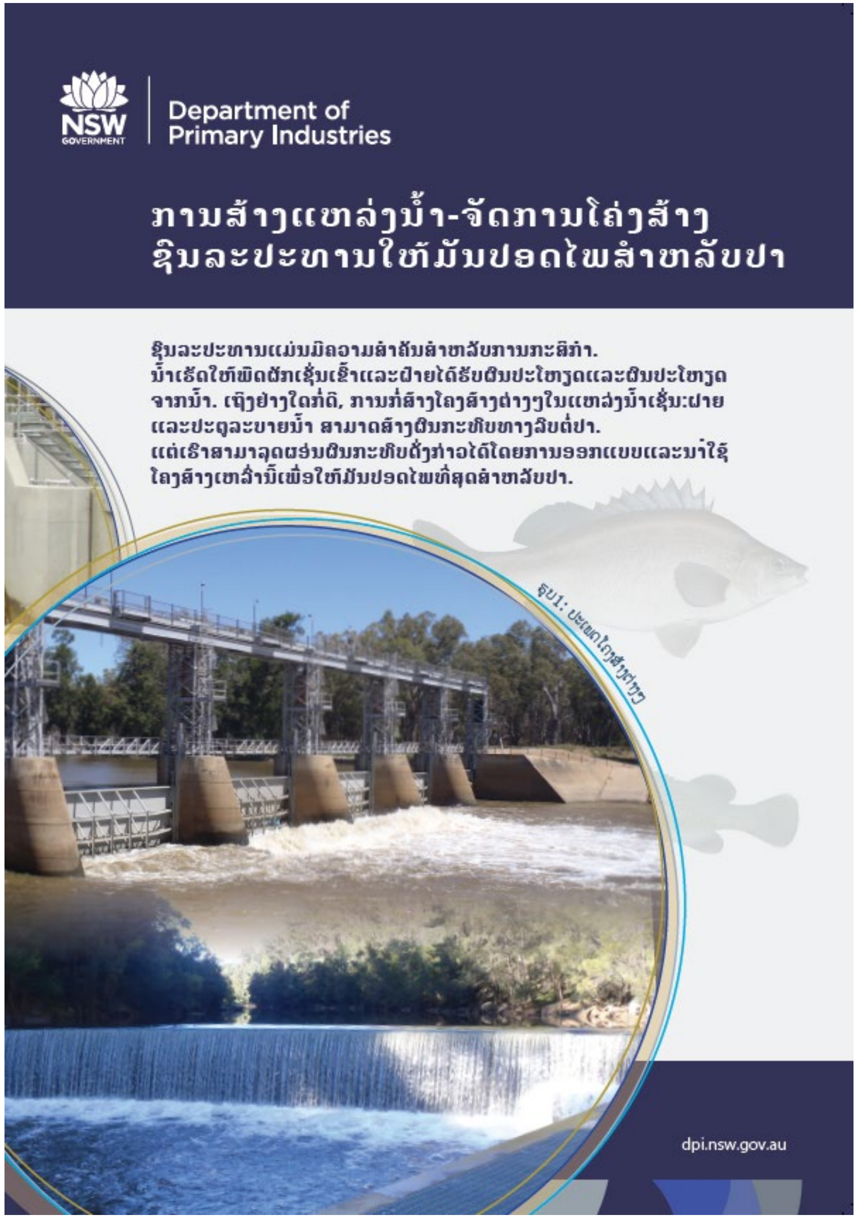
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Department of Primary Industries
ການສ້າງແຫລ່ງນ້ຳ-ຈັດການໂຄ່ງສ້າງ
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ນ້ຳເຮັດໃຫ້ພືດຜັກເຊັ່ນເຂົ້າແລະຝ້າຍໄດ້ຮັບຜົນປະໂຫຍດແລະຜົນປະໂຫຍດ
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ແລະປະຕູລະບາຍນ້ຳ ສາມາດສ້າງຜົນກະທົບທາງລົບຕໍ່ປາ.
ແຕ່ເຮົາສາມາລຸດຜ່ອນຜົນກະທົບດັ່ງກ່າວໄດ້ໂດຍການອອກແບບແລະນຳໃຊ້
ໂຄງສ້າງເຫລົ່ານີ້ເພື່ອໃຫ້ມັນປອດໄພທີ່ສຸດສຳຫລັບປາ.
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ຜົນກະທົບຂອງໂຄງສ້າງຕ່າງໆຕໍ່ປາ
ຫລາຍປີຜ່ານມາ, ໂຄງສ້າງໃນແມ່ນ້ຳເຊັ່ນ: ຝາຍ, ເຂື່ອນ ແລະ
ປະຕູລະບາຍນ້ຳແມ່ນໄດ້ກີດຂວາງການເຄື່ອນຍ້າຍຂອງປາ ແລະ
ການຂຶ້ນລົງຂອງປາ, ຄວາມອຸດົມສົມບູນ ແລະ ຄວາມລາກ
ຫລາຍຂອງປາກໍ່ລົດລົງ.
ຮູບ2. ປາທຽມ ໃຊ້ວັດແທກຜົນກະທົບຂອງປາ ໃນເວລາຜ່ານໂຄງສ້າງ
ການແກ້ໄຂບັນຫາ
ເນື່ອງຈາກວ່າລະບົບຊົນລະປະທານແມ່ນການຂະຫຍາຍ
ຕົວແລະຍົກລະດັບຕະຫລອດ, ມັນມີນຶ່ງດຽວໂອກາດທີ່ຈະ
ແກ້ບັນຫານີ້ໄດ້. ນະວັດຕະກຳ ຈະຊ່ວຍຍົກຜົນຜະລິດປາ
ແລະ ປັບປຸງການຫາປາ, ທາດອາຫານ ແລະ ຊີວິດການ
ເປັນຢູ່ຂອງຄົນໃນຊຸມຊົນໄດ້.

ໂຄງສ້າງທີ່ປອດໄພ ສຳຫລັບປາທີ່ລ່ອງລົງ

ມັນມີຫລາຍວິທີງ່າຍໆທີ່ເຮົາສາມາດປັບແປງ ແລະ ປັບປຸງໂຄງສ້າງຊົນລະປະທານໃຫ້ມີຄວາມປອດໄພສຳຫລັບປາ.

1. **ປ່ອຍປາຢູ່ເທິງນ້ຳລົ້ນ.** ໃຊ້ໂຄງສ້າງຊົນລະປະທານທີ່ລະບາຍນ້ຳແບບນ້ຳລົ້ນ ບໍ່ແມ່ນແບບນ້ຳລອດພື້ນ ເພາະປະຕູລະບາຍນ້ຳແບບນ້ຳລອດພື້ນມັນເຮັດໃຫ້ປາບາດເຈັບຫລາຍກວ່າແລະອັນຕະລາຍຫລາຍສຳຫລັບປານ້ອຍ.
2. **ສ້າງຈຸດບ່ອນປາຈະຕົກໃສ່ໃຫ້ມັນອ່ອນນຸ່ມ.** ສ້າງຈຸດບ່ອນນ້ຳລົ້ນຈະຕົກລົງໃສ່ໃຫ້ມັນເລິກທີ່ສຸດ, ສະນັ້ນ ປາຈະບໍ່ກະແທກ/ຕຳໃສ່ພື້ນທີ່ເຮັດດ້ວຍຊີມັງ ຫລື ວັດຖຸທີ່ແຂງ. ຮັກສາລະດັບຄວາມເລິກຂອງນ້ຳຢູ່ເທິງແລະກລັງປະຕູລະບາຍນ້ຳໃຫ້ໄດ້ 70%. ຍົກລະດັບນ້ຳຫລັງປະຕູລະບາຍນ້ຳໂດຍໃຊ້ແຜນຮັບນ້ຳ ຫລື ສ້າງວັງນ້ຳເລິກຢູ່ຈຸດນ້ຳຕົກໃສ່.
3. **ຍົກລະດັບໂຄງສ້າງນ້ຳລອດພື້ນ.** ຖ້າຫລີກລ່ຽງການນຳໃຊ້ປະຕູລະບາຍນ້ຳແບບນ້ຳລອດພື້ນບໍ່ໄດ້, ອັດຕາການບາດເຈັບຂອງປາສາມາດລຸດຜ່ອນໄດ້ໂດຍການໃຊ້ວິທີດັ່ງລຸ່ມນີ້:

a. **ສ້າງຈຸດລະລົມນ້ຳຢູ່ກລັງປະຕູລະບາຍນ້ຳ.** ຈຸດນ້ຳຕົກສຸດທ້າຍຂອງປະຕູລະບາຍນ້ຳຄວນປັບລະດັບຄອຍຊັນໃຫ້ໄກຈາກໂຄງສ້າງຂອງປະຕູລະບາຍນ້ຳ, ສະນັ້ນ, ມັນຈະຊ່ວຍລຸດຜ່ອນຄວາມສ່ຽງແລະອັນຕະລາຍຕໍ່ປາເວລາມັນມີການກະແທກ.

b. **ເປີດປິດປະຕູລະບາຍນ້ຳ ແບບ "drowned state".** ຮັກສາລະດັບນ້ຳຢູ່ຕອນທ້າຍຂອງປະຕູລະບາຍນ້ຳໃຫ້ເທົ່າກັນກັບຈຸດປ່ອຍນ້ຳລອດພື້ນ. ອັນນີ້ມັນຈະເຮັດໃຫ້ປາໄດ້ຮັບບາດເຈັບໜ້ອຍລົງ.

c. **ຮັກສາໃຫ້ມັນຕໍ່າທີ່ສຸດ.** ຍອັບວ່າຄວາມແຕກຕ່າງລະຫວ່າງລະດັບນ້ຳຕອນເທິງແລະລຸ່ມເພີ່ມຂຶ້ນ, ສະນັ້ນ ຄວາມໄວຂອງນ້ຳຈິ່ງຫລາຍຂຶ້ນແລະເກີດການກະທົບກະແທກຂຶ້ນ.

d. **ປັບລະດັບ ຄວາມສູງ ຂອງປະຕູທາງປາເຂົ້າໃຫ້ສູງຂຶ້ນ.** ຍອັບວ່າປະຕູເປີດທີ່ມີຊ່ອງແຄບໆເປີດຂຶ້ນ (ເອີ້ນວ່າລວງສູງຂອງປະຕູທາງປາເຂົ້າ) ເຮັດໃຫ້ປາໄດ້ຮັບການກະແທກຢູ່ພື້ນຂອງທ້າຍປະຕູລະບາຍນ້ຳ. ການປ່ອຍນ້ຳຜ່ານປະຕູລະບາຍນ້ຳທີ່ໜ້ອຍທີ່ສຸດ ຈະຮັບປະກັນຄວາມສູງຂອງປະຕູທາງປາເຂົ້າ

e. **ໃຫ້ຮັດປະຕູລະບາຍນ້ຳເວລາປາເຄື່ອນຍ້າຍຂຶ້ນລົງ.** ໃຫ້ຫລີກລ່ຽງການເປີດປິດປະຕູລະ ບາຍ ນ້ຳລອດພື້ນໃນຊ່ວງເວລາໄຂ່ປາແລະປານ້ອຍໄຫລລົງກລັງປະຕູລະບາຍນ້ຳ. ອັນນີ້, ມັນກໍ່ຍາກທີ່ຈະໄດ້ຮັບຜົນ, ແຕ່ມັນກໍ່ເປັນວິທີທີ່ດີທີ່ສຸດທີ່ຈະບໍ່ໃຫ້ປາໄດ້ຮັບບາດເຈັບແລະຕາຍໃນຊ່ວງເວລາມັນລ່ອງຈາກອ່າງເກັບນ້ຳຫາແມ່ນ້ຳຂອງ.

ມັນໃຊ້ໄດ້ !

ຈາກການນຳໃຊ້ບົດແນະນຳນີ້ໄດ້ຊ່ວຍປາເປັນຈຳນວນຫລວງຫລາຍຂຶ້ນແລະລ່ອງປາງປອດໄພ, ພອ້ມທັງປົກສູງຜົນຜະລິດດ້ານປະມົງຢູ່ອ່າງແມ່ນ້ຳຂອງແລະອ່າງແມ່ນ້ຳເມີຣີແດລິງ ປະເທດອົດສະຕາລີ.

ຢູ່ບ້ານປາກປິ່ງ ຂອງ ສ ປ ປ ລາວ ການປັບປຸງປະຕູລະບາຍນ້ຳແມ່ນໄດ້ນຳຜົນປະໂຫຍດຕໍ່ການປະມົງໃນອ່າງດັ່ງກ່າວ. ປະຕູລະບາຍນ້ຳຢູ່ອ່າງປາກປິ່ງ ແຂວງບໍລິຄຳໄຊ ແມ່ນໄດ້ສ້າງຂຶ້ນໃນປີ 1960, ມັນໃຊ້ເພື່ອປ້ອງກັນນ້ຳຖວ້ມບາເຂົ້າໃນຊ່ວງລະດູຝົນ ແລະ ເກັບກັກນ້ຳເພື່ອໃຊ້ໃນຊ່ວງລະດູແລ້ງ

ປະຕູລະບາຍນ້ຳປະກອບດວ້ຍ 3 ປະຕູນ້ຳລອດພື້ນຊື່ງໃຊ້ແຮງງານຄົນເປີດປິດ. ປະຕູດັ່ງກ່າວນີ້ໄດ້ຕັດການເຊື່ອມຕໍ່ລະຫວ່າງແມ່ນນ້ຳຂອງແລະອ່າງປາກປິ່ງ, ກີດຂວາງການຂຶ້ນລ່ອງຂອງປາແລະລະບົບນິເວດຂອງແມ່ນ້ຳ.

ແຜນການສຶກສາຄົ້ນຄວ້າໂດຍການສະໜັບສະໜູນທຶນຈາກອົງການເອເຊຍອາ ໃນຊ່ວງ ປີ່ງທີດສະວັດກວ່າ ໄດ້ຟື້ນຟູການໄປມາ ຫລື ຂຶ້ນລ່ອງຂອງປາ ຢູ່ປະຕູລະບາຍນ້ຳ (ຮູບທີ3). ມັນເປັນໂຄງການທຳອິດໃນຂົງເຂດແມ່ນນ້ຳຂອງຕອນລຸ່ມຊື່ງສາທິດແບບປະສົມປະສານກັນລະຫວ່າງທາງປາຂຶ້ນແລະທາງປາລ່ອງ.

ຂັ້ນຕອນທຳອິດແມ່ນໄດ້ແກ້ໄຂບັນຫາຂອງການເຄື່ອນຍ້າຍຂຶ້ນຈາກແມ່ນ້ຳຂອງຫາອ່າງປາກປິ່ງ. ທາງຜ່ານປາແບບແຂ້ວຕົ່ງໄດ້ຖືກສ້າງຂຶ້ນ, ຊື່ງສາມາດເຮັດໃຫ້ປາຫລາຍກວ່າ 170 ຊະນິດສາມາດຂຶ້ນໄດ້ ແລະ ປາຈຳນວນຫລາຍກີໂລໄດ້ເຂົ້າໄປເຖີງອ່າງດັ່ງກ່າວ.

ຂັ້ນຕອນທີ 2 ແມ່ນໄດ້ແກ້ໄຂບັນຫາການລ່ອງລົງຂອງປາຈາກອ່າງປາກປິ່ງລົງສູ່ແມ່ນ້ຳຂອງ. ປະຕູລະບານ້ຳໂຕເກົ່ານ້ຳລອດພື້ນແມ່ນມີປາຜ່ານລົງສູ່ນ້ຳຂອງ ປະມານ 100-170 ຊະນິດ. ຈາກນັ້ນ, ໄດ້ມີການຕິດຕັ້ງປະຕູລະບາຍນ້ຳໃໝ່ແບບນ້ຳລົ້ນແທນ ແລະ ສ້າງວັງນ້ຳເລິກເພື່ອເປັນຈຸດຮັບນ້ຳລົ້ນລົງ. ຜົນຂອງການສຶກສາ

ຮູບ3. ທາງຜ່ານປາໄດ້ຮັບການຟື້ນຟູທັງສອງແບບໃຫ້ປາຂຶ້ນແລະລ່ອງລົງໄດ້ຢູ່ອ່າງປາກປິ່ງ. ທາງຜ່ານປາແບບແຂ້ວຕົ່ງແມ່ນສຳຫລັບໃຫ້ປາຂຶ້ນໄປທາງອ່າງ ແລະ ປະຕູລະບາຍນ້ຳທີ່ເປັນມິດຕໍ່ປາແມ່ນຕິດຕັ້ງສຳຫລັບໃຫ້ປາລ່ອງຈາກອ່າງປາກປິ່ງລົງສູ່ແມ່ນ້ຳຂອງ.

ສະແດງໃຫ້ເຫັນວ່າປະຕູໃໝ່ນີ້ເຮັດໃຫ້ອັດຕາການບາດເຈັບຂອງປາໜ້ອຍລົງ.

ປະຕູລະບາຍນ້ຳນີ້ແມ່ນລະບົບໂຄງການຂອງປະເທດອົດສະຕາລີ ແລະ ອົບສົ່ງທາງເຮືອມາ ສ ປ ປ ລາວ, ປະກອບແລະຕິດຕັ້ງຢູ່ອ່າງປາກປິ່ງປະມານ 1 ມື້ຄ່າເວັດ-ໄວແລະມີປະສິດທິພົນ.

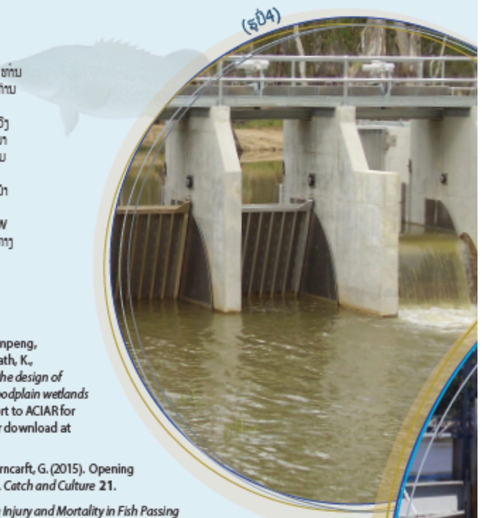
ວິທີແກ້ໄຂນີ້ແມ່ນໄດ້ຊ່ວຍໃຫ້ປາທີ່ມີການປະສົມພັນ ຫລື ກໍາລັງຈະເລີນເຕີບໂຕໃນອ່າງສາມາດກັບຄືນຫາແມ່ນ້ຳຂອງໄດ້, ສະນັ້ນ, ມັນໄດ້ຊ່ວຍປະຊາກອນປາປູ່ນໃໝ່ ລະບົບນິເວດປະມົງແລະການຫາປາ.

ປັດຈຸບັນມີຫລາຍໂຄງການທີ່ຄ້າຍກັບໂຄງການນີ້ກໍາລັງຈັດຕັ້ງປະຕິບັດໃນອ່າງມີເຣແດລິງ ປະເທດອົດສະຕາລີ. ນຶ່ງໃນແບບປາງ

ທີ່ດີແມ່ນ ປາຍ ປາລາກູດ ໂກ ເມືອງ ແກບີສິກ ທາງໃຕ້ຂອງວັດ ນິວຊາວເວ. ມີແມ່ນ້ຳຍາວ 90 ກິໂລແມັດ ໄດ້ເປີດໃຫ້ປາທຳມະຊາດເຄື່ອນຍ້າຍໄປມາໂດຍຜ່ານທາງຜ່ານປາແບບປະຕູ ສຳຫລັບໃຫ້ປາຂຶ້ນ ແລະ ໃຊ້ປະຕູລະບາຍນ້ຳແບບເປັນມິດຕໍ່ປາສຳຫລັບໃຫ້ປາລ່ອງ (ຮູບ4)

(ຮູບທີ4) ແມ່ນ້ຳຊື່ງມີຄວາມຍາວ 90 ກິໂລແມັດໄດ້ເປີດຊ່ອງທາງໃຫ້ປາໄດ້ເຄື່ອນຍ້າຍໄປມາໂດຍການຕິດຕັ້ງທາງຜ່ານປາແບບປະຕູທາງຕັ້ງ ແລະ ປະຕູລະບາຍນ້ຳທີ່ເປັນມິດຕໍ່ປາຢູ່ຝາຍ ຍາລາກູນທາງໃຕ້ຂອງປະເທດອົດສະຕາລີ.

(ຮູບ4)



ສະແດງຄວາມຮູ້ບຸນຄຸນ

ບົດແນະນຳສຳຫລັບທາງປາລ່ອງນີ້ແມ່ນອີງຈາກການສຶກສາຫລາຍປີຂອງ ທ່ານ Craig Boys ຈາກ (NSW Department of Primary Industries); ທ່ານ Brett Pflugrath (UNSW); ດຣ Lee Baumgartner (CSU ມະຫາວິທະຍາໄລຊາລສ); ດຣ ອຸດົມ ພອນຄຳພັນ; ທ່ານ ທອງຫລອມ ພົມມະວົງ ; ທ່ານ Garry Thorncraft; ທ່ານ ທູສອນ ວໍລະສານ (ມະຫາວິທະຍາໄລແຫ່ງຊາດ); ທ່ານ ດວງຄໍາ ສິງຫານຸວົງ ແລະ ທ່ານ ນາງ ຄໍາແຫຼງ ຫອມສົມບັດ (ສູນຄົ້ນຄວ້າການປະມົງ); ແລະ ທ່ານ Brett Kelly (AWMA Water Control Solutions). ການສຶກສາຄົ້ນຄວ້າແລະເຮັດບົດແນະນຳສະບັບນີ້ແມ່ນໄດ້ຮັບການສະໜັບສະໜູນຈາກສູນຄົ້ນຄວ້າກະສິກຳນາໆຊາດຂອງປະເທດອົດສະຕາລີ (ACIAR, project FIS/2012/100), NSW Department of Primary Industries ແລະ UNSW ຈ່າຍຄ່າເດີນທາງ ແລະກິນຢູ່ໃຫ້ ທ່ານ Brett Pflugrath.

Find out more

Boys, C. A., Pflugrath, B. D., Singhanouvong, D., Phonekhampeng, O., Thorncarft, G., Phommavong, T., Vorasan, P., Homsombath, K., Baumgartner, L., Fowler, T. and Kelly, B. (2020). *Improving the design of irrigation infrastructure to increase fisheries production in floodplain wetlands of the Lower Mekong and Murray-Darling Basins.* Final Report to ACIAR for project FIS/2012/100. ACIAR, Canberra, 76pp. Available for download at www.aciar.gov.au

Boys, C. A., Singhanouvong, D., Phonekhampeng, O. and Thorncarft, G. (2015). Opening Lao floodplains for migrating fish: not just an uphill battle. *Catch and Culture* **21**.

Pflugrath, B. D. (2017). *Quantifying Stressors and Predicting Injury and Mortality in Fish Passing Downstream Through Weirs and Turbines.* Doctorate of Philosophy Thesis, UNSW. 158 pp.

Pflugrath, B. D., Boys, C. A., Cathers, B. and Deng, D. Z. (2019). Over or under? Autonomous sensor fish reveals why overshot weirs may be safer than undershot weirs for fish passage. *Ecological Engineering* **132**: 41-48.

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