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Achieving fish passage outcomes at irrigation infrastructure; a case study from the Lower Mekong Basin

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ABSTRACT

Irrigation infrastructure expansion threatens the diversity of freshwater fish worldwide. Irrigation infrastructure creates migration barriers which can block access to important nursery, feeding and spawning habitat. Lao PDR is a landlocked country situated within the Lower Mekong River Basin where there is a substantial dependency on rice and fish for food, income and livelihoods. The country is experiencing an unprecedented boom in irrigation infrastructure investment, with modernisation programs being implemented in every province. Despite significant investment in infrastructure upgrades, and the potential impact on freshwater fish, little consideration has been given to fish passage solutions. In 2008, we commenced a fish passage program in Lao PDR. The intent of this case study is to outline the pivotal elements of the program of knowledge development and transfer, in the context of river connectivity and fisheries management in Lao PDR. We also highlight challenges in international research in development and lessons learned.

1. Background and context

1.1. Irrigation and fisheries

River development for irrigation and water supply is greatly impacting global aquatic resources (Nilsson, Reidy, Dynesius, & Revenga, 2005). Irrigation infrastructure is essential to help meet food demands of a growing global population and is expected to expand significantly over the next two decades (Döll & Siebert, 2002). Irrigation infrastructure, however, can adversely impact aquatic fauna, especially fish (Anderson, Moggridge, Warren, & Shucksmith, 2015; Benejam, 2016; Mbaka & Wanjiru Mwaniki, 2015; Mueller, Pander, & Geist, 2011). Fish are particularly susceptible to altered flow regimes, migration pathway obstructions and restricted access to essential habitats (Lucas & Baras, 2001).

There can be significant environmental, social and financial cost if the migration needs of fish populations are not considered and protected at the time infrastructure design and installation. Examples of this can be seen throughout the world. In the North America, the Columbia River salmon fishery crashed following dam construction and required $US 7B (over 50 years) invested from hydropower profits into applied research and rehabilitation to save the fisheries resource base (Williams, 2008). Within the Murray-Darling Basin, Australia, the extensive expansion of river regulation involving dam and weir construction over the past century has contributed to a 90% decline in native fish populations (Koehn, Lintermans, & Copeland, 2014). These examples highlight two points. Firstly, that many countries around the world have a shared experience when facing the challenge posed to fisheries by river infrastructure development, and secondly, that it can be of significant environmental, social and financial cost if the migration needs of fish populations are not considered and protected at the time infrastructure is designed and installed. Specific engineering solutions, supported by strong guidelines, legislation and policy, are needed to ensure fish are protected both now and in the future.

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There has been extensive investment into development of fish passage technologies to minimise the impacts of developments like hydropower and irrigation on fisheries (Baumgartner, Reynoldson, Cameron, & Stanger, 2009; Baumgartner, Zampatti, Jones, Stuart, & Mallen-Cooper, 2014; Stuart, Zampatti, & Baumgartner, 2008). However, this investment has largely been focused in the developed world and investment has not been matched in the developing world. Globally it is in the developing world where the expansion of river infrastructure, whether for hydropower or irrigation supply, is the greatest, and communities are still largely dependent on aquatic resources. Failure to address this global inequity in investment in fish passage research and development will impact some of the world's largest freshwater fisheries, and the vulnerable and impoverished people who rely on them for their health and livelihoods.

Most recently scientists have begun to call for a more collaborative global effort of science and knowledge sharing to improve the efficiency and adoption of best-practice fish passage research and development (Baumgartner et al., 2014; Silva et al., 2018).

The Lower Mekong Basin (LMB) and broader Asian region is a critical part of this collaborative effort. Irrigation infrastructure is expanding at a significant rate with little consideration for environmental impacts and potential mitigation strategies. Although individual governments are concerned for their fisheries and other aquatic resources, there is currently no formal regional coordination of on-ground initiatives between governments, industry, foreign aid providers, and research agencies. Without coordination there is a risk of investment in redundant research, or worse still, applying technology that will not work in the local context. Global information sharing is therefore critical to drive sound policy and actions required to promote inland fisheries sustainability whilst still supporting the economic development of the region.

1.2. Fisheries in the Mekong region

The Mekong River supports one of the most productive inland fisheries in the world (Hortle, 2009). Its productivity stems from being a large tropical river system with a predictable monsoon inundating large areas of wetlands (Baran, Geurin, & Nasielski, 2015; Dudgeon, 2000), coupled with a biodiverse fish fauna of 900–1000 species (Valbo-Jorgensen, Coates, & Hortle, 2009). Many species migrate seasonally between different habitats, which has implications for maintenance of fisheries in the context of development of dams and other water management structures (Baran, 2010; Halls & Kshatriya, 2009; Valbo-Jorgensen et al., 2009; Ziv, Baran, Nam, Rodríguez-Iturbe, & Levin, 2012). Barriers on these pathways can interrupt important lifecycle stages and can result in large-scale population collapses. For instance, Pak Mun Dam (Mun River, Thailand) reduced daily fish catches in upstream reaches by 60–80%, and 169 species became locally extinct (Roberts, 2001). Such reduced fish availability can impact negatively on livelihoods and human nutrition (Orr, Pittock, Chapagain, & Dumaresq, 2012).

The Lower Mekong Basin fisheries have substantial economic and nutritional importance. More than 80% of rural households in Lao, Thailand and Cambodia and 60–95% of households in the Mekong delta in Vietnam were involved in capture fisheries (Hortle, 2007). The yield of fish and other aquatic animals (OAAs; such as molluscs and crustaceans) is estimated to be 1.3–2.7 million tonnes per year, based on both consumption studies and wetland productivity analyses (Hortle & Bamrungrach, 2015). The amount of freshwater fish and OAAs consumed in 2000 averaged 34 kg/capita/year; this constituted 48%, 47%, 80% and 59% of the animal protein in the Mekong regions of Lao PDR, Thailand, Cambodia and Vietnam, respectively (Hortle, 2007). The first sale value of the fishery, based on a yield of 2.3 million tonnes, has been estimated to be US$17 billion (Nam et al., 2018). In the comparatively small economies of Cambodia and Lao PDR, the inland fishery is equivalent to 18% and 13% respectively of gross domestic production (Nam et al., 2018).

A common issue among rural households, especially following periods of rapid rural development, is fishery decline. This can be particularly damaging to poor rural communities as their livelihood strategies are generally highly reliant on wild fisheries productivity (Garaway, 2005). If fisheries decline, protein must be bought, or caught, from elsewhere, which reduces disposable labour and income resources (Millar et al., 2018). But this can be avoided if rural development programs are designed to promote both agricultural production and fisheries productivity enhancement. These win-win outcomes should therefore be important components of rural infrastructure programs.

1.3. Water management and river (dis)connectivity

Dry season cropping can increase agricultural productivity, but it requires water to be captured and stored. In this context, the Lower Mekong basin is facing an unprecedented level of irrigation development (Hoanh et al., 2009). Increased irrigation development alone has led to construction of numerous (in excess of 10,000) low-level structures which limit the movement of migratory fish across the Lower Mekong Basin (Daming & Kung, 1997). These irrigation infrastructures were installed to improve water security, but they negatively impact fish migration (Le, Nguyen, Wolanski, Tran, & Haruyama, 2007).

Unfortunately, irrigation infrastructure can delay or prevent fish passage at the onset of the wet-season, thus reducing the habitat area available for fish reproduction and growth (Baumgartner, 2005). Additionally, when pre-spawning fish accumulate below these barriers they become vulnerable to overexploitation and disease (Baumgartner, 2006). As a result, fish either spawn at the wrong time, in the wrong place, or do not spawn at all, therefore compromising successful recruitment. Over time, the impacts of irrigation infrastructure reduce fisheries diversity and productivity. Considering many people rely on fish for income and protein, irrigation infrastructure may on one hand provide security for rice production, but on the other, negatively impact the fisheries resource base.

Aside from physical barrier effects, regulators and associated levy banks significantly change the upstream habitat (Geist & Hawkins, 2016). For instance, most areas developed for rice production are those that flood frequently. These floodplain wetlands are productive and excellent for cultivation; however, regular flooding can damage crops. So floodplains are often levied and fitted with regulators to prevent drown-out events (Baumgartner et al., 2012). Such interruptions can significantly alter upstream habitat to a slow-flowing impoundment and can have negative impacts on fish communities (Pander, Mueller, & Geist, 2015).

1.4. Opportunities for remediation

Irrigation infrastructure presents a unique set of opportunities for remediating fish passage with a high probability of success. Irrigation is generally on land with low relief (e.g. floodplains) and hence the regulators and weirs that divert and control water are also relatively low-level structures, which results in shorter, lower-cost fishways than at high dams. Conversely, hydropower projects at large dams have other significant issues for fish passage that do not occur at irrigation infrastructure (Baumann & Stevanella, 2012). The first is hydropower turbines, which can cause mortalities of fish. The second is that flow is used to generate energy and using water to facilitate fish passage – through effective attraction and operation – is a significant conflict because of the subsequent loss of power. The third is downstream passage at very high spillways presents a much higher risk for fish than low-level irrigation infrastructure, where downstream passage is highly achievable (Prado & Pompeu, 2014).

1.5. The problems are global

In other areas of the world, fishways are used to maintain pathways for migratory fish in order to prevent large-scale fish community declines (Clay, 1995). Fishways are simply channels or pathways around or through an obstruction that enable fish to move upstream and downstream of the barrier. Fish swim through these channels and are able to complete their migrations. In particular, the development of upstream fish-passage facilities has advanced considerably in both Australia and the USA over recent years (Bunt, 2001; Mallen-Cooper & Stuart, 2007; Santos et al., 2012; Stuart & Berghuis, 2002). But it is also evident that providing downstream passage is equally important (Agostinho, Pelicice, Marques, Soares, & de Almeida, 2011).

The science justifying fish passage implementation is sound. Yet, management agencies often consider that mitigating the environmental impacts of irrigation infrastructure is an unnecessary expense, and consequently many programs proceed without fish-related considerations. Such situations are exacerbated because, institutionally, irrigation and fisheries departments are separated. If agricultural production and fisheries yield are considered in a holistic manner, there is a substantial justification for fish passage outcomes being considered as an "impact investment". That is, the costs of the initial capital outlay can be returned rapidly in highly productive systems. As a hypothetical example, a fish yield of 67–137 kg/ha/year has been estimated for wetlands in the Lower Mekong Basin, and a first sale value in the early 2000s of US$1.20–2.00/kg (Hortle, 2009; Hortle & Suntornratana, 2008). Using these data, restoration of a hypothetical wetland of 300 ha to full fisheries productivity, using fish passage technology, would return a value greater than the cost of the project within 5 years assuming the fishway cost US$150,000 (Fig. 1). The estimated economic benefit, although crude, and not including discounted future income, highlights positive net benefits. Multiplier effects from trade, nor any estimate of the associated livelihood benefits (nutrition/health and employment) from the increased fish supply would also improve the long-term benefits. It is also important to appreciate that the fish are produced by the functioning ecological system requiring little or no human input, unlike an aquaculture or other animal husbandry operation.

Many irrigation upgrade programs are taking place because existing structures, which were constructed decades ago using dated construction techniques, have fallen into disrepair (Nguyen-Khoa, Smith, & Lorenzen, 2005). Irrigation modernisation, where old infrastructure is replaced with new designs, results in structures with extended operational life (upwards of 40–50 years). These replacements provide a once-in-a-generation opportunity to increase fisheries productivity; provided that the net "benefit" of doing so justifies the capital "cost". So it is important that fishway solutions are developed and implemented for local species and contexts. It is equally important that detailed cost-benefit analyses are completed to support the inclusion of fish passage into financing business cases.

2. Case studies in adaptive management of fishway designs

Adaptive management strategies have been applied to fish passage projects worldwide for several decades (Walters, 1997). Fishway designs are constantly being developed, implemented, refined and then modified for implementation at other sites. Australia has a long history of successfully applying adaptive management strategies to improve fish migration (Barrett & Mallen-Cooper, 2006). From 1910 to 1985, Australian fisheries managers applied North American fishway designs to mitigate the impact of barriers (Mallen-Cooper & Harris, 1990). As the fishways were originally designed for salmon species, results were sub-optimal, providing limited passage for Australian native fish due to

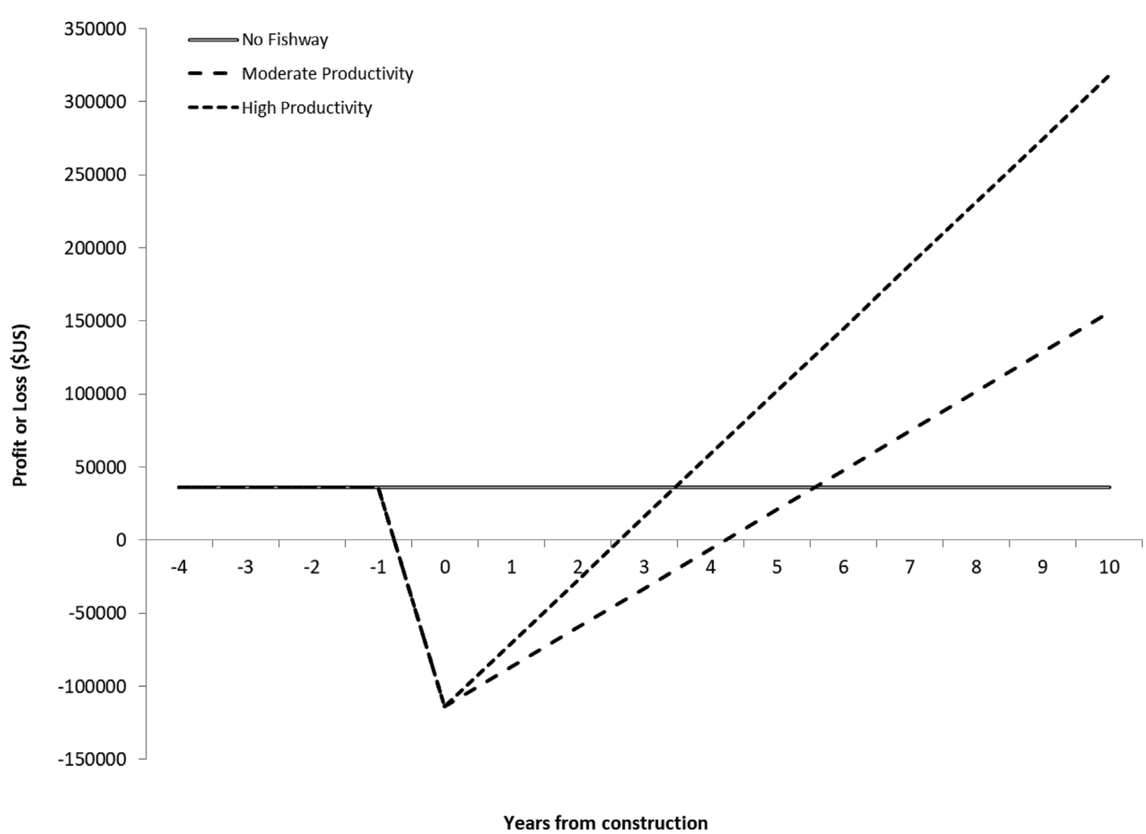

Fig. 1. Payback periods for fish passage construction. Assumes (i) a fishway construction cost of $US150,000, (ii) price at first sale of $1.20 per kg, (iii) wetland size of 300 Ha; (iv) No maintenance costs; (v) two scenarios; fish productivity rehabilitated to high productivity (120 kg.Ha, solid dark grey) and moderate productivity (75.kg.Ha, light grey). The horizontal solid line depicts a no fishway scenario. These estimates are illustrative-only and do not account for any discounting or operational costs.

inherent biological differences (Mallen-Cooper & Brand, 2007). Targeted research sought to determine how best to apply the technology to Australian systems (Mallen-Cooper, 1996).

Researchers used experimental fishways to determine the optimal internal hydraulics based on the swimming ability of Australian native fish (Mallen-Cooper, 1992). These data were analysed and applied to construct fishways based on robust criteria determined for small and large native species (Mallen-Cooper, 1996). Several highly successful fishways were constructed on the basis of these initial studies which yielded some very specific design criteria to provide passage for large fish such as floor slope, maximum velocities, design types and slot dimensions (Mallen-Cooper, Stuart, Hides-Pearson, & Harris, 1995). Later research determined that smaller species were also attempting to migrate, but were unable to ascend fishways designed for large species (Stuart, Zampatti, et al., 2008). Further targeted research was performed and fish passage guidelines were altered to improve functionality and accommodate fish with poorer swimming ability (Stuart, Baumgartner, & Zampatti, 2008). New and improved designs are now being implemented at a wide range of sites (Stuart et al., 2008). But the challenge begged, how to best apply these approaches and successes in the Lower Mekong region where fishways were a novel and untested concept?

There is no single fishway design that can adequately accommodate all fish species (Clay, 1995). A fishway can only 'minimise' the impact that regulator construction creates. The degree of benefit will be largely determined by the operating design characteristics of the fishway. For instance, some fishway designs may be better-suited to commercially important fish only (such as short, steep fishways for salmon in the Northern Hemisphere) (Williams, 2008). Alternatively, a fishway may be designed for a broader range of smaller species and river flows but be more costly to build and operate (for instance, low-gradient, multi-species vertical-slot fishways) (Baumgartner & Harris, 2007; Schwalme, Mackay, & Lindner, 1985; Stuart & Mallen-Cooper, 1999; Winter & Van Densen, 2001). The cost of the fishway also needs to fit within the cost limitations of the overall construction budget and have clear fish passage objectives, so a balance is needed between operational effectiveness and project budget. Ideally, the cost of a fully-functioning fishway should be included into all irrigation infrastructure projects from concept to completion. Furthermore, long term monitoring should also be financed to ensure longer term fisheries yield and ecological responses can feedback into adaptive management frameworks. Where the benefits demonstrably exceed the costs, it should be the case that a fish passage is included.

At the technical level, there are several requirements to build an effective fish pass in a developing country. These include:

- Background
  - ➢ Consult with local irrigation bodies and villages to ensure local perspectives and operation parameters are captured in planning.
  - ➢ Consider the local fish fauna, especially the minimum and maximum size of fish, and the season and flows on which these are fish are likely to be migrating, whether benthic or pelagic.
  - ➢ Understand the local river hydrology over the annual hydrological cycle and link this to the season/period of migration. This defines the operating ranges; especially the range of upstream and downstream water levels. These are the fundamental building blocks of fishway design and are sometimes overlooked, which prevents the fishway functioning and passing fish.
- Design
  - ➢ Entrance location; if fish cannot locate an entrance, or is delayed in doing so, then the fishway will be ineffective. The entrance must be effective over the full complement of flows on which fish are migrating. General design principles are to: locate the entrance at the upstream limit of migration (near the weir face), maintain entrance discharge as a distinguishable flow (i.e. not masked by other turbulent flow), use additional flow to provide high attraction.
  - ➢ Fishway channel. Select a suitable design; there are many fishway types that exist and can be adapted to a range of scenarios. Internal hydraulics (depth, velocity, turbulence) must be suited to local species.
  - ➢ Exit location; the fishway exit must be located to ensure there is resting availability nearby or that tired fish will not be swept downstream back into the fishway. The outlet location also needs to meet similar requirements as the entrance, such as attraction, to be effective at downstream passage and to ensure fish do not simply get swept back downstream through the regulator.
- Operation
  - ➢ Consider operations and maintenance; ensuring that locals are trained in fishway operation and work to ensure maximum efficiency during the fish migration period.
  - ➢ Monitoring; to ensure that the fishway is performing as designed and ensuring that long term benefits and responses are quantified.

3. Developing fishway programs in the Lower Mekong Basin

To set a new paradigm in a new country, it is necessary to engage with local communities and authorities, to explain processes and seek formal endorsement to proceed. Making plans to develop the first functional fishway for the Lower Mekong began in 2006 with an approach to the Mekong River Commission (MRC), the multi-government agency overseeing river management in the LMB, seeking its guidance and support for the proposed research. The MRC technical advisory body for fisheries management was the target for the initial approach. This group comprised high level delegates from fisheries agencies across the LMB. Initial discussions highlighted various successes from other countries, but focused mainly on Australian outcomes. Feedback was positive yet delegates were somewhat skeptical of whether fish passes could work in the region. At that stage, the managerial focus was on large dams where fish passage provided substantial challenges. Passing fish at irrigation infrastructure was not seen to be an issue that required a solution. The technical advisory body subsequently requested proof of concept. The request provided official endorsement, and stimulated awareness of the research in national and regional river management institutions.

The initial contact with MRC facilitated relationships, internationally and across institutions, universities and governments. On ground contacts are critical elements of successful international programs. Technical expertise needs to be linked to the correct political and management arrangements to drive all facets of research and deliver the outcomes. But to deliver meaningful outcomes it is essential to also develop strong personal connections, trust and common ground (Campbell & Barlow, 2017). Informal networking can achieve this, especially if mixed with structured workshops to identify research questions and facilitate knowledge sharing.

Knowledge sharing can reveal several information gaps essential to progress a fish passage program. Firstly, the full extent of irrigation development, and planned future development, is often not documented. Thus, one of the critical elements of a successful fish passage program – what barriers need to be remediated? - often remains unknown (Table 1). A central tenet of fishway construction is understanding, identifying and mapping various types of migration barriers because this defines the type of solutions that can be implemented. Innovative use of satellite imagery and GPS, followed by prioritization of barriers, can reveal significant information with respect to potential impact of remediation (Baumgartner et al., 2016). Combining desktop mapping phase with field validations allows barriers to be physically inspected, photographed and catalogued (Fig. 2). Such efforts can help to understand the local hydrology, construction techniques (and quality) and rank sites for potential future mitigation work. Often it is revealed that the degree of irrigation development is much greater than

Table 1
Critical features of water infrastructure and relevance to fisheries impacts and fishway design.

Design feature	Relevance to fisheries	Mitigation considerations
Maximum head differential	Creates a physical barrier	Determines the overall fishway length
Width	Affects the fish accumulation zones.	Wider structures may require multiple fishways or innovative passage solutions
Hydrology	Defines drownout points, frequency and how long the structure remains a barrier	Fish pass structures need to operate over the majority of flows up until drownout
Location in system	Fisheries diversity is generally higher in lowland reaches.	Fishways in lowland reaches need to pass significantly more species than upland sites
Type	Weirs, culverts, road crossings, dams, barrages, bridges can all block fish passage	The type of structure can significantly impact fish passage options
Existing fishway	May already be providing some passage or may not be working at all	May still require a new solution, refurbishment or maintenance
Discharge method	Water discharged in different ways can affect the survival of downstream migrants	Gates that discharge water over the top (overshot) can provide safer hydraulic conditions than sluice gates that discharge water underneath (undershot)
Conditions immediately downstream of structure	Hard surfaces immediately downstream of structures can injure downstream migrating fish if collision occurs	Deeper and longer plunge pools free of solid objects reduces the risk that downstream migrating fish will strike surfaces and be injured
Gate design	Influences downstream survival and fish behaviour	Overfall gates can create better conditions for entrance design and placement

recognized, even by provincial or national agencies (Fig. 2).

Understanding the types and extent of fish migration barriers are important knowledge gaps to address. But these alone do not demonstrate proof of concept for potential fish passage solutions.

4. Common techniques to optimize fishway design

There are four common approaches to developing design criteria for fish passage.

Firstly, the swimming ability of fish can be tested in flumes or swim tunnels (Castro-Santos, 2005, 2004; Haro, Castro-Santos, Noreika, & Odeh, 2004). Fish are introduced into the flume to swim in controlled experiments under a range of different hydraulic scenarios. These can provide useful information on fish responses under controlled conditions but there are major limitations in applying these data to fishway design. The primary one is that it does not test swimming ability in differing turbulence; this is a fundamental design criterion of fishways and ignoring this aspect has led to many failed fishways (Mallen-Cooper, 1996). Flume experiments do not test fish behaviour in different fishway designs, so passage through a particular sized orifice or slot is unknown. These experiments also do not account for ground-speed; that is, the fish swimming faster than the water velocity to make forward progress, although this can be overcome by using conservative application of the results. Data from these experiments have been used to design long culverts but we are unaware of case studies where these types of experiments have effectively been applied to fishway design.

Secondly, physical model studies and 3-D computer modelling (Computational Fluid Dynamics - CFD) of fishways can be used in fishway design (Parsons, 2005). These can be useful for identifying strengths and weaknesses of different designs from a hydraulic perspective but ultimately rely on existing swimming ability and behaviour data, which was lacking for Mekong fish.

Thirdly, fishways can also be assessed in laboratory environments with full-scale models (Castro-Santos & Haro, 2003; Mallen-Cooper, 1992, 1994). The advantage over flume experiments is that fish response is volitional, and fish can be tested in the exact hydraulic conditions of the fishway design, including turbulence and depth, while variables such as discharge, water levels, species, fish size and sample number, can be controlled very accurately. The significant disadvantages are that fish generally need to be handled/herded to introduce them into the experimental fishway and the logistics of capturing, transporting, holding and feeding means that few species and sizes can be tested; and fish may not be in a migratory mode when tested, leading to conservative results (Mallen-Cooper, 1994, 1999). The limited number of species that can be tested in the above two methods is a severe limitation in a megadiverse system like the Mekong, where hundreds of species may be attempting passage under a complex range of hydraulic conditions, and each may have a different capacity to navigate fishway hydraulics.

Fourth, is implementing *in-situ* experiments with model fishways, under field conditions with wild migrating fish (Baumgartner et al., 2012; Mallen-Cooper & Stuart, 2007). The fundamental advantage is that it provides volitional and realistic data on swimming ability and behaviour through different fishway designs. The disadvantage is that experimental *in-situ* conditions are much more difficult to control than in laboratory environments and the species and size composition of migratory fish cannot be controlled. Given the species-rich environment of the Mekong and the need for accurate data that could be readily applied to fishway design, we decided to use *in-situ* experiments, acknowledging the difficulty of field experiments in a river with highly varying water levels.

5. Developing a full scale upstream fishway study in Lao PDR

An experimental field site was selected at the Pak Peung wetland, adjacent to the Mekong River in the Paksan Province in Lao PDR (Fig. 3). The 500 ha wetland had been isolated from the Mekong River by an outflow regulator approximately 5 m in height. Interviews with local villagers indicated significant fishery declines upstream of the regulator, as well as high catches of fish which accumulated below the regulator. *In-situ* experiments with various fishway designs conclusively showed that a vertical-slot design was most appropriate, while simultaneously providing information on swimming ability of various species as well as the timing of migrations (Baumgartner et al., 2012). These findings were used to design a permanent fishway which also served as a demonstration site.

A key part of implementation in any developing country is local consultation, at both the district and provincial level. For instance, when a vertical-slot fishway design was presented to villagers at Pak Peung, significant safety concerns were flagged. It was deemed by community leaders that children would undoubtedly "play" in the fishway. A traditional vertical-slot fishway with high walls and an open surface posed an unacceptable drowning risk. So at Pak Peung the vertical slots were redesigned in accordance, and with respect to, the wishes of the community, who would ultimately take long-term ownership of the structure. Subsequently a child-friendly cone-shaped fishway was developed and installed, with a more open, shallower, channel (Fig. 3).

6. Considering bi-directionality of fish movement

Moving fish upstream is often only part of the problem. In Australia,

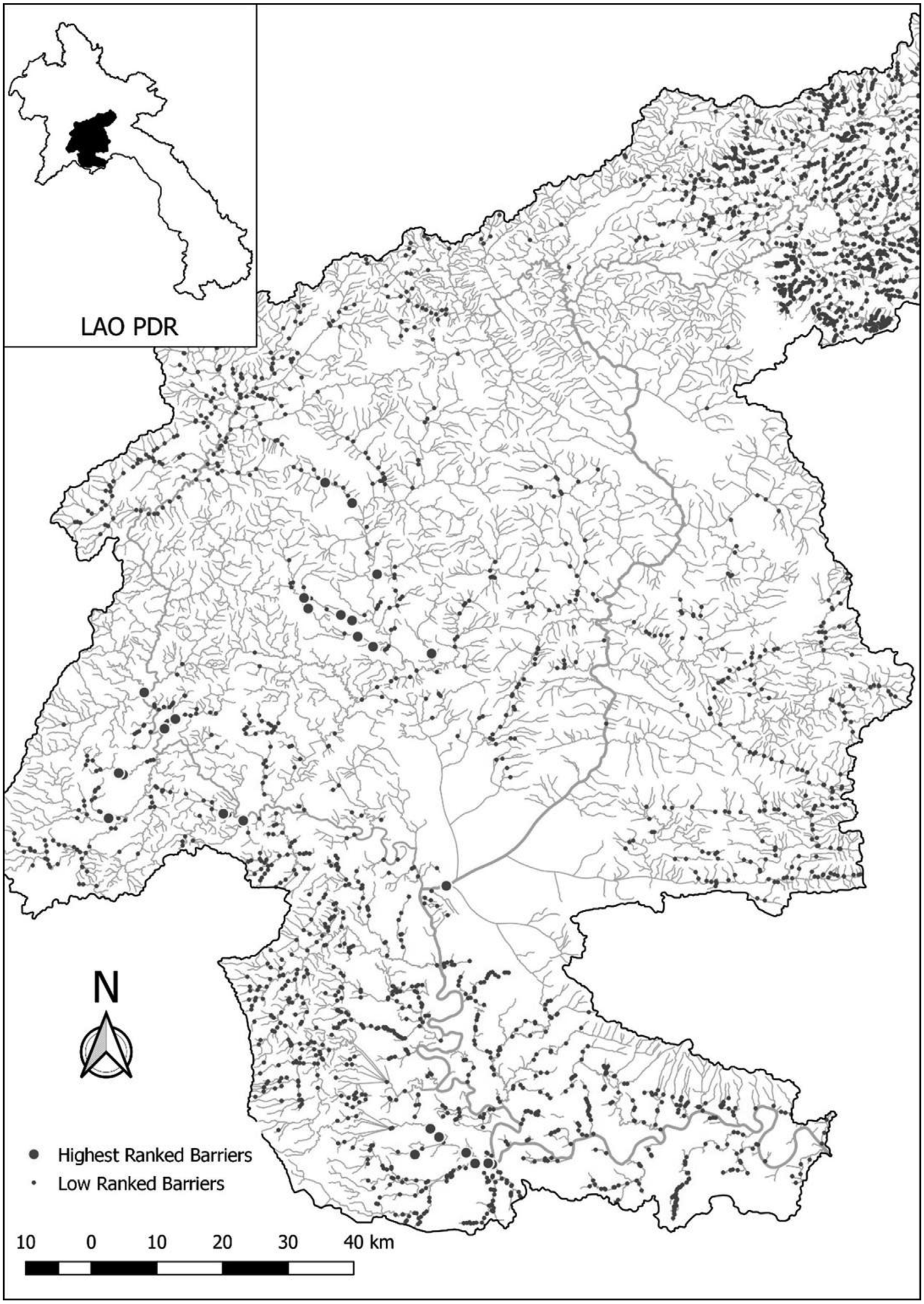

Fig. 2. Example of fish passage barriers that have been catalogued, visited and prioritized in the Nam Ngum catchment, Lao PDR. Over 3000 barriers, less than 6m high were identified in the prioritization process.

it took many decades to understand that fish passage is a bidirectional issue (Baumgartner et al., 2014). Adopting a holistic approach is the best method and requires a conceptual understanding of fish movement at any given site. Often such understanding is hard to achieve because available information is generally fishery-dependent and biased towards adult fish. For instance, most contemporary knowledge about fish migration and seasonality in the Mekong comes from catch data. Such data focuses largely on adult fish and until very recently, few data

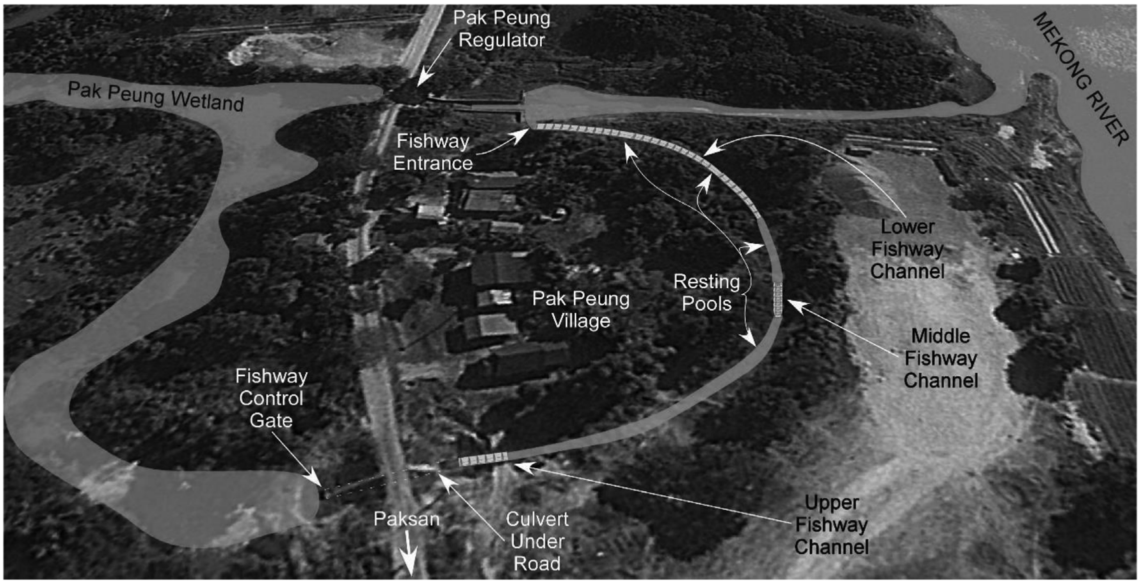

Fig. 3. Conceptual layout of the Pak Peung wetland, and fishway. In central Lao PDR. The Pak Peung regulator blocks upstream migrants moving from the Mekong to the wetland when water levels rise early in the rainy season. The fishway was constructed to reconnect this continuum and allow fish to move upstream to access feeding, spawning and nursery habitat.

were available on distribution and abundance of eggs and larvae. At Pak Peung, many species recorded moving through the demonstration fishway were juvenile white fish. White fish are those which spawn in the Mekong mainstem but which seek nursery refuge in floodplain habitats. The observations at Pak Peung offer an insight into species ecology because these fish reside in the wetland temporarily, increase in size, and then return to the Mekong as the wet season subsides. In any case, these direct observations suggest that solutions are needed to enable the fish to move downstream to the Mekong. It is important that any structure providing upstream passage does not create an ecological trap, where fish are unable to return downstream (Pelicice & Agostinho, 2008).

Downstream movement of fish can introduce a range of additional passage considerations. For instance, sluice gates can cause fish to be injured by physical strike, rapid and extreme pressure changes (barotrauma), and shear pressure (the interface between water moving in opposing directions) (Pflugrath, Boys, & Cathers, 2018). In some instances, the impact can result in substantial injury and mortality (Baumgartner, Reynoldson, & Gilligan, 2006). The findings suggested that high percentages of fish were injured as they passed through undershot-style sluice gates. Cumulatively, irrigation regulators could be physically harming millions of fish each year, across the Lower Mekong Basin, simply through the course of normal operations.

Technology helped to determine characteristics of irrigation infrastructure that may be impacting fish. Sensorfish (an electronic device that simulate a fish moving downstream) (Deng, Carlson, Duncan, Richmond, & Dauble, 2010), hyperbaric chamber facilities (Brown et al., 2014), and computational fluid dynamics were modelled at different physical structures. The results unequivocally demonstrated that water flowing over weir gates (overshot weirs, layflat gates) with deep plunge pools lead to far better survival of fish than do undershot weirs (Marttin & De Graaf, 2002). Consequently, the final stage of fish passage rehabilitation at the Pak Peung site involved constructing a fish-friendly downstream regulator with forward tilting gates. Thus, the migratory life-cycle of upstream to downstream was complete.

7. Capacity building program

Having a program underpinned by robust science is important, but it is only one component. When working in developing countries the ultimate outcome is to train local staff to build capacity sufficient for local agencies to deal with fish passage issues (Millar et al., 2018). The old adage, “Give a man a fish and you feed him for a day, teach a man to fish and you feed him for life” applies equally to developing country fish passage work. It would be relatively simple for a technical team of fisheries and engineering experts to arrive in a country, design a fishway, oversee construction and then leave. Such a process may yield a functional fishway which operates for a short period of time. But it offers little in terms of building local capacity. So, equally important as the scientific proof of concept, is the training and empowering of local people to understand and be part of the decision making processes. Implicit in this process is a strong framework for decision making where "benefits" and "costs" are clearly articulated and accounted for when the business case is made.

Building the experimental fishway at Pak Peung village was a considerable undertaking, involving extensive earth works, form setting and concrete work. In many developing countries it is impossible to work in remote regions without local support. The best way to garner such support is to directly involve local people, whether it be through the village directly, or district and provincial offices. So it was deemed important that construction was organized through contracts with the local villagers and government officers. Tenders were called from local contractors and local “nibans” (village leaders) took an active role in selecting and awarding the tenders. Engaging locals brings income to the village, a new set of skills, and importantly, pride in community “ownership” in the fishway (Fig. 4). At Pak Peung, the village leader became an advocate for the research, and villagers were engaged as active research team members, using their fish identification knowledge and developing data recording skills to the benefit of themselves and the project.

Location is another important aspect of a successful project because demonstration sites are invaluable for government policy makers as well as investment agencies interested in scaling out the results. Pak Peung is relatively close to Vientiane, the capital of Lao PDR, and provides easy access to a facility at which the principles, infrastructure, benefits and community engagement with fishways can be understood and appreciated through direct observation. Demonstration sites can also be used as a communication tool. For example, a fish passage conference in Vientiane in 2016, “applying innovation to secure fisheries productivity”, attracted 160 delegates from 14 countries. The

Fig. 4. Engaging in construction (top) and monitoring (bottom) of Pak Peung fishway and regulator was an important component of project success (Photos courtesy of Jim Holmes).

demonstration site was an important tool to demonstrate that advances in fish passage technology could deliver substantial ecological and social benefits (Baumgartner, Boys, Barlow, & Roy, 2017).

An important legacy from existing work was training future leaders in natural resource management. Fishway design and application has now been included into the national higher education Biology curriculum, as a direct result of increased knowledge of fishways and ecosystem management stemming from the involvement of staff from the National University of Lao in the program. All undergraduates now learn about fish passage as part of the standard undergraduate agriculture course, and many of them include fisheries monitoring at the research site in their course work. Beyond national training, operationalizing the fishway is a significant and ongoing task.

8. Operationalizing fish passage

Lower Mekong hydrology is complex and there are distinct differences between main channel and wetland environments. In wetland environments, headwater levels are maintained by coordinating a series of regulator gates. The gates serve to drain water from the wetland as the wet season commences, thus protecting rice crops from inundation. Early in the wet season all gates are fully open, so there is little headwater variation. The Mekong River, on the downstream side of the wetland, rises rapidly as the rainy season progresses. Eventually the level rises so high that a reverse head operation occurs (the downstream side of the regulating gates is higher than upstream). At this stage all gates are closed to prevent upstream flooding of rice crops and the fishway effectively becomes a temporary barrier. Thus, there is a complex interaction between headwater and tailwater which is largely unsynchronized.

So effective fishway operation is a balancing act, requiring locals to manipulate headwater levels to maintain operational efficiency. Yet local staff have no formal background in engineering or ecology, and Australian scientists cannot be based on site indefinitely. A solution to ensure functionality has been to install remote cameras. The cameras send Australian scientists daily emails. It allows real-time monitoring of water levels. Calls can be made to local villagers when it is apparent that gate operations require adjustment. Instructions are provided and fishway operation is maintained. Over time, locals acquire the ability to self-manage gate operations and the need for advice and intervention is slowly subsiding.

Provided day-to-day operations are maintained, there is a need to provide broader-scale fishery management (Baird, 1994). Prior to fishway construction there was substantial fishing pressure below the regulator. Fish were accumulating in large numbers and locals exploited the resource. Fishway completion provided a new potential fishing location. Fish were no longer dispersed in a deep section downstream of a regulator. They were funneled through a shallow concrete channel and were substantially easier to catch. Upstream villagers, expecting increased productivity in the wetland, became concerned that villages closer to the fishway would simply use the structure as a fishing station. This concern prompted substantial community interaction to develop solutions to provide more equitable access to the resource. Local district fisheries officers drafted a community co-management strategy. The strategy prohibited fishing in the fishway and established a fisheries conservation zone upstream from the structure. Harsh penalties are enforced for those breaching these regulations. Since operation of the fishway and implementation of the management plan, upstream villages are now reporting catches of species that have not been recorded in the previous twenty years (Millar et al., 2018).

9. Scale out and including industry partners

One of the ultimate goals of any international development program is to expand from small-scale research sites to a situation where large-scale adoption becomes the norm (Campbell & Barlow, 2017). But such an undertaking is challenging and requires many years of on ground action, proof of concept demonstration and networking with the relevant departments. For fishway programs, there are several levels of engagement essential to ensure successful scale-out.

Firstly, at the technical and scientific level it is important that biologists and engineers work together to develop robust solutions

(Clay, 1995). Ideally, this should be jointly undertaken with irrigation officials and fisheries department representatives. Often there is a lack of clear legislation or policy governing fish passage requirements. And there are presently no strict engineering guidelines which have been based on Lower Mekong ecology. Technological advances will therefore require an iterative adaptive management approach. Fishways will often contain design flaws and nuances which will be revealed with structured research and development (Clay, 1995). Such findings are not to be lamented. The important message is to learn from flaws by revising specifications and applying improved designs to the next project. Biologists, engineers and officials need to be part of this process. Ideally, an overarching panel of experts would provide review and quality control of designs to ensure that lessons are passed on, and provide continuity of expertise to younger staff.

Secondly, at the design level it is important that engineers and biologists have some prior experience with local conditions. Too often the approach in development is to apply designs developed elsewhere in the local context (Mallen-Cooper & Brand, 2007). Time and again such undertakings have led to failure and the perception that fishways do not work (Agostinho, Agostinho, Pelicice, Almeida, & Marques, 2007; Schwalme et al., 1985; Winter & Van Densen, 2001). To ensure a fully functioning structure requires a complex understanding of local species, hydrology (especially upstream and downstream water levels), swimming abilities, ecological function, engineering design and hydraulics. All of these skills need to come together, in a local context, to deliver an effective fishway that provides outcomes for fish (Clay, 1995). All sites are unique and will have a specific design or application. Prior knowledge with international fishway development is just as important as understanding local context. A multi-skilled team approach is needed to gain the best outcomes at any given site.

Thirdly, proof of concept is essential. Irrigation development is proceeding at an unprecedented rate in the Lower Mekong Basin. Many donor bodies are investing in rural infrastructure programs to meet poverty reduction targets (Cavallo, Lawrence, & Imhof, 2008). But most programs have a sole focus on irrigation. Fisheries are rarely considered, largely because of the widespread perception that irrigation programs have little impact on fish. But there have been some exceptions. The benefits of fishways have already been recognized by the World Bank and the Asian Development Bank through incorporation of fishways into several irrigation rehabilitation projects. Fourteen fishways have been constructed in southern Lao (Fig. 5) and up to 26 are being considered as part of a Northern Lao Irrigation Infrastructure project. These projects have only proceeded because proof of concept was demonstrated and villagers perceived to benefit. The aim of developing win-win outcomes for both farmers and fishermen was an attractive proposition and led to significant investment. It was important to note that, at these sites, strong collaboration occurred among engineers and biologists. The collaboration was formed early in the construction process and allowed solutions to be workshopped and designed from early concept stages. Integrating fishway design with planned irrigation operations is the only way to ensure functional fishways are constructed.

10. Lessons learned

It is instructive from an international development perspective to examine the factors that have contributed to the success of the fishways program in Lao.

10.1. Strong leadership and constructive collaboration from international and local leaders. A highly beneficial aspect of the team collaboration was having an international fishway expert permanently established in-country. In addition to professional expertise, this provided an invaluable communication link between the international and Lao team members. The alternative model of fly in and fly out arrangements can constrain relationships and offer limited ability to provide day to day oversight. So often a mixed model is beneficial with a core team based in-country, and international scientists regularly visiting.

10.2. *Technical expertise* was developed over many years of fishways research internationally and this has been directly applied to an area of need in Lao PDR. The science outputs and the applied nature of the results from the Lao work are now recognized globally.

10.3. Long-term funding by the Australian Centre for International Agricultural Research has enabled the team to design and implement a logical sequence of projects. This is essential in research which by its nature is seasonal as well as multi-faceted. Proof of concept takes time, especially in countries where the concept has not previously been demonstrated.

10.4. Communication where all team members have been advocates within Lao PDR, and internationally, through direct discussion with government, workshops, international symposiums, policy papers, science papers, TV exposure, as well as site demonstrations. Communication in both English and local language is essential.

10.5. Availability of a demonstration site at Pak Peung fishway has provided a facility at which the principles, infrastructure, benefits and community engagement with fishways can be understood and appreciated through direct observation. It has also provided a tool to train the next generation of natural resource managers.

10.6. Positive change in natural resource management. Fishways are restorative, in that they lead to more fish and improved livelihoods, as distinct from most natural resource management initiatives which are designed to reduce further degradation. The improved situation engenders political support.

10.7. Active engagement in scale-out by team members has been essential in securing commitment from donor agencies and in ensuring correct application of the results to new sites.

10.8. Technological innovation. Developing countries, by their very nature, can be rapid adopters of new technologies. It is counter-productive to repeat old mistakes from the developed world when we can introduce state-of-the-art technology, such as sensorfish (Deng et al., 2010), modern construction techniques or monitoring technologies.

10.9. Holistic approach. Considering the whole life cycle and bi-directional movements is essential to develop effective fish passage remediation. Large tropical rivers have a unique ecological function which is completely tied to seasonal hydrology. Considering hydrology and ecology is essential to ensure solutions work over the majority of the annual cycle.

10.10. Being flexible and adaptive. Working in developing countries is difficult. Projects need to navigate a complex set of climatic, political and logistical difficulties. An adaptive and responsive approach is required. Often, pre-determined five year plans need to be completely changed as the realities of local contexts become apparent.

10.11. Demonstrating the cost-benefit. Irrigation agencies often deem fish passage as an additional and unnecessary cost. On the one hand, calorie production is enhanced by irrigation (i.e. more rice) and on the other hand nutrition is made worse (less protein from fish). Fish passage facilities can redress this imbalance, but it is important that there is a strong economic case.

11. Conclusions

River development is a global issue and there is a trend of fisheries declines in areas where migration has been blocked. The application of fishway technology, to provide upstream and downstream connectivity, has potential to help rehabilitate areas of existing fisheries decline, and to reduce the risk of future collapses. Such outcomes are important in regions where inland capture fisheries provide significant human nutrition and income benefits. Irrigation modernisation programs offer a once-in-a-generation opportunity to ensure Lower Mekong communities benefit from functional fishways being incorporated into the design process. But fishway design is a precise science with many technological nuances which require collaboration between engineers, biologists and local communities. When these groups work together

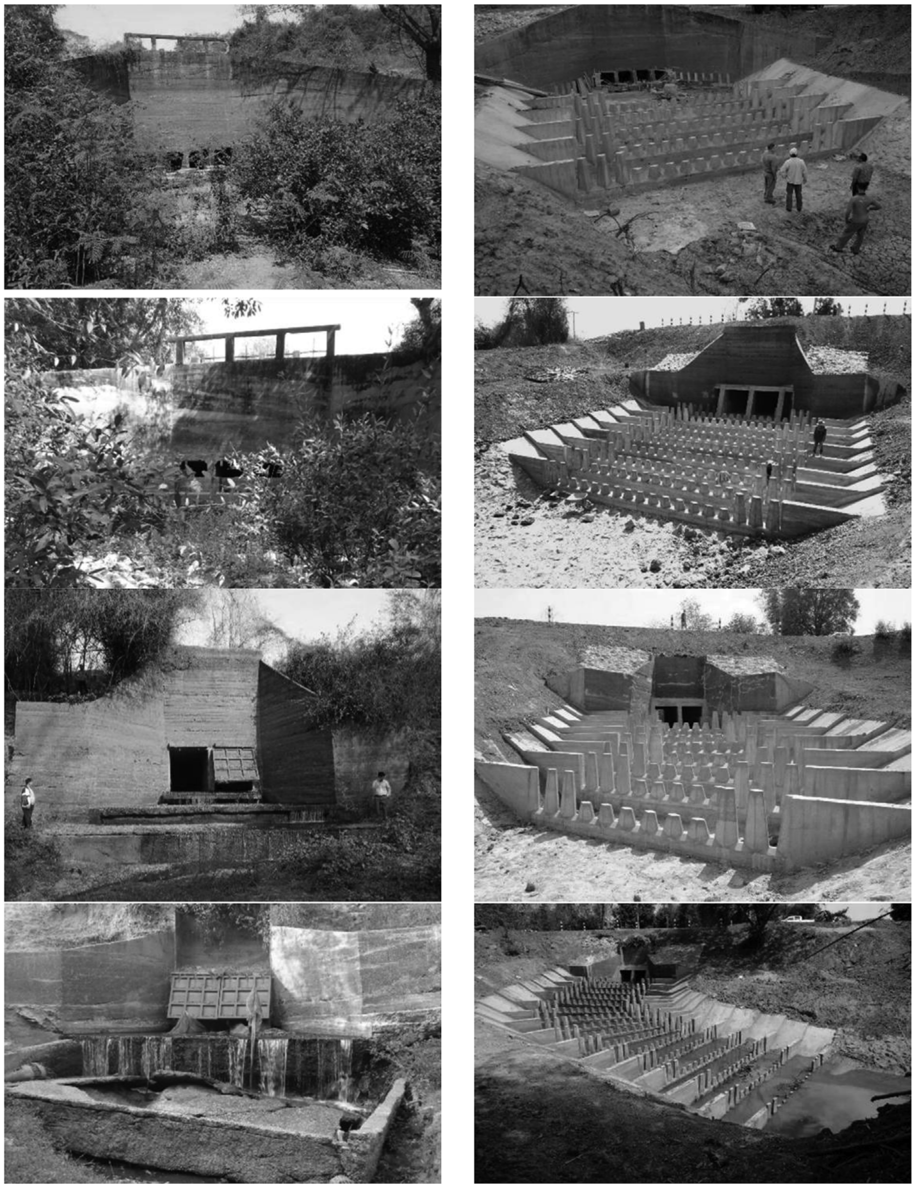

Fig. 5. Before (left) and after (right) pictures of extension activities. Here the World Bank partnered with the Lao irrigation department to include fish passage in the modernisation of several regulators in Southern Lao PDR.

with irrigation developers, significant positive impacts arise for both fish and irrigators. If successes in Lao PDR can be applied to other Lower Mekong countries, then long-term positive change can be achieved.

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