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Final report

Small research and development activity

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2 Executive summary

2.1 Background

Recent work by the Mekong River Commission and the fisheries agencies of Cambodia, Lao, Thailand and Vietnam have demonstrated that valuable commercial and subsistence fishery stocks undertake migrations that are significant for survival, growth and reproduction. Barriers to migratory fish movements are therefore a key threatening process against the future subsistence and commercial use of these fisheries resources. Increasing development of Lower Mekong floodplains must consider potential impacts on fish passage because migratory fish form the major source of animal protein for most rural communities in the basin.

In other areas of the world, fish passage facilities (such as fishways or fish passages) are effective in maintaining pathways for migratory fish in order to prevent population declines. The construction of effective fishways requires targeted experimentation that seeks to develop the fish swimming criteria necessary to facilitate the passage of target species. Fish passage management guidelines are currently poorly defined in Lao PDR and other lower Mekong countries. This is partly because the empirical criteria required to construct effective fishways are yet to be developed. Presently, the absence of such information has river development projects progressing without the necessary requirements for fish passage. Whilst immediate effects may be localised, the long-term obstruction of fish passage will inevitably create large-scale declines in upstream and downstream fish assemblages. This will threaten the sustainability of many river communities reliant upon fish as a vital resource throughout the Mekong Basin.

2.2 Project Activities

The present project aimed to complete a proof-of-concept study to demonstrate the benefits of fishway construction for floodplain fish species of central Laos. A project team comprising scientists from Australia, and Lao P.D.R (in collaboration with Thailand) completed a series of experiments investigating the potential to use vertical slot fishways to restore connectivity between the Mekong River and a small floodplain wetland The team constructed an experimental fishway facility to demonstrate the potential for this technology to rehabilitate floodplain fisheries in central Laos. This involved engaging the local community and gathering local support for the work through a series of meetings and workshops. Establishing a local network of contacts and actively involving villagers in the work led to the timely construction of an experimental facility which was installed at a floodplain regulator in Pak San (Central Laos).

2.3 Achievements and New Knowledge

Experiments were highly successful and exceeded initial expectations. Main achievements for the project included:

- The passage of over 15,000 fish from 108 species through the experimental structure including catches of threatened species such as Jullien's Golden Barb (*Probarbus jullieni*).
- Determination of appropriate cues for migration activity and an increased understanding of Mekong River fish ecology
- The identification of a suitable design (Vertical slot fishway) and optimal characteristics (1:15 slope) which can facilitate passage of high numbers of fish in both Laos and Australia.

- Increased awareness for potential to apply fish passage technology to help rehabilitate floodplain fisheries in Central Laos.
- A review of the operation of existing fishway facilities in Thailand and Cambodia.
- Direct involvement of district and village staff in experimental and construction work.
- Raising the profile of fish passage restoration and floodplain health with donor organisations (World Bank, Wetlands Alliance, World Wide Fund for Nature), riparian governments (Laos and Thailand) and professional staff in both Australia and Lao
- Direct demonstration that fishways can provide passage for many species of fish at floodplain regulators which will help generate ecological outcome and provide food security for communities reliant upon wetland capture fisheries.
- Dissemination of project activities and results through two major workshops, a local study tour and the preparation of scientific manuscripts.
- Identifying knowledge gaps and future research priorities which are necessary to help to rehabilitate degraded fisheries and improve the economic livelihood of river communities throughout the Lower Mekong Basin.

2.4 Conclusions

The project successfully achieved the objective of demonstrating that vertical slot fishways can provide passage for Lower Mekong fish species at low head weirs. Results suggested that a vertical slot fishway constructed on a 1:15 (6%) slope with small slot widths (150mm) and moderately sized cells (1000 mm X 1500 mm) was suitable for the majority of migratory species and size classes in Central Laos. However, some species which prefer fast flowing water may not ascend a fishway on this slope. Migration rates were substantially influenced by river flow which suggests that the design of permanent fishway installations must make careful consideration of local hydrology to perform efficiently. Fishway efficiency must be optimised at times of water level increases to ensure maximum fish passage rates. Careful consideration of these design aspects will provide functional fishways that have potential for widespread application.

The major outcome arising from this work is the realisation that development projects seeking to construct floodplain regulators could now provide fish passage by applying vertical slot fishways to the optimal design specifications. The species composition and total abundance of fish caught as part of this initial study demonstrate that a vertical slot fishway would be suitable at low head weirs, although other alternative low-cost designs should be considered to increase the potential for wider application at other wetlands throughout the Lower Mekong Basin. The Long term benefits of this work will help to rehabilitate wetlands and provide assist millions of people who rely on floodplain fisheries for food security and income.

3 Introduction

3.1 Importance of fisheries in the Mekong region

The Mekong is one of the world's major catchment systems, and is generally recognised as the 10th largest in the world in both discharge and length. It drains a total area of 795,000km^2 and is over 4,000kms in length. Over 60 million, from six countries, people reside within the catchment. The river has immense importance in terms of benefits and ecosystem services (fisheries, soil fertility, navigation, irrigation, ground water recharge) and cultural values for the people of the region. It also contains some of the world's most unique aquatic communities, which include freshwater dolphins, giant catfish, stingrays, and approximately 1000 freshwater fish species.

Lao PDR is an entirely land-locked country which relies heavily on the Mekong for its economic, social and cultural values. In central Lao, the Mekong supports a large population of subsistence farmers and fishermen who rely heavily on regular flooding of floodplain areas to increase productivity. Increased development of this region reduces floodplain-river connectivity and has a detrimental impact on the movement of migratory fish. Determining effective methods to reduce these impacts is essential for the long term survival of these subsistence communities and the sustainability of essential resources.

Fisheries are immensely important throughout the lower Mekong basin (the LMB, which is the Mekong drainage within Lao PDR, Thailand, Cambodia and Vietnam). In food security terms, fish and other aquatic animals provide on average 48% and 79% of the animal protein intake in Lao PDR and Cambodia respectively. From a livelihood perspective, more than 80% of rural households in the Mekong basin in Thailand, Lao and Cambodia are involved in capture fisheries, and up to 95% of the rural households in the Viet Nam delta. In economic terms, the capture fishery has a first-sale value of between US$2,000-4,000 million per year. The annual yield from the capture fishery in the LMB is about two million tonnes, which is approximately 2% of the total world marine and freshwater catch.

3.2 The impact of water management structures on fisheries production

The Mekong supports a large population of subsistence farmers and fishermen who rely heavily on regular inundation of floodplain areas to increase productivity. Increased irrigation development in the four LMB countries has led to construction of numerous (in excess of 10,000 in Thailand alone) low-level (generally less than 6 m) water regulation devices which limit the movement of migratory fish. Consequently, many fish species cannot complete essential movements between rivers and floodplains to completion their lifecycles. The proliferation of structures such as roads and irrigation weirs individually (and cumulatively) delay or prevent fish passage onto the floodplain at the onset of the wet-season, thus reducing the habitat area available for fish reproduction and growth. In addition, weirs create artificial aggregations of pre-spawning fish which are extremely vulnerable to overexploitation and disease. These fish either spawn at non-preferred times, in sub-optimal habitats, or do not spawn at all. Over time, these impacts reduce the diversity and productivity of the fishery and the benefits of development projects (such as improved road transport and more secure water supplies) which are thus negatively offset by lost fisheries productivity.

Many fish species within the region are highly migratory, and require connectivity among river reaches to maintain access to feeding areas, spawning grounds and refuge habitats. The creation of barriers on these important pathways can interrupt important life-cycle stages and can result in large-scale fish population collapses. For instance, following construction of the Pak Mun Dam (Mun River, Thailand) daily fish catches in upstream reaches had declined by 60-80%. Overall, the construction of the dam led to the disappearance of 169 fish species from upstream reaches. This can be particularly damaging to rural communities as their livelihood strategies are generally reliant on wild fisheries productivity.

3.3 Using fish passage technology to reconnect wetlands

In other areas of the world, fishways are effective in maintaining pathways for migratory fish in order to prevent large-scale fish community declines. Fishways are simply channels around or through an obstruction that contain flows that complement the swimming ability of target species. 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 Australia over recent years and has contributed to large-scale increases in fish numbers.

In recent times, organisations such as the Mekong River Commission and ACIAR have invested substantial amounts of funding into determining the scales of fish migration within Lao, and the wider Mekong Basin. These projects have used methodologies such as radio telemetry or tagging and have revealed important information on the scale and timing of fish migrations throughout the region and provided excellent data on the broad nature of fish migrations. Information now exists to partly predict impacts of water development infrastructure but previous fish migration studies have provided few data in terms of the swimming ability of target species or information on the migratory requirements of species which are too small for tagging or tracking. These smaller fish are an important food source but little is known of their biology or migratory requirements. This information is vital if the effects of river development projects are to be adequately mitigated.

Two major approaches, field or laboratory based, can be used to collect these data. Whilst laboratory studies are acceptable, it is often logistically difficult to collect and house enough fish (from enough species) to perform the trials. In addition, it is difficult to replicate the wild cues for migration in a laboratory environment which can create inconsistencies in the dataset. Field-based approach using wild migrating fish to collect the necessary swimming and environmental data offers several advantages:

- If field trips are timed with environmental cues, excellent sample sizes can be expected as fish will be “motivated” to migrate.
- Data can be collected for a wide range of fish species, size classes and life history stages.
- The work can be undertaken at any site where fish migration is impeded; therefore information can be collected at a number of key sites.

Field-based projects of this nature can be undertaken over a relatively short timeframe and provide swimming ability information for many species. The development of fish passage facilities can then be specifically applied to areas within the known distribution of these species to ensure wild populations and fisheries are preserved. The absence of such information has river development projects progressing without the necessary requirements for fish passage. Whilst immediate effects may be localised, the long-term obstruction of fish passage will inevitably create large-scale declines in upstream and downstream fish assemblages. This will threaten the sustainability of many river communities reliant upon fish as a vital resource throughout the Mekong Basin.

3.4 Objectives of this study

Several fishways have been constructed in the Lower Mekong Basin, but none demonstrate evidence of attempting to incorporate knowledge of local species and hydrology into fishway design. The present study sought to determine whether a vertical slot fishway can be designed to provide passage for Lower Mekong fish species attempting to access floodplain habitat. Experimental manipulations of flow and turbulence were used, under field conditions, to determine the optimal design criteria to guide potential application at other sites in the Lower Mekong Basin. Cues to migration and the influence of changing water levels were also investigated.

4 Overview of Methods used

4.1 Project Team

This study was successfully completed through the establishment of collaborations among five different agencies. Industry and Investment NSW and the Department of Employment Economic Development and Innovation (QLD) who are actively involved in fish migration ecology research in Australia. These organisations were essential collaborators to help transfer fish passage technology principles to Lao PDR. Lao collaborators included Living Aquatic Resources Research Centre and the National University of Laos. Both of these organisations provided a mix of government and academic expertise required to facilitate both research and management outcomes from the project. The Thai Department of Fisheries were also included as a collaborator and provided expertise in fishway design that could be directly applied from practical experience in many different river systems.

4.2 Study Site

The study was conducted at a floodplain regulator adjacent to the Mekong River at Pak Peung village (Bolikhamxay province) in central Laos. The concrete regulator was originally constructed (in the 1960s) to prevent inundation of extensive floodplain rice crops during increases in Mekong River level during the wet season. The regulator is 10m high and contains three manually-operated sluice gates which release water from an upstream wetland. Each gate is capable of delivering a maximum 80 $ML.day^{-1}$ (0.93 $m^3.s^{-1}$). Gates are initially operated to drain the associated wetland to prevent crop damage following high rain evens (early in the wet season). The gates are adjusted daily and during this period fish might move downstream (from the floodplain to the river) through the sluice gates, but upstream passage (from the river to the floodplain) is completely precluded. The gates are closed during high Mekong levels to prevent further crop damage from water entering the wetland (usually later in the wet season). Under these conditions, the regulator is a barrier to both upstream and downstream fish movements.

4.3 Experimental Fishway Unit

An experimental fishway unit was constructed to determine whether technical fishways are capable of providing passage for local migratory species at the Pak Peung site. A vertical slot fishway, constructed initially out of plywood, then later reinforced mild steel (1.5mm diameter) was installed parallel with the left hand (looking downstream) training wall downstream of the regulator and secured in place with a combination of sandbags and high-tensile cable. A block and tackle with an endless chain was used to manipulate the slope of the fishway and a sandbag wall was erected to direct flow through the unit. The fishway unit comprised four pools, each of which were 1500 mm long x 1000 mm wide. The vertical slots were 1.4 metres high with a slot width of 150 mm.

4.4 Sampling strategy (2008)

An initial pilot study was carried out in 2008. It was initially planned to perform a series of replicated experiments using a randomised block design (See section 4.5). The Mekong River, however, rose extremely quickly during the initial stages of the study (1:20 year flood). Despite obtaining some data, the site had to be decommissioned due to high water levels. Water levels fell temporarily allowing additional experiments to be completed (with the fishway established on a 1:10 slope) but then the large-flood had completely inundated the study site within four weeks of commencement. Despite the flood conditions, preliminary data provided an initial indication that vertical slot fishways could provide passage for Lower Mekong Species.

4.5 Sampling strategy (2009)

To minimise the risk of inundation, experiments in 2009 commenced a month earlier than during the pilot phase. Fish were subsequently collected from two locations within the fishway over a period of 44 days between April and July 2009 and this strategy sought to compare fish communities attempting to ascend the fishway (control) with fish successfully ascending (treatments). Treatments involved randomly establishing the fishway on different floor slopes, moderate (1:15 or 6%) or steep (1:8 or 12%), and quantifying the number of fish successfully ascending. Experimental treatments began by carefully adjusting the fishway until the required slope was attained. Once the desired hydraulic conditions were achieved, fish passage was assessed by placing a fish trap (1500 mm x 1000 mm X 400mm; 6 mm mesh) upstream of the last baffle. The control sought to quantify the number of fish attempting to ascend the fishway and provided a basis for comparison with the slope treatment replicates. Controls began by establishing an attraction flow for fish to approach the fishway. The trap was then positioned downstream of the attraction jet and any fish attempting to migrate upstream were collected.

Each control and treatment replicate ran for 2 hours after which the trap was retrieved and any fish were identified, measured (total length) and weighed. Replicates were completed each day between 0700 and 1700. It was unknown whether the structure of migratory fish communities would vary with time of day. To control for this potential effect the fishway was assessed using a randomised block design where one 'block' was completed every three days. Experimental treatments and the control were subsequently assigned to one of three potential time periods each day (Morning; 0700 – 1000, Midday: 1100 – 1300, Afternoon: 1400 - 1700). The three replicates (control and two treatments) were completed each day but three days were required to complete all time of day and treatment combinations. A total of 6 full blocks were completed over the study period. No night sampling was conducted due to poor lighting and limited access to the study site.

4.6 Fishermen surveys

Fieldwork conducted also included a census of local fishers to act as a basis for comparisons with fishway data. Fishers were surveyed on a daily basis for 44 days between May and June 2008. All surveys were conducted upon the completion of fishing activities. Research staff recorded the total catch (including species), gear used, time fished and fisher gender. Catches were standardised to effort (catch per hour) and the length of individual fish and total weight of all fish were also recorded.

4.7 Cone Fishway Trials

Recent work in Queensland has produced a new type of fishway design with high potential for application in the Lower Mekong Basin. The cone fishway is a concrete channel which has been separated into pools by a series of conical baffle ridges. Each ridge contains four cone baffles which are placed within the concrete channel at 1000 mm centres. This design has a substantially lower capital cost than vertical slot fishways and the prototype was constructed for $US120. These low costs present substantial opportunities for potential application at the village or district level. It is also known to have hydraulics suited to many species and size classes. A prototype was subsequently constructed and a short-term assessment was undertaken during the 2009 sampling event to determine whether the design can also provide passage for Lower Mekong species.

The cone fishway could only be operated for 6 days during the assessment period. The fishway was then decommissioned due to increasing tailwater level. In this short time a total of six replicates were completed (two hour durations). Work was undertaken between 1500 and 1700 on six consecutive days in May 2009. Fish passage was assessed by placing the fish trap was set at the exit and to capture any fish that successfully ascended. All fish were identified and measured.

A typical cone fishway installation in Queensland, Australia

The prototype cone fishway trialed at Pak Peung regulator

4.8 Genetic Collections

Throughout the fieldwork components, fin clips were retained from a sub-sample of 30 fish of each species and a DNA library has been established. Fish collected by local fishers and within the fishway had a small portion of the caudal (tail) fin removed and immediately stored into an eppindorf tube containing 100% Ethanol. Each tube was labelled with the length of the fish and date collected and subsequently stored in the laboratory at LARReC. Though genetic typing was not a direct requirement of the project, the team took the opportunity to commence collections of samples should they be required by researchers any time in the future.

4.9 Data analysis

Data were analysed using S-PLUS and PRIMER V6.0. Differences in length distributions of fish collected from control and treatment samples were compared using a Kolmogorov-Smirnov (KS) pairwise comparison. This test computes a test statistic (ks) which is based on the largest difference between two cumulative length-frequency distributions. The length frequency data of all fish species were then pooled to construct length frequency histograms for each treatment and control.

Differences in fish community structure among experimental blocks, fishway slope and time of day were investigated using Permutational Analysis of Variance (PERMANOVA). All tests were based on square-root transformed data using Bray Curtis Similarities (with 999 permutations). 'Block' was treated as a fixed factor but both floor slope and time of day were random. It was largely unknown at the commencement of the study whether different species migrated at different times of the day. This was identified as a factor which could potentially confound experimental results if slope experiments were conducted in different diurnal periods. Preliminary analysis identified no differences in fish community structure could be attributed to time of day so it was removed as a factor from subsequent analysis to permit further exploration of the effect of floor slope and experimental blocks. Two-Way Analysis of Similarities (ANOSIM) was subsequently used to determine whether the fish communities among experimental groups (treatment and controls) or among daily experimental blocks. This test sought to identify both the effect of fishway slope and also any natural change in fish communities as time progressed through the experiment. In all ANOSIM tests, 999 Monte-Carlo randomisations were used to calculate approximate probabilities and Gobal R-values. Sample differences plotted using non-metric multi-dimensional scaling ordinations to visually represent any group differences.

5 Overview of key results

Detailed results are given in Appendix 1 (including tables and figures). For brevity, only a general summary of findings is given here. It is anticipated that data to support the submission of two scientific manuscripts will arise from this project.

5.1 Fish Passage data

5.1.1 Pilot trial of experimental facility (2008 only)

The fishway trials were originally designed with a randomised block design which required sampling to be conducted at different times of day to determine diurnal changes in the degree of fish passage. However, due to flooding, only a single block was able to be completed during the first round of sampling. The initial round of experiments sought to determine the influence of different slopes on fishway effectiveness (3% slope; 6% slope and 10% slope). The fishway provided passage for 50 species of which 40% (20 species) were riverine fish attempting to access the Pak Peung wetland. The remaining 60% (30 species) were floodplain species attempting to recolonise the wetland from the river. Preliminary results suggested that a fishway with a steep slope (10%) was successful at passing a large number of species and size classes. Trials on a 3% slope were unsuccessful due to low attraction flows and there was little improvement in fish passage between 6% slope and 10% slope. This initial trial therefore acted as a 'pilot' study which provided a basis for determining the optimal operating parameters for a larger-scale trial (scheduled for 2009). This trial would subsequently seek to investigate fish passage through floor slopes of 6% (1:15), 12% (1:8) and a control where fish would be collected from outside the fishway.

In addition to fishway experiments, a series of short-term water-column trapping collections were undertaken to determine whether fish migrate 'pelagically' (i.e. near the water surface) or 'benthically' (i.e. near the bottom). If fish migrate wholly at the surface, fishway entrance design is simpler because a shallower entrance is needed. Preliminary data demonstrated that a majority of fish migration occurs at the surface. There were no differences in fish length between the surface and bottom, indicating that similar sizes of fish were attempting to gain passage. More fish, however, were collected from the surface (n = 1,320) than at the bottom (n = 308). Five species sampled from the bottom were not collected at the surface and these included cryptic species such as loaches (*Botia* spp) and spiny eels (*Mastacembellids*). Fifteen species were collected from the surface but were absent from bottom samples. These included the more pelagic *Rasbora* spp and a range of Cluepeids. These differences suggest that the provision of fishways with full depth entrances would be needed to facilitate the passage of all migratory fishes, though a surface entrance would still be suitable for a large proportion of fish.

5.1.2 Survey of local fishers

A total of 26 fishers were surveyed during the study period for a combined catch of 2,564 fish and a total weight of 41.85 kg. In total, local fishermen caught 54 species but of these a high proportion (85%) were riverine species whilst few floodplain species were sampled (15%) Fishers were both male (n = 13) and female (n = 13) although females fished much more frequently. Only two male fishermen surveyed actually fished on more than one occasion compared with six females. Fish were collected by either lift net, toum trap or cast nets. Lift nets were only used by females whilst toum traps and cast nets were only used by males. More lift netting (77.73 hours) was performed than either cast netting (21.35 hours) or toum trapping (10.5 hours).

Fish species composition and catch varied among each technique. More species were collected by lift netting (n = 52 species) than cast netting (n = 39) or toum trapping (n = 3). Four species captured via cast net were not collected lift netting. In contrast, 15 species captured via lift netting were not collected in cast nets. Lift netting yielded many more fish (n

= 1800 or 23.26fish/hr) and had a much higher yield (per unit effort) than cast netting (n = 297 fish total; 13.91 fish/hr). Whilst lift netting generally collected higher numbers of fish, cast netting returned a greater biomass (0.34 kg/hr compared with 0.12 kg/hr).

Some species collected from fishway traps were not collected by fishermen. This discrepancy with fishway data likely arose because fishermen were actually targeting larger-bodied riverine species because of their higher monetary value and also as a protein source. Although fishermen caught more species the size of fish caught was comparable with those sampled within the fishway. These initial results suggested that the fishway was providing passage for most migratory species at the site and provided additional confidence to proceed with a series of additional trials in the following wet season.

5.1.3 Experimental fishway trials (2009 only)

Fish were collected over a wider size range during the study (19 – 285 mm) but the greatest proportion of captured fish were relatively small (< 100 mm) in all experimental treatments. Fish collected from the control group were significantly smaller than fish collected from either of the two treatment groups. Some smaller species were almost virtually absent from catches during steep slope experiments. In contrast, catches of larger fish increased with steeper slope. The most number of fish were collected during moderate slope treatments (1:15; n = 7,666) but the most species (n = 52) were collected from control samples (Table 1). Species appeared to fall within three main groupings based on passage success within the experimental unit. Firstly, there were species which only migrated when the fishway was established on a steep slope. These species (n = 20) were either absent, or collected in extremely low abundances during control and moderate slope treatments. Another group of fish which were collected only from control groups (n = 14) and were absent from treatments. The final group of fish (n = 39) were collected from both control and treatment groups irrespective of fishway slope.

A 3-factor analysis (based on the randomised block design) identified significant differences among blocks (PERMANOVA; Table 2) which arose from a progressive change in migratory fish community from the beginning to the end of the study period. Many fish were migrating at the commencement of experiments but numbers gradually decreased with time. Differences in fish community composition were also detected among different floor slopes (PERMANOVA; Table 2) because of changes in relative abundances of several species among experimental treatments. This was largely due to the high number of individuals that were collected from the moderate slope group overall, and the absence of several species from control samples. For instance, *Parambassis siamensis*, *Rasbora rubrodorsalis* and *Xenentodon cancilla* were collected in significantly higher abundances from control samples than either treatment sample. In contrast, several species such as *Barbonymus gonionotus*, *Rasbora dusonensis* and *Osteochilus lini* were more frequently collected from the two treatment groups rather than the control. These differences in fish community composition provided separation of treatment groups in ordinal space (Figure 1). No significant differences among different diurnal periods (daylight only) indicated that the structure of the migratory community did not vary during daylight hours (PERMANOVA; Table 2).

5.1.4 Cone fishway trials

A total of 389 fish from 24 species were collected during the brief sampling period. The most common species were all cyprinids and included *Barbonymus gonionotus* (n = 176), *Rasbora rubrodorsalis* (n = 48) and *Esomus longimanus* (n = 34). Both riverine (n = 16) and black (n = 8) species were collected and two species not captured within the vertical slot fishway (both *Crossocheilus* spp) were collected from the cone fishway. A range of sizes (31 mm – 175 mm) were collected from the fishway but most individuals were less than 100 mm. Despite only a very short sampling period, passage rates and species richness suggest that a more detailed assessment of this design is warranted. The low overall capital outlay provides a high probability of uptake if a longer term assessment yields more species and size classes.

5.2 Influence of river flow on fish passage

In 2009, daily mean fish passage was relatively high early in the study but decreased substantially during the final stages. The commencement of the study period coincided with a sharp increase in water level within the Mekong River (from 2.39m to 4.40m) following substantial rainfall events in upper catchments. Water levels eventually peaked and as the river level fell the total number of fish species and individuals collected substantially declined from both treatment and control samples. A correlation between river level and total fish migration numbers identified a poor relationship (R = 0.09) which occurred because most increases in fish migration occurred during the initial level rise suggesting that change in water level, may be a more meaningful factor. Migration rates were subsequently plotted against change in daily level and a much stronger correlation was observed (R = 0.53). These observations provide preliminary evidence that migration rates and changing hydrograph could be inherently linked but the relationship was not consistent across species. *Xenentodon canciloides* continued to use the experimental fishway during a falling hydrograph whilst *Rasbora dusonensis*, *Barbonymus gonionotus*, *Osteochilus lini*, *Cyclocheilichtys armatus* and *Rasbora daniconius* were only collected during a rising hydrograph. These species were notably absent whenever levels in the Mekong were falling.

5.3 Preliminary implications of field results

These results provided the necessary information to demonstrate that fishways will be a useful management tool to help maintain and, if required, rehabilitate fish communities in regulated floodplain wetlands of the Lower Mekong Basin. High numbers of fish were collected from many different life history stages. These fish were all migrating upstream at the regulator site and were actively attempting to access the upstream wetland. Many of these fish were riverine species which further highlights the importance of maintaining intermittent lateral connections between the Mekong River and floodplain wetlands. Other species were blackwater (or principally wetland species), that were seeking access to filling wetland areas from dry season refuges, an important process for repopulating wetlands.

Strong correlations between river flow and fish movement provide evidence that hydrological changes provide an important cue for fish migration in the Mekong River. Most production in large rivers occurs during periods of floodplain inundation. It is therefore logical that fish are largely cued to access floodplain habitat during increased flows. Many fish species, however, have different lateral migratory requirements depending on life history stage or time of year. In tropical rivers, application of fishways to facilitate fish passage is complicated by high migratory biomass, variable hydrology and higher species richness than in temperate zones. The identification of three broad migratory groups of fish suggests that Mekong species have widely varying swimming abilities and migratory cues. Fish with stronger swimming abilities readily ascended the experimental unit and were captured in relatively high abundances from the fishway exit. In contrast, fish with poorer swimming abilities were only trapped under control conditions. These different scenarios suggest that whilst the construction of fishways on moderate slopes will provide good passage for most species, a proportion would still be unable to ascend.

This study highlights the importance of field experiments in providing an excellent indication of the likely fishway design criteria. While advantageous over laboratory experiments the present study cannot substitute for the construction of a permanent facility. Permanent fishways require careful design and knowledge of the local hydrology to be truly effective. A challenge for the Lower Mekong Basin is to design a vertical slot fishway which maintains functionality with large fluctuations in river level over a migration season. Although developing engineering solutions for such a degree in water level variation are relatively straightforward, it is important to note that the direct application of fishway criteria determined in this study should include careful consideration of species composition to ensure the most effective solution at any given site. A natural progression from this preliminary study is to therefore apply the design criteria at a permanent fishway at a floodplain regulator in central Laos.

Setup of the experimental fishway on the left training wall

Upstream view of the fishway. The sandbag wall was used to control flows through the structure

An important commercial and sustenance species, Snakehead, trapped migrating through the fishway

The project team removing a trap from the fishway exit

The fishway being decommissioned and removed as high water again inundates the site

Local villagers remove the PVC headwater pipe

6 Summary of Extension Activities

6.1 Lao National Study Tour (June 2008)

Mr Douangkham Singhanouvong (LARReC) organised a study tour of representatives from various GoL agencies to inspect and learn about the experimental fishway. A delegation of 16 staff arrived on site from Vientiane on 10th June. Project staff performed a number of activities to demonstrate the success of the experimental fishway. These included trapping demonstrations, fish processing (length, DNA extractions, otolith removal) and explanations of fishway operation. The tour delegates were also given two presentations over dinner. Dr Lee Baumgartner (NSW DPI) gave a presentation on fishway assessments and provided an overview of fishway effectiveness in Australia. Mr Douangkham Singhanouvong (LARReC) gave a presentation on initial research findings and outlined a procedure for establishing a fishway construction program for the lower Mekong Basin. Delegates were then offered the opportunity to ask questions of the presenters.

The overall outcome of the site study tour was one of genuine enthusiasm for the operation and construction of fishways. The group actively discussed aspects of Mekong fish biology and quickly grasped important aspects of fishway design such as entrance location and trap design. The group were impressed that a comparison of species caught by local fishermen with those ascending the fishways were extremely similar. Few large-bodied fish were migrating at the time of sampling and delegates were concerned that the number of large-bodied fish caught within the fishway was low. However, large fish are known to migrate later in the season and the project team suggested that it would be worthwhile undertaking some further sampling in September to try and collect these species.

The overall success of the tour led to an invitation for Mr Singhanouvong, Garry Thorncraft and Dr Oudom Phonekhampeng to give presentations on fishways to a Mekong River Commission workshop in Luang Prabang.

Garry Thorncraft addresses NRM and NGO representatives at the national study tour

Participants of the national study tour

6.2 First Lao Technical Workshop on Fishways (February 2009)

The first Lao Technical fishway workshop was held on 23rd February, 2009. The event was hosted by LARReC and co-organised with National University of Lao. The workshop was designed to give an overview of research activities being undertaken in Lao P.D.R and also to disseminate information on fishway designs used elsewhere in the world. In total, 33 people took part in the workshop and participants were from a range of backgrounds and disciplines.

The workshop commenced with an overview of the importance of fish passage by Dr. Vanthong Phengvichit (LARReC) who introduced the LARReC capture fisheries director Mr Douangkham Singhanouvong. Mr Singhanouvong presented a summary of the existing project in Lao P.D.R and gave an overview of different fishway designs listing the advantages and disadvantages of each. Dr Oudom Phonekhampeng then summarised the work completed to date and gave an outline of work to be finalised in 2009. Mr Singhanouvong presented an Australian-produced video which summarises the operation and effectiveness of different fishway designs. The video was well-received by participants who obtained an improved understanding of fishways options for different sites. Dr Lee Baumgartner gave an overview of results obtained from sampling activities in 2008. His presentation focused on three main aspects of data collection; fishway gradient trials, fishway entrance design and fisher surveys. Preliminary data demonstrated that vertical slot fishways are capable of providing passage for Lower Mekong Species. The importance of fishway entrance design was also discussed.

Participants listen to introductory remarks at the fish passage workshop

Dr Lee Baumgartner presents information of fishway entrance design

All participants at the fish passage workshop

Poster presentations were also prepared by LARReC and NUOL

6.3 Review of Existing Fishway Facilities – Thailand (February 2009)

The project team (Dr Lee Baumgartner, *NSW DPI*; Mr Garry Thorncraft, *NUOL*; Mr Tim Marsden, *QDPI&F*; Mr Douangkham Singhanouvong, *LARReC*, Dr Oudom Phonekhampeng, *NUOL* and Ubolratana Suntornratana*, Thai DOF)* departed Vientiane to review existing fishways Thailand and Cambodia. The team initially travelled from Sakhorn Nakhorn to Mukhadarn to visit a number of existing fishways constructed as part of the Nam Khan irrigation project. The project has a total value of 450,000,000 Baht (approximately $AUD20M) and will be completed in 2009. It has taken a total of five years to complete.

The project involved the construction of five new dams each of which contained a submerged orifice fishway. The project team visited a site at Suvadi which was the first fishway completed as part of the Nam Khan project. The fishway contains 18 pools and is constructed on a 5m high dam. The fishway was monitored in 2006 and 2007 and up to 57 species have been recorded within the structure. Monitoring has been undertaken both day and night but more fish migrate during daylight hours. The fishway is protected from poaching by a fishing closure which extends 500m downstream of the structure. There are a number of species present downstream of the dam which are not sampled within the fishway. During maximum operating head, the fishway pools would have a headloss of 270mm.

The project team meet with construction engineers and fishway designers in Mukdaharn - Thailand

The project team inspect the Suvadi fishway - Thailand

A trap containing over 1,500 fish is retrieved and inspected by delegates during the study tour

Project staff demonstrate fish processing activities to participants of the national study tour

The team were then invited to visit the construction site of the last dam to be constructed which is approximately 50km from Mukdaharn. The dam is being constructed to provide irrigation water and is located just upstream of the Mekong River confluence. The team met with the project director. He explained that the fishway design (submerged orifice) is considered the best possible design in Thailand and that specifications were provided by Thai Department of Fisheries. He was interested in the project being undertaken in Lao and explained that he would be interested in exploring other fishway design options if plans were available and backed up by research. There are a number of large-scale irrigation projects planned in Northern Thailand over the next five years and the probability of uptake following our project is high provided the data was sound.

6.3 Review of Existing Fishway Facilities – Cambodia (February 2009)

The team travelled from Mukhadarn to Siem Reap (Cambodia) to assess the only functional vertical slot fishway in the Mekong Basin at the Stung Chinit Irrigation Facility. The fishway was designed in Australia and modelled on an existing fishway at the Ben Anderson Barrage in Bundaberg (Queensland). The fishway had suitable hydraulics but there were several design characteristics that would limit functional operation for Mekong fish species. The fishway entrance location is excellent under low flows but would be compromised during the wet season when the river rose. The design of the internal baffles also incorporated a design fault copied from the original fishway in Australia where the baffle returns were too short. This results in sub-optimal hydraulics under certain conditions.

6.4 Knowledge Gaps and Opportunities Workshop (November 2009)

A Knowledge Gaps and Opportunities workshop was held on 18th November, 2009. The event was organised by National University of Lao, but hosted by LARReC. The workshop was designed to summarise the last two years' research activities undertaken in Lao P.D.R and also to disseminate information on fishway designs used elsewhere in the world. In total, 43 people took part in the workshop and participants were from a range of backgrounds and disciplines. The workshop commenced with an overview of the importance of fish passage and a statement of the overall importance of fish in the lower Mekong Basin by Dr Chris Barlow (ACIAR). Mr Douangkham Singhanouvong presented a summary of the existing project in Lao P.D.R and gave an overview of different fishway designs listing the advantages and disadvantages of each. Dr Oudom Phonekhampeng then summarised the work completed to date and gave an outline of work to be finalised in 2009. Mr Jim Barrett (MDBA) gave a presentation on the benefits on using an expert panel approach to fishway design activities and highlighted several examples from Australia which may be of use to fisheries managers in Laos.

Dr Lee Baumgartner gave an overview of results obtained from sampling activities in 2008. His presentation focused on three main aspects of data collection; fishway gradient trials, fishway entrance design and fisher surveys. Combining 2008 and 2009 data revealed that over 16,000 fish from 107 species were collected within the fishway. The importance of fishway slope and the influence on velocity and turbulence were discussed. Preliminary results were presented which suggested that a fishway with a moderate slope (1:15) was successful at passing a large number of species and size classes.

A component of the existing project is to construct a permanent fishway at the Pak San site. The preliminary data presented by Dr Baumgartner was subsequently used to develop a series of fishway design specifications for the site at Pak San. Mr Tim Marsden and Garry Thorncraft used the initial data to present three options for fish passage mitigation and the expected cost of each.

These were:

> Option 1: Construct a bypass channel with hydraulic conditions equivalent to the vertical slot fishways (Approx cost $US20K)
>
> Option 2: Construct an additional culvert under the road with fish-friendly hydraulics. It would contain an entrance which links to the right training wall of the existing regulator (Approx cost $US40K)
>
> Option 3: Construct a vertical slot fishway that will operate over a wide range of flows at the site (approx cost $US100K)

A discussion session provided positive feedback for the project. Villagers from Pak Peung (Bolikhamxay province) demonstrated strong support for the project and discussed the opportunity to include fishway operation into local fisheries management plans. The village requested information on the maintenance and operation requirements of fishways so that they can ensure functionality into the long-term.

Wetlands Alliance also demonstrated strong support and further suggested that the success of this project could be used to form the basis for a World Bank or Asia Development Bank funding bid to rehabilitate a large number of floodplain regulators over a large spatial scale. However, this necessitated the identification of priority sites for remedial works and also the provision of a guidelines document which could be used to help facilitate large-scale construction. These were both seen as important components of any future works program.

World Wide Fund for Nature also expressed support for the work and expressed an interest in facilitating contact with regional district officers seeking advice on fish passage projects. WWF expressed an interest in integrating the management and design of floodplain infrastructure within existing program objectives particularly within a fisheries co-management framework.

7 Achievement of objectives

Objective 1: To Establish design criteria for fishways in Lao PDR

no.	Activity	outputs/ milestones	Completion date	Comments
1.1	Establish project co-ordinating committee and undertake site selection with engagement of local community	A co-ordinating committee comprising project staff and relevant community members Agreement with local community to support the project Co-ordinating committee determine experimental design and dissemination pathways for data	Feb 2008	The project co-ordinating committee was established early in the project and have already met three times to discuss developments and maintain work plans associated with the project. An agreement with the local community was forged in March 2008 and local villagers actively participated in project activities. The experimental design was finalised before May 2008 and the dissemination of our research program began immediately.
1.2	Manufacture one temporary experimental fishway channel to determine the swimming abilities of floodplain species	The construction of fishway units	Mar 2008	This was achieved in April 2008. However, the unit was badly damaged in flood waters between July and September 2008 which necessitated unscheduled repairs November 2008.
1.3	Perform field experiments with wild migratory fish with participation of key stakeholder groups	A list of specific criteria to enable the construction of functional fishways Improved understanding of fishway hydraulics Improved knowledge of migratory fish biology Identification of community co-management issues	Jul 2009	Criteria required for the construction of vertical slot fishways was determined. The experiments demonstrated that a fishway with a 1:15 slope, 150mm slot widths with 1.5 X 1.0 m cells provided passage for the majority of fish species at the study site. The strong swimming ability of many Mekong species required the project team to develop a new approach to fishway hydraulics. Rather than proceed with conservative hydraulics (which is the common method) it became apparent early in the project that fishways could be constructed on steep slopes. This formed the basis of more detailed experiments in 2009 which were extremely successful. The project substantially advanced the body of knowledge on migratory fish of the lower Mekong Basin. Improved understanding of fish behaviour and migratory cues now provide a solid basis for the development of new fishway designs and further experimentation.

PC = Partner Country, A = Australia

Objective 2: To test, adapt and demonstrate the benefits of fishways

no.	Activity	outputs/ milestones	completion date	Comments
2.1	Construct one permanent fish passage facility to act as a demonstration site for wider application throughout Lao PDR	One permanent fishway to provide passage at a key site	Dec 2009	This section of the work experienced substantial delays. Floods initially delayed the completion of experiments in 2008 which precluded the identification of optimal design criteria. Secondly, the cost of construction materials had almost tripled since the SRA was submitted in 2006. A plan to finalise construction was discussed with local villagers (Pak Peung) and initial construction could not begin until March 2010.
2.2	Perform a detailed assessment of permanent structure during the wet season and determine fish passage efficiency	Data on the effectiveness of vertical slot fishways in Lao Improved understanding of fishway operation and assessment	N/A	Delays in construction and an increase in expected costs mean that this objective will not be completed as part of the current SRA, though local organisations such as NUOl and LARReC will complete those studies when construction is completed and the fishway s is operational in 2011.

PC = Partner Country, A = Australia

Objective 3: To disseminate the data to relevant stakeholders and the wider scientific community

no.	Activity	outputs/ milestones	completion date	Comments
3.1	Prepare a final report and management plan	Final project report published and management plan officially endorsed	Dec 2009	The final report is completed and a long-term fishway management plan is currently being developed by riparian countries.
3.2	1st Lao Thai Fishway Technical Workshop	One-day joint workshop to review fishway development status	Dec 2009	The team held two workshops, one focused at researchers and managers and the other focused at higher level government officials from Thailand and Lao P.D.R.
3.3	Communicate the results to key groups and stakeholders	Presentation at Mekong River Commission technical workshop Preparation of distributional documentation Co-ordinating committee to present results to respective stakeholders	Dec 2009	Members of the project team have given three presentations to Mekong River Commission Officials throughout the project. Many posters, agenda papers, brochures and other material were distributed at the two workshops. Results have been discussed with non-government organisations such as Wetlands Alliance and World Wide Fund for Nature. Both organisations are currently actively involved in dissemination activities at both a local and regional scale.

8 Impacts Achieved

8.1 Scientific impacts

The project has made a number of significant scientific impacts. A key component of the first year was to gain appreciation and understanding for the impacts of migration barriers on fish and also the development of mitigation options. The project enhanced this knowledge by providing scientific evidence of floodplain regulators acting as a barrier to lateral migrations between the main river and floodplain habitat. Many species of fish were collected downstream of the regulator actively attempting to migrate into water flowing from the upstream wetland. These fish were extremely motivated to migrate and in many instances were actively leaping from the water. The collection of this scientific information has greatly enhanced the understanding of the migratory requirements of Mekong species and also provided insight into the cues for migrations.

The greatest scientific impact from this study is the discovery that vertical slot fishways can effectively provide fish passage for fish seeking access to the floodplain. This is the first time that fishway designs have been progressed in the Mekong Basin with the specific intent of providing passage for local species. The results are based on a robust experimental design and are extremely publishable in international scientific journals. The first manuscript arising from this work is attached to this report. The work has achieved its goal of providing a 'proof of concept' for fishway construction and has provided a foundation for future work in the area.

8.2 Capacity impacts

The greatest capacity impacts of this project are:

- The transfer of fish passage technology principles from Australia to Lao PDR
- An understanding of fishway design and assessment principles by Lao researchers
- Transfer the results to other key sites in Thailand
- Identify the advantages and disadvantages of fishway design to inform future construction

The transfer of technology principles is an ongoing task. Fish passage development in Australia has taken over 25 years to achieve a program that is now being applied on a large scale in the eastern states. The program has been built on the foundations of solid scientific inquiry that enabled the development strategic plans to facilitate the construction of suitable fishway designs.

The main capacity impact from this project has been to facilitate a cultural change among NRM groups in Thailand and Laos by demonstrating that the effects of migration barriers can be adequately mitigated. This initially required the involvement of Lao researchers in aspects of fishway construction and assessment techniques. This has proven difficult, particularly because it is widely assumed that the effects of a dam or weir can be adequately mitigated through re-stocking. Whilst this may be suitable in the short-term, it is often only applicable for certain species and does not effectively mitigate habitat changes or alterations to flow regimes associated with increased river development. The team are progressively contributing toward this culture shift by actively involving people at the village, district, provincial and government level.

8.3 Community impacts

Community impacts have been localised and have focused largely on impacts in the vicinity of the study site in Pak San.

8.3.1 Economic impacts

In many areas of the LMB, fisheries have changed dramatically. In some areas this is to the point where economic fisheries are beginning to collapse and river communities subsistence fisheries are becoming adversely affected. The construction of suitable fishways will be a useful management tool to help offset the effects of river development projects, and prevent further declines of fish communities as areas of the LMB experience increasing river management works. In reaches where dramatic declines in fish abundance have occurred, the economic benefits of fish passage construction will be obvious. The financial status of families upstream of migration barriers will improve substantially as fisheries are restored (Category one). As fish communities rehabilitate over time, the establishment of sustainable fisheries will again provide a source of food and income for many river communities. Economic impacts will be initially realised upon completion of a permanent fishway at the Pak San site. It is expected that the fishway will facilitate the upstream migration of thousands of migratory fish. Once completed, these fish will regain upstream access to a wetland where passage has been blocked by the construction of a regulator. Fishermen upstream of the regulator are expected to realise increases in fish catches following fishway construction.

8.3.2 Social impacts

Laos is a land-locked country and river communities are highly reliant upon fish as a source of protein. The greatest social impact arising from this project will be the reinstatement of a viable fishery in the wetland upstream of the regulator which will provide an additional protein source for local communities. The construction of fishways could provide a point source area for exploitation of fish to occur, especially during peak migration periods. This will necessitate community engagement and education to ensure the fishways provide maximum ecological benefit the LMB. Community co-management of aquatic resources is currently being developed by groups such as the Mekong River Commission as a solution to allow progression from the existing open-fishery (unregulated) into a more manageable rights-based closed-fishery (regulated and managed). In essence, local communities attain ‘ownership’ of the resource (in this case a fishway) and are provided guidance in developing mechanisms to sustainably manage the resource and prevent unsustainable overexploitation. Each village on the floodplain develops its own fisheries management plan in co-operation with local government authorities. Then, wider-scale catchment-based management plans are developed, in consultation with other communities, to protect ecologically-important upstream fish migrations. This approach is currently being pursued with the local community at Pak San and will be progressed as the permanent fishway nears completion.

8.3.3 Environmental impacts

The adoption of fish passage technology, in areas of reduced migration opportunities, will help create sustainable fisheries throughout the lower Mekong basin. The construction of fishways provides substantial ecological benefits to riverine systems by providing access to habitat, food and spawning areas. They also reduce the extent and frequency of unnatural aggregations (i.e. downstream of migration barriers). If fishways are operated continuously, and are constructed to specifications that suit local species, substantial rehabilitation of fish populations can be expected (and is widely demonstrated in the scientific literature).

The construction of a permanent fishway at the Pak San site will provide measurable improvements to the local fish community. Initial experiments yielded over 50 species of migratory fish attempting to migrate upstream. The construction of a permanent fishway will provide access to the floodplain for feeding and spawning. The successful application of fish passage technology will provide proof of concept for technology that can help to rehabilitate floodplain fisheries in the Lower Mekong Basin. Fish passage technology, once defined, can then be applied at low headbarriers to fish migration.

9 Conclusions and recommendations

9.1 Conclusions

The project successfully achieved the objective of demonstrating ‘proof of concept’ that vertical slot fishways can provide passage for Lower Mekong fish species at low head weirs. Results suggested that a vertical slot fishway constructed on a 1:15 (6%) slope with small slot widths (150mm) and moderately sized cells (1000 mm X 1500 mm) was suitable for the majority of migratory species and size classes in Central Laos. However, some species which prefer fast flowing water may not ascend a fishway on this slope. Migration rates were substantially influenced by river flow which suggests that the design of permanent fishway installations must make careful consideration of local hydrology to perform efficiently. Fishway efficiency must be optimised at times of water level increases to ensure maximum fish passage rates. Careful consideration of these design aspects will provide functional fishways that have widespread application at similar sites throughout the Lower Mekong Basin. Long term benefits of this approach would help to rehabilitate wetlands and provide assist millions of people who rely on floodplain fisheries for food security and income.

9.2 Recommendations

The major recommendation arising from this work is that any major development projects seeking to construct floodplain regulators could now provide fish passage by constructing vertical slot fishways to the optimal design specifications. The species composition and total abundance of fish caught as part of this initial study demonstrate that a vertical slot fishway would be suitable at low head weirs, although other alternative low-cost designs can be considered. Dealing with fish passage issues, however, is a challenging and evolving area. Quite often solutions which are entirely applicable to a particular site or location cannot be directly applied to another due to differences in species, flow, geography or social/cultural issues. These factors necessitate an adaptive approach which requires rigorous research to underpin the management action, which is the construction of fishways to rehabilitate floodplain regulators. The research needs to be robust but flexible so that the results from research activities have widespread application at different sites. Adaptive management combined with direct experience for key managers and researchers is the key to ensuring that an effective solution is implemented at any given site.

A fish passage workshop held in Vientiane, Lao PDR, in November 2009 identified a number of specific knowledge gaps which would follow on from this existing work. The four major issues were:

1. A lack of quantitative data in Lao PDR regarding the current scale of floodplain development and the impact of works already undertaken,

2. A need to research appropriate low cost fishways which are suited to lower Mekong species which have been validated under field conditions,

3. Poor quantification of socio-economic impacts of floodplain development (whether positive or negative) and whether any mitigation works increase fish production

4. A lack of appropriate contacts for developers and district-scale conservation officers can obtain design advice on fishway construction.

Addressing these four issues would substantially advance fish passage in the Lower Mekong Basin by helping to understand the geographic extent of fish migration obstruction, developing additional fishway designs for application at a wide range of barriers, understanding potential social and economic benefits and establishing a central contact point for advice on fish passage issues. Advancing each of these areas over the next five years would address key knowledge gaps that current preclude the effective management and rehabilitation of floodplain fisheries.

10 References

10.1 References cited in report

See Appendix 1

10.2 List of publications produced by project

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Baumgartner, LJ, Marsden, T, Singhanouvong, D, Phonekhampeng, O, Stuart, I, Thorncraft, G (In prep). Optimising fishway design for floodplain regulators in tropical systems: A case study from the Mekong River. Target: River Research and Applications

Baumgartner, LJ, Marsden, T, Singhanouvong, D, Phonekhampeng, O, Stuart, I, Thorncraft. G (In prep). Observations on migratory behaviour of lower Mekong fish species. Target: Ecology of Freshwater Fish

11 Appendixes

11.1 Appendix 1: Manuscript prepared for publication

Target Journal: *River Research and Applications*

Optimising fishway design for floodplain regulators in tropical systems: A case study from the Mekong River

Lee J. Baumgartner, Tim Marsden, Douangkham Singhanouvong, Oudom Phonekhampheng, Ivor G. Stuart , Ubolratana Suntornratana, Garry Thorncraft

ABSTRACT

Fish passage through an experimental vertical-slot fishway facility was assessed at a floodplain regulator on the Mekong River in Central Laos between April and July 2009. Experiments sought to determine the influence of floor slope (1:15 or 1:8) on passage success with a view to developing a series of optimal design criteria for the construction of vertical-slot fishways at other barriers to fish passage in the Lower Mekong Basin. A total of 14,661 fish from 73 species were captured during the experiments. Catches were dominated by riverine (white) (n = 51; 69% of total) and floodplain (black) species (n = 15; 20%) which represented 19 families in total. The work demonstrated that fish were actively attempting to gain upstream passage and displayed strong migratory behaviour during river level rises. Migratory activity was greatest during sharp rises in water level, but reduced substantially when river level fell. Fish community composition varied greatly among different floor slope and control groups. More species were collected from control samples but the greatest number of fish was collected when the fishway was configured on moderate slopes (1:15). A range of size classes were also collected from control samples and moderate slope treatments samples but when established on a steeper gradient, catches were dominated by larger fish. The study successfully demonstrated that vertical slot fishways can provide passage for species attempting to move laterally onto Mekong River floodplains. The construction of these structures may therefore represent a suitable management tool to help reinstate migration pathways at small-scale migration barriers.

INTRODUCTION

Floodplain ecosystems are important ecological assets accounting for much of the natural production in large river systems (Bayley, 1995). Virtually all floodplain systems require regular flooding to maintain connectivity with main river channels and regular inundation of releases nutrients and restores lateral connectivity (Junk *et al.*, 1989). Floodplain soils are extremely fertile and high nutrient loads favour agricultural development (Bayley, 1995). Regular flooding however, decreases the agricultural productivity of the floodplain because it is difficult to permanently crop areas that are frequently inundated (Islam and Braden, 2006; Sparks, 1995). This paradox has necessitated the development of engineering solutions such as levee banks, regulators and sluice gates to reduce inundation events. These engineering structures either reduce or eliminate natural floodplain functions and productivity quickly decreases, particularly in areas of intensive development (De Graaf, 2003; Thoms, 2003). Reductions in productivity and accessibility subsequently facilitates the decline of floodplain fauna which has been observed in many rivers throughout the world (Kingsford, 2000).

The Mekong is one of the world’s major catchment systems. It drains a total area of 795,000km^2, is over 4,000km in length and supports over 60 million people. Fisheries are immensely important throughout the lower Mekong basin providing on average 48% (Lao PDR) and 79% (Cambodia) of the animal protein intake (Pagdee *et al.*, 2007; Hortle, 2007b; Valbo-Jørgensen *et al.*, 2007). More than 80% of rural households in the Mekong basin in Thailand, Lao and Cambodia are involved in a capture fishery which has a first-sale value of between US$2,000-4,000 million per year (Hortle, 2007a). The annual yield from the capture fishery in the lower Mekong Basin is about two million tonnes, which is approximately 2% of the total world marine and freshwater catch. Whilst the development of floodplain ecosystems has had a worldwide impact of fisheries production, impacts on the Mekong River are becoming increasingly apparent (Hortle *et al.*, 2008)

The Mekong River has an extensive floodplain system extending from the lowland reaches of Laos and terminating in large and complex wetland systems in Thailand, Vietnam and especially Cambodia (Kummu *et al.*, 2005). The Mekong River floodplains are among the most productive in the world, but a lack of ecological understanding precludes effective management of the system (Campbell, 2005). Fish of the Mekong floodplains are adapted to high natural mortality through early sexual maturation and high fecundity (Lowe-McConnell, 1987). These adaptations provide resilience to fishing exploitation provided floods of adequate duration and magnitude frequently inundate floodplain habitat and help to maintain productivity (Bayley, 1995). Construction of dams in the upper Mekong however, are beginning to reduce incidences of flooding in downstream reaches, and inundation events are declining in frequency (Lu and Siew, 2006). Further development of floodplain systems with agricultural infrastructure are also reducing lateral connectivity in many areas (Nguyen and De Silva, 2006; Jorgensen and Poulsen, 2000). Continued development of these important ecosystems requires the development of effective mitigation techniques which can restore lateral connectivity with the main river channel.

In large rivers, most rehabilitation efforts for fish are focused on developing fishways for main channel barriers to longitudinal connectivity (Clay, 1995; Odeh, 1999; Stuart *et al.*, 2007). Fishways can be unsuccessful in large biodiverse rivers particularly at high barriers (> 12m) where large-scale habitat changes, reductions in flow regimes and water quality issues often have a much greater impact than reduced connectivity (Fernando Mayer and Angelo Antonio, 2008). Many fishways, however, have been successfully developed to pass a wide range of species and size classes at smaller structures (< 6m) (Andersen *et al.*, 2007; Barrett and Mallen-Cooper, 2006; Baumgartner and Harris, 2007; Bunt, 2001; Hamano *et al.*, 1995; Mallen-Cooper and Brand, 2007). In many instances these can provide passage for high numbers and biomasses of fish over relatively short time periods (King and Torre, 2007; Kowarsky and Ross, 1981; Mallen-Cooper, 1996; Roscoe and Hinch, 2009; Schmetterling *et al.*, 2002; Schwalme and Mackay, 1985; Stuart *et al.*, 2008a; Stuart and Mallen-Cooper, 1999; Stuart *et al.*, 2008b). Importantly, engineering specifications for these fishways are well-known and can be applied to any small barrier provided local hydrology, species composition and ecological objectives are clearly defined and understood.

Several fishways have been constructed in the Lower Mekong Basin, but none demonstrate evidence of attempting to incorporate knowledge of local species and hydrology into fishway design (Sripatrptasite, 2005). The present study sought to determine whether a vertical slot fishway can be designed to provide passage for Lower Mekong fish species attempting to access floodplain habitat. Experimental manipulations of flow and turbulence were used, under field conditions, to determine the optimal design criteria to guide potential application at other sites in the Lower Mekong Basin. Cues to migration and the influence of changing water levels were also investigated.

METHODS

Study Site

The study was conducted at a floodplain regulator adjacent to the Mekong River at Pak Peung village (Bolikhamxay province) in central Laos. The concrete regulator was originally constructed (in the 1960s) to prevent inundation of extensive floodplain rice crops during increases in Mekong River level during the wet season. The regulator is 10m high and contains three manually-operated sluice gates which release water from an upstream wetland. Each gate is capable of delivering a maximum 80 ML.day^{-1} (0.93 m^{3}.s^{-1}). Gates are initially operated to drain the associated wetland to prevent crop damage following high rain evens (early in the wet season). The gates are adjusted daily and during this period fish might move downstream (from the floodplain to the river) through the sluice gates, but upstream passage (from the river to the floodplain) is completely precluded. The gates are closed during high Mekong levels to prevent further crop damage from water entering the wetland (usually later in the wet season). Under these conditions, the regulator is a barrier to both upstream and downstream fish movements.

<u>Experimental Fishway Unit</u>

An experimental fishway unit was constructed to determine whether technical fishways are capable of providing passage for local migratory species at the Pak Peung site. A vertical slot fishway, constructed out of reinforced mild steel (1.5 mm width) was installed parallel with the right hand training wall downstream of the regulator and secured in place with a combination of sandbags and high-tensile cable. A block and tackle with an endless chain was fitted to an overhead gantry and used to manipulate the slope of the fishway. A sandbag wall was erected upstream of the structure to direct flow from the regulator through the experimental unit. The fishway unit comprised four cells which were 1500 mm x 1000 mm. Vertical slots were 1.4 metres high with a nominal slot width of 150 mm.

<u>Experimental Design</u>

Fish were collected from two locations within the fishway over a period of 44 days between April and July 2009 and sought to compare fish communities attempting to ascend the fishway (control) with fish successfully ascending (treatments). Treatments involved establishing the fishway on different floor slopes, moderate (1:15 or 6%) or steep (1:8 or 12%), and quantifying the number of fish successfully ascending. Experimental treatments began by carefully adjusting the fishway until the required slope was attained. Once the desired hydraulic conditions were achieved, fish passage was assessed by placing a fish trap (1500 mm x 1000 mm X 400mm; 6 mm mesh) upstream of the last baffle.

The control sought to quantify the number of fish attempting to ascend the fishway and provided a basis for comparison with treatment replicates. Controls began by establishing the fishway on a moderate slope to provide an attraction flow for fish to approach the fishway. The trap was established downstream of the attraction jet and any fish attempting to enter the fishway were collected.

Each control and treatment replicate ran for 2 hours after which the trap was retrieved and any fish were identified, measured (total length), weighed and subsequently released. Replicates were completed each day between 700 and 1500. It was unknown whether the structure of migratory fish communities would vary with time of day. To control for this potential effect the fishway was assessed using a randomised block design where one 'block' was completed every three days. Experimental treatments and the control were subsequently assigned to one of three potential time periods each day (Morning; 700 – 1000, Midday: 1100 – 1300, Afternoon: 1400 - 1700). The three replicates (control and two treatments) were completed per day but three days were required to complete all time of day and treatment combinations. A total of 6 full blocks were completed over the study period.

<u>Data Analysis</u>

Data were analysed using S-PLUS and PRIMER V6.0. Differences in length distributions of fish collected from control and treatment samples were compared using a Kolmogorov-Smirnov (KS) pairwise comparison. This test computes a test statistic (ks) which is based on the largest difference between two cumulative length-frequency distributions. The length frequency data of all fish species were then pooled to construct length frequency histograms for each treatment and control.

Differences in fish community structure among experimental blocks, fishway slope and time of day were investigated using Permutational Analysis of Variance (PERMANOVA). All tests were based on square-root transformed data using Bray Curtis Similarities (with 999 permutations). 'Block' was treated as a fixed factor but both floor slope and time of day were random. It was largely unknown at the commencement of the study whether different species migrated at different times of the day. This was identified as a factor which could potentially confound experimental results if slope experiments were conducted in different diurnal periods. Preliminary analysis identified no differences in fish community structure could be attributed to time of day so it was removed as a factor from subsequent analysis to permit further exploration of the effect of floor slope and experimental blocks. Two-Way Analysis of Similarities (ANOSIM) was subsequently used to determine whether the fish communities among experimental groups (treatment and controls) or among daily experimental blocks. This test sought to identify both the effect of fishway slope and also any natural change in fish communities as time progressed through the experiment. In all ANOSIM tests, 999 Monte-Carlo randomisations were used to calculate approximate probabilities and Gobal R-values. Sample differences plotted using non-metric multi-dimensional scaling ordinations to visually represent any group differences.

RESULTS

General catch information

Fish were extremely motivated to migrate. During regular collections fish were physically observed to jump from the water whilst attempting upstream migrations and frequently attempted to ascend the apron of the adjacent weir. In total, 14,661 fish from 73 species were captured during the experiments (Table 1). Catches were dominated by riverine (white) species (n = 51; 69% of total) but several floodplain (black) species were also recorded (n = 15; 20%). Species represented 19 families in total, but 96% of the catch represented only five families (Cyprinidae = 69%; Ambassidae = 22%, Belonidae = 4%; Clupeidae = 1%; Mastacembelidae = 1%) and 34 species comprised less than 10 individuals (Table 1). Three species *Parambassis siamensis* (n = 3,277)*, Barbonymus gonionotus* (n = 3,206), *Rasbora dusonensis* (n = 2,625) comprised 62% of total catch. Eight species were unable to be indentified and are presently undergoing more detailed taxonomic classification.

Influence of fishway slope

Most individuals were collected during moderate slope treatments (n = 7,666), but the most species (n = 52) were collected from control samples (Table 1). Species appeared to fall within three main groupings based on passage success within the experimental unit. Firstly, there were species which only migrated when the fishway was established on a steep slope. These species (n = 20) were either absent, or collected in extremely low abundances during control and moderate slope treatments. Another group of fish which were collected only from control groups (n = 14) and were absent from treatments. The final group of fish (n = 39) were collected from both control and treatment groups irrespective of fishway slope.

A 3-factor analysis (based on the randomised block design) identified significant differences among blocks (PERMANOVA; Table 2) which arose from a progressive change in migratory fish community from the beginning to the end of the study period. Many fish were migrating at the commencement of experiments but numbers gradually decreased with time. Differences in fish community composition were also detected among different floor slopes (PERMANOVA; Table 2) because of changes in relative abundances of several species among experimental treatments. This was largely due to the high number of individuals collected from the moderate slope group overall, and the absence of several species from control samples. For instance, *Parambassis siamensis*, *Rasbora rubrodorsalis* and *Xenentodon cancilla* were collected in significantly higher abundances from control samples than either treatment sample. In contrast, several species such as *Barbonymus gonionotus*, *Rasbora dusonensis* and *Osteochilus lini* were more frequently collected from the two treatment groups rather than the control. These differences in fish community composition provided separation of treatment groups in ordinal space (Figure 1). No significant differences among different diurnal periods indicated that the structure of the migratory community did not vary during daylight hours (PERMANOVA; Table 2).

Effect of flow on fishway use

Daily mean fish passage was relatively high early in the study but decreased substantially during the final stages (Figure 2). The commencement of the study period coincided with a sharp increase in water level within the Mekong River (from 2.39m to 4.40m) following substantial rainfall events in nearby catchments. Water levels eventually peaked and the total number of species and individuals collected substantially declined from both treatment and control samples. Attempting a correlation between river level and total fish migration numbers identified a poor relationship ($R = 0.09$) which occurred because most increases in fish migration occurred during the initial level rise suggesting that change in water level, may be a more meaningful factor (Figure 2) Migration rates were subsequently plotted against change in daily flow and a much stronger correlation was observed ($R = 0.53$; Figure 3). These observations provide preliminary evidence that migration rates and changing hydrograph could be inherently linked but the relationship was not consistent across species. *Xenentodon canciloides* continued to use the experimental fishway during a falling hydrograph whilst *Rasbora dusonensis*, *Barbonymus gonionotus*, *Osteochilus lini*, *Cyclocheilichtys armatus* and *Rasbora daniconius* were only collected during a rising hydrograph. These species were notably absent whenever levels in the Mekong were falling.

Size class differences

Fish were collected over a wider size range during the study (19 – 285 mm) but the greatest proportion of captured fish were relatively small (< 100 mm) (Figure 3). Fish collected from the control group were significantly smaller than fish collected from either of the two treatment groups (KS: $ks_{ctrl\ vs\ 100} = 0.240$, $p < 0.001$; $ks_{ctrl\ vs\ 200} = 0.415$, $p < 0.001$). *Clupeichtys aesiamnesis*, *Amblypharyngodon clulabhornae* and *Eosomis* spp were almost virtually absent from catches during steep slope experiments and no fish less than 40mm was able to ascend steep floor slopes. Changes in the catch of fish less than 100mm contributed to significant differences between both treatment groups (KS: $ks_{100\ vs\ 200} = 0.182$; $p < 0.001$). In contrast, catches of larger fish were higher on steeper slopes. Some species, including *Rasbora dusonensis*, *Barbonymus schwanenfeldii*, *Rasbora daniconius* and *Osteochilus lini* were poorly represented from control samples, but were more abundant when slope increased. Substantially more fish (80 – 120mm) were collected on moderate slopes whilst a greater proportion of fish (120 – 160 mm) were collected during steep slope trials.

DISCUSSION

Fishway design considerations

Vertical slot fishways are the most widely used and successful fishway design in the world (Clay, 1995). The ability for the design to cope with fluctuating headlosses and large tailwater variations provide applicability at many different types of migration barriers (Mallen-Cooper and Stuart, 2007). The present study identified migratory fish were able to negotiate an experimental vertical slot fishway installed at a floodplain regulator on the Mekong River. The fishway provided passage for many species and size classes and offered important insights into fish behaviour that will influence the design of future fishways for the Lower Mekong Basin.

The identification of three broad migratory groups of fish suggests that Mekong species have widely varying swimming abilities and migratory cues. Fish with stronger swimming abilities readily ascended the experimental unit and were captured in relatively high abundances from the fishway exit. In contrast, fish with poorer swimming abilities were only collected under control conditions. These different scenarios suggest that whilst the construction of fishways on moderate slopes will provide good passage for most species, a proportion would still be unable to ascend. Many tropical species have different lateral migratory requirements depending on life history stage or time of year (Coops *et al.*, 2006). In tropical rivers, the use of fishways to facilitate passage is complicated by high migratory biomass, variable hydrology and higher species richness than in temperate zones. It is therefore difficult to adequately design a single fishway that can provide passage for all migratory fish into suitable habitats (Pelicice and Agostinho, 2008).

Many species of fish were observed to migrate through the experimental fishway but there were substantial differences in ascent success between control and treatment groups. Moderate slopes suited most species and size classes but there were some species which were only collected during controls or steep slope treatments. Changes in fishway hydraulics may explain some of these observed differences. Fishways with high flow and turbulence are widely understood to limit the passage of some species (Tarrade *et al.*, 2008; Liu *et al.*, 2006). This type of behaviour was likely exhibited by the group of fish collected from control samples but absent when slope increased. High turbulence is a frequent contributor to decreased passage success and is known to disorient fish with poorer swimming abilities (Rodríguez *et al.*, 2006). This is frequently observed in large Australian rivers where inappropriate turbulence profiles in vertical slot fishways inhibit the passage of some species (Stuart *et al.*, 2008b). Under these circumstances, reducing floor slope may be a useful mechanism to increase passage of some species but the decrease in associated attraction flows would likely inhibit the passage rates of others (Lindmark and Gustavsson, 2008).

An additional solution for fish passage in this situation is the construction of multiple fishways. For instance, high slope fishways with increased discharge and attraction would provide an effective passage solution for strong-swimming species (Pon *et al.*, 2009). Providing an additional fishway with conservative hydraulics would then cater for poorer-swimming species (Stuart *et al.*, 2008b). The cumulative benefit of both structures would provide a solution that facilitates the passage of most migratory species at any given site. Cost, however, is a major limiting factor in any fishway construction exercise (Barrett and Mallen-Cooper, 2006) and constructing multiple fishways requires a high capital outlay. In the Lower Mekong Basin, such solutions would be most applicable to larger development projects with high budgets. Fish passage solutions in the Lower Mekong may therefore require a design which is low cost and provides effective passage for a majority of species within a target flow range.

Previous work has identified turbulence, and not flow, is a major limiting factor for poor swimming fish (Tarrade *et al.*, 2008; Wu *et al.*, 1999). Reductions in turbulence can be achieved through the addition of sills into the middle of each vertical slot (Mallen-Cooper *et al.*, 2008). Adding sills into fishway baffles reduces the overall slot area and overall discharge but has the added advantage of maintaining high velocities which can provide attraction. Retrofitting these devices into vertical slot fishways has been demonstrated to enhance the passage of poor swimming species, whilst still permitting the passage of stronger swimmers (Mallen-Cooper *et al.*, 2008). Experimentation with middle sills was not considered as part of the existing study but could provide substantial increases in fish passage given the differences in fish responses to altered slopes. Retrofitting sills to steep fishways would provide an inexpensive mechanism to increase functionality whilst reducing construction costs and should be considered when further developing fishway concepts for tropical rivers.

Undertaking research in an experimental facility provides an excellent indication of likely fishway design criteria but it cannot substitute for the construction of a permanent facility. Permanent fishways require careful design and knowledge of the local hydrology to be truly effective. A challenge for the Lower Mekong Basin is to design a vertical slot fishway which maintains functionality with large fluctuations in river level over a migration season. Engineering solutions for such a degree in water level are relatively straightforward, but it is important to note that the direct application of fishway criteria determined in this study should include careful consideration of local fish species to ensure the most effective solution at any given site. A natural progression from this preliminary study is to therefore apply the design criteria at a permanent fishway at a floodplain regulator. A subsequent biological assessment of this structure would provide increased confidence in the ability for Vertical slot fishways to be more widely applied at other sites.

Ecology of fish migrations

Large numbers of fish were collected from many different life history stages. These fish were all migrating upstream at the regulator site and were actively attempting to access the upstream wetland. Many of these fish were riverine species, and almost all individuals were sub-adult, suggesting that many species were attempting to access nursery habitat within the upstream wetland. Tropical fish exhibit fast growth rates in floodplain habitats and many riverine (white) species are known to access floodplains for growth and development (De Graaf, 2003). Of particular note was the collection of numerous juvenile Jullien's golden carp *Probarbus jullieni*. This species has declined significantly throughout the Lower Mekong Basin and the disconnection of floodplain habitat has been a major factor in this species appearing on the IUCN red list (Baird, 2006). Collections within the experimental fishway are direct evidence that provision of fish passage may provide an important mechanism to help restore lateral connectivity of this, and other species to important nursery habitat.

This work has also substantially enhanced the understanding of the impacts of migration barriers on lateral movements between the Mekong River and its floodplain. Data provided evidence of floodplain regulators acting as a barrier to lateral migrations between the main river and floodplain habitat. The first was evidenced by the strong motivation for migratory fish to gain upstream access. Fish were extremely persistent and continually sought an upstream path but the number of migratory fish collected was strongly linked with river level. This observation provides evidence that hydrological changes provide an important cue for fish migration in the Mekong.

Flows are widely reported as an important cue for fish performing both longitudinal and lateral migrations (Beyers and Carlson, 1993; Gehrke *et al.*, 1999; Humphries *et al.*, 1999; Nilsson *et al.*, 2005). Most production in large rivers occurs during periods of wetland inundation (Copp, 1989) which may account for increased attempts for fish to access floodplain habitat as water levels increased. The response to falling water levels was equally obvious. Fish that fail to quickly leave floodplain habitat during receding water levels risk becoming stranded when wetland habitat becomes disconnected (Jones and Stuart, 2008). Limiting migratory behaviour to periods of rising water levels would substantially reduce the risk of stranding and could provide an ecological explanation for reduced fishway catches during flow reductions.

Long term maintenance of river-floodplain connectivity will provide important ecological outcomes for the region. Fish community-based analyses have identified a high degree of connection among different reaches of the Mekong River (Kang *et al.*, 2009). Recent studies have further provided genetic data demonstrating a high degree of connectivity among different reaches. For instance, the identification of a single stock of Siamese mud carp *Henicorhyncus siamensis* in the lower Mekong River basin below the Khone Falls suggests that freshwater habitats in Cambodia and Vietnam are connected within the species full range (Adamson *et al.*, 2009). Massive annual harvests of these and other floodplain species should contribute to stock depletion but persistence of a single stock suggests a high capacity for dispersal and connectivity among sites (Adamson *et al.*, 2009). This high degree of connectivity among floodplain habitats suggests that maintenance of migration pathways is extremely important for the long term maintenance of species. Given that many of these species are short-lived, large-scale floodplain disconnection could facilitate rapid declines in these interconnected populations. The construction of fishways is therefore a potential management tool which can help provide lateral connectivity necessary for the long term maintenance of both riverine and floodplain species.

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Table 1. Total number of fish caught from the experimental fishway unit over the study period. Numbers refer to all species pooled across blocks for all experimental controls and treatments performed.

Species name	Ecology	Family	Floor slope			Grand Total
			Control	1:15	1:8	
Parambassis siamensis	white	Ambassidae	819	1948	510	3277
Barbonymus gonionotus	white	Cyprinidae	160	1552	1494	3206
Rasbora dusonensis	black	Cyprinidae	1	1567	1057	2625
Barbonymus schwanenfeldii	white	Cyprinidae	0	651	9	660
Hampala dispar	white	Cyprinidae	277	249	56	582
Rasbora rubrodorsalis	black	Cyprinidae	252	248	81	581
Xenentodon canciloides	white	Belonidae	406	136	17	559
Rasbora daniconius	black	Cyprinidae	28	303	169	500
Paralaubuca typus	white	Cyprinidae	62	262	24	348
Unknown 3	-	-	320	0	0	320
Osteochilus lini	white	Cyprinidae	4	149	144	297
Esomus metallicus	black	Cyprinidae	10	181	2	193
Amblypharyngodon chulabhornae	white	Cyprinidae	179	11	0	190
Clupeicthys aesiamnesis	white	Clupeidae	155	0	0	155
Esomus longimanus	black	Cyprinidae	28	73	0	101
Osteochilus schlegelii	white	Cyprinidae	0	8	86	94
Henicorhynchus ornatipinnis	white	Cyprinidae	2	57	34	93
Unknown 2	-	-	2	15	72	89
Puntius partipentazona	white	Cyprinidae	33	2	34	69
Raiamas guttatus	white	Cyprinidae	2	37	28	67
Epalzeorhynchos fretatum	white	Cyprinidae	0	0	54	54
Hampala macrolepidota	white	Cyprinidae	22	25	1	48
Macrognathus semiocellatus	white	Mastacembelidae	46	0	0	46
Badis ruber	white	Badidae	31	10	0	41
Puntius orphoides	white	Cyprinidae	1	20	18	39
Osteochilus hasselti	white	Cyprinidae	2	11	22	35
Probarbus jullieni	white	Cyprinidae	4	22	8	34
Cephalocassis borneensis	white	Ariidae	0	32	2	34
Rasbora trileneata	black	Cyprinidae	32	1	0	33
Henicorhynchus siamensis	white	Cyprinidae	27	3	2	32
Rasbora pauciforata	black	Cyprinidae	0	21	7	28
Sinibrama melrosei	white	Cyprinidae	0	25	2	27
Mastacemblus armatus	white	Mastacembelidae	15	0	1	16
Scaphognathops stejnegeri	white	Cyprinidae	2	4	10	16
Labiobarbus siamensis	white	Cyprinidae	0	5	11	16
Macrognathus siamensis	white	Mastacembelidae	15	0	0	15
Nemacheilus platiceps	black	Nemacheilinae	12	0	2	14
Puntius jacobusboehlkei	white	Cyprinidae	0	0	10	10
Puntius brevis	white	Cyprinidae	1	9	0	10
Rasbora aurotaenia	black	Cyprinidae	0	0	9	9

Cyclocheilicthys armatus	white	Cyprinidae	0	2	6	8
Unknown 6	-	-	1	4	2	7
Barbicthys laevis	white	Cyprinidae	1	4	2	7
Acanthopsoides delphax	white	Cobitinae	4	0	1	5
Hypsibarbus vernayi	white	Cyprinidae	1	2	2	5
Pristolepis fasciata	white	Nandidae	1	2	1	4
Oreochromis niloticus	black	Cichlidae	3	1	0	4
Amblyrhynchichthys truncatus	white	Cyprinidae	0	2	2	4
Acanthopsis spp	black	Cobitidae	4	0	0	4
Hemibarbus labeo	white	Cyprinidae	1	2	1	4
Scaphognathops spp	white	Cyprinidae	1	2	1	4
Cyclocheilicthys repasson	white	Cyprinidae	0	1	2	3
Anabas testudineus	black	Anabantidae	3	0	0	3
Unknown 7	-	-	3	0	0	3
Cyclocheilichthys apogon	white	Cyprinidae	0	0	3	3
Unknown 1	-	-	1	0	2	3
Trichogaster microlepis	black	Osphronemidae	3	0	0	3
Thynnichtys thynnoides	white	Cyprinidae	0	0	3	3
Brachygobius mekongensis	white	Gobionellinae	2	0	0	2
Chitala ornata	white	Notopteridae	0	2	0	2
Barbonymus altus	white	Cyprinidae	0	2	0	2
Mystus mysticetus	white	Bagridae	1	0	1	2
Cyprinus carpio	white	Cyprinidae	0	1	1	2
Notopterus notopterus	white	Notopteridae	0	0	2	2
Labiobarbus leptocheilus	white	Cyprinidae	1	0	0	1
Squalidus atromaculatus	white	Cyprinidae	1	0	0	1
Nandus oxyrhynchus	black	Nandidae	1	0	0	1
Unknown 4	-	-	1	0	0	1
Hypophthalmichthys molitrix	white	Cyprinidae	0	0	1	1
Yasuhikotakia longidorsalis	black	Botiinae	0	1	0	1
Unknown 8	-	-	1	0	0	1
Acrossocheilus iridescens	white	Cyprinidae	1	0	0	1
Tetradon cambodgiensis	white	Tetraodontidae	0	1	0	1
		Grand Total	2986	7666	4009	14661

Table 2. PERMANOVA results for differences in fish community structure among factors assessed during the experimental study. df refers to degrees of freedom, SS is sum of squares, MS is mean squares, PS-F is the Psuedo-F value and P is the probability based on multiple permutations of the data

Effect	**df**	**SS**	**MS**	**Ps-F**	**P**
Among Blocks	5	25,498	5,099	1.77	0.015
Slopes (Blocks)	12	24,502	2,041	1.94	0.001
Time of Day (Blocks)	12	12,911	1,075	1.03	0.416
Blocks X slope X time of day	14	14,496	1,035	1.07	0.404

Table 3. Length statistics for species captured within the experimental fishway facility. For brevity, only species with 10 or more individuals have been included. n refers to the total number of fish measured, mean ± SD refers to the mean of all measured fish and one standard error, min is the smallest fish measured and max is the largest fish measured.

Species name	**Family**	**n**	**Mean ± SD**	**Min**	**Max**
Amblypharyngodon chulabhornae	Cyprinidae	94	34±7	20	75
Badis ruber	Badidae	31	35±5	25	45
Barbonymus gonionotus	Cyprinidae	643	61±16	29	116
Barbonymus schwanenfeldii	Cyprinidae	36	45±10	31	80
Clupeicthys aesiamnesis	Clupeidae	25	37±4	30	45
Esomus longimanus	Cyprinidae	72	54±9	40	80
Esomus metallicus	Cyprinidae	92	53±9	34	75
Hampala dispar	Cyprinidae	358	44±11	25	127
Hampala macrolepidota	Cyprinidae	48	38±9	25	75
Henicorhynchus ornatipinnis	Cyprinidae	93	67±12	35	115
Henicorhynchus siamensis	Cyprinidae	30	36±25	20	125
Labiobarbus siamensis	Cyprinidae	14	91±12	70	111
Macrognathus semiocellatus	Mastacembelidae	46	138±20	100	176
Macrognathus siamensis	Mastacembelidae	15	145±34	42	191
Mastacemblus armatus	Mastacembelidae	16	130±37	65	200
Nemacheilus platiceps	Nemacheilinae	14	48±13	33	78
Osteochilus hasselti	Cyprinidae	32	127±25	95	195
Osteochilus lini	Cyprinidae	201	105±17	19	145
Osteochilus schlegelii	Cyprinidae	51	106±10	81	134
Paralaubuca typus	Cyprinidae	235	50±7	29	87
Parambassis siamensis	Ambassidae	945	46±8	24	92
Probarbus jullieni	Cyprinidae	36	69±9	50	84
Puntius jacobusboehlkei	Cyprinidae	10	155±24	132	195
Puntius orphoides	Cyprinidae	39	56±7	45	85
Puntius partipentazona	Cyprinidae	20	34±3	28	41
Raiamas guttatus	Cyprinidae	69	61±12	42	111
Rasbora aurotaenia	Cyprinidae	25	79±7	64	90
Rasbora daniconius	Cyprinidae	412	60±10	22	96
Rasbora dusonensis	Cyprinidae	618	76±10	24	105
Rasbora rubrodorsalis	Cyprinidae	351	36±9	21	79
Scaphognathops stejnegeri	Cyprinidae	17	46±6	35	62
Xenentodon cancilloides	Belonidae	452	158±40	20	285

Figure 1. Multidimensional Scaling Ordination of fish communities captured during control (black triangle), 100 mm (white circle) and 200 mm (grey square) treatments assessed during this study.

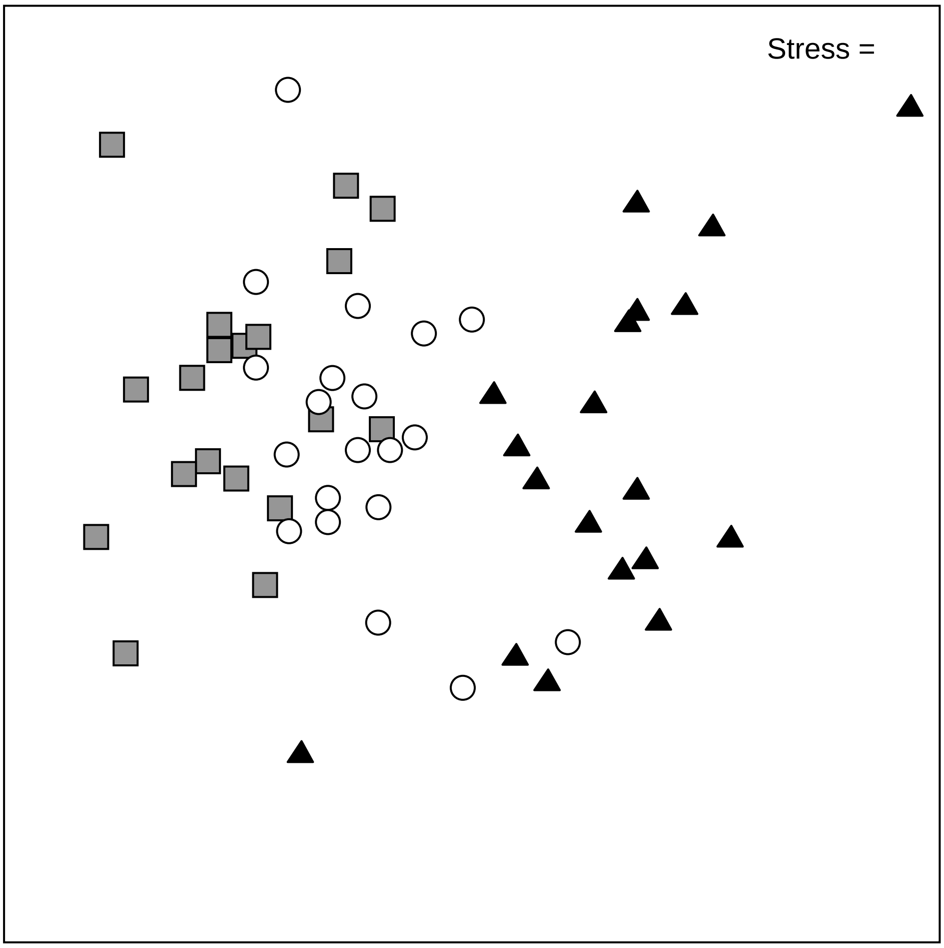

Figure 2. Relationship between daily fish catches and Mekong River level over the study period. Data is only presented where fishway trapping was conducted on consecutive days. Data is presented for all species pooled and five of the most abundant species collected.

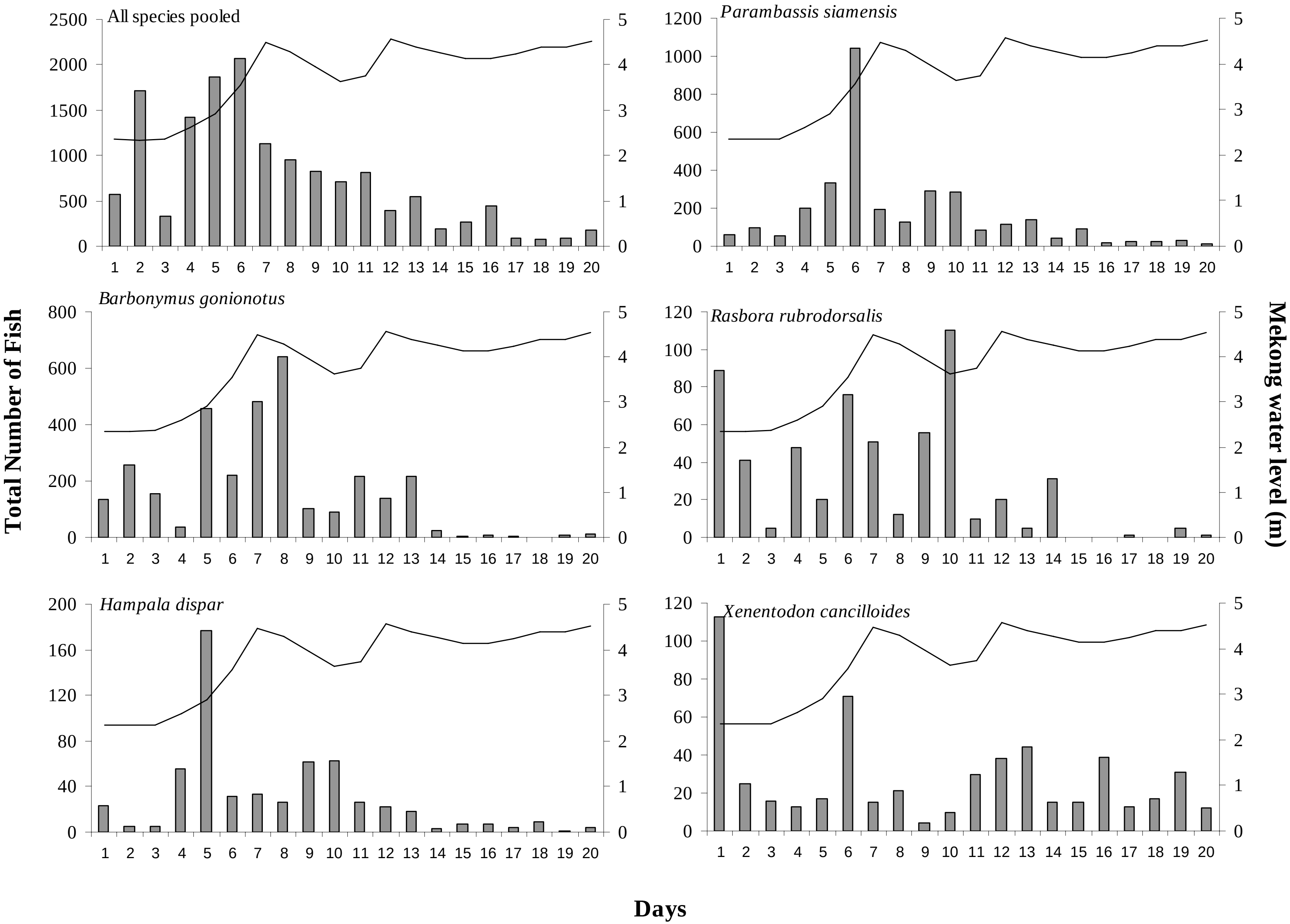

Figure 3. Scatterplot of the relationship between change in water level and migratory fish movements.

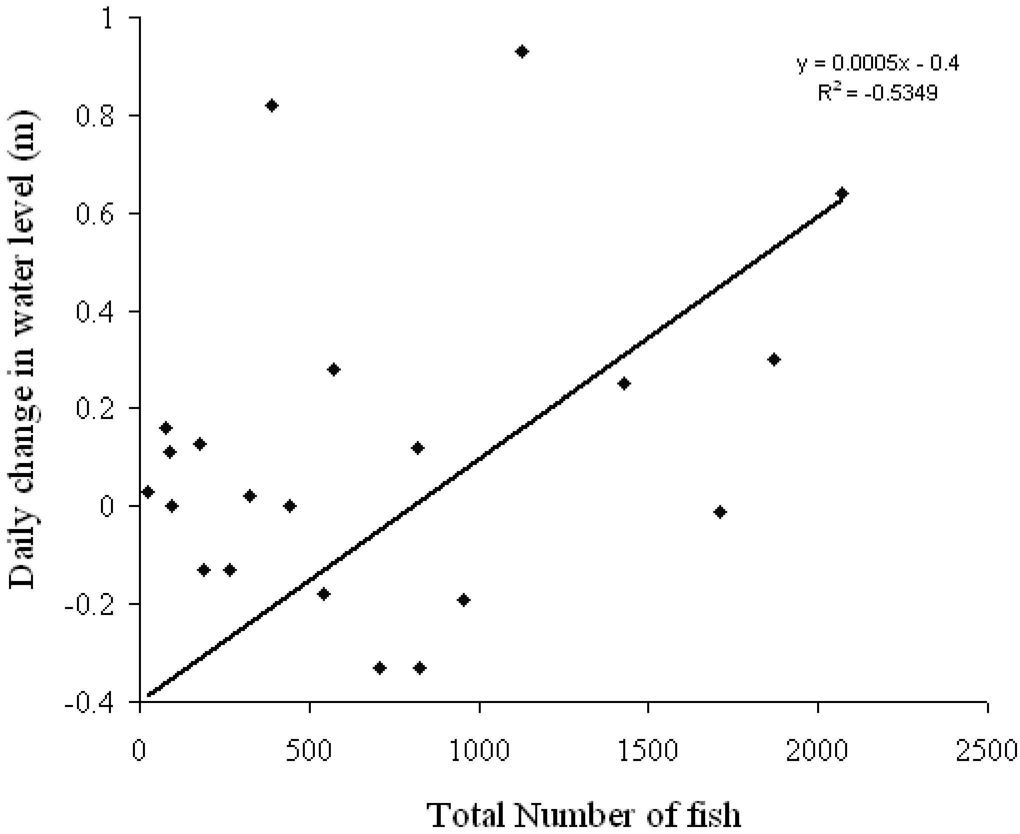

Figure 4. Length distributions of fish collected in each experimental treatment and control. Values are pooled across all species and experimental blocks.