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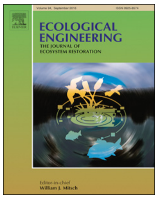

Comparing fishway designs for application in a large tropical river system

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ABSTRACT

River infrastructure poses a serious threat to diverse and productive fish stocks in many tropical river-floodplain systems; particularly the Lower Mekong River, where the fisheries are vital for food security. Dams and weirs block fish migration pathways and prevent access to feeding, spawning or nursery habitat. Fishways are becoming increasingly important for mitigating the effects of barriers; however, knowledge regarding their effectiveness for the biodiverse tropical river systems is still scant. This study examined the effectiveness of differing low-cost fishway designs for rehabilitating degraded floodplain fisheries in the Lower Mekong Basin (LMB) in Laos: (1) vertical slot; (2) submerged orifice — 150 mm square opening; and (3) submerged orifice — 300 mm square opening. Day and night *in situ* field experiments were undertaken to compare the abundance, biomass, species richness and size range of fish able to pass through each design with relatively low drops between pools (i.e. 150 mm each) and low water velocities (i.e. 1.71 ms^{-1}). Passage of a total of 73 species was supported by the fishway designs at a similar abundance, biomass, species richness and size range of fish, during both the day and night; although, the vertical slot design supported a different suite of fish species to that of the other two designs during the day. This suggests that each of these fishway designs could be successfully used to support the rehabilitation of fisheries in the LMB and potentially other large tropical river systems with relatively diverse migratory fish communities and variable hydrological characteristics. However, the vertical slot provides greater design and operational flexibility over the submerged orifice designs particularly in tropical systems with inherently variable hydrology. The final fishway design choice ultimately depends on the fish species and size classes being prioritised for restoration and the unique hydrological characteristics of the site.

1. Introduction

The development of large tropical river-floodplain systems worldwide for irrigation and energy requirements, poses a threat to fisheries sustainability (Oldani and Baigún, 2002; Ziv et al., 2012). Large tropical river-floodplain systems typically contain highly productive and diverse fish communities that provide important environmental, social and economic benefits to their neighbouring human populations (Dudgeon, 2000; Winemiller, 2003). Yet, they are rapidly being exploited to construct dams, weirs, floodplain regulators and other management structures, which impede access to fish spawning, feeding and nursery habitat, and thereby prevent the completion of important life history stages (Dugan et al., 2010; Pringle et al., 2000). The fish in impacted systems often fail to spawn at all or do not recruit effectively (Pringle et al., 2000). Over time, these impacts reduce the diversity and productivity of the fishery, and ultimately the benefits of development projects (such as increased water security) may become negatively offset by the loss in fisheries resources (Baumgartner, 2016; Orr et al., 2012).

Recently there has been a growing emphasis on the use of fishways to ameliorate the barrier impacts caused by infrastructure in large tropical river systems (Baumgartner et al., 2012; Oldani and Baigún, 2002). Many fishway designs are available, with some of the more commonly used ones including vertical slot, pool and weir (e.g.

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submerged orifice) and Denil passes (Baumgartner et al., 2012; Stuart and Berghuis, 2002). However, despite the growing emphasis on the use of fishways, and the large number of designs available, little consideration has been given to empirically comparing their effectiveness to date (Foulds and Lucas, 2013; Schwalme et al., 1985). Much of the existing knowledge regarding the effectiveness of fishway designs has been for temperate species, and/or has come from laboratory-based trials (Mallen-Cooper, 1992), while little of the knowledge has been obtained via *in situ* field-based experiments (Baumgartner et al., 2012). In addition, most *in situ* studies only consider one design (Oldani and Baigún, 2002; Stuart et al., 2007), and/or have focused on the outcomes for individual economically important species, such as salmonids (Williams et al., 2012). Thus, *in situ* experiments that compare fishway designs and consider outcomes for whole fish communities, are likely to be fundamental for informing fishway design selection to maximise the sustainability of fisheries, particularly in large tropical river systems like the Mekong, where the fisheries play a critical role in supporting food security (Baumgartner et al., 2012).

The Mekong River is one of the largest rivers in the world, with a total length of 4800 km, and a drainage area of 795 000 km^2 (Lu and Siew, 2006). Its basin stretches from the Tibetan highlands all the way to the South China Sea through six countries: China, Myanmar, Lao PDR, Thailand, Cambodia and Vietnam (Dutta et al., 2007). The river is essentially regarded as a tropical system, apart from the relatively small upper section located in the Tibetan highlands (Kummu and Varis, 2007). Fish and other aquatic animals are immensely important throughout the Lower Mekong Basin (the LMB, which is the Mekong drainage within Lao PDR, Thailand, Cambodia and Vietnam), and provide on average 48% and 79% of the animal protein intake in Lao PDR and Cambodia, respectively (Hortle, 2007). However, the LMB is currently facing an unprecedented level of irrigation development (Orr et al., 2012; Ziv et al., 2012). Many dams, weirs and regulators are being constructed annually, and there are substantial concerns for the welfare of fisheries resources largely in part because of the impediments being imposed upon their migrations (Orr et al., 2012; Ziv et al., 2012). There is an urgent need to develop robust criteria, for fishway design, to incorporate into future development projects.

Presently there are two fishway designs which have been implemented in the LMB. Firstly, a vertical slot fishway was constructed in Cambodia (Bernacsek, 1997). The design was a direct copy of a similar system installed in Australia and has been recommended for installation at other sites (Baumgartner et al., 2012). Secondly, submerged orifice fishways have been extensively constructed in Thailand (Jutagate et al., 2001). These designs are primarily based on specifications developed for Northern Hemisphere salmonids (Roberts, 2001) and include both large and small orifices. In both cases, there was no evidence that local ecology was taken into account when these fishways were designed and constructed. But local species may differ from those upon which the original designs were based.

This study experimentally performed a preliminary examination on the effectiveness of existing fishway designs for rehabilitating degraded floodplain fisheries in the LMB in Laos. We sought to assess the characteristics of designs that had been previously used. These included (1) vertical slot (1400 mm high with a slot width of 150 mm); (2) submerged orifice — 150 mm square opening; and (3) submerged orifice — 300 mm square opening fishways. These fishway designs were based on existing fishways installed in the LMB. Determining success is an important pre-cursor to more detailed fishway experiments on internal hydraulics and performance. The study specifically focused on (1) vertical slot fishways, since they can operate with widely fluctuating headwater and tailwater conditions, and earlier investigations suggested that LMB fish species can use them (Baumgartner, 2016; Baumgartner et al., 2012); and (2) submerged orifice fishways, since despite being largely developed for salmonids, these fishways are still being widely constructed throughout tropical rivers globally (Baumgartner et al., 2012; Rodríguez et al., 2006). No comparative analysis has previously been performed of these fishways under field conditions in the Lower Mekong.

We aimed to assess fishway effectiveness during both the day and night to consider the potential influence of variation in diel fish movement patterns (Hard and Kynard, 1997; Morgan and Beatty, 2006). We hypothesised that (1) all of the fishway designs would be capable of supporting the movement of a range of LMB fish species and size classes during both the day and night; and (2) the vertical slot design would support the movement of a greater abundance, biomass and species richness of fish owing to its greater capacity to function under variable hydrological conditions. We assumed that the designs would significantly differ in terms of hydraulics. For the purposes of this comparative study, we did not attempt to standardise hydraulics. The intent was to investigate any fish passage differences in designs presently being implemented.

2. Methods

2.1. Study site

The LMB comprises 78% of the total Mekong River basin area, and has two distinct seasons — a wet season from June to October and a generally dry season for the rest of the year (Lu and Siew, 2006). Mean annual precipitation in the LMB ranges from over 3000 mm in Lao PDR and Cambodia to 1000 mm in the semi-arid Korat Plateau in Northeast Thailand (Mekong River Commission, 2003). The Mekong River level usually begins rising in May and peaks in September or October, with the average peak flow at 45,000 m^3 s^{-1}. Flows then start receding again and reach their lowest levels in March and April, at approximately 1500 m^3 s^{-1} (Kite, 2001).

The study was undertaken at a floodplain regulator, next to the Mekong River at Pak Peung village (Bolikhamxay Province) in the LMB in central Laos. The regulator was installed in the 1960s to prevent inundation of floodplain rice crops throughout periods of rising Mekong water levels during the wet season (Baumgartner et al., 2012). It is 10 m high and has three sluice gates, which can control water exchange between an upstream wetland and the river. The regulator completely obstructs upstream fish movements (from the river to the floodplain), but fish may move through the gates, from the floodplain to the river, when they are open (Baumgartner et al., 2012).

2.2. Fishway channel

At the time of this study, a concrete channel was being prepared for the construction of a permanent fishway adjacent to the regulator, between the river and the wetland. The permanent fishway was being constructed as part of a longer-term study, and local fish migration data were needed to inform its design requirements (Baumgartner, 2016). A steel fabricated fishway was placed within the concrete channel and comprised four pools, which were 1500 mm × 1000 mm in size. Larger pool sizes were considered, but accommodating a larger pool size would require greater volumes of water, which would increase the overall weight of the fishway. It was also expected that mostly small-bodied black species (fish that only live on the floodplain), grey species (fish which live in both the main stem and floodplain) and sub-adult white species (those species that live predominantly in main channel habitats), would attempt to access floodplain habitat, so a smaller pool size was selected (Baumgartner et al., 2012). The entrance to the concrete channel was situated at the upstream limit of migration on the Mekong River side of the regulator. Discharge through the channel was controlled by a sluice gate installed on the upstream side. Water levels in the channel were dependent on Mekong River levels, which vary with local rainfall. Nevertheless, the fishway channel was adjusted prior to the commencement of each experimental replicate, so that the water level in the fishway entrance aligned with that in the Mekong tailwater; thus protecting internal hydraulics. The fishway channel was operated at a depth of 1 m, and standardised to have a headloss of 150 mm between pools.

2.3. Experimental design

Fishway design effectiveness (i.e. vertical slot; submerged orifice — 150 mm square opening; and submerged orifice — 300 mm square opening) was examined through two randomised block experiments — one day experiment and one night experiment. For the day experiment, there were 15 replicate trials for each design (i.e. 15 blocks). Each replicate trial ran for three hours, and each block was completed in a single day during daylight hours. Fishway designs (i.e. treatments) were randomly assigned for testing during one of three times per day (0800, 1100 or 1400 h) to allow for potential interspecific differences in diel activity periods, and thus fish migration rates (Baumgartner et al., 2012). All 15 blocks were completed during the rainy season between May and June 2012 (*sensu* Baumgartner et al., 2012). The night experiment was undertaken in the same manner, with the following exceptions. Specifically, there were four replicate trials for each design (i.e. four blocks). Each experimental block was spread over three nights, with treatments randomly assigned for testing during one of those nights. The night trials commenced at 1900 h and ran until the following morning. To account for different sample times, all catches were standardised to fish per hour for analysis.

Prior to the commencement of each replicate trial, all baffles were removed and the upstream control regulator was fully opened to flush fish from the channel. Baffles were then reinstated according to the required experimental treatment. Headlosses among pools were measured for consistency and a fish trap (2 mm mesh; cone design) was set to capture any upstream migrating fish. The trap was 1.5 m (high) × 1.5 m (wide) × 1 m (deep) and was set at the exit of the most upstream baffle prior to the commencement of each replicate. Flow was then introduced into the fishway. Upon completion of each replicate test, the fish trap was collected and all fish identified, counted, weighed, measured (TL) and released upstream into the wetland. The baffles were then removed, the fishway flushed to remove fish, and the next replicate commenced.

2.4. Data analyses

Analyses were undertaken separately for each experiment, and focused on identifying differences in fish passage rates among the three treatments to determine which one was most effective. Thus, all count data were initially converted to the standardised rate of fish trapped per hour of sampling. Initially, a generalised linear model, using a Poisson distribution, was used to compare the number of grey species and number of white species using each of the three fishway treatments (black species were not included in the analysis because they occurred in very low numbers). The effect of the blocks was partitioned by using generalised estimating equations in the Genmod procedure (SAS 9.3, SAS Institute 2013).

A randomised block design ANOVA was undertaken for each experiment to assess the effect of fishway treatment on the: (i) average abundance (Catch Per Unit Effort); (ii) average biomass (Biomass Per Unit Effort); (iii) average number of species (Species Per Unit Effort) and (iv) median, 10th percentile, and 90th percentile of the lengths of fish trapped per hour of sampling. To satisfy the assumptions of ANOVA, all CPUE data were square-root transformed (x + 0.5) and BPUE data were $\log_e(x + 1)$ transformed. Species richness and length data did not require transformation because they were already homoscedastic and approximated a normal distribution. In all ANOVAs, significant effects were followed up using pairwise comparisons and Scheffe's correction for Type I errors.

Multivariate community analyses were also undertaken separately for each experiment to examine whether there were differences in the structure (the relative abundance of taxa) and/or composition (the presence or absence of taxa) of fish communities passing through each fishway treatment, using $\log_{10}(x + 1)$ and presence-absence transformed CPUE (average catch per hour) data, respectively. Similarities between samples for the community structure data were calculated using the Bray-Curtis resemblance measure, while similarities for the community composition data were calculated using the Jaccard Similarity measure. PERMANOVA [PERMANOVA + for PRIMER] (Anderson et al., 2008), was then used to formally test for treatment effects, and any effects deemed to be significant ($P < 0.10$) were followed up using pairwise comparisons. Taxa contributing most to variation in communities among treatments were assessed using the similarity percentages procedure (SIMPER in Primer v6 (Clarke and Warwick, 2001)). In each SIMPER analysis, species were considered most important in separating the treatments if they contributed ≥ 5% of total dissimilarity and their standard deviation ratio (Dissimilarity/Std.dev) was ≥ 1.

3. Results

3.1. Overall results

Overall, 8689 individuals, consisting of 73 species, and ranging in size from 19 mm to 315 mm (TL), were captured from the three fishway treatments during this study (Table 1). For both the day and night experiments, each fishway design supported the passage of communities comprised of between 32 and 49 species (Table 1).

3.2. Day experiment

A total of 4430 individuals, consisting of 57 species, and ranging in size from 19 mm to 300 mm, were captured from the three fishway treatments during the day experiment (Table 1). Thirteen species were unique to this experiment (Table 1).

3.2.1. Fishway use by grey and white species

There were significantly more grey (mean = 5.8 grey species per block) than white (mean = 1.3) species using the fishways ($\chi^2 = 10.77$, df = 1, $P = 0.001$) and this difference was independent of whether the fishway was a vertical slot or a submerged orifice design (i.e. there was no interaction between the influence of species type and fishway treatment) ($\chi^2_{\text{species type} \times \text{treatment}} = 1.53$, df = 2, $P = 0.46$).

3.2.2. Abundance, biomass, species richness, length

There were no significant differences in the abundance, biomass and species richness of fish using the three fishway treatments (abundance: F = 0.14, df = 2,28, $P = 0.8703$; biomass: F = 1.02, df = 2,28, $P = 0.3733$; species richness: F = 2.16, df = 2,28, $P = 0.1388$) (Fig. 1). Likewise, there were no significant differences in the 10th percentile, median or 90th percentile of lengths of fish captured in the three experimental fishway treatments (10th percentile length: F = 1.23, df = 2,28, $P = 0.3069$; median length: F = 1.08, df = 2,28, $P = 0.3549$; 90th percentile length: F = 0.51, df = 2,28, $P = 0.6079$) (Fig. 2).

3.2.3. Community structure and composition

Fish community structure varied marginally according to fishway treatment (Pseudo-F = 1.54, df = 2, 28, $P = 0.05$). The structure of the fish community collected by the vertical slot treatment differed to that of the community collected by the submerged orifice 150 mm treatment ($\text{Pseudo-F}_{\text{vertical slot Vs submerged 150 mm}} = 1.52$, df = 1, 14, $P < 0.02$), largely due to the presence of higher abundances of *Crossocheilus atrilimes* (Siamese algae eater), *Rasbora aurotaenia* (Pale rasbora), *Parachela* spp. and *Raiamas guttatus* (Burmese trout) in the vertical slot treatment (Table 2). In comparison, the structure of the fish community collected by the submerged orifice 300 mm treatment did not differ to that of the community collected by either the submerged orifice 150 mm or

Table 1
List of fish species caught during the day and night experiments. V-slot = vertical slot; Sub-150 = submerged orifice 150 mm; Sub-300 = submerged orifice 300 mm.

Species name	Species type	V-slot		Sub-150		Sub-300	
		Day	Night	Day	Night	Day	Night
Acanthopsis spp.		X				X	X
Acanthopsoides hapalias	White	X		X	X		X
Akysis varius	White				X		
Amblypharyngodon chulabhornae	Black	X	X		X	X	X
Amblyrhynchichthys truncatus	Grey		X				X
Anabas testudineus	Grey	X					
Badis ruber	Grey				X		
Barbonymus schwanenfeldii	Grey	X	X	X	X	X	X
Chela laubuca	Grey				X		
Chitala ornata	Grey				X		
Clupeichthys aesarnensis	Grey					X	
Crossocheilus atrilimes	White	X	X	X	X	X	X
Crossocheilus siamensis	White					X	
Cyclocheilichthys armatus	Grey		X				
Cyclocheilichthys repasson	Grey		X	X		X	X
Esomus metallicus	Grey		X	X	X	X	
Hampala dispar	Grey	X		X	X	X	X
Hampala macrolepidota	Grey	X			X		
Hemibagrus nemurus	Grey				X		
Hemibagrus spilopterus	Grey						X
Hemibagrus spp.					X		
Hemibagrus wyckioides	Grey						X
Henicorhynchus siamensis	Grey	X		X	X		
Homaloptera smithi	White	X	X	X	X	X	X
Hypsibarbus lagleri	Grey	X		X	X	X	X
Kryptopterus geminus	Grey				X		
Labiobarbus leptocheilus	Grey	X	X	X	X	X	X
Labiobarbus siamensis	Grey	X	X	X	X	X	X
Macrognathus semiocellatus	Black		X	X	X	X	X
Macrognathus siamensis	Black	X			X	X	X
Mastacembelus armatus	Grey	X			X	X	
Mystacoleucus ectypus	White		X	X	X		X
Mastacembelus favus	White	X				X	
Mystacoleucus marginatus	Grey	X			X		X
Mystus mysticetus	Grey		X	X			X
Nandus oxyrhynchus	Grey				X	X	
Nemacheilus spp		X			X	X	X
Ompok bimaculatus	Grey				X		
Osteochilus hasselti	Grey	X	X	X	X		
Osteochilus lini	Grey	X	X	X	X	X	X
Oxyeleotris marmorata	Grey				X		
Pangasius pleurotaenia	Grey		X		X		
Parachela oxygastroides	Grey		X		X	X	
Parachela spp.		X	X	X	X	X	X
Parambassis siamensis	Grey	X	X	X	X	X	X
Parasikukia maculata	Grey					X	
Pristolepis fasciata	Grey	X		X	X		X
Probarbus jullieni	Grey	X	X	X	X	X	
Pseudomystus siamensis	White				X		
Puntioplites falcifer	Grey	X	X	X	X	X	X
Puntius brevis	Grey	X	X	X	X	X	X
Puntius orphoides	Grey			X			
Puntius partipentazona	Grey	X			X		X
Puntius spp.		X					
Raiamas guttatus	Grey	X	X	X	X	X	X
Rasbora aurotaenia	Grey	X	X	X	X	X	X
Rasbora daniconius	Grey	X	X	X	X	X	
Rasbora paviana	Grey						X
Rasbora steineri	Grey	X	X	X	X	X	X
Rasbora trilineata	Grey	X	X			X	X
Scaphognathops stejnegeri	Grey	X			X		
Schistura spp.				X		X	
Sikukia gudgeri	Grey	X	X	X	X	X	X
Thynnichthys thynnoides	Grey	X	X	X	X	X	X
Trichopodus microlepis	Grey					X	
Trichopodus trichopterus	Grey					X	
Trichopsis vittata	Black					X	
Unknown 1		X		X		X	
Unknown 2		X	X			X	X
Unknown 3		X				X	X
Unknown 5		X		X			
Xenentodon sp.		X	X	X	X	X	X
Yasuhikotakia longidorsalis	Grey	X	X	X	X	X	X

vertical slot treatments (Pseudo-F $_{\text{submerged 300 mm Vs submerged 150 mm}}$ = 1.01, df = 1, 14, *P* = 0.42; Pseudo-F $_{\text{submerged 300 mm Vs vertical slot}}$ = 1.18, df = 1, 14, *P* = 0.17).

Fish community composition also varied significantly according to fishway treatment (Pseudo-F = 1.92, df = 2, 28, $P < 0.002$). The composition of the fish community collected by the vertical slot treatment differed to that of the communities collected by the two submerged orifice treatments (Pseudo-F $_{\text{vertical slot Vs submerged 150 mm}}$ = 1.72, df = 1, 14, $P < 0.001$; Pseudo-F $_{\text{vertical slot Vs submerged 300 mm}}$ = 1.34, df = 1, 14, $P < 0.01$), largely due to Burmese trout and *Puntius brevis* (Swamp barb) both occurring in more samples in the vertical slot treatment than in those from the submerged orifice treatments (Table 2). In comparison, the composition of the fish community collected by the submerged orifice 300 mm treatment did not differ to that of the community collected by the submerged orifice 150 mm treatment (Pseudo-F = 1.03, df = 1, 14, *P* = 0.377).

3.3. Night experiment

A total of 4259 individuals, consisting of 60 species, and ranging in size from 20 mm to 315 mm, were captured from the three treatments during the night experiment (Table 1). Fourteen species were unique to this experiment (Table 1).

3.3.1. Fishway use by grey and white species

As for the day experiment, there were significantly more grey (mean = 15.9 grey species per block) than white (mean = 3.6) species using the fishways ($\chi^2 = 2.57$, df = 1, *P* = 0.1092) and this difference was independent of whether the fishway was a vertical slot or a submerged orifice design (i.e. there was no interaction between the influence of species type and fishway treatment) ($\chi^2_{\text{species type} \times \text{treatment}} = 0.48$, df = 2, *P* = 0.7876).

3.3.2. Abundance, biomass, species richness, length

The submerged orifice 150 mm treatment passed a greater abundance, biomass and species richness of fish than the other treatments during the night experiment (Fig. 3), although these differences were not statistically significant due to the high level of variability present (abundance: F = 0.26, df = 2,4, *P* = 0.7841; biomass: F = 0.1, df = 2,4, *P* = 0.9107; species richness: F = 0.23, df = 2,4, *P* = 0.8066). Also, similarly to that for the day experiment, there were no significant differences in the 10th percentile, median or 90th percentile of lengths of fish using the three experimental fishway treatments (10th percentile length: F = 0.51, df = 2,6, *P* = 0.6237; median length: F = 0.48, df = 2,6, *P* = 0.6392; 90th percentile length: F = 0.49, df = 2,6, *P* = 0.6372) (Fig. 4).

3.3.3. Community structure and composition

Neither fish community structure (Pseudo-F = 1.45, df = 2.23, 3, *P* = 0.21) nor composition (Pseudo-F = 1.38, df = 2.08, 3, *P* = 0.18) varied significantly according to fishway treatment during the night

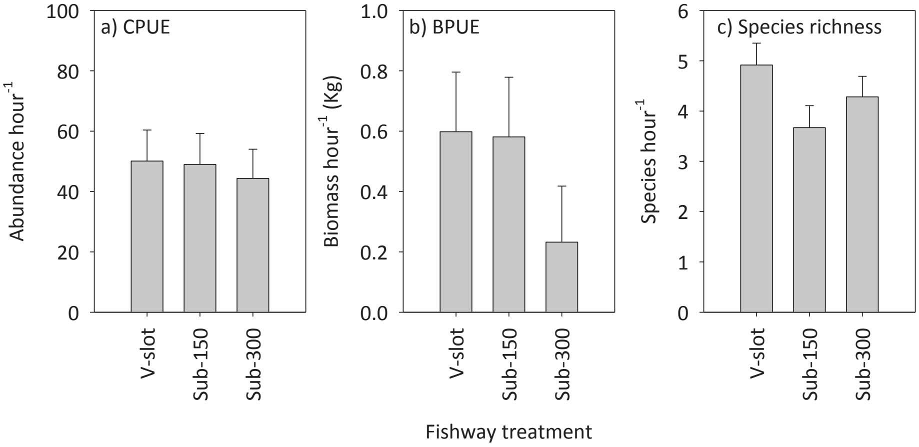

Fig. 1. Mean (+1 SE) abundance (CPUE in catch h^{-1}) (a), biomass (BPUE in kg h^{-1}) (b), and species richness (taxa h^{-1}) (c) of fish caught using each fishway during the day experiment. See Table 1 for an explanation of the treatments.

experiment.

4. Discussion

Developing solutions that mitigate barriers to fish movement is critical for the restoration of fisheries in many large tropical river-floodplain systems (Baumgartner et al., 2012). The results from this study supported our first hypothesis that vertical slot and submerged orifice (150 mm and 300 mm square opening) fishway designs would both be capable of supporting the movement of a range of LMB fish species and size classes during both the day and night. In comparison, our results did not provide any support for our second hypothesis that the vertical slot design would facilitate the movement of a greater abundance, biomass and species richness of fish overall. Nevertheless, the vertical slot design supported the movement of a different suite of fish species to that of the other two designs during the day, suggesting that the final selection of fishway design in tropical systems must be considerate of the species being prioritised for restoration and the attributes of the target site.

4.1. Effectiveness of the three fishway treatments

Studies undertaken in temperate systems have highlighted the challenging nature of designing fishways that can accommodate a wide range of migration requirements among species, life history stages, flow regimes and/or times of year (e.g. Foulds and Lucas, 2013; Mallen-

Table 2
Average abundance ($\log_{10}$ (CPUE + 1)) and prevalence (i.e. proportion of samples) of fish species identified by SIMPER as important in between-treatment variability for the day experiment. See Table 1 for an explanation of the treatments.

Species	Abundance			Proportion of samples		
	V-slot	Sub-150	Sub-300	V-slot	Sub-150	Sub-300
Crossocheilus atrilimes	**2.29**	**1.97**	**2.5**	0.93	0.87	0.94
Rasbora aurotaenia	**1**	**0.55**	**1.21**	0.67	0.53	0.69
Raiamas guttatus	**0.65**	0.07	0.56	0.8	0.13	0.25
Puntius brevis	**0.65**	**0.51**	**0.62**	0.67	0.47	0.56
Parachela spp.	**0.73**	0.18	0.46	0.6	0.13	0.38
Osteochilus lini	**0.79**	**0.92**	**0.56**	0.6	0.67	0.56
Hypsibarbus lagleri	**0.54**	0.44	0.56	0.6	0.4	0.75
Xenentodon sp.	0.34			0.47	0.07	0.19
Parambassis siamensis	0.63	**0.57**	**0.77**	0.4	0.4	0.38
Thynnichthys thynnoides	**0.64**	**0.76**	**0.42**	0.4	0.27	0.19

Bold values represent species that contribute 5% or more to overall Bray-Curtis similarity between treatments, underlined values contribute 5% or more to compositional similarity differences between, but not within treatments, unformatted text values contribute 5% or more to within but not between treatment similarity. SIMPER was not undertaken for the night experiment because there were no significant treatment effects during that experiment.

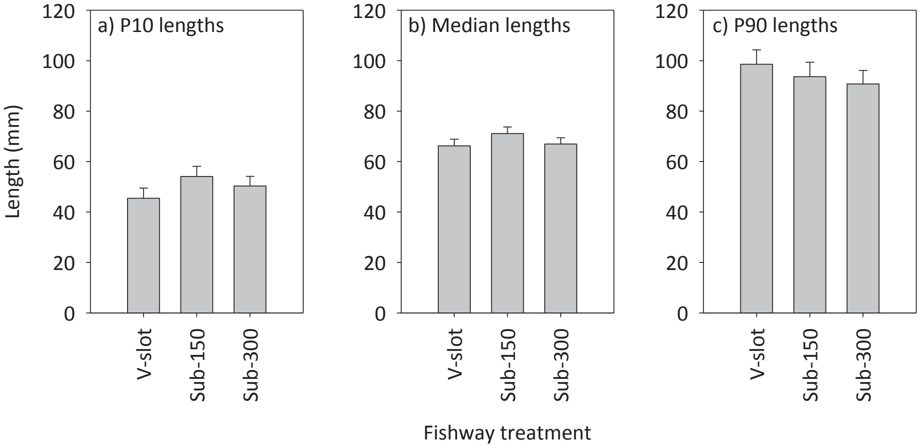

Fig. 2. Tenth percentile, median and 90th percentile fish lengths (pooled across all species) for each treatment from the day experiment. See Table 1 for an explanation of the treatments.

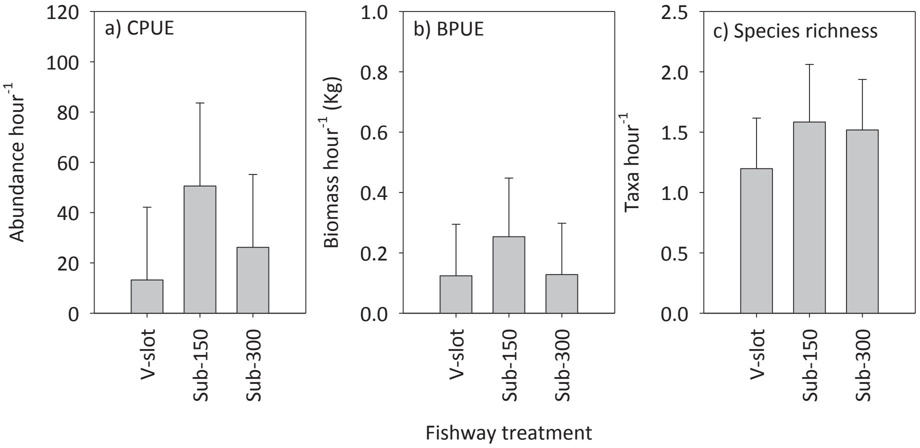

Fig. 3. Mean (+ 1 SE) abundance (CPUE in catch hour^{-1}) (a), biomass (BPUE in kg h^{-1}) (b), and species richness (taxa h^{-1}) (c) of fish caught using each fishway during the night experiment. See Table 1 for an explanation of the treatments.

Cooper and Stuart, 2007). The task of designing fishways that can meet these requirements is likely to be even more challenging in tropical rivers, because of their relatively high migratory biomass, high species richness and variable hydrology (Oldani and Baigún, 2002). Nevertheless, for both the day and night experiments in this study, each fishway design supported the passage of fish communities with similarly diverse ranges of species and size classes, although the day and night communities, overall, had differing species compositions as expected. Furthermore, the species richness' and size ranges observed from each fishway was similar to those recorded in the adjacent channel connecting the Mekong River and floodplain wetland, suggesting that the fishway designs (according to the specifications tested) would be effective in helping to restore fish passage at floodplain regulators in the LMB, irrespective of any potential diel variation in fish community composition.

There were no significant differences in the abundance, biomass and species richness of fish among treatments, during both the day and night experiments. Several Australian studies have found vertical slot fishways to support a greater abundance, biomass and species richness than pool and weir-type fishways in tropical river systems (e.g. Stuart and Berghuis, 2002; Stuart and Mallen-Cooper, 1999), and have attributed the greater abundances, biomasses and species richness' to the fact that vertical slot fishways have: (1) relatively large slot areas to allow high abundances of fish to navigate through them (Clay, 1995); (2) the ability to pass much larger fish species, as there is no restriction based on the physical orifice size if an appropriate slot width is selected (Baumgartner, 2016); (3) a slot arrangement that enables benthic and surface-dwelling fish to choose any depth in the water column to migrate to the next pool (Mallen-Cooper, 1992); and (4) a greater operational range than pool and weir-type fishways (Stuart and Mallen-Cooper, 1999; Stuart et al., 2008). Thus, while the vertical slot design did not pass a significantly different abundance, biomass or richness of fish under controlled conditions in this study, it has greater operational flexibility and better internal hydraulics and would therefore perform better under a wider range of flows than the submerged orifice design.

More grey than white species were found to be using the fishways overall for both the day and night experiments, and too few black species were observed to be included in the analysis. The dominance of grey species in this study may not be all that surprising, given that the study was undertaken during the wet season when such species tend to move back into floodplain lakes and swamps (Ferguson et al., 2011). By contrast, in a prelude to the current study, Baumgartner et al., (2012) investigated key design criteria for a vertical slot fishway at the same site and found catches to be dominated by white species. The authors attributed this result to the fact that most of the white species captured were juveniles, trying to take advantage of nursery habitat in the upstream wetland (Baumgartner et al., 2012). Thus, the dominance of black, grey or white species is likely to be seasonal, and dependent upon broader ecological processes (i.e. spawning) that might be occurring elsewhere in the catchment. The role of fishways is to then ensure that fish have access to appropriate habitat when required by different life history stages.

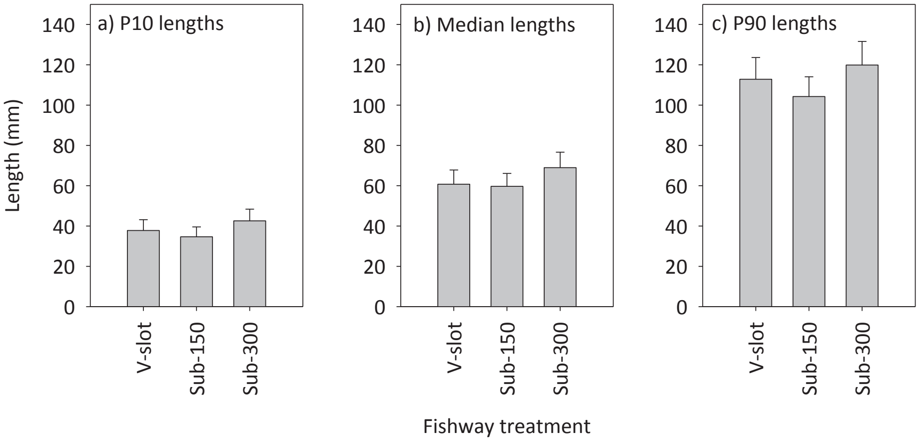

Fig. 4. Tenth percentile, median and 90th percentile fish lengths (pooled across all species) for each treatment from the night experiment. See Table 1 for an explanation of the treatments.

This study was unable to explicitly assess fishway performance for supporting the passage of large-sized individuals, because fisherman were observed to be catching many of the larger individuals in the river-wetland connection channel just downstream of the floodplain regulator and experimental fishway channel. It had been intended for these fishermen to provide an assessment of the local river-floodplain fish community for the fishway communities to be compared against as part of a broader evaluation of fishway benefits, but many of the fishermen ended up biasing their catch efforts towards larger individuals. Consequently, we recommend that future studies of fishway performance and/or management options be undertaken without the effects of fishermen catching larger-sized individuals immediately downstream of the fishway(s) to negate the risk of potential size-structure bias.

Despite the absence of large fish, and the similar abundances, biomasses and species richness' of migrating fish supported by the fishway designs for both the day and night experiments, there were higher occurrences and abundances of small pelagic cyprinid species in the vertical slot fishway than in the other two fishways during the day. According to Tummers et al., (2016), the effectiveness of a fishway design in supporting fish passage for a particular fish species, will be largely determined by the hydraulic conditions (particularly flow velocity and turbulence) provided by the fishway design, in combination with the species' swimming ability. In this experiment, all designs contained an average slot or orifice velocity of 1.71 m.s^{-1}, but the vertical slot (64 W m^{-3}) and the submerged orifice 150 mm (45 W m^{-3}) fishways had much lower average turbulence values than the submerged orifice 300 mm (178 W m^{-3}) fishway. The accepted standard international orifice opening size in pool-and-weir fishways is 300 mm, but this design worked sub-optimally in this study. In fishway design comparisons undertaken by Stuart and Mallen-Cooper (1999) and Stuart and Berghuis (2002), turbulence conditions were similarly found to be lower in the vertical slot fishway than in a pool-and-weir fishway (noting that it had a 300 mm orifice). It was argued in both of these studies that the lower turbulence conditions probably aided the ascent of small fish (Stuart and Mallen-Cooper, 1999; Stuart and Berghuis, 2002). However, reducing the orifice size created a situation where ecological performance and turbulence matched that of the vertical slot fishway in our study. These observations, combined with those of Stuart and Mallen-Cooper (1999) and Stuart and Berghuis (2002), then provide two possible fishway designs that performed similarly in an ecological and hydraulic sense under the same hydrology; but begs the question of which design would be best to choose for a given installation?

4.2. Implications for choosing a suitable fishway design

The growing prevalence of fish barriers as a consequence of river infrastructure developments represents a major risk to the management of fish stocks in many large tropical river-floodplain systems, especially in those like the Mekong, where the fish stocks are imperative for the food security of the riparian countries. This study indicates that vertical slot and submerged orifice (150 mm) fishways could both be successfully used to support the rehabilitation of fisheries in the LMB and potentially other large tropical river systems with variable hydrological characteristics and relatively diverse migratory fish communities. However, the ultimate choice of fishway design will rest upon the species being targeted for conservation and the specific characteristics of the location.

The first key element in choosing an effective fishway design should involve defining the migratory fish community and setting ecological targets for success (Baumgartner et al., 2012). Ideally, the fishway should provide passage for all target species. The second key element should then involve gaining an appreciation of the local hydrology, and in particular, how the targeted fish species respond to alterations in hydrological conditions (e.g. through consideration of their swimming modes, swimming capabilities, behaviours and life history stages) (Baumgartner et al., 2012; Tummers et al., 2016). If for example, a planned fishway is being targeted to support a migratory community that possesses many large species, and the site has a wide operational headwater range, then a vertical slot design may be an optimal solution as it will provide greater flexibility with respect to fish size and flow range. Alternatively, if the migratory community is likely to be mainly comprised of small benthic species, then a submerged orifice fishway may suffice.

The third, and perhaps most important key element in choosing an effective fishway design involves ensuring that internal fishway hydraulics are adequate for the target species. The two fishway types generate different internal hydraulic characteristics which fish need to navigate even if upstream and downstream water levels were similar between treatments, or if energy dissipation levels in the pools were of the same level (Rajaratnam et al., 1989). Our study is therefore the first, but critical stage, in implementing a successful fishway program across the LMB.

Considering fishways are already being constructed, but important hydraulic data are not being considered, there is a risk that inadequate fishways will be built. Our study has already identified differences among the two designs being implemented. The next research stage is to identify which hydraulic characteristics are driving the observed differences. This is important because there are many aspects of internal fishway hydraulics impacting upon fish ascent success, which can be effectively controlled with suitable engineering designs. Recent literature indicates that not only velocities and velocity distributions are important, but that other hydraulic parameters such as shear stress, kinetic energy, turbulence intensity, circulation patterns, and the formation of eddies of different sizes can affect fishway performance (Branco et al., 2013; Rajaratnam et al., 1989; Santos et al., 2012).

In our study for instance, we identified that more small-bodied pelagic cyprinid species ascended the vertical slot fishway than the submerged orifice fishways. Such observations can form part of the decision-making process when selecting a final design, but further investigations on hydraulics are needed to identify fishway design aspects that are driving differences (Rajaratnam and Katopodis, 1991).

A two-staged approach is required. Firstly, long-term (i.e. multi-year) studies are needed to assess the performance of the existing fishway designs for different fish life-history stages over a range of seasons and flow conditions. Such assessments will also be necessary for determining the consequences of successful fish passage, and in turn, placing fishway passage estimates in the broader context of riverscapes and integrated catchment management (Cooke and Hinch, 2013). Secondly, more detailed laboratory or *in situ* studies are needed which better-control internal hydraulics (Marriner et al., 2016). Understanding hydraulic factors influencing fishway ascent success is of paramount importance for scale-out and ensuring successful projects are implemented at the catchment scale (Baki et al., 2017). Applying designs that have been developed for fish species from other catchments will lead to inadequate outcomes and is not recommended for future application in the Lower Mekong Region. Solutions must be tailored to local species and conditions.

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