# Perspective: Towards environmentally acceptable criteria for downstream fish passage through mini hydro and irrigation infrastructure in the Lower Mekong River Basin

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Tropical rivers have high annual discharges optimal for hydropower and irrigation development. The Mekong River is one of the largest tropical river systems, supporting a unique mega-diverse fish community. Fish are an important commodity in the Mekong, contributing a large proportion of calcium, protein, and essential nutrients to the diet of the local people and providing a critical source of income for rural households. Many of these fish migrate not only upstream and downstream within main-channel habitats but also laterally into highly productive floodplain habitat to both feed and spawn. Most work to date has focused on providing for upstream fish passage, but downstream movement is an equally important process to protect. Expansion of hydropower and irrigation weirs can disrupt downstream migrations and it is important to ensure that passage through regulators or mini hydro systems is not harmful or fatal. Many new infrastructure projects (<6 m head) are proposed for the thousands of tributary streams throughout the Lower Mekong Basin and it is important that designs incorporate the best available science to protect downstream migrants. Recent advances in technology have provided new techniques which could be applied to Mekong fish species to obtain design criteria that can facilitate safe downstream passage. Obtaining and applying this knowledge to new infrastructure projects is essential in order to produce outcomes that are more favorable to local ecosystems and fisheries. © *2014 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4867101]

## I. MEKONG RIVER ECOLOGY

Fish in tropical floodplain rivers are adapted to large seasonal hydrological changes between wet and dry seasons. Reproduction and growth are optimized during the wet season inundation whilst localized processes in refuge habitat dominate during the dry season.[1] Floodplain habitat is inundated during the wet season and can either dry completely or to a series of refuge pools during the dry season.[2] During the wet season, floodplains are important sources of spawning, nursery, and feeding habitat for both adult and juvenile fish.[3] High connectivity of habitats, which allow for the free movement of fish within and between main-stem and floodplain habitats, is therefore critical for productive fish communities in tropical rivers.[4]

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The Mekong River is the largest river in Southeast Asia and 12th longest river in the world.[5] It has an estimated length of 4350 km, drains an area of 795 000 $km^2$, and discharges 457 $km^3$ of water annually. The system is home to an extremely diverse fish community (estimated at up to 900 species) including megafauna such as the Giant Mekong catfish (*Pangasianodon gigas*) and Giant freshwater stingray (*Himantura chaophraya*).[6] It is also home to the critically endangered Irrawaddy dolphin (*Orcaella brevirostris*).[7] The system has a high degree of species endemism dominated by main-channel specialist (white), floodplain specialist (black), and more generalized channel and floodplain (grey) species.[6] Fish have a strong economic and social value in the Lower Mekong River Basin (located in Lao PDR, Thailand, Vietnam, and Cambodia),[8] with the Mekong River capture fishery accounting for 2% of the total annual global harvest and involving more than 80% of households. The fishery has a value at first sale between $US 2 and 4 billion. Besides economic importance, fish are also an important source of protein and calcium for people; accounting for 48% (Lao PDR) and 79% (Cambodia) of total animal protein consumption.[9]

Migratory habits have been defined for very few Mekong species, but species generally have requirements to move upstream, downstream, and laterally into wetland habitats.[10,11] Migrations are seasonal, some species preferring to move in the wet season and others in the dry.[12] It is thought that most migrations are spawning-related, but this is presently unquantified for many species. Upstream migrations can be large-scale, with some species traversing hundreds of kilometers.[13] Downstream migrations involve juvenile and larval stages.[14] Interruptions to migration routes may have substantial effects on Mekong fish fauna and impact critical life history stages.

## II. DEVELOPMENT IN THE LOWER MEKONG RIVER BASIN

The Mekong is a typical tropical floodplain river; with inundating rains during the wet season and low base flows during the dry season. Mekong floodplain soils can be extremely fertile and ideal for agriculture. But because of peak seasonal flooding events, regulators are required to protect irrigated and rain-fed crops from excessive inundation while also retaining irrigation water in wetlands during the dry season.[15] Larger regulators, fixed-crest dams, and other engineering structures (0–12 m high) are also common on tributary streams throughout the Lower Mekong River Basin[16] and are similarly operated to provide flood protection and regulate irrigation flows.[17] These types of infrastructure block the movement of nutrients and aquatic organisms within and between channel and floodplain habitats, thus compromising the ecology of the river system.[18]

Research has demonstrated that different designs of irrigation regulators can affect migrating fish.[19,20] Studies from Australia[20] and Bangladesh[19] demonstrate that sluice gates (particularly "undershot" designs that release water beneath the gate[20]) cause high mortality of downstream-migrating larvae and juvenile fish, but that other designs, such as those that spill water over a fixed, have the potential for substantially greater fish survival rates.[20] Many low-head (<6 m) hydropower, flood control, and irrigation networks in the Lower Mekong River Basin are rapidly expanding, or being re-designed, to meet the needs of a growing population and agricultural sector. Many different species and life history stages, including adult, juvenile, and larvae, are involved with both upstream and downstream migration in the Mekong. It is therefore essential to understand the physical processes that may be affecting fish survival. Identifying and then incorporating "fish-friendly" criteria into the design phase of new structures is preferable, because retrofitting mitigation measures after initial construction can be costly.

Potentially, one of the greatest threats to fish fauna in the Mekong region is the rapid expansion of hydropower development.[21] About 20% of the world's electricity is generated by hydropower[22] and it is becoming the fastest growing renewable energy source. The total estimated hydropower potential of the Lower Mekong River basin is 30 GW, including both large and small installations.[23] Hydropower developments have economic and livelihood benefits,[24] but potentially damaging social and environmental impacts.[13] Currently, 14 mainstem dams are planned for the Mekong River alone and hundreds, if not thousands, of smaller units are planned for tributary streams and floodplain wetlands on low head (<6 m) structures. These smaller units could quickly dominate infrastructure on tributary streams and cause disruption of critical upstream and downstream fish migrations. The Lower Mekong Basin has many thousands of tributary streams, each of which supports important capture and sustenance fisheries. At present, most research and management focus is on mitigating the impacts of large main-stem development projects. Increased development of tributary streams, however, could have an equally substantial ecological impact if fish are not considered during design, construction and operation of new infrastructure projects.[25]

## III. DEVELOPING "FISH-FRIENDLY" DESIGN CRITERIA TO FACILITATE DOWNSTREAM MIGRATION

Most recent research has focused on mitigating impacts on upstream movement.[26] However, most upstream moving fish that may be migrating to spawn, will subsequently produce passively drifting larvae or juveniles. These fish, in addition to the adult migrants, will also need to move downstream at some stage. It is important that engineering solutions applied to river development projects protect both upstream and downstream migrants to effectively mitigate connectivity impacts on fisheries. The design criteria for upstream passage, however, cannot be directly applied to downstream passage. Fishways for upstream passage are designed to minimise velocity and turbulence to provide conditions that support conditions for fish to volitionally ascend. Downstream passage, especially through infrastructure, is often non-volitional and therefore largely focuses on excluding fish from areas of welfare concern through screening and diversions; or using behavioural techniques such as bubble curtains or strobe lights; or by providing hydraulic conditions to allow safe passage through the turbine itself. The degree of engineering required to safely pass fish largely depends on the overall operating head and discharge. There is a rapid expansion of small-scale river infrastructure projects (<6 m) throughout the Mekong basin which could have substantial impacts on fish but little biological data is available to help provide safe downstream passage. If acquired, it could be readily applied to new infrastructure projects.

Downstream moving fish that pass through an irrigation regulator or mini hydro plant experience similar hydraulic conditions and there are three main processes which can influence welfare.[27] During an initial approach, there is an increase in pressure as the fish approaches the deepest point in the weir pool or dam. The fish then either enters a draft tube or moves under a gate, where it experiences a rapid decompression and gains velocity. The velocity often exceeds the critical swimming ability, rendering the fish susceptible to physical strike. The fish then enters the river downstream and can be subjected to shear stress, where discharged water collides with the tailwater. Each of these processes could lead to fish injury or mortality but the likelihood of such is dictated by the operating head, regulator or hydro plant design, site hydrology, and individual species tolerances. The relative importance of these mechanical stressors (physical strike, shear stress, and decompression) varies among fish species and it is clear that current mitigation options, developed largely for salmon smolt, are unlikely to be readily transferrable for the protection of other freshwater species which have different physiological tolerances.[28,29] For fish found in the Lower Mekong Basin, design criteria need to be developed for a diverse range of species with differing physiological, anatomical, and life-history characteristics. If tolerances of individual species are known, there is great potential to incorporate this information to the design of river infrastructure to provide positive outcomes, especially at low-head installations where hydraulic conditions are not as extreme.

## IV. USING TECHNOLOGY TO UNDERSTAND BIOLOGY

Internationally, advances across a broad range of in-field technologies, such as the balloon-tag recapture technique,[30] biotelemetry,[31] and sensor fish,[32] have provided a greater understanding of the hydraulic conditions experienced by large migrating fish at different river infrastructure. Targeted experimental work has also provided design criteria which can help to protect smaller fish (such as larvae and juveniles).[20] Biological information provided by these mechanisms has been applied in different contexts to help understand how live fish respond to different stressors. For instance, the tolerances of fish to shear stress and pressure change are typically established under controlled laboratory conditions.[33] Laboratory studies allow variables to be isolated in a way that is not possible in field studies. For instance, a fish passing through a turbine or under a sluice gate may experience shear stress, physical strike, and rapid decompression all during a single downstream passage, making it impossible to determine which stressor is responsible for injury. By isolating a single form of stressor, researchers can have significantly more confidence in the cause of injury and can assess responses over a large range of exposure levels. Field studies still have an important role to play to validate laboratory-generated models and to verify fish passage outcomes post-construction for new or improved infrastructure technologies.

### A. Strike injuries

Any type of hydropower generation generally requires the rotation of a turbine or engine, powered by a blade propeller system. Fish entrained into turbines may experience blade strike injuries,[34] which can often be fatal.[35] Similarly, a fish moving downstream through an irrigation regulator could strike the downstream apron, gate or dissipation sills when travelling at a high velocity. The likelihood for fish to experience strike is dependent on several factors, including water velocity, gate design, blade rotation speed, blade spacing, and fish length.[3] By considering these variables, mathematical modelling can be used to predict the probability of strike.[35] A technique known as bio-indexing has proven successful in identifying operational ranges that can minimize blade strikes and maximize fish survival.[35] The application of sensorfish, with an inbuilt gyroscope and pressure sensor can also help to understand at what stage of passage a fish is likely to experience strike and if it is likely to be fatal.

### B. Shear stress injuries

Fluid shear stress describes the interaction that occurs between two masses of water moving in different directions.[36] Any fish trapped in the boundary between the two intersecting water bodies would be involuntarily torn in opposing directions (known as "shear stress"), which can cause injury or death at elevated levels of shear.[37] Fish are exposed to various levels of shear on a daily basis.[36,37] Fluid shear can occur in natural riffles, at the base of waterfalls, or in eddies and backwaters. When fish are exposed to unusually high levels of shear, fluid shear becomes a substantial welfare issue. The use of shear flumes, where fish can be exposed to user-defined levels of shear stress created by a high pressure jet, is a useful way of identifying the upper tolerances of fish.[37,38]

### C. Pressure-related injuries

All fish that pass through a regulator or mini hydro turbine experience pressure change,[33] the severity of which is dictated by the route of passage, type of infrastructure, and the operating head. A rapid decompression can expand gas-filled organs in the fish or cause gas in the blood to come out of solution. These conditions lead to barotrauma injuries, which may include rupturing of the swim bladder, internal haemorrhaging, exophthalmia (eye pop), and emphysema of internal organs such as the gills, heart, abdominal cavity, eyes, and fins.[33] Because a large range of pressure changes may be experienced in the field, laboratory studies similarly need to expose fish to a suitably large range of pressure changes. To determine critical tolerances that result in injury and death, laboratory investigations typically involve the use of purpose-built barometric chambers[33] These chambers allow fish to be held for an extended period to acclimate them to a given depth and pressure prior to exposing them to rapid (within a fraction of a second) decompression, thereby simulating passage through a weir or turbine. Unlike chambers typically used to study the barotrauma associated with recreational angling, chambers used to study the barotrauma associated with infrastructure passage need to generate pressures significantly below those of atmospheric levels and at significantly faster rates.[39]

## V. APPLYING BIOLOGICAL KNOWLEDGE TO FUTURE INFRASTRUCTURE PROJECTS

The expansion of existing irrigation and mini hydro networks is inevitable not only for the Mekong and its tributaries but also for most river systems throughout the world. However, there is an urgent need to ensure that rapid development does not compromise the sustainability of fisheries that provide important social, economic, and ecosystem services during a time of unprecedented population growth and climate change. The Mekong River Commission hydro guidelines document specifically identify fish as requiring special consideration in dam design.[40] The barrier effect that dams could have for migratory species, fish biodiversity will have subsequent consequences for people's livelihoods. At present, there are no formal design criteria for acceptable fishways, downstream passage facilities or hydro dam operations for hydro developments in the Lower Mekong Basin. There is also little legislative protection, other than the Mekong agreement[41] to govern sustainable development. Developers concerned about protecting downstream migrants should therefore apply the precautionary principle in the context of best available science.

Significant progress has been made in determining "fish-friendly" design criteria to promote improvements in the downstream passage survival of salmon smolts at dams throughout the Colombia River basin.[25] However, the North American perspective also illustrates how difficult and costly it can be to mitigate fish passage impacts once infrastructure is built. In the Columbia river alone, more than US$7 billion has been spent (since 1950) on efforts to save iconic salmonid species[25] by constructing fishways, stock enhancement, screening irrigation diversions, habitat rehabilitation, and providing downstream passage. Whilst this has helped save salmonids from extinction, there still is a strong reliance on hatchery production throughout the entire catchment.[25]

Therefore, there is an urgent need to better understand the potential risks faced by migrating fish at existing and proposed infrastructures. In some instances, the installation of certain mini-hydropower units on existing irrigation structures may have the potential to provide renewable power to regional areas, while actually improving the downstream passage of fish. These may offer an alternative to passage through damaging regulator gates that can cause injury and mortality. If so, widespread application of these units on low-head structures could help to maintain capture fisheries, provide options for cheap sustainable power in rural areas, and assist with the development of regional industry. But until more data are gathered to assess the real risks faced by fish at proposed projects the potential for ecological damage may not be known until declines have occurred;[42] as has been observed with similar developments in other systems.

The completion of laboratory trials to determine the susceptibility of Mekong species to shear stress, blade strike, and pressure change is an essential first step to influencing future infrastructure design.[41] As experiments progress it will become clearer which species and life stages (e.g., eggs, larvae, juveniles, or adults) will require additional consideration during infrastructure design and operation. Ideally, the tolerances of susceptible fish species (such as fragile drifting fish eggs and larvae) should be used to develop criteria that can inform the engineering design phase. After infrastructure construction, field studies should be conducted to validate any assumptions made during the laboratory and design phases. If required, additional mitigation measures (e.g., screening, although this may not be effective for drifting eggs and larvae that are common in the Lower Mekong River basin) may be warranted, or further improvements can be adaptively incorporated into future construction projects.

At present, low-head river development projects throughout the Lower Mekong River Basin are completed for either power generation or irrigation outcomes, and very rarely consider all fish species. Incorporation of biological criteria into these projects can mean that positive outcomes are generated for fish. Given the cultural and economic importance of fish among Lower Mekong River communities, facilitating sustainable river infrastructure at the myriad of low-head development projects is an essential step for maintaining food security while also improving livelihoods of people in the Lower Mekong Basin.

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