Maintaining River Connectivity for Enhanced Inland Fisheries Productivity

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In many countries in Southeast Asia, massive infrastructure expansion not only on land but also in waterways has been among the main focus of the governments' current national development plans. This is understandable because the priorities of most governments now dovetail towards expanding connectivity for improved economic growth, poverty alleviation, crop productivity, water availability, and power generation. Such development is exemplified in the case of Indonesia, especially in Java and Sumatera Islands, where infrastructure development has been raised to high levels including the establishment of intensive water infrastructures. Reports have shown that more than three thousand dams and weirs have been built so far in Indonesia and the Government of Indonesia has continued to construct 65 large weirs from 2019 until 2024. Construction of weirs in Indonesia is mainly intended for agricultural irrigation although recently, weirs are also being used for flood prevention. Indonesia has been endowed with fertile soil, and most of its people rely heavily on rice production to supply the staple food required primarily for local consumption. Therefore, a better irrigation system that secures water during the entire year is necessary, and this is fulfilled by constructing dams and weirs where water can be retained in the catchment area during the rainy season, and stored so that during the dry season, water is available to be utilized for irrigating the agricultural lands, for enhancing the economic outlook of the country.

It is true that the construction of infrastructures in waterways contributes to enhanced economic growth but such water infrastructures could also contribute to the depletion of the inland fishery resources because most of fish migration routes could be interrupted by the constructed barriers. Currently, the most common water infrastructures constructed are weirs, which are built of solid concrete and meant to control the amount and flow of water in rivers for agricultural irrigation purposes as well as for flood prevention and control. In the process however, weirs could prevent not only the deep waters to drain but also the outflow of soil, silt or sand, resulting in non-circulation of the water and depleting it of oxygen, and eventually affecting adversely the whole ecosystem. Weirs could also block the migration routes of some fishes, leading to the disruption of the life cycle of fishes that cannot swim upstream to spawn leading to possible disappearance of some freshwater fish species. Nonetheless, such predicaments had been addressed as some weir construction now comes with fish passes that provide entrance and exit to fish during the completion of their life cycles.

Inland fisheries are among the most important contributors to the economic development of many Southeast Asian countries, alleviating poverty and ensuring food security in rural communities. The sustainability of inland fisheries is however dependent on the quality of the freshwater fishery resources, aquatic habitats, and the ecosystem as a whole. In attaining such sustainability, mitigation strategies are necessary to strike a balance between maintaining the quality of the freshwater fishery resources and aquatic habitats, and ensuring the acceptable construction of infrastructures such as dams or weirs for economic development. Nowadays, some problems have been associated with dams/weirs construction, including the possible blocking of the connectivity of fish migration, sedimentation in still water, reduction in water quality and nutrients, habitat alterations, and diversion of water supply to irrigation systems and power generation.

One of the strategies adopted to address the blocking of fish migration connectivity, is the construction of fish passes, also known as fishway, or fish ladder, or fish passage depending on the design, in dams and weirs to reconnect the upstream and downstream waters of rivers. Fish passes facilitate the migration of fish from downstream to upstream or from upstream to downstream to complete their life cycles. Fish that swim from downstream can enter the fish pass inlet located downstream of a dam. Construction of fish passes is now being promoted globally to maintain river connectivity notwithstanding the construction of infrastructures for economic development. However, the appropriate design of a fish pass is dependent on the local fishery resources that live in certain aquatic habitats. Therefore, it is necessary to understand the fish migration behavior and the swimming ability, especially of the native freshwater fish species, prior to the construction of fish passes.

Global Water Infrastructure Development

In the world today, there are about 16.7 million units of man-made reservoirs that can store about 16,201 km^3 of water and inundating a total area of more than 400,000 km^2, and another 59,071 units of more than 15 m high large dams had been constructed (Lehner *et al*. (2015); ICOLD (2018); FAO (2018); Funge-Smith (2018)) as shown in **Table 1**. These infrastructures irrigate about 261 million ha or about 18 % of the total agricultural lands that account for 40 % of the total yield from agriculture. These water infrastructures are known to affect the rivers by changing their hydrology and resulting in the inability of fish to complete their life cycle. An example of a newly constructed big weir in Indonesia is shown in **Figure 1**. Meanwhile around the world, construction of large reservoirs and dams continues as shown in **Figure 2** and **Figure 3**.

Table 1. Total water infrastructures in the world

Water infrastructures	Output
Total man-made reservoirs	16.7 million units
Total number of large dams above 15 m	59,071
Total volume of water stored in reservoirs (km^3)	16,201
Total area inundated by reservoirs (km^2)	> 400,000
Amount agricultural lands irrigated	18 % (261 million ha) Producing 40 % of crop yield

*(**Source:** Lehner et al. (2015); ICOLD (2018); FAO (2018); Funge-Smith (2018))*

Figure 1. Perjaya Weir, Martapura, Indonesia
(Source: BBWS VIII Sumatera Documentation)

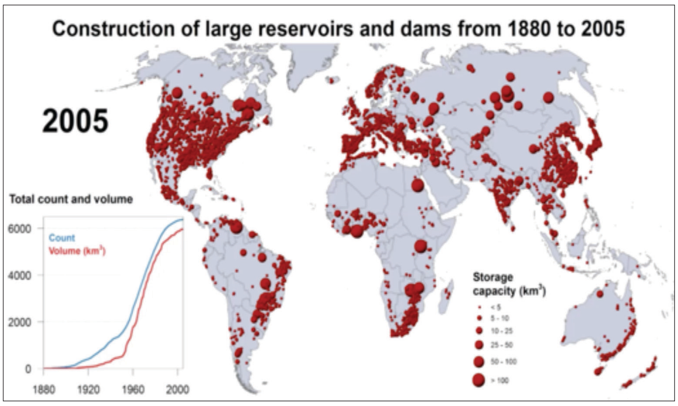

Figure 2. Development of reservoirs in the world (1880-2005)
*(**Source:** Global Hydrolab, 2014)*

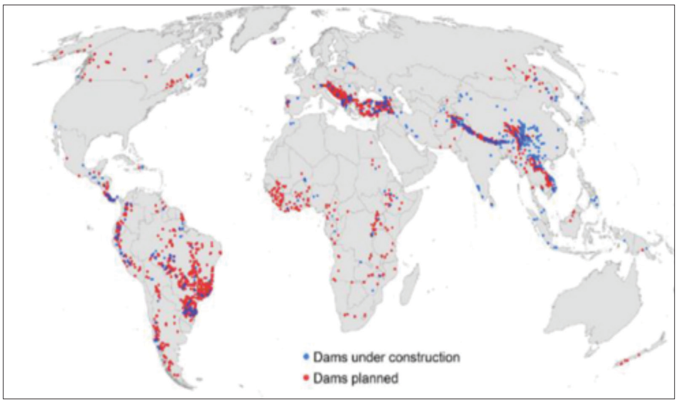

Figure 3. Global trend in planned dam construction
*(**Source:** Plumer, 2014)*

Main Objectives of Water Infrastructures

The benefit of water infrastructures such as weirs and dams, is that they tend to balance development with conservation of environmental resources. Specifically, aside from conforming to the UN Sustainable Development Goals (SDGs) 2030, these structures also ensure food security by serving as habitats for fishery resources that bring about fisheries products and food ingredients; socioeconomic development by providing the source of electric power and domestic water supply; environmental protection through their ability to adjust water levels so that the occurrence of flooding is prevented; financial security by generating the means for ecotourism and water sports, earning income for the communities and the country; and sustainable aquaculture development by serving as hosts for floating fish cages where aquatic species could be raised in large quantities providing additional incomes to communities.

Along the lines of the UN SDGs 2030, the President of Indonesia issued President Decree of Republic of Indonesia No. 59/2017 concerning SDGs Implementation and Achievements in Indonesia, and the strategic plan for local and national development which include the sustainability of fisheries.

Issues Associated with Water Infrastructure Development

Generally, weirs could be considered as beneficial water structures, especially their function in generating power, improving navigation in rivers, controlling floods, and serving as spillway for dams. However, the resulting impoundments across rivers could also have negative effects on the aquatic environment, like increased in siltation that leads to reduced oxygen in the water harming the aquatic species and choking the invertebrates that inhabit in the waters, and degrading the fish spawning grounds. Most importantly, weirs could disrupt the migration routes of fish species that travel upstream or downstream as part of their life cycles.

Table 2. Problems and solutions related to weirs and reservoirs development in Indonesia

Problems	Potential solutions
Blocking connectivity of rivers disrupting the migration routes of freshwater fishes while completing their life cycles	Construction of fish passage
Sedimentation in water	Installation of sediment traps
Deteriorating water quality and nutrients	Promotion of Pesticide Control and Land Use Management
Habitat alteration	Maintaining floodplains in upstream and downstream areas
Diversion of irrigation systems	Adoption of Spillway Management

*(**Source:** Baumgartner & Wibowo, 2018)*

Similar concerns had also been raised with regard to the development of water infrastructures in Indonesia. The problems and corresponding possible solutions are summarized in **Table 2**.

Nevertheless, most of the proposed solutions have not yet been fully researched in Indonesia. For example, as what was found out at the Irlandia and Barotrauma Spillway in Ireland, migrating eels are being chopped by turbines in weirs (**Figure 4**). These incidents could also happen in weirs and dams in Indonesia. Therefore, there is a need to monitor such situations in the constructed weirs and dams in Indonesia, and report similar incidences to concerned agencies in order that solutions that address such issues are established.

Figure 4. Incidences where eels are cut into pieces and killed by turbines installed in weirs
*(**Source:** O'Connor, 2016)*

It is therefore necessary for Indonesia to establish some policies that could regulate and properly manage the generation of water supply. Such regulations are important considering that there are many uses of inland waters and there are significant economic commodities that could be derived from the inland water resources. Without proper management, the country might gradually lose such resources. Moreover, the connectivity of rivers should be maintained to protect, conserve, and secure biodiversity in inland water resources.

Importance of Inland Fisheries for Economic Development

Inland fisheries had been recognized as an economically important sub-sector of the fisheries in Southeast Asia because of its contribution to income generation and food security of the peoples. Although mostly seasonal, inland fisheries are operated in waters shared by the other development sectors, notably irrigation, public or domestic water supply, and power generation. For the purpose of these other development sectors, various cross-river infrastructures are constructed such as dams and weirs, among others. However, more often than not, such construction does not take into consideration the possible impacts of these cross-river infrastructures to the fishery resources. It is therefore with such a backdrop that fish passes should be constructed together with those cross-river infrastructures to maintain the connectivity of the habitats of fishery resources (Pongsri *et al*., 2016).

Considerations on the Types of Fish Passes

A fish passage or fishway is a channel designed to facilitate fish to pass through man-made transverse construction (Katopodis & Eng, 1992). The presence of infrastructures across rivers that are not equipped with fish passes would result in ecosystem imbalance in rivers, impacting on the fishery resources. According to Maryono (2008), fish passes could be of two types, *i.e.* natural and technical types. Natural fish passes could be circular weirs (bypass channel fishway), constructed fish ramps, or constructed river bed ramp and slope. The technical types could include: pool passes, vertical slot (vertical slot passport), denile passes/counter flow passes, fish locks, fish lifts, and so on (**Figure 5**).

Choosing the type of fish pass to be constructed depends on government priorities and in accordance with the conditions of the river and the transverse cross-river infrastructures (**Table 3**). Nonetheless, consideration should be taken in constructing fish passes as a technical solution, to minimize the negative impacts of reduced connectivity between the upstream and downstream waters. On the possible impacts of dams on biodiversity, as in the case of Indonesia, some concerns had been raised that include: limited number of studies and study sites, use of limited fishing gears, no standardized methods applied over the long term, surveys that depend on fishers' catch with few on biodiversity, insufficient information on nocturnal/diurnal and demersal behavior of aquatic species. In this regard, there is a need to conduct more detailed research on fish biodiversity in order to generate data that could be used to mitigate the impacts of future river development projects.

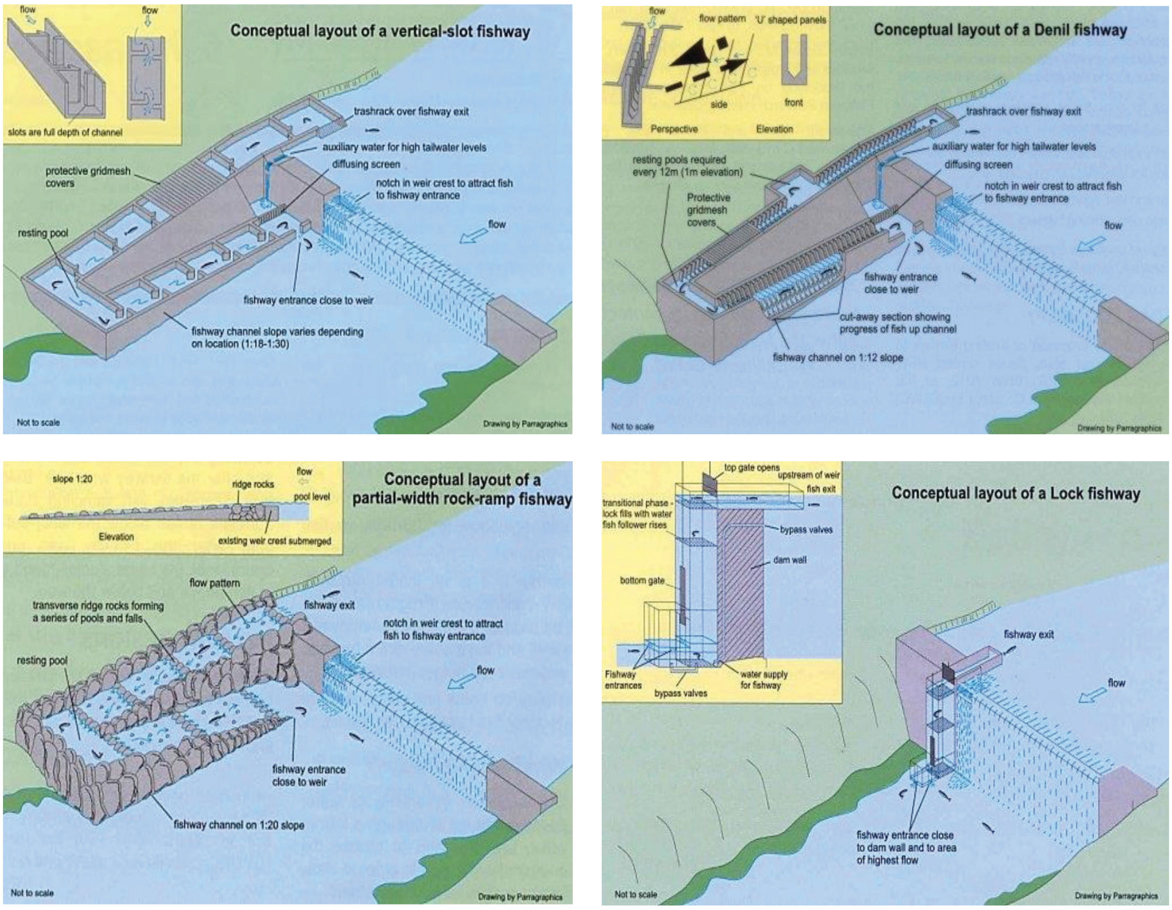

Figure 5. Some examples of fish passes *(clockwise from top left)*: vertical-slot fishway, denile fishway, lock fishway, and rock-ramp fishway
*(**Source:** Department of Primary Industries, 2020)*

Table 3. Scheme for ranking priority in fishway construction

No.	Criteria	Priority factor 5	Priority factor 3	Priority factor 1	Score
1	River size	Large	Medium	Small	…
2	Location in system	Tidal/core habitat	Non-tidal/non-core habitat	Montane (elevated area or highland)	…
3	Threatened species	Endangered	Threatened	None	…
4	Upstream habitat	Abundant	Moderate	Limited	…
5	Downstream obstruction	None	Rare	Many	…
6	Proportion obstructed	More than 66 %	Between 33 % and 66 %	Less than 33 %	…
7	Drownout passage	Rare	Occasional	Frequent	…
8	Barrier type	Crested	Pipe	Culvert	…
9	Fishway cost	Low	Medium	High	…

*(**Source:** Thorncraft & Harris, 2000)*

Case study in Indonesia

In the case of Indonesia where the report of the World Factbook (2017) indicated that the country is the fourth most populous in the world and its population is expected to increase in the next few years, one of the solutions established by the Government to ensure food security is to build water infrastructures to sustain economic development with attendant efforts to address their adverse effects on the other ecosystems, such as decreased productivity of inland fishery resources. Although there are also several other factors also contribute to the decreased productivity of inland fisheries that are also being addressed, which include human population growth, habitat degradation, hydrological changes, overfishing, pollution coming from industrial and household wastes, introduction of invasive aquatic species as competitor of local aquatic species, and climate change.

Plans for the construction of four fishways had been approved in Indonesia. The Perjaya Weir in Martapura located in Poso, which has not yet been equipped with fish path or fish route, but for the other three weirs, fishways have already been constructed. These are the Perjaya Weir in Ogan Komering Ulu (South Sumatera Province), Batang Hari Weir in West Sumatra, and Wawatobi Weir in South Sulawesi (Maryono, 2008). Results of the study conducted on the fishery resources in Komering River, have shown that before the fish pass was constructed, there were 50 species, after 15 years there were 48 species, and now there are only 40 species. The same findings were also recorded at Citarum River, where the mahseer fish species had disappeared after ten years.

One of the largest water infrastructures that have been developed in Indonesia is Perjaya Weir which supports the agriculture sector of South Sumatera. Despite being utilized for irrigation system, the Perjaya Weir has also recently been opened for recreational purposes attracting local and non-local tourists, especially during national holidays. Surrounding the weir, are many stalls offering variety of fruits and vegetables, as well as fish stands where fishers sell fresh native fish caught from the river, such as giant featherback (*Chitala* sp.), Hampala barb (*Hampala macrolepidota*), snakehead (*Channa striata*), "seluang" (*Rasbora* sp.), catfish (*Hemibargus nemurus*), and others.

C. striata is one of the famous fishes in South Sumatera with high nutritional value, and protein that can reach up to 25.2 % and 6.2 % albumin. The fish is believed to accelerate the healing process in patients after surgeries. In addition to the high nutritional content, *C. striata* can also be processed into delicious ready-to-eat meals such as fish cake (pempek), fish soup (pindang), and others. Nevertheless, there is one weakness of the fish pass constructed in Perjaya Weir, where fishes have difficulties to swim upstream and downstream as the exit gate is very close to the irrigation tunnel with fast water current, and baffles which were designed for salmon (not for the native fishes) to pass (**Figure 6**).

Figure 6. Fish passage in Perjaya Weir, Martapura, Indonesia
*(**Source:** Nizar, 2014)*

Figure 7. Sulewana Weir, Poso, Indonesia

For the Sulawena Weir located in Poso, Indonesia (**Figure 7**), although there is an existing fish pass, this was designed for upstream migration of fishes. In such a situation, eels while migrating downstream will have to swim near the turbine at the middle of the river, risking their safety.

Issues and Concerns

There are many reasons why despite the number of weirs and dams constructed in Indonesia, only three had been equipped with fish passes. These include: limited knowledge about fish passage; inadequate water space for inland fisheries; insufficient information on the ability of various species of fish to make use of fish passage; limited coordination between concerned government agencies and stakeholders; and national priority set only on food security of people without taking into consideration the protection and conservation of the fish species. Along this line, the SEAFDEC Inland Fishery Development and Management Department (IFRDMD) and the Research Institute for Inland Fisheries and Extension (RIIFE) based in Palembang, Indonesia, and with funding support from the Australian Water Partnership (AWP), have been promoting the concept of a fish pass as an engineering solution to maintain connectivity in existing weirs and dams throughout Indonesia. The AWP is an international cooperative initiative that helps developing countries in the Indo-Pacific region, and beyond, to work towards the sustainable management of their water resources, and actively supporting the UN SDGs.

SEAFDEC/IFRDMD and RIIFE have mapped three potential sites in Indonesia for this study. These include the Perjaya Dam in South Sumatera, another one in Java Island to observe the movements of eel species, and a third dam in Poso, Sulawesi Island. In order to share knowledge about the fish passage, especially the efforts of IFRDMD, RIIFE, and other agencies working on irrigation, the Workshop "Water Resources Management to Secure Aquatic Biodiversity for Sustainable Development" was organized online on 5 October 2020, hosted by the Sulewana Weir in Poso, Indonesia, and participated by representatives from Indonesia's Ministry of Marine Affairs and Fisheries, BBWS VIII, Public Works and Irrigation Office of South Sumatera Province, East Ogan Komering Ulu Fishery Office, IFRDMD, RIIFE, and fishers.

The Workshop recommended that the development of water infrastructures to increase rice production could be continued but at the same time, such development should not harm the fishery resources. The participants (**Figure 8**) also expected

Figure 8. Participants in the Workshop on Water Resources Management to Secure Aquatic Biodiversity for Sustainable Development

to spread the knowledge gained during the Workshop to other stakeholders to increase fish production and minimize the impact of water infrastructures on the other economic sectors.

Appropriate Design of an Effective Fish Pass

According to Bunt *et al*. (2012), the effectivity of a fish pass consists of attraction and passage efficiencies, and constitutes the proportion of a fish stock present downstream that enters and successfully negotiates the facility with minimal delay. An effective fish pass design requires extensive integration of biological and hydraulic data (Castro-Santos *et al*., 2009). Variation of fish morphology should be considered especially among large fish species. The hydraulic structure and the morphology of fish should be considered to produce selective fish passes, since several morphological characters such as body length, body shape, and structure of fins affect the swimming functions and performance of fish. Mallen-Cooper (1999) suggested that the following steps could be taken into account for assessing the efficiency of fish passes, and for adapting the measures and possible adjustments for non-salmonids: 1) identification of the migratory fish species; 2) testing the experimental fish passes for various fish species (using different settings such as slope, flow velocity, turbulence); design and construction of fish passes based on the test results; and assessment of the fish passes. The capacities of fishes to swim and leap depend on the species and size of individual fishes, their physiological condition and the ambient temperature of the water (Larinier, 2002). To be effective, a fish pass must allow target fishes to successfully pass through it, therefore knowledge of swimming capabilities of fishes is crucial for effective fish pass designs (Katopodis *et al*., 2019).

Furthermore, fish species often get stressed or suffer injuries and loss of scales during migration. A primary measure of successful migration is that the fishes arrive at their habitats with sufficient energy reserve to spawn successfully. Stress in fish is known to affect the timing of reproduction, behavior during spawning, and the survival of offspring (Schreck *et al*., 2001). These factors should be considered part of a more generalized approach in defining the ideal fish pass, and in optimizing the designs with respect to both biological and operational ideals. According to Castro-Santos *et al*. (2009), the ideal fish pass must take into consideration the following factors: 1) any individual of any native fish species wishing to move upstream or downstream must be able to pass through the fish pass without experiencing any delays; 2) their entry in the fish pass must be immediately followed by successful passage; 3) no temporal or energy lost during migration; 4) no stress, disease, injury, predation, or other fitness-relevant costs associated with passage; and 5) costs of construction and operations of fish pass must be minimum.

Nonetheless, fish pass structures should be designed on a site-specific basis and rely on the comprehensive knowledge to adapt the structures to local conditions. Knowledge of the response of fish to certain conditions and factors that attract and repel them is critical for a successful fish pass design (Williams *et al*., 2012).

Insights on Fishways in the Lower Mekong River Basin

Mekong fish species migrate for several purposes, including spawning, feeding, and taking refuge (in deep pools), in both directions upstream and downstream. Migration takes place throughout the year and throughout the life cycle of fish (*i.e.* as larvae, juveniles, sub-adults, and adults). Migration peaks occur at the onset and during the wet season. For the approximately 30 fish species in the Mekong River, there are certain thresholds or changes in water level, discharge or current that could trigger migration. Based on fishers' experience, approximately 11 fish species make use of the first rainfall of the wet season (sometimes in combination with the lunar cycle) to start their migration. Furthermore, some nine species react to turbidity or water color while five species use the appearance of insects as a trigger for migration (Baran, 2006). Nevertheless, spawning and migration triggers can act independently. Spawning triggers also act on species that do not migrate, and migration can occur for purposes not related to reproduction (Baran, 2006).

Design of fish passes

An important factor to be considered in the planning of fish passes is the swimming capability of fish species (Williams *et al*., 2012), as their swimming speed is not consistent but rather depends on influencing factors such as body shape, size, muscular system, oxygen saturation, water temperature, and behavior. Effective fish passes in large dams in the Mekong River require consideration of diverse species with different sizes and swimming capabilities. Consequently, fish pass facilities also not only the small-sized species, those with weak swimming capabilities, but also large fishes. Among the Mekong fish species, the swimming capabilities of "weak" species and age classes are estimated based on the experience from temperate rivers.

Tropical rivers are characterized by large variation of water flow. Thus, in large dams in tropical rivers, turbulent flows may occur across vast areas below turbines and spillways, which could lead to impairment of the orientation among fishes. Most of the existing fish passes have been built for small- or medium-sized dams (up to 15 m high). For large dams, many challenges remain, including those constructed in multi-species tropical rivers. The efficiency of upstream fish pass depends on fish finding the entrance to the passage (perceptibility) and the passability of the fish pass.

There are multiple challenges in designing effective fish passes, especially with regard to the large-scale fish passes, migration of large species, migration peaks with high biomass, and the high diversity of species, all constituting different requirements. Nonetheless, fish pass solutions should provide multiple migration corridors along the riverbed, in mid-channel sections, along the shore line, within the mid-water column, and at the surface.

Figure 9. Lower fishway channel in Pak Peung Wetland Mekong Basin
*(**Source:** Baumgartner, 2016)*

In large dams, the areas where fishes are attracted by high-flow velocities (below turbines and spillway) must be relatively close to the entrance of fish passes to prevent the fish from spending much time and energy searching for entrance. A comprehensive evaluation of the applicability of the available fish passes requires assessment of the current biological monitoring of the fish assemblages of concern to determine the type, number and biological characteristics of fish that are to pass the fishways. The potential efficiency of a fish pass in the context of Mekong River could be estimated by comparing the characteristics of the Mekong migratory fishes with those fishes passing the fishways in water infrastructures in other countries and regions. Different species will have different requirements for fish pass and different responses to upstream and downstream conditions (**Figure 9**). For large multi-species rivers, vertical-slot fish passes and nature-like bypass channels are likely to provide the best solutions but still further research is necessary for these types of fish passes.

Invasive alien species in Mekong River

Dams, urbanization, expansion of agriculture, trans-boundary road development, and other rapid development activities also exacerbate the spread of invasive alien species (IAS). Once an invasive alien is established in a system like in the Mekong River, such introduction is essentially irreversible.

Among the faunal species, tilapia (*Oreochromis* spp.), common carp (*Cyprinus carpio*), pacu (*Colossoma macropomum*), and the sucker mouth catfish (*Hypostomus* spp.) are spreading in parts of the Lower Mekong Basin. Another serious concern is the golden apple snail (*Pomacea canaliculata*), which was believed to have been introduced to Taiwan and the Philippines as means of supplementing the protein needs of the rural poor. These snails soon escaped into waterways, quickly spreading not only through waterways but also in irrigation canals. They rapidly developed into serious pests in many areas of cultivated rice land in Asia, and as a result, over half of rice fields in the Philippines are infested with the golden apple snail (Miththapala, 2007).

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