The MRC is funded by contributions from its Member Countries and Development Partners, including Australia, the European Union, Finland, Flanders/Belgium, France, Germany, Japan, Luxembourg, the Netherlands, New Zealand, Sweden, Switzerland, and the United States of America.
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# ACRONYMS AND ABBREVIATIONS

<table>
<thead>
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<th>Description</th>
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<tbody>
<tr>
<td>ACIAR</td>
<td>Australian Centre for International Agricultural Research</td>
</tr>
<tr>
<td>FAO</td>
<td>Food and Agriculture Organization of the United Nations</td>
</tr>
<tr>
<td>GIS</td>
<td>Geographic Information System</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>LMB</td>
<td>Lower Mekong Basin</td>
</tr>
<tr>
<td>MAFF/Japan</td>
<td>Ministry of Agriculture and Forestry and Fisheries of Japan</td>
</tr>
<tr>
<td>MRC</td>
<td>Mekong River Commission</td>
</tr>
<tr>
<td>NGO</td>
<td>Non-government Organization</td>
</tr>
<tr>
<td>O&amp;M</td>
<td>Operations and Maintenance</td>
</tr>
<tr>
<td>PIT</td>
<td>Passive integrated transponder</td>
</tr>
<tr>
<td>QGIS</td>
<td>Quantum GIS</td>
</tr>
<tr>
<td>Lao P.D.R.</td>
<td>Lao Peoples Democratic Republic</td>
</tr>
<tr>
<td>US-DOI</td>
<td>Department of the Interior of United States of America</td>
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INTRODUCTION

Background
The Mekong River and its tributaries support the largest inland fishery in the world - producing over 2 million tons per year, providing essential food and livelihoods for over 40 million people. There are over 1,000 freshwater fish species and almost all the fish found in rivers and streams migrate to complete their life cycle – to spawn, disperse from dry season refuges, and to feed.

Throughout the Lower Mekong Basin (LMB) there are, however, tens of thousands of barriers to fish migration – such as dams, weirs, regulators, floodgates, and road crossings. These barriers have a significant impact on fish diversity and production, with fish unable to complete their life cycles and by concentrating fish into areas where they can be over-exploited. The cumulative impact of these barriers in the LMB fish populations is large and has long term implications for the continued productivity of this system.

Restoring migration pathways and providing fish passage can restore life cycles and fish productivity. High dams have been built on the Mekong mainstream and in upper catchments to provide hydroelectricity, but the most numerous barriers to fish migration are low-level structures (e.g., < 7m), used for irrigation. The present guideline is aimed at providing fish passage solutions at these, and other, lower barriers so fish migration can be restored.

It is important to note that the most effective solution for fish passage is to have no barrier, so fish can migrate freely upstream and downstream. Hence, the first option to be considered for an existing site is barrier removal; or for a new site, alternative water management. This approach depends on an analysis of the functions that the structure is serving (e.g., water storage, irrigation diversion, road crossing) and whether that function is still needed or can achieved by other means.

For barriers that need to be retained, the most common fish passage solution for upstream migration is the provision of fishways, which are generally channels of water around an obstruction with low water velocities and rest areas that fish can pass. For downstream migration at low level structures, the designs of weir crests, plunge pools and sluice gates are important. For the purposes of this document, when the term “fishway” is used, it refers to a structure that provides upstream or downstream migration.

Upstream and downstream fishway projects often focus on design and construction, but effective installation and operation is dependent on 6 steps:

- Step 1. Fishway design
- Step 2. Fishway construction
- Step 3. Fishway operation
- Step 4. Fishway maintenance and inspection
- Step 5. Fishway monitoring
- Step 6. Fishway adjustment
The following guideline is organized around these 6 steps. An ongoing theme is that both biologists and engineers are needed to implement a successful project. Design principles and key design criteria are described in these steps, as well as common mistakes in design. The guideline emphasizes: continuity between these steps, engagement of stakeholders, and responsibilities at different steps. Continuity is provided from Step 1 by developing construction methods, an operations and maintenance plan, and a monitoring plan, alongside the concept and detailed design. Engagement with experts, local communities and operators also starts in Step 1 and is critical for ultimate project success.

The responsibilities in fishway construction are clarified. The design engineers need to ensure in Step 1 that the fishway can be easily constructed, while the on-site construction in Step 2 is the responsibility of the fishway builder (or contractor), including environmental protections and safety.

Guidance on quality control during construction is provided; a key part of this is independent inspections as construction progresses; by both biologists and engineers to ensure that there are no deviations from the detailed design. Commissioning of the fishway at the end of construction is an important step, which tests that the fishway is built and functioning as designed. It includes a check of physical dimensions and a wet commissioning with water flowing through the fishway to check hydraulics (water levels between pools and depths). Once the fishway has been successfully commissioned the builder can move off-site and can be paid. Following construction is a defects liability period (generally 52 weeks) where the builder is fully responsible to correct any construction defects that arise or develop in the fishway in that period.

In Step 3 fishway operation is described. Importantly, this involves: i) integrating fishway operation into the whole weir or sluice gates, so that flow patterns can guide fish to the fishway entrance, and ii) guiding downstream migrating fish through the safest pathway.

All fishways require regular maintenance and it is a significant factor in the long-term success of the fishway. Hence, Step 4 describes the requirements for inspections and maintenance. Fishways that are not maintained or operated correctly lead to ineffective fish passage.

Step 5 is fishway monitoring, which is essential to determine if the fishway is passing fish effectively. It is surprising how many projects assume that their constructions are successful and fail to conduct any monitoring of fish migration at the structure. To truly determine if a fishway has increased the fisheries productivity of a system, a rigorous monitoring program is required that assesses: i) fish passage upstream and downstream at the fishway and weir, ii) changes in fish populations, and iii) the socio-economic benefits in surrounding villages to assess catches, income, and livelihoods.

Step 6 is adjustment of the fishway, which can follow commissioning, inspection, or monitoring. It is important to note that adjustment may be required after the defects liability period or may result from issues not considered in design. Hence, it is wise for a project to have additional funds for ongoing modifications and for monitoring to take place within the first year if possible.

Following these 6 steps will ensure that the fishway project is successful.
**Who this guideline is intended for**

This guideline is intended for specialist engineers and biologists embarking on a fishway design at a low level (< 7m) weir in the lower Mekong Basin. Many of the concepts, however, are universal to fish passage design and can be applied to a wide range of regions.

**Fish-Friendly Irrigation**

The present guideline is part of a broader initiative of the Mekong River Commission (MRC) on *Fish-Friendly Irrigation*. The initiative aims to address fish passage and blocked migrations, within a broader holistic objective of an integrated irrigation system that optimizes agricultural production, fish production and biodiversity.

The present Guidelines on Fishway Design is one component of that strategy, aimed at developing a fish passage solution for a single site, and it assumes that weir removal is not an option. A second component is a strategic methodology of prioritizing multiple sites for fish passage, which is published by the MRC (*Guidelines to Prioritizing Existing Fish Passage Barriers in the Lower Mekong Basin*). These two components address fish passage and restoring migration. However, this does not address all the issues or opportunities for fish within agricultural systems. As fish passage is progressed, *Fish-Friendly Irrigation* aims to encompass a broader range of issues including:

- managing fish migration laterally into, and out of, irrigation systems,
- maintaining fish habitat in irrigation systems,
- creating community-managed, habitat refugia for blackfish,
- creating habitat refugia for other aquatic animals (OAAs),
- minimizing pesticide / fertilizer use,
- integrating rice production, fish production (in irrigation systems, outside of aquaculture) and water use.
- Appropriately managing aquaculture in agricultural systems
- Appropriately regulating fish harvest
- Minimizing use of illegal practices

Together these provide a holistic system which protects biodiversity, people, and fisheries resources.

**Background on Fish Migration in the Mekong**

For any fishway project, site-specific information on seasonal fish migrations is always needed. The following is a brief introduction to fish migration in the Mekong that is intended for a fishway designer unfamiliar with the region. More detailed information can be found on the website of the Mekong River Commission (https://www.mrcmekong.org/).

In the Lower Mekong Basin (LMB) there are some general patterns of migration that are well known. Fish spawn and migrate along the entire Mekong, but the middle and lower zones have significant floodplain nursery areas and spawning areas with major migrations between the two
zones (Figure 1). Fish also migrate within the upper, middle, and lower reaches, as well as long distances between all three zones (Figure 1).

In addition to migration along the mainstream, fish migrate entirely within tributaries as well as migrating from the mainstream into tributaries to spawn, followed by downstream migrations to nursery and feeding habitats. The timing of these upstream and downstream migrations is variable depending on fish species and life cycles. However, there are migration peaks during the spring (February-March), as the most important time, followed by the onset of the flood (June-July), and then when the water is receding (November) (MRC.2020).

As well as longitudinal migrations upstream and downstream, there are lateral (sideways) migrations on and off floodplains – these are important for spawning, feeding, and nursery areas. The diversity of migration means that fishway design in the Mekong often needs to pass small (e.g., 5cm) up to very large (100-300 cm) fish migrating upstream. All these fish also migrate downstream, in addition to larvae drifting downstream, so the design of sluice gates and weirs are also important to ensure safe passage downstream.
Figure 1: Generalized migration systems in the Lower Mekong Basin
(Source: M. Mallen-Cooper, modified from Poulsen et al., (2002a))
STEP 1: FISHWAY DESIGN

At each barrier, there will be a varying degree of site-specific design work required. This will be influenced by whether it is a new site or an existing site. The process is always easier to facilitate at a new site if the design can be integrated into engineering drawings from the inception stage. This will ensure that the fishway functions in conjunction with the existing structure and flow regime, while delivering optimum fishway outcomes.

Fishway design is a multi-disciplinary process of biology, hydrology, and engineering. Effective design depends on understanding fish movement and behavior and translating these biological aspects into engineering criteria. It requires close collaboration between engineers and fish biologists, as well as with the structure owner and operator, to ensure the final design is practical to operate and maintain.

1.1. Design Team

Fishway design is a consultative process using existing expertise and local knowledge to enhance the quality of the outcome. The design team should include or consult with stakeholders e.g., biologist, engineer, operator and proprietor or fishers. The design team requirements are as follows:

- **Biology**
  - Fish scientist, preferably with experience in fish passage projects and a knowledge of local fish biology and movement behavior.

- **Engineering and Hydrology**
  - Design engineer, with extensive civil and irrigation experience; preferably with knowledge of hydrology, hydraulics and fishway design.

- **Operations**
  - Local irrigation officials must be involved at every step of the fishway design process from the beginning to ensure they are able to operate the fishway easily.

- **Proponent**
  - The presence of the funding agency at all elements of the fishway design process ensures that decisions can be made more readily (e.g., in terms of expenditure), thus avoiding delays.

1.2. Principles of Fishway Design

There are four design principles for fishway design that ensure effective fish passage. These are summarized here to provide background to this section but explained in further detail throughout this document:

**Principle 1. Address upstream and downstream migration**

- Migration is cyclic and occurs in both upstream and downstream directions. For migratory fish to complete their life cycle they need to pass a barrier easily and safely in
both directions, with no mortality and low stress. Prevent fish from entering irrigation
offtakes on the upstream side of the barrier.

**Principle 2. Integrate biology, hydrology, and hydraulics**

- Identify fish species; maximum and minimum size that are migrating; and swimming
capability (size can generally be used to estimate this).
- Migration season and river flow.
- Range of water levels on the upstream and downstream sides of the barrier.
- Integrate these data to calculate design velocity, design depth, design discharge, and
fishway gradient.

**Principle 3. Locate and design the fishway entrance to attract fish**

- If fish cannot locate the fishway entrance, they cannot use the fishway.
- Ensure hydraulic conditions and flow patterns guide fish to the fishway entrance.
- Consider entrance location and attraction flows to guide fish.

**Principle 4. Size the fishway to meet the migratory fish biomass**

- Large streams have higher migratory fish biomass (kilograms) than small streams and
require larger fishways. Although there is generally little data on migratory biomass,
stream size and mean river flow can be used to indicate this aspect.

### 1.3. Fishway design phases

**Phase 1 - Data Collection and Analysis**

The key aspects of data are listed here while a more complete list is provided in Annex 1.

**Essential data**

- **Biology**
  - Minimum size of fish migrating (see example in Figure 2).
  - Maximum size of fish migrating (see example in Figure 2).
  - Migration season (see example in Figure 3).
  - Upstream limit of migration for fish at different flows.
- **Water levels (hydraulics) (Figure 4)**
  - Maximum and minimum upstream (headwater) levels in migration season (Note: Estimates can be used for concept design but surveyed accurate levels are required for detailed design).
  - Maximum and minimum downstream (tailwater) levels in migration season.
  - Maximum difference in upstream and downstream level in migration season.
- **Engineering plans, if available.**
- **Riverbed condition downstream (Figure 4)**
  - The downstream riverbed (No. 7 in Figure 4) is either *stable* (e.g., bedrock) or *variable* (e.g., sand or gravel). A variable bed will have variable minimum
tailwater levels (No. 5 in Figure 4) and will require a longer fishway to accommodate potentially lower water levels.

- Available space (footprint) for fishway.

**Additional data**

- **Biology**
  - Observations of fish behavior below the barrier to determine the *upstream limit of migration* for the location of the fishway entrance. This will likely vary under high and low flows, with fish congregating in different areas. This can affect the design of gates, crests, abutments, or embankments; or it may require multiple fishway entrances.
  - Important species for food security and livelihoods.
  - Threatened species.
  - Other known or observed fish behavior relating to ---surface, bottom, edge of the river or the central deep channel (thalweg).

<table>
<thead>
<tr>
<th>Fish Size</th>
<th>Migration Abundance</th>
</tr>
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<tbody>
<tr>
<td>Large (1000-3000mm)</td>
<td><img src="example.png" alt="Example only" /></td>
</tr>
<tr>
<td>Medium (500-1000mm)</td>
<td><img src="example.png" alt="Example only" /></td>
</tr>
<tr>
<td>Small (100-500mm)</td>
<td><img src="example.png" alt="Example only" /></td>
</tr>
<tr>
<td>Very small fish (20-100mm)</td>
<td><img src="example.png" alt="Example only" /></td>
</tr>
<tr>
<td>Larvae (downstream migration only)</td>
<td><img src="example.png" alt="Example only" /></td>
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*Figure 2:* Example of fish size data used to design a fishway.
Figure 3: Example of the season of upstream and downstream migration with monthly flows.

Figure 4: Essential Data on water levels required for a fishway design.

- **Hydrology**
  - River discharge. Daily data is preferable for analysis.
- **Hydraulic**
Flow patterns downstream at different flows, to help determine entrance conditions
Flow patterns upstream at different flows to ensure fish are not swept back down the structure or into an upstream irrigation channel.

Structure and site conditions
- Operation of weir/sluicegate
- Access for construction equipment
- Location of diversion offtakes which need to be avoided when siting the fishway exit

Data collection methods
- Review literature.
- Examine databases of fish species, fish catches, water levels and flows.
- Interview academic experts, researchers, government officials, local people, and fishers on site.

Data analysis
- Hydrology and hydraulics
  - Frequency of upstream and downstream water levels in fish migration season.
  - Frequency magnitude and duration of flows (discharge e.g., m$^3$/s)

Phase 2 – Meeting of Design Team to discuss data
1. Meeting of full Design Team, to review existing data and analysis: identify data gaps – especially of Essential Data; and initiate steps to fill data gaps where practical. Ideally this meeting would occur on site to discuss any specific issues which may be significant.
2. Discuss operational changes (e.g., barrier removal or opening gates) to improve fish passage in addition to a fishway. This may reduce the cost of the fishway and provide greater fish passage.
3. Preliminary discussion of possible fishway design types noting that simple fishways with low operation and maintenance are preferable.

Phase 3 – Site Inspection with stakeholders

Phase 3 is a site inspection with the full design team and stakeholders, which includes:
- Engagement with local people and local fishers to:
  - provide further information to all stakeholders on the project.
  - gather further local information.
  - Ensure their vision for the site is adequately captured in the final design
- Discussion and confirmation on-site of the collected data from Phase 1 and 2.
- Confirm operation of the structure.
- Identify site constraints or opportunities.
- Discuss potential fishway entrance location and conditions at different flows.
- Discuss the potential fishway designs that could be undertaken at the site.
- Consider upstream and downstream passage.
Agree on how the preferred fishway design will be decided upon.
Ensure any local opinions or issues are considered prior to concept design

Phase 4 - Design workshop and report

This workshop allows fishway design issues to be identified and discussed with input from all the relevant stakeholders and experts including local fishers. The proceedings and outcomes of the workshop should be accurately recorded by a person with sufficient technical understanding (e.g., engineering, biology, hydrology). For each issue, record the: design objective/intent, design assumptions, operational constraints.

The issues need to be discussed and confirmed are:
1. Target species
2. Target size range of fish.
3. Water levels.
4. Flow conditions for fish attraction below the barrier over the range of flows for fishway operation. The two approaches are to: use existing conditions or modify the structure, operation or fishway design to provide more optimal conditions.
5. Entrance and exit points of the fishway.
6. Suitable fishway types for options analysis in Phase 5.
7. Downstream migration measures.
8. How the fishway is to be incorporated into the existing or new barrier.
9. Operation and maintenance requirements for the fishway and their design implications.
10. The design of the monitoring program and if traps / microchip readers need to be included in design.

A Design Workshop Report will document these issues.

Phase 5 – Options Analysis and Concept Design

The objectives in Phase 5 are to compare the fishway options, select an option, and then develop a single design. Included in this phase are:

1. **Options Analysis**
   - Analyze advantages and disadvantages of each identified fishway design from Phase 4.
   - Select a single design for concept development.

2. **Fishway Channel (passage) Design**
   - Detailed hydraulic design:
     - Use the selected water levels to determine the maximum difference of these levels, which partly determines the fishway length.
     - Use the target size range of fish and swimming ability to determine the: i) maximum water velocity and hence “head loss” (the “step height” or difference in upstream and downstream water levels in a fishway pool. See Annex 4 for more information) between pools, and ii) maximum turbulence which is used to calculate the fishway pool volume (pool depth, width, and length).
     - Calculate fishway discharge.
Calculate changes in depth, velocity, and turbulence with water level changes at the exit and entrance.

Hydraulic design needs to be documented in a report which then also becomes part of the detailed design report.

Preliminary Structural design:
Structural design should be conducted to secure structural safety by considering loads in the fishway, dynamic characteristics of the foundation ground, climatic conditions, and construction cost.

3. Fishway Entrance (attraction) Design

The objective of fishway entrance (attraction) design is to ensure fish are guided to the fishway entrance, and can easily locate and enter the fishway, without excess stress or delay. It involves the design of the weir, gates, abutments, banks, fishway discharge, attraction flow and auxiliary flow.

Considering the fishway entrance can influence which side of the river to build the fishway on. Some fish will migrate upstream along the inside bend of a river, while other species choose the deepest channel in the middle. However, the primary attractant for fish is flow, so designing attraction flows next to the fishway will attract most fish.

Physical modeling in a hydraulics laboratory, of the weir/sluice gate with a fishway entrance, is often used on large projects. The scale of the models are 1:10 to 1:25 and a wide range of river flows and conditions can be simulated. Physical modeling has proven to be a very valuable tool to design the fishway entrance location, gates, and spillway to provide appropriate flow conditions that guide fish to the fishway (Figure 5). Computer modelling (CFD) in 3D is also being used and is likely to become more useful.
Figure 5: Scale physical model (1:25 scale) of a dam and fishway entrance that was used to design fishway entrance conditions.

4. **Fishway exit location**

- The fishway exit needs to be located at a sufficient distance from: i) the weir crest or sluice gates so there is static water, to prevent fish being drawn back downstream; and ii) irrigation channel offtakes, to prevent river fish being drawn into irrigation systems.

5. **Fishway exit gate**

- Fishways are often equipped with an exit gate (or control gate) that can turn the fishway on or off. The objectives of these gates are to block flow to i) conserve water in the dry season; ii) enable dewatering for maintenance; or iii) protect the fishway in large floods.

- The role of the exit gate is not to control flow in the fishway for fish passage by partially closing the gate; these gates must be operated 100% open or closed. Partially closing the gate creates a high head loss and highwater velocity, so that fish accumulate downstream of the gate but cannot pass through the gate and compete their migration.

- The hydraulic design of the fishway (including selecting the range of water levels and ensuring the fishway is long enough and has a sufficiently low gradient) ensures that the gate is not required to control flow – only the pools and baffles in the fishway channel are needed to do this.
6. **Downstream migration measures**

- At an irrigation structure with a fishway, fish can pass downstream: i) through the weir/sluice gate, or ii) through the fishway. If the only flow downstream is through the fishway then fish will pass safely through the fishway - as any design criteria for turbulence for upstream passage will provide safe downstream passage. If most of the downstream flow is over the weir crest or through sluice gates, downstream migrating fish will use this flow, so the design of weir crests and gates are important.
- Overshot gates provide safer downstream passage than undershot gates, which can injure and kill fish.
- Plunge pools are needed on the downstream side of weirs to provide a cushion of water for fish. A safe plunge pool criterion is a depth that is 40% of the total difference in upstream and downstream water levels.
- Downstream-migrating fish can also be susceptible to being drawn into irrigation offtakes. To prevent this fish screens can be used at the offtake, to ensure fish complete their migration in the river.

7. **Operation and Maintenance (O&M)**

- Consideration of operation and maintenance is necessary in concept design and needs to be reviewed by the owner/operator to ensure it is practical.

8. **Monitoring**

- Consideration of fish monitoring is needed in the concept design to allow space for fish-traps and methods of lifting traps.

9. **Preliminary CAD drawings**

- These drawings provide: a weir section with water levels (like Figure 4), typical cross-section of the fishway channel, a long section of the fishway, fishway entrance and exit, other key features such as gates or monitoring equipment. The drawings are not for tender or construction, which is detailed design in the next phase.

10. **Reporting**

- Reporting will either combine the Options Analysis and description of Concept Design or separate them into two reports.
- The Options Analysis Report will include the background information and data on biology and hydrology, water levels, and design assumptions and decisions.

11. **Peer Review**

- A review by an external party who has no stake in the project should also be undertaken to give an independent assessment of the viability of the fishway design. Once this process has been completed and all stakeholders have agreed on an option for detailed design, the final fishway design can be completed.
Phase 6 – Detailed Design

1. **CAD drawings for Construction and Design Report**

The detailed design phase includes full structural design and an analysis of the most efficient construction method (i.e., constructability), incorporating practical operation and maintenance into design. The detailed design phase will incorporate all the information collated throughout the previous design phases to produce:

- set of detailed design drawings for tender and construction,
- construction instructions,
- a design report, and
- communications and quality control plan for construction
- three post-construction plans for: i) commissioning, ii) operation and maintenance, and iii) monitoring of the fishway.

The construction instructions need to be specific. Misinterpretation of the design by construction crews can lead to the complete failure of the design and as such, instructions should be comprehensive enough that construction crews are able to implement the design easily. To this end, the communications plan would include the construction contractors (fishway builders) and the design team, to ensure the team’s involvement and accessibility to the site during construction.

The whole design team should review the detailed design drawings and ensure that the final product has not been compromised wherever changes have been made. Following any final changes, the whole design team should then agree upon, and endorse, the final design prior to tendering for construction.

2. **Commissioning Plan**

Commissioning occurs when fishway construction is complete. It is a formal inspection of all physical specifications (dry commissioning) and hydraulic function (wet commissioning). It is generally done with the contractor (builder) on site with all construction equipment, so that identified defects can be fixed. Once commissioning is complete and approved, including rectifying any defects, the contractor can be paid.

The Commissioning Plan includes dry and wet commissioning. Dry commissioning needs to check:

- Physical levels, dimensions, and tolerances to be checked. It is important, therefore, to put tolerances into the detailed CAD drawings. For example, all pool-type fishways need the baffle of each pool to drop by the same amount, which is independent of pool length. Because this drop determines the hydraulics and water velocities, it has a tight tolerance (e.g., 1.5 % between baffles and 3% for all fishway baffles).
- Any moving parts that need to be tested, such as exit gates.
- Quality of all construction and materials.

Dry commissioning identifies any structural issues or faults, and procedures to rectify them.
Wet commissioning is done with water flowing in the fishway and through the weir or sluice gates. It has two components of:

1. testing the hydraulics of the fishway channel (depth and head losses per pool), and
2. testing/adjusting flow patterns downstream of the fishway to provide appropriate attraction flows

The main hydraulic design criteria to check in the fishway channel is the head loss at every baffle, which determines the maximum water velocity. Tolerances need to be specified in the Commissioning Plan; for example, 10% variation in head loss from the design is generally acceptable. If head losses are not within design tolerances, then modifications can be made to the fishway rectify it.

Water depths must also be measured in wet commissioning, but these are more dependent on accurate surveyed levels of water and the structure before and during construction. Hence, quality control throughout construction is more critical. It is also important to check depths under the full range of flows (at the peak of the rainy and dry seasons).

Dry and wet commissioning is done when the fishway is complete and before the builder and equipment have left the site. Commissioning is done by staff that are independent from the builder (often government agencies), but also needs to be done while the builder is on-site in case modifications are required. The modifications are the responsibility of the builder and can only relate to construction defects and the execution of the agreed plans from the detailed design and tender.

The second component of wet commissioning, which is adjusting flow patterns downstream of the fishway, requires the owner and operators on site as it overlaps with operation of the structure. Guidance on this aspect is provided in Section 1.4.3. and 0.

Final payment to the fishway builder should only be done after any identified construction faults are rectified and dry and wet commissioning has been successful.

### 3. Operation and Maintenance Plan

A fishway requires long-term management and maintenance to prolong its service life and function. The fishway designer needs to clearly describe the life of materials, and where and when maintenance is needed. The O&M Plan needs to be reviewed and accepted by the owner and operator of the structure. The most common maintenance on low-level fishway used at irrigation structures is removal of timber, sand, and rocks, which disrupts the fishway hydraulics and prevents fish migrating. Further information on operation and maintenance is provided in Step 3.

### 4. Monitoring Plan

A Monitoring Plan provides objectives and methods of monitoring fish in the fishway to assess its effectiveness. Monitoring assesses the species, number, size, and biomass of fish attracted to the fishway and passing through the fishway. Fishway monitoring is discussed in Step 5.
Summary

Figure 6 provides a summary of the design phases. Note that multiple site visits may be necessary in later phases to confirm weir operation and entrance conditions.

<table>
<thead>
<tr>
<th>Phase 1: Data Collection and Analysis (Literature, interview and site inspection)</th>
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<td>- Water levels, flow data</td>
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If necessary, the Design Team will revisit the site

<table>
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<th>Phase 2: Meeting of Design Team to discuss data</th>
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<tr>
<td>- Review existing data and identify data gaps to fill</td>
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<td>- Discuss operational changes</td>
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<td>- Identify possible fishway designs</td>
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<th>Phase 3: Site Inspection with stakeholders</th>
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<tr>
<td>- Engage with local people and fishers</td>
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<tr>
<td>- Discuss data on-site; confirm levels</td>
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<td>- Confirm operation</td>
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<td>- Discuss fishway entrance location and flow conditions</td>
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<th>Phase 4: Design workshop</th>
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<tr>
<td>- Confirm target size range of fish</td>
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<td>- Confirm water levels</td>
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<tr>
<td>- Discuss entrance and exit points of fishway</td>
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<tr>
<td>- Operation and maintenance for a fishway</td>
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<tr>
<td>- Decide on suitable fishway options</td>
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<th>Phase 5: Options Analysis and Concept Design</th>
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<tr>
<th>Phase 6: Detailed Design</th>
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<td>- CAD drawings and Design Report</td>
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<tr>
<td>- Commissioning Plan</td>
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<tr>
<td>- O&amp;M Plan</td>
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<tr>
<td>- Monitoring Plan</td>
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Figure 6: Summary of the phases in fishway design.

1.4. Developing Fishway Design Criteria

1.4.1. Overview: integrating biology, hydrology, and hydraulics

Fishway design can be grouped into three components:
1. **Attraction**, which relates to fishway entrance and weir/gate design.
2. **Passage**, which relates to fishway channel design, and
3. **Exit**, which relates to location and conditions for a safe exit.

**Figure 7**: Components of fishways design: 1) Attraction, 2) Passage and 3) Exit.

Most of the design work is *Attraction* and *Passage* and Figure 8 shows how key design criteria are used in these two design components.
Figure 8: Flow chart of key elements of fishway design.
The flow chart in Figure 8 shows how biological, hydrological, and hydraulic design criteria interrelate, and then determine civil engineering design criteria that are used to build a fishway. For example:

- the minimum size of fish that are migrating (biology) determines the maximum water velocity and turbulence (hydraulics), which then determine the fishway pool size, channel width and gradient (civil engineering).
- the maximum size of fish that are migrating (biology) determines the minimum depth and pool volume (hydraulics), which then also determine the fishway pool size, channel width and gradient (civil engineering).
- the migration season (biology) determines range of data to examine for upstream and downstream water levels (hydraulics); this then determines the fishway channel depth which is a primary criterion for design (civil engineering). (e.g., if fish are only migrating in the rainy season, then only the data on water levels during the rainy season are used for fishway design, while water levels in the dry season are not used).

The following sections discuss each of these key design criteria in detail, while further information is provided in Annex 2.

1.4.2. Fishway channel (passage) Design

**Biological criteria**

Fishways need to be sized to pass the migratory biomass (kilograms of fish) present in the river. Fish migration can occur in pulses so there can be high numbers and migratory biomass of fish arriving at a fishway in a short period of time. So, it is essential that the length, width, and depth (i.e., volume) of the fishway cells can accommodate the maximum number of fish expected at a site. There are usually very little quantitative data on migratory biomass. However, stream size is often a very good indicator of fish biomass - large streams with higher flow generally have higher migratory fish biomass (kilograms) than small streams.

For fishway design, the maximum amount of flow in the fishway is desirable to attract and pass the migratory biomass of fish. In small streams, 100% of stream flow can sometimes be used in the fishway, but in large rivers the fishway would be too large and costly to pass all the river flow. As a compromise at sites with high discharge, 10% of river flow is considered the minimum fishway flow to attract and pass fish.
**Migration season**

Migration season is used to help determine water levels for the fishway design (Figure 3). Upstream and downstream water levels vary at a site due to the largest flood in the rainy season and the lowest flow in the dry season, as well as operation of gates and sluices (Figure 4). Fish migration does not occur uniformly throughout the year so understanding the migration season enables the fishway designer to select the range of water levels that occur when fish are migrating (Figure 4). The peak of upstream migration may also differ from the peak of downstream migration (Figure 4), and significantly, downstream migration includes drifting eggs and larvae that need to pass safely, as well as returning adult fish.

On the mainstream of the Mekong River there are known migration peaks during the spring (February-March), considered the most important time, followed by the onset of the rainy season (June-July), and then when the water is receding (November) (MRC 2020). In the Mekong mainstream, downstream migration of larvae - which drift in the flow - occurs throughout the year, although there are peaks at the onset and during the rainy season. Irrigation infrastructure is on tributaries of the Mekong River; nevertheless, some of the patterns and seasonality in the Mekong mainstream are likely to be similar in tributaries. There are also migrations that occur entirely within tributaries, so site-specific information is needed for fishway design.

**Maximum and minimum size of fish**

Fundamental to fishway design is understanding the species of fish that exist in the river or stream; in particular, the maximum and minimum size of fish. The maximum size of fish determines the minimum space and pool volume (including depth and slot width or gaps in baffles), while the minimum size of fish – with the weakest swimming ability - determines maximum water velocity and turbulence for upstream passage.

For downstream passage it is also important to know the size range. In the LMB it may be necessary to accommodate downstream movements of eggs and larvae, as well as sub-adult and adult fish.

Swimming behavior is important as some fish use surface waters while some species swim along the bottom. If specific data is unavailable, expert knowledge and interviews can be used with local people and fishers.

To select the target species and size range, considerations include:

1. Fish species and sizes needing to pass the barrier to complete their life cycle.
2. Representative fish in terms of size (large fish and small fish) and swimming behavior.
3. Endangered species.
4. Main species in the fisheries.
5. Species of important to the livelihoods of local people.

The objective in fishway design is to enable as many species as possible to pass. A diversity of species and sizes provides a robust food web for fish, and hence a robust ecosystem.
From the available information the Design Team will select a diverse range of target fish species and a suitable size range for the fishway; not narrowing down to only one or two species. For reference to determine the target fish, Annex 2 indicates fish species in the LMB classified into categories or guilds that have similar habitat needs and migratory behaviors. Annex 3 also shows major migration patterns of the Mekong fish.

**Hydraulic criteria**

**Water levels in the fishway**

The upstream and downstream water level ranges for the fishway are determined by the water level variation in the migration season (Figure 4). These levels are selected to allow for changes in headwater (upstream level) and tailwater (downstream level) while fish are migrating. Headwater levels for the fishway need to accommodate the minimum depth for fish plus changes in water levels due to weir/sluice gate operation or increases that might occur during high flows. Tailwater levels for the fishway also need to accommodate the minimum depth for fish plus increases that might occur during high flows, as well as accommodating the minimum flow.

Sites with relatively stable headwater, and variable tailwater, are easier to design solutions for, than those with highly variable headwater.

It is important to know the type and stability of riverbed downstream (Figure 4) as this can influence the long-term water level downstream. If the riverbed is hard rock, then the water level downstream is likely to be stable, but if the riverbed is sand or gravel it can be unstable and can erode; then the downstream water level can drop, making the fishway ineffective. If an unstable riverbed is present, it is good design practice to reduce the minimum tailwater – typically by 0.3m, but it will depend on the site and local information concerning the river.

The minimum levels are used with *minimum depth* criteria for fish (see following sections) to determine the *fishway channel depth*.

**Maximum difference in upstream and downstream water levels**

The maximum difference in headwater and tailwater levels is a key criterion that sets the length of the fishway. For example, a maximum difference in headwater and tailwater of 2m, combined with a design gradient of 1:30, would produce a 60m long fishway (2m by 30).
Note that the maximum difference is not necessarily the highest headwater less the lowest tailwater levels, because at higher headwater levels there is often higher downstream levels (with higher flows) with less difference between the two.

**Water depth and Pool volume**

The water depth in the fishway is determined by the size of large fish, and can be influenced by swimming capability, behavior (needing more depth or space for fish to feel safe and enter the fishway), or the migratory biomass. In general, water depth needs to be at least two times the largest fish’s body depth (U.S Fish and Wildlife Service, 2019). For example, if the maximum length of fish is 50 cm, then the minimum depth should be 100 cm. The pool length and width need to be at least three times the maximum length of the largest fish (MRC, 2019).

Depth also needs to be enough to minimize predation of small fish by birds. Generally, the depth required for large fish will provide sufficient protection for small fish. If, however, a fishway was designed only for small fish then a minimum depth of 50 cm should be used in pools. It is worth noting that predation of small fish by birds usually occurs when the fishway is poorly designed and fish cannot easily ascend – they then accumulate in the pools and are preyed upon.

**Maximum water velocity**

Water velocity is the speed of the water – if it is faster than the swimming speed of the fish, then fish cannot ascend the fishway. It is therefore important to know the swimming ability of the weakest swimming fish. Swimming ability is related to fish size, so the smallest fish generally has the weakest swimming ability. In channel-type fishways that have distinct drops in water, the drop height – called “head loss” – is directly related to the maximum water velocity, which can be calculated using formulas (Annex 4).

Straight channels with no pools are sometimes used in fishway design to connect different sections; in this case there is uniform velocity across the channel. Again, the maximum water velocity should not exceed the swimming ability of the weakest swimming fish. If there is no site-specific data, a general rule is that 0.3 m/s will provide passage for all fish, with a maximum of 0.5 m/s (MRC, 2019).

**Maximum turbulence**

In a fishway, fish need to negotiate water velocity and turbulence. Turbulence is violent or unsteady movement of air or water. High turbulence impedes fish movement because fish are disoriented and cannot find the direction due to air bubbles, lateral and longitudinal waves, and spiral flow.

Turbulence is a key design criterion in fishways and is often overlooked. Turbulence is not measured on site but is calculated in design from the volume in a single fishway pool and maximum water velocity, using pool head loss (O’Connor et al., 2015). Turbulence in a fishway is the measure of the dissipation of energy (water mass and water velocity) from flowing water.
entering the fishway pool, and the pool volume (length, width, and depth) available to dissipate that energy (O’Connor et al., 2015). The formula for turbulence is in Annex 4.

As larger pool volumes result in lower turbulence, it is better to enlarge pool volumes to curb turbulence. Although a short-length fishway with small pools is less costly than a long-length one with large pools, it generates more turbulence. Turbulence can also occur when pools are short and wide – this can cause a lateral (sideways) wave, making it difficult for fish to ascend the fishway.

Turbulence needs to be low enough for the weakest swimming fish. If there are no site-specific data the maximum turbulence should be 40 Watts per cubic meter (W/m³) as an initial criterion (MRC, 2019), although 26 W/m³ has been used in Australia for very small (2 cm) fish (Bice et al., 2017).

**Civil Engineering criteria**

**Fishway channel depth and light**

At the upstream (exit) of the fishway the channel depth is determined by the minimum depth for fish plus the headwater range (maximum and minimum water levels during fish migration season); for example, a minimum depth of 1 m for fish plus a headwater range of 0.5 m provides a channel depth of 1.5 m. Importantly, this channel depth becomes the minimum throughout the whole fishway channel. An additional “freeboard” is typically added to contain any splashing water in the fishway channel; in the previous example, a free board of 0.3 m would result in fishway channel that is 1.8 m deep.

At the downstream end, the channel depth follows the same logic of minimum depth for fish plus the tailwater range. The tailwater range (minimum and maximum downstream water levels) is usually greater than the headwater range, so the downstream fishway channel is deeper.

Fishway channels also need natural light levels. Some species of fish do not pass-through darkened tunnels, which can happen in fishway channels that have covered sections.
Pool size and channel width

Pool size and channel width is determined by the depth and space needed for the largest fish; and the pool volume required to keep turbulence low enough for the smallest fish. If migratory biomass is high, a large pool size is also needed.

The largest fish also influences the gap within baffles that fish use (e.g., the width of slots in a vertical-slot baffle, gaps between rocks in rock-ramp fishways, or gaps between cones in cone fishways). Generally, the width of the gap should be at least 50% of the length of the largest fish, although 30% has been used for some species. These criteria are rarely limiting in design because maximizing discharge in the fishway (see 10% of streamflow in next section Fishway Entrance Design), results in large gaps in baffles to pass the discharge. Small gaps are to be avoided because they are susceptible to blocking by debris.

Slope or gradient

Fishway slope or gradient is determined by the head loss (water level drop between fishway pools) and the pool length. For example, a head loss of 0.1 m combined with a pool length of 4 m produces a gradient of 1:40. Combined with pool size and discharge, gradient governs maximum velocity and turbulence. In the case that the slope gradient is too steep, small fish cannot swim up due to high velocity and high turbulence. Steep gradient increases water velocity, and as a result, increases turbulence. A slope with low gradient and long length is optimal for small fish because it has low water velocity and lesser turbulence (Figure 9).

Figure 9: Steep slope prevents some small fish from ascending a fishway (above). Long and lower gradient enable more species to swim up a fishway (below).
1.4.3. Fishway entrance (attraction) design

**Biological and Hydraulic criteria**

**Upstream limit of migration**

It is essential to locate the fishway entrance near the *upstream limit of migration* so that fish can easily find it. The upstream limit of migration is a boundary between turbulence generated by flow from the weir, and the quiet area just downstream that fish can reach (Figure 10). Fish tend to approach strong flows and then accumulate at the upstream limit. At low and high flows, the upstream limit of migration can change – moving further downstream at higher flows.

In the LMB, there can be a significant difference in water levels between the rainy and dry season. So, it is important to benchmark the *upstream limit of migration* under a range of flows; rather than during one season or a “spot” measurement at a single point in time.

It is desirable to locate the fishway along a riverbank where fish migrate. Fish tend to ascend rivers along riverbanks because these areas have lower water velocity and lower turbulence than in the middle of the river. Small fish, especially, tend to use the lower velocities along riverbanks because they have low swimming abilities.

Fish sometimes migrate up rivers using the inside, which provides a shorter total distance and often lower water velocity. Logically, a fishway should be in the inside bend. However, as sediments, sands and stones are easily accumulated in the inside bend, they sometimes block the fishway. In this case, it is better to locate the fishway in another area and induce fish to move there by generating attraction flows.

**Avoid competing flows**

The flow from the fishway entrance needs to be easily detected by fish and not masked by competing flows or turbulence, which prevents fish from finding the entrance. A small “offset”
is typical in fishway design, where the entrance is offset toward the bank to ensure that that flow from the fishway is delivered in protected, non-turbulent, water (Figure 11).

**Figure 10**: Examples of the upstream limit of migration, shown as a dashed red line. (Photos: from Martin Mallen-Cooper)
Minimize recirculating flows

Recirculating flows can occur downstream of weirs and sluice gates. They are usually caused by a large static area on one bank immediately downstream of the weir (Figure 12), or caused by gate operation (Figure 14). In this situation migrating fish follow the direction of recirculating flows and then do not find the fishway entrance.

The large static area can be eliminated by using a wall or rocks in the space (Figure 13); this reduces recirculating flow and creates straight flow lines from the downstream side of the fishway entrance. With gated weirs or sluice gates, recirculating zones are caused by closing gates farther from the fishway entrance while closer gates remain fully open (Figure 14).
Figure 12: Recirculating flows caused by a large static area downstream of a fishway.

Figure 13: Wall or rocks placed to eliminate large space near the bank and prevent recirculating flows.
Figure 14: Recirculating flows caused by gate operation.

**Target 10% of streamflow for the fishway**

Fishway discharge or flow rate (e.g., m³/s) is a primary consideration in providing sufficient attraction for fish. At least 10% of river flow for a fishway is desirable (Mullen-Cooper et al., 2018). This flow can be a combination of a fishway flow (along the entire fishway) and auxiliary flow in the lower section of the fishway.

The larger the fishway discharge is, the more that upstream-migrating fish can be induced to the fishway entrance. A high fishway discharge also attracts downstream-migrating fish to the upstream exit, which helps prevents fish from entering an irrigation offtake or passing over a weir crest.

A larger fishway discharge, however, also enables more trash to enter the fishway. In this case, a trash screen needs to be attached to the fishway exit, which is good design practice in all fishways.

It is important to note that increasing fishway discharge increases turbulence, so the pool volume of the fishway must also be increased to ensure the maximum allowable turbulence is not exceeded (formulas of discharge and turbulence are shown in Annex 4). If fishway discharge is increased with the same pool volume, water velocities and turbulence increase which makes it more difficult for fish to ascend.

**Civil engineering criteria**

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<tr>
<th>Civil Engineering design criteria</th>
<th>Location of fishway entrance</th>
<th>Design of attraction flows: weir crest/gates/abutments/stilling basin</th>
<th>Gate operation</th>
<th>Auxiliary flow in fishway</th>
<th>Fishway channel size</th>
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</table>
Location of the fishway entrance

As discussed earlier, the location of the fishway entrance needs to be at the upstream limit of migration. Using this criterion there are two approaches to design: i) using existing flow conditions, and ii) changing the flow conditions with the design of weir crests, abutments, or gates.

To achieve a fishway entrance at the upstream limit of migration, it is normally located close to the base of the weir. The fishway channel, therefore, is either recessed into the weir, or has a “switchback” layout that goes downstream and then upstream (see Annex 4). On large weirs and sluice gates, sometimes a smaller barrier weir (or small crest) is used downstream of the main weir, which guides fish to a fishway entrance (Annex 4).

Attraction flow, weir crests, gates, abutments

Attraction flow is the flow pattern over the weir or sluice gate that guides fish to the fishway entrance. Fish have the tendency to move along a strong flow following the upstream limit of migration; this feature can be used in fishway design to create appropriate attraction flows.

If the flow from the weir crest is much greater than from the fishway, it induces fish to gather and stay in front of the downstream side of the weir (Figure 15a). Installing a gate near the fishway provides attraction flows to guide fish to the fishway entrance (Figure 15b). At high river flows, attraction flows next the fishway are used to restrict high flows and turbulence, thus providing the upstream limit of migration at the fishway entrance (Figure 10c, Figure 43).

Typically, attraction flow is delivered next to the fishway entrance using either: i) a permanent notch in a fixed-crest weir (Figure 11), or ii) a gate (Figure 10c). It is important that attraction flow be close to the fishway entrance but not disrupt and break up flow from the fishway. Flow from the fishway entrance needs to be a discrete separate flow that is easily detected by fish. To achieve this, often the fishway entrance is “offset” toward the bank and slightly away from the attraction flow to provide a small area of static water (Figure 11). If gates are used to provide attraction flow, this needs to be part of the Operation Plan.

Figure 15: Weir and fishway shown with a) no attraction flow, and b) with attraction and auxiliary flow.
A special case is a high discharge, highly turbulent site. The same Biological and Hydraulic design criteria apply, as explained in the previous section. However, more design is required of abutments, gates, and the downstream stilling basin to ensure a protected zone of low turbulence which: i) is at the upstream limit of migration, and ii) enables flow from the fishway entrance to be easily detectable by fish. In large projects physical modelling (1:10 to 1:25 scale) in hydraulics laboratories is the industry standard to determine these conditions (Figure 12).

**Integrating minimum downstream flows into design**

Fishways often have the function of delivering the minimum flow for the river downstream, because they are releasing flow when weir gates are closed, or the upstream level is below the weir crest. These aspects can be integrated into the fishway design and attraction flows. These flows may be for drinking water, irrigation or for the environment.

The minimum downstream flow sets the maximum discharge for the fishway and attraction flow. If the fishway design flow exceeds the minimum flow requirement, then the fishway exit gate is often used to reduce flow and the fishway then fails to pass any fish (see Fishway Operation 0 and Figure 44).

For designs that use a fixed permanent notch for attraction flow, the combined fishway and attraction flow needs to be less than (or equal to) the minimum downstream flow. If the attraction flow is gated - and hence can be adjusted or turned off – then only the fishway flow needs to be less than (or equal to) the minimum environmental flow. In summary:

\[
\text{Permanent notch attraction flow} \\
\text{“Fishway design flow + Attraction flow } \leq \text{ Minimum downstream flow”}
\]

\[
\text{Gated Attraction Flow} \\
\text{“Fishway design flow } \leq \text{ Minimum downstream flow”}
\]

**Auxiliary flow**

Auxiliary flow is additional flow that is introduced into the entrance pool of the fishway to increase discharge and attraction at the entrance (Figure 15, Figure 43). It is especially useful at high tailwater levels when the entrance velocity can be very low. If auxiliary flow is used the fishway entrance needs to be wider to pass the extra discharge.

**1.4.4. Downstream migration measures**

**Background**

As described earlier, fish migrate upstream and downstream. In the Mekong River and tributaries, a common migration pattern is for adult fish to migrate upstream and downstream; and for the eggs and larvae to drift downstream. Hence, downstream passage needs to accommodate both adult fish and larvae. In most cases a specific downstream fish passage (or “fishway”) is needed, such as a weir gate, plunge pool.
Peak upstream fish migration often starts at the beginning of the rainy season and extends through the season. Downstream migration can occur at any time but is more likely in the second half of the rainy season, although larvae can be expected any time of the year. In these conditions, most of the flow at irrigation structures will pass through the weir or sluice gates and not the fishway.

Adult and juvenile fish can be injured passing through undershot gates (Figure 16a) or over weirs with shallow downstream concrete areas. Larvae are particularly susceptible and may die if they pass through undershot sluice gates, due to water pressure and shear changes. Overshot gates (Figure 16b) provide a much safer passage.

Fishers often target aggregations of fish below a weir. This can also happen on the upstream side of a weir because adult fish cannot find a route downstream. Those fish have a high risk of malnutrition and death because they cannot reach productive downstream habitats which provide sufficient nutrition for their growth. It is therefore important that fish passage solutions be discussed with the local community and a community co-management plan be considered.

If fish can pass upstream to spawning habitat using a fishway, then these issues of downstream migration, especially of eggs and larvae, need to be considered.

Figure 16. Examples of a) undershot gate (or sluice gate), and b) overshot gates (forward tilting) with deep downstream plunge pool, installed at Pak Peung regulator (Lao PDR). (Source: M. Mallen-Cooper, L.J. Baumgartner)
Fixed-crest weirs

Fixed-crest weir have no gates and are usually made of concrete, rocks, or sheet pile. Rock weirs have a gradually sloping (e.g., 1:6) downstream face and provide effective downstream passage if the rocks are not large (e.g., 0.5m) and spaces between the rocks are filled in with smaller rocks.

Concrete or sheet pile weirs are either vertical or have a steep-sloping downstream face. Fish that pass over these weirs can be injured or die if they land in shallow water. Downstream passage is provided at these weirs by providing a deep tailwater or a deep plunge pool. Physical and computer modelling has shown that to provide safe fish passage the tailwater depth needs to be 40% of the maximum difference in headwater (upstream) and tailwater (downstream) (Figure 17) (Mallen-Cooper et al., 2018).

Larger concrete weirs or dams can have a sloping face with a smooth upturned end (“ski-jump”) which also provides safe passage of fish.

Gated weirs

Gated weirs can use undershot gates (often called sluice gates) or overshot gates. Undershot gates pass fish safely if they are fully lifted from the water, but this only occurs in high flows, while partly open undershot gates injure fish. Preferably all gates should be an overshot design, but some undershot gates can be retained to pass high flows. Overshot gates need to also have a plunge pool with the same 40% depth criterion.

1.4.5. Lateral (sideways) migration measures

Lateral migration can be into wetlands, floodplains, and irrigation systems. Generally, the same principles and designs of fish passage apply. In irrigation systems, however, there are likely to be a range of fish passage objectives. In some cases, the objective might be to encourage fish in
and out of the irrigation system, or parts of the system, while in other cases the objective might be to prevent fish entering an area that might dry, so fish screens would be used. Those objectives need to be considered in a holistic plan of fish-friendly irrigation.

1.4.6. Other considerations in design

Operation and maintenance

Operation and maintenance (O&M) need to be considered in all aspects of design. Fishways need to be simple to operate and maintain. Importantly, there needs to be discussions with the owners and operators of the structure to ensure that O&M is practical on-site. These discussions need to occur in the site visit and during concept and detailed design stages. The costs of operation and maintenance need to be agreed by the asset owner in the early stages of design.

Location of the fishway exit

The fishway exit is generally set in the upper reach of the weir to prevent fish from entering offtake channels or washing back over the weir or gate because fish tend to follow the current. Figure 18 depicts an exit that is not appropriate because fish may enter the offtake channel, or drift downstream over the weir. Therefore, the prevention measures are considered as follows:

1. Locate the fishway exit as far as possible from the weir body or offtake channel
2. Increase the velocity of surface currents approaching the fishway exit
3. Attach a screen in front of an offtake channel
4. Extend a fishway corridor and walls the upstream side

![Fishway exit too close to an offtake.](Image)

**Figure 18:** Fishway exit too close to an offtake.

Fish capture protection

Fishways can be susceptible to increased fish capture. This issue needs to be managed as part of a community-led plan. Part of the plan might include measures such as:
- Security cameras
- No entry zone around a fishway
- V-shape crown on the fishway side wall (Figure 20)
- Regular patrols of a fishway
- Net covering a fishway (Figure 19)

Figure 19: Fishway covering to prevent fish capture.

Figure 20: V-shaped crown to discourage access.

Note that covering a fishway to prevent fishing needs to ensure that there is sufficient light (e.g., Figure 19).

Resting pools

High barriers require long fishways with low gradients. These long fishways require resting pools for fish (Figure 21). Resting pools have very turbulence (e.g., 15 W/m³) and areas of very low water velocities (e.g., 0.1 m/s), providing areas for fish to rest. Hence, they are larger pools than other pools in the fishway.

Resting pools should be located along the fishway at every 2-3 m of height. They should also have structure or habitat, which enables small fish to hide from predators, and provides further areas of low turbulence (Mallen-Cooper et. al., 2018).

Figure 21: Resting pools in a fishway.


31
Debris management

Most sites have floating debris. This can block fishways which then blocks fish migration. Trash racks and floating debris booms are useful upstream of the fishway exit to prevent clogging of the fishway.

![Trash rack and debris boom at fishway exit](image)

Figure 22: Trash rack and debris boom at fishway exit.
(Source of photo: “Masterclass in Fish Passage Engineering Design, Construction, Ecology and Monitoring” (Martin Mallen-Cooper).

Design life

The detailed design documents need to include the intended design life of various components (e.g., concrete may be 75 years, while mechanical components might by 25 years). The material quality and components should be commensurate with the intended design life of the fishway. Generally, the design life of the fishway should match or exceed the expected life of the barrier.

Monitoring

Monitoring of fish needs to be considered in the concept and detailed design stages (Figure 23). Easy and safe access into the fishway is required to catch fish. Monitoring requires fish-traps which need to be lifted safely, so lifting gear may be required. Local information on the biomass likely to be caught and captured is useful in designing these facilities. Smalls streams may only catch 20 kg in 24 hours, but large streams can catch 500 kg of fish.
Figure 23: Example of a fish trap for a fishway, considered in the concept design phase.

1.4.7. From Design Criteria to Key Performance Indicators, and common mistakes

All the fishway design criteria described in this section are used to develop Key Performance Indicators (KPIs) that are used in Construction (esp. inspections and commissioning, defects liability period), Maintenance, Inspection, Monitoring and Adjustment; that is, the entire life of the fishway. For example, if the design specification of a pool head loss is 100 mm ± 10 mm, that specification becomes a specific KPI for that project that is used and independently measured at every fishway baffle in Wet Commissioning, and in every ongoing Inspection. It is used to assess the effectiveness of maintenance and to correlate with fish passage in monitoring.

The design criteria and KPIs are used to identify the common mistakes in fishway design which include:

Fishway channel (passage) design

Biology

- Underestimating migratory fish biomass
Fishway too small
  - Selecting a migration season that is too short
    - Fishway not operating in migration season because water levels for design not appropriate water levels.
  - Overestimating the smallest fish that is migrating
    - Selected water velocity and turbulence too high
  - Underestimating the largest fish
    - Fishway too small or too shallow

Hydraulics
  - Minimum upstream water levels selected for design is too high
    - Fishway too shallow or dry (Figure 24).
  - Maximum upstream water levels selected for design is too high
    - Fishway has too much flow and is too turbulent
  - Minimum downstream water levels selected for design is too high
    - Fishway not long enough and is higher than tailwater level, with high turbulence and water at entrance with compromised fish passage.
  - Maximum downstream water level is too low
    - Fishway entrance underwater at high flows; little entrance attraction; little fish passage.
  - Maximum water velocity too high (very common mistake)
    - Fish cannot ascend fishway
  - Maximum turbulence too high (very common mistake) (Figure 25)
    - Fish cannot ascend fishway

**Figure 24:** Fishway exit is higher than upstream water level river and connection canal.

Fishway entrance (attraction) design
  - Entrance not located at the upstream limit of migration (very common mistake)
    - Fish cannot find fishway (Figure 26)
- Entrance masked by turbulent flow due to design of abutments, banks, or gates (very common mistake)
  - Fish cannot find fishway
- Recirculating flows due to design of abutments, banks, or gates
  - Fish cannot find fishway
- Low discharge in fishway compared to the river
  - Very little attraction and fish cannot find fishway

Figure 25: High turbulence in a fishway.

Figure 26: Fishway entrance located too far downstream, so that migrating fish miss the fishway.
Downstream fish passage

- Undershott sluice gates used
  - Injuries and mortalities of fish, especially at low flows and small gate openings and low flow. Note that injuries to larvae drifting downstream could be extensive but not observed.

- No plunge pool on downstream side.
  - Injuries and mortalities of fish, especially at low flows and small gate openings. When fish fall directly onto shallow water on concrete it can be very harmful.

Other issues

- Inadequate protection of adjoining banks
  - If there are spaces between a fishway and a riverbank, water enter the spaces during the rainy season and erodes the bank (Error! Reference source not found.). Therefore, some parts of a bank should be lined by concrete or masonry to prevent soil erosion (Error! Reference source not found.).

- Inadequate protection of adjoining structures
  - The detailed design must consider the protection of adjoining structures. A constructor should confirm the design and methodology onsite with the Design Team. The constructor should then carefully excavate a river or a stream near any foundations to avoid any damages to the structures.
  - Figure 29 shows a bridge that collapsed during fishway construction because a constructor dug too close to the bridge pilings. The bridge pilling then became vulnerable to water flow in a river.

- Post-design issues
  - In addition to mistakes in design, there are also mistakes made by inadequate operation, and lack of maintenance, inspections, and monitoring. These are discussed elsewhere in this guideline.

Figure 27: Bank erosion near a fishway. Note also that the entrance is too far downstream of the upstream limit of migration near the weir.
1.5. Fishway type and selection

1.5.1. Fishway type

Fishways for low-level barriers can be classified into four groups: pool-type, hybrid rock/concrete, Denils and rock-ramps (nature-like). High barriers usually require mechanical fishways such as fish lifts and fish locks, which are not addressed in this guideline. It should be noted, however, that fish locks have been used at low barriers, with the knowledge that there would be high Operation and Maintenance costs compared to the following fishway types.
The groups of fishway types are shown in Figure 30 and a brief description of the main fishway types follows, with more detail provided in Annex 4.

**Pool-type fishways**

Pool-type fishways are channels that are divided into pools by baffles. Water can flow over the top of the baffles in a series of weirs that can be horizontal (Figure 31a), V-shaped or sloping asymmetric (Figure 31b) designs; or water can flow through a submerged orifice. Cone fishways (Figure 31e) are a pool-and-weir fishway with vertical cones on the weir; the cones reduce discharge and operate over a wider headwater range compared with horizontal weirs.

Numerous designs combine both weirs and orifices, such as the Ice Harbor design (Figure 31d): it has two overflow sections, two submerged orifices and a non-overflow central baffle. Another
well-known, pool-type fishway is the vertical-slot, which has full-depth slots between pools; these enable function at widely varying headwater and tailwater levels, while maintaining constant water velocities and turbulence.

The trapezoidal weir (Figure 31f) design partly fits in the pool-type category but has a central high flow section that provides passage of large fish and attraction flow, while providing low water velocities and turbulence on the sides for small fish.

**Rock-concrete hybrid**

These are rocky channels divided into pools by precast concrete units that link together (Figure 31g). They provide fish passage between the units and have a trapezoid cross-section that provides a central section that passes high flows. They are sometimes called “Dragon’s teeth” fishways.

**Denil fishways**

Denil fishways (Figure 31h) use a series of symmetrical, closely spaced, ‘U’ or ‘W’ shaped baffles, in a narrow steep channel. They create a low velocity zone (using a countercurrent) at the base of the baffle which fish use to ascend. The main advantage of Denil fishways is that they can be built on steeper slopes compared with pool-type fishways. However, they are turbulent designs, requiring resting pools every 6 to 10 m of length, and are not used at high barriers. The complex baffles tend to collect debris, which can then block water flow and restrict fish migration.

**Rock-ramp (“nature-like”) fishways**

Rock ramp or “nature-like” fishways are rocky channels on low gradients (e.g., 1:30 – 1:50) that simulate a rocky stream bed. They are carefully engineered, with the gradient measured, and rocks interlocked from the downstream section working upwards. Large (e.g., 0.5 to 1.0 m diameter), high-quality rock is used, and entire ramp is often lined with geotextile or secured with sheet pile at the downstream end to prevent undermining, erosion, and loss of the structure. The design can be random rocks or ridges in a horizontal or V profile that create small weirs and pools.

**Full-width rock-ramp** fishways (Figure 31i) cover the entire river or stream width, so that all river flow passes down the rock-ramp, which provides an ideal entrance that fish find easily. **Partial-width rock-ramp** fishways (Figure 31j) occupy part of the river or stream channel, often passing around an obstruction in a similar layout to a pool-type fishway.

**Bypass channels** (Figure 31k, l) are channels around an obstruction that simulate a natural stream. They are characterized by very low gradients (e.g., 1:100 to 1:200). They mostly use rocks, but the low gradient means that they are less engineered that the steeper rock-ramps.
Figure 31: Examples of fishway types: a) overfall weir (pool-and-weir), asymmetric weirs (Source: MAFF, Japan), c) vertical-slot (Source: M. Mallen-Cooper), d) Ice Harbour (Source: MAFF, Japan), e) cone (Source: Jarrod McPherson), f) trapezoidal weirs (Source: M. Mallen-Cooper), g) rock-concrete hybrid (Source: Matt Gordos), h) Denil, i) full-width rock ramp (Source: M. Mallen-Cooper), j) partial-width rock-ramp (Source: M. Mallen-Cooper), k) high discharge bypass channel (Source: M. Mallen-Cooper, l) low discharge bypass channel (Source: Wayne Stancill).
1.5.2. Fishway selection

Fishways vary in their ability to: operate at different water levels; pass different sizes and species of fish; and function in small or large rivers. These relate to the key design principle of integrating biology, hydrology and hydraulics (Section 1.2); and to the Key Design Criteria in Section 1.4.

Table 1 lists the major fishway types for low-level weirs and their key characteristics, which all align with data that is collected in Phase 1 of Fishway Design (page 2). Each of the fishways have been scored against each characteristic but these are a guide only and represent common applications of each design. They are not definitive and represent the ease with which each fishway design can meet the criteria. Each of the fishways can be built on different gradients and sizes, which influences their performance. Most fishways, for example, can pass small fish if conservative design criteria (i.e., water velocity, turbulence, gradient) are used - although Denil fishways are not good at passing small fish, even at low gradients.
Table 1. A comparison of fishway types and characteristics. The scoring is qualitative and is based on the functional characteristics of each design, and the ease with which each fishway design can meet the criteria.
<table>
<thead>
<tr>
<th>Headwater variation</th>
<th>Vertica l slot</th>
<th>Cone</th>
<th>Submer ged orifice</th>
<th>Overflo w weir</th>
<th>Asymmet ric weirs</th>
<th>Trapezoi d</th>
<th>Rock-concret e hybrid</th>
<th>Den il</th>
<th>Rock-ramps (Nature-like)</th>
<th>Full widt h</th>
<th>Parti al widt h</th>
<th>Bypa ss chan nel</th>
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Stream discharge
The variation in upstream (headwater) water levels during the fish migration season is a key defining characteristic of different fishways (Figure 2) and helps select a design. More variable headwater levels are more difficult to accommodate in fishway design. Variation in downstream (tailwater) water levels is included in Table 1 although this aspect relates equally to fishway entrance design.

Ease of passing different sizes of fish is included in Table 1, as well as fish behavior. Stream discharge is an important characteristic, because fishways vary in their ability to provide a high discharge and attraction for fish. Fishways vary in their construction footprint which can influence the design decision. Finally, public safety is important; mostly this concerns the risk of people in the fishway and being able to get out easily.

The fishways have widely varying characteristics which reflect their design. The vertical slot fishway has a slot in the baffle that is the full depth of the fishway channel so theoretically it can be any depth and accommodate any range of headwater and tailwater, while keeping the same hydraulics of turbulence and water velocity. Indeed, the first vertical slot fishway at Hell’s Gate on the Fraser River in Canada has baffles that are 13m deep to accommodate widely varying river levels (Clay, 1995). The width of the slot can also be adjusted to accommodate small or large fish; at the Xayaburi Dam Fishway in Laos PDR the slots are up to 1.5 m wide which are intended to pass large Mekong fish species up to 3m long. More typical slot widths of 0.3m pass fish up to 1.0 m long (Stuart et al., 2008), while low-gradient (e.g., 1:30), low-turbulence (e.g., 25 Watts/m³) examples of vertical-slot fishways pass fish as small as 20 mm long (Bice & Mallen-Cooper, 2017).

<table>
<thead>
<tr>
<th></th>
<th>Low (mean 1 -25 m³/s)</th>
<th>High (mean &gt; 25 m³/s)</th>
<th>Construction</th>
<th>Small footprint (available area)</th>
<th>Public safety</th>
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**KEY**

- ✔️✔️✔️ Excellent
- ✔️✔️ Very good
- ✔️ Good
- - Not good

The table above includes various attributes of fishways, such as stream discharge, construction footprint, small footprint availability, and public safety. Each attribute is rated on a scale of excellence to not good, with specific details provided in the text.

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Cone fishways are a variation of pool-type fishways with flow over the top of the baffle through cones, rather than through a single deep slot. This feature limits the headwater range compared to a vertical slot but can be an advantage at sites with very low discharge or periods of zero flow. Cone fishways are presently designed with low gradients, low discharge, and very low turbulence, passing fish between 10-300mm (Stuart & Marsden, 2019). They can also be built with wide channels, such as the example at Pak Peung in Laos PDR (Baumgartner et al., 2020) and potentially pass high discharge through the middle of the channel, like a trapezoid fishway.

The tailwater range of cone fishways is partially limited to the height of the cones, although this is much less important than headwater range, as fishways still partly function as they are submerged by rising tailwater. Most of the other fishways, except the vertical-slot and full-width rock-ramps, have similar limitations with high tailwater. Cone fishways pass surface fish well but may be more limited in passing bottom-dwelling (benthic) fish as these fish need to swim to the surface to pass between the cones.

Submerged orifice fishways have an orifice in the bottom of the baffle so they have a wide headwater range because the orifice is below the water. These fishways generally do not pass large fish (> 100cm) well although this is mainly because the orifice is not large enough. If enlarging the orifice is considered in design, it should be noted that this also increase discharges and turbulence, so larger pools are required. Submerged orifice fishways do not pass surface fish well as there is no surface flow in the fishways. Combination designs such as the Ice Harbor Design overcome this aspect with overflow weir and submerged orifices, but the headwater range becomes limited by the overflow weirs. Submerged orifice fishways also do not pass very small fish well, although most examples of this design have high turbulence.

Overflow weirs are a simple design but have the headwater range. If the headwater is too high there is too much flow in the fishway with too much turbulence, and if the headwater is too low there is no flow in the fishway. These designs are therefore impractical except where the headwater is very stable. Large examples of overflow weir fishways have been used to pass salmon. These fishways do not pass small fish well - unless they are specifically designed with very small head losses - and do not pass bottom-dwelling fish well. They are also sensitive to tailwater fluctuations with rising tailwater because the downstream baffle is submerged which produces a diffuse attraction flow. Asymmetric weir fishways are like overflow weirs but have a slightly wider headwater range and tailwater range.

Trapezoid weir fishways have a wider headwater range than Overflow or Asymmetric weirs, like a Cone fishway. They pass bottom-dwelling fish as well as surface fish because there are also slots in the sides of the baffle. Trapezoid weir fishways are not known to pass large fish (> 100cm). An advantage of this design is that it can pass high attraction discharge through the central section of the fishway, although this could reduce passage of very small fish (< 5cm).

The rock-concrete hybrid uses pre-cast units in a rock-lined channel. It has a very wide channel (5-15m) that passes a high discharge which is good for attraction of fish, but it also creates a large footprint for construction. The channel has a “V” cross-section so that the headwater range is effective up to 1m. Surface and bottom dwelling fish can use this type of fishway, but depth is usually 0.75 to 1.5m which would restrict passage of large fish (>1.0m).
Denil fishways have sensitive hydraulics that are dependent on a specific depth, so they require a stable headwater and have a very limited headwater range. They do not pass very small fish (< 5cm), large fish (100-300cm), or surface-dwelling fish. They are a very compact fishway with a small footprint.

Rock-ramp fishways that are the full width of the stream act like a natural rocky riffle, if they are on a low gradient. Hence, they operate over a wide range of flows and pass a wide size range of fish. Some rock-ramps may be shallow, which can restrict passage of large fish (> 100cm).

Partial-width rock-ramps and bypass channels are a channel around a barrier. Compared with full-width rock-ramps, the major functional differences are that they operate over a narrow range of headwater and tailwater. Present examples tend to be shallow, so they do not pass fish > 50 cm well.

The characteristics in Table 1 refer to function. Fishway selection is a balance of cost and function. Cost-sensitive factors often relate to design life of the fishway (longer life with more durable materials is more costly), and the balance of Capital Cost and Operation and Maintenance (O&M) Cost (lower initial capital cost will usually result in greater O&M cost). The extent in investment in fish passage at the site then relates to the value of the site for food, fisheries, and biodiversity. The balance of these factors will be unique for each site and needs to be developed with all stakeholders.

1.6. Culverts

Culverts are tunnels that pass water under roads or rail crossings. They use pipes or pre-cast concrete sections that are square or rectangular and can also be an arch or elliptic in cross-section.

Culverts can be overlooked as barriers to fish passage because there is often little difference in water levels upstream and downstream. However, they form a major barrier to fish migration by creating high water velocities. This happens because culverts form a constriction or choke point in the stream, so the water velocity speeds up to compensate (See formula \( Q = VA \) in Annex 4). The water velocities are then greater than the swimming ability of fish.

Design criteria for fish passage in culverts are different to fishways. Maximum water velocities in fishways cannot be used for fish passage in culvert design. In a fishway these high velocities occur over a short distance, through a baffle or step, and every fishway pool is a small resting area. In a culvert there is long distance of uniform velocity without resting areas.

There are no swimming ability data for Mekong fish in culverts, but a general rule is that 0.3 m/s will provide passage for all fish in straight channels, like culverts, with a maximum of 0.5 m/s (MRC, 2019). As an example of using 0.3 m/s as a criterion, a stream discharge (flow) of 10.0 m³/s would require a culvert with 3 m² cross-sectional waterway area (e.g., 6 m wide by 0.5 m deep).
New road or rail crossing

If a new road or rail crossing is proposed on a stream, then the options for fish passage in order of preference are:

1) A bridge, which allows the stream to continue without constriction, hence providing excellent fish passage. Note that bridges can be pre-cast concrete and easily transported to site.
2) A wide culvert that is 1¼ times the stream width, either without a floor (arch design) or a floor that is lower than the stream bed. Like a bridge in that the stream flows unimpeded at low to medium flows and the riverbed is continuous.
3) Large culverts with baffles.
4) Large culverts without baffles (use 0.3 m/s mean velocity for fish passage).
5) Small culverts. These should only be used where fish passage is not a priority, as they provide very little fish passage.

Remediation of existing culverts

The main problems that arise for fish passage in existing culverts are:

(1) high water velocities and lack of resting areas, as described earlier,
(2) the downstream water level is much lower than the culvert,
(3) shallow water depth in the culvert.

Structural problems can also occur with bank erosion around the culvert exit and entrance.

If the site is a high priority for fish passage, then a new bridge or new wide, deep culvert is the preferred option for remediation. If a new structure is not feasible and the culverts are retained - then baffles, weirs, blocks or plates can be tried in the culvert to create low water velocities and rest areas for fish migration. As each culvert site and hydrology is unique, monitoring of fish is advisable to ensure culvert modifications pass fish.

Figure 32: Road crossing showing downstream level lower than culvert that is impassable for fish.

If the downstream water level is much lower than the culvert there are two options: i) raise the water level downstream with a small rock-ramp fishway and install baffles or rocks in the culvert, or ii) build a fishway around the culvert.

More information is provided in Annex 7.
STEP 2: FISHWAY CONSTRUCTION

To ensure that fishway construction does not negatively impact the environment, hydrology, water quality or agricultural production, it should be properly managed and inspected throughout the construction process.

2.1. Local involvement

Before starting construction, the contractor and local government staff need to meet with fishers and residents near the construction site, to fully explain the project and construction plan. The meeting will explain the objectives, methods, and duration of the construction, and ask them if there are any potential issues related to a construction. The meeting is an opportunity to determine how much involvement the local community expect in the project and to capture any significant local issues that need to be addressed prior to commencement.

Identifying the ultimate outcomes that the local community would like to see is crucial at this stage, as it will influence parameters for design and construction. Using local contractors, where possible and appropriate, is also essential to help the local community understand the design and its long-term operation. This can build a sense of community ownership and pride as they are actively involved in developing and implementing the solutions (Baumgartner et al., 2020).

2.2. Construction Plan

A Construction Plan, normally developed by the contractor, clarifies the work description, construction schedule, construction management/materials/method, safety procedures and environment protection measures, etc. The plan must consider weather, geological, environmental, and biological conditions, and must demonstrate that all factors can be addressed under existing budget conditions.

The contractor should draft the Construction Plan by taking the following factors into consideration:

(1) Construction should be restricted to months with the least fish movement and low flows, to minimize impacts on fish and water quality. This timing is site-specific, as periods of decreased fish movement vary depending on location, altitude, hydrology, and weather.  
(2) The riverbed and banks should be returned to their original profile and stability, so that long-term fish movement and habitat is not compromised.  
(3) Cofferdams should be designed to tolerate an unexpected flood and underground water from seepage or springs.  
(4) Sediment retention procedures should be used to minimize sediment flow from construction into nearby waters.
2.3. Construction management

The aim of construction management is to complete construction within the work period, maintain Quality Assurance and Quality Control of construction, and meet safety and environmental pollution goals (Figure 33).

Site inspection at commencement

The Design Team and constructor should inspect structures around a fishway site before construction to avoid any damages to them. They also need to obtain engineering drawings of structures where a fishway will be installed and structures near a construction site, such as a bridge. Especially, they should understand the characteristics of the structure foundation. These aspects are an essential part of detailed design but should be reviewed immediately before construction.

Schedule management

Schedule management ensures that construction is completed within the work period. This is particularly important when work is intended to start and finish within the dry season, when it is easier to build in rivers and streams.

Finished work management

Finished work management confirms whether each finished part of the structure satisfies the precision, e.g., dimensions, quality and quantity specified in design documents. Two measurement methods are used:
- Direct measurement uses visual assessment and site measurements (Figure 30).
- Indirect measurement uses photos to assess the same factors.

Figure 33: Construction management showing the sub-components.
Quality management

Quality Assurance (QA) and Quality Control (QC) ensures that the construction meets physical and chemical requirements. This depends on regular inspections (see next Section 2.5) and on detailed specification in the engineering (CAD) drawings detailed design report.

Figure 34: Direct measurement of a block slope length
(Source of Photo: MAFF/Japan)

Figure 35: Quality measurement of soil compaction.
(Source of Photo: MAFF/Japan).

Safety and environmental management

Safety and environmental management seek to avoid any accidents and pollution during construction. To ensure safe management, the contractor should:

- Follow all laws related to construction, safety procedures and environmental protection,
- Check safety measures on site every day so that laborers can work without injury,
- Install safety signs and guard fences in areas next to roads,
- Prohibit third parties from entering the construction site without approval (Figure 36),
Train operators and laborers to safely operate machinery and conduct any construction work (Figure 37),
Curb any pollution generated from the construction site e.g., vibration, noise, dust, and sediments.

2.4. Points to note when constructing a fishway

The contractor should minimize changes in river or stream condition during construction by considering the following points (Annex 8 also shows summary of potential impacts of fishway construction and solutions.)

Timing of construction

Restrict construction to months with low flows and the least fish movement, to minimize impacts on fish, as well as water quality. The months of least fish movement vary depending on location, altitude and hydrology and should be investigated for each site.

Temporary work

Temporary work is in support of the main fishway construction and is important to secure the quality of construction, river flow, and to reduce environmental impact of construction. The main temporary work is coffer-damming which is used to drain excessive water from a construction site and create dry conditions. It also maintains flow from upstream to downstream around the construction site. Other temporary works can be needed to curb soil run-off and water contamination. Main temporary works (dewatering, soil erosion and contamination prevention) are shown in Annex 6.

Wash equipment

To avoid water contamination, the contractor should wash all construction equipment daily after use.

Restore waterway bed and banks

Riverbeds and banks should be restored to their original profile and stability after construction so that long-term fish movement at the site is not compromised.
2.5. Regular Inspection and oversight

2.5.1. Roles and responsibilities in inspections

Inspection of contractors and construction operations is essential to ensure that work is done correctly based on contract and design documents. Engineering expertise and fishway design expertise – preferably from the original design team - are needed to provide inspections, coordinating with the Provincial Agriculture and Fisheries Office and the District Agriculture and Fisheries Office.

These staff are not paid by the contractor and are independent (typically paid by government or the funding agency). Their roles are to:

- Examine structural work including elevations by measuring and photographing
- Ensure compliance with contract and design documents
- Verify contractor work log
- Address problems on site and examine field changes

The responsibilities in inspections are:

- Provide Quality Control of all aspects of the construction
- Understand the project site, design documents, contract, materials, and construction methods
- Complete construction without construction failures
- Record what was learned and share with others
- Develop good working relationships with the Design Team and the contractor, while maintain independence.

2.5.2. Points of inspection

At the beginning of construction, the staff doing the inspection and the contractor agree to quality control points, and a timetable of inspections and meetings. Both use the same set of full design documents and specifications which provides details of materials, methods, and quality control of construction. Key Performance Indicators (KPIs) and standards are agreed.

During inspections the dimensions should be measured, and the quality of materials and components checked at repeated intervals (e.g., weekly) (Figure 38). The objective is to ensure that they meet the specifications in the design documents and contract. Inspections should be timed to examine completed work and confirm progress of construction at the following main stages:

- Start existing facility demolition or excavation at the site
- Completion of temporary work
- Establishment of fishway foundation
- Completion of any formwork before pouring concrete
- Any design changes
Completion of main components, such as pools, slopes, entrance, and exit
Completion of fishway construction

Figure 38: Inspection of steel works and channel base.
(Source of Photo: MAFF/Japan).

An inspection for the full Design Team is necessary during construction and at commissioning to ensure that any design errors can be addressed prior to the de-mobilization of construction crews.
Inspections should carefully examine the following points (Poacher et.al., 2002):

- The level of the floors and the sills (and of all sections which control discharge, velocities and head drops in the facility) should be verified at each stage, especially in the downstream section where there might be a tendency to build the installation too high due to limitation of demolition work.
- A pool of sufficient size remains at the foot of the installation. Contractors fill pools out of concern for the structure being undermined.
- The structure should have no sharp edges to prevent injury to migrators. Particular attention should be paid to the interconnection with the existing facility, to corners, deflectors, and traverses, and equally importantly to the edge of any metal sections of baffles. Rubber flaps can be used to prevent migrators entering passages that have no exit, or zones where they may injure themselves.

Fishway design should adhere to the design specifications, with specific tolerances. Sample tolerances are provided in Annex 7.

At the end of construction, inspections should carefully examine the whole of the structure, which then enables full dry and wet commissioning (see Commissioning Plan on page 10 & following Section 2.6). This final inspection should be conducted before the flood season.

Notes on Quality Control:

**Soil:** Quality and type of soil at the construction site should be matched with the specifications.
**Construction:** Construction should be done in a dry condition in principle. Backfill and banking should not include organic matter such as grass stumps and roots. Any slopes should be compacted.

**Steel rebar:** Steel rebar should meet material specifications for strength and be placed as indicated in design documents with no deviations from indicated sizes. Steel rebar should be fixed well not to slip off. Construction laborers should not go on top of steel rebars to avoid damages to the rebar and personal injury. They should assemble scaffolding boards to conduct steel rebar work.

**Concrete:** Concrete should meet the quality indicated in the material specifications. Concrete joints should be set in weak points of the shearing force. Ensure that concrete curing is effective. (Concrete could shrink and produce crazing when the surface dries too quickly). Concrete shall reach a minimum compression strength of 34.5 MPa after 27 days. No more than 20 minutes between pours where concrete forms a bond with previously poured concrete (Stancil, 2018).

### 2.6. Commissioning

Commissioning occurs at the completion of construction and follows the Commissioning Plan (see page 10) developed as part of Detailed Design. Importantly, it is done by staff that are independent from the builder (often government agencies), but also needs to be done while the builder is on-site in case modifications are required. It is important to note that minor structural adjustments are likely to be required to fishways in almost every case; this is not a failure of the design or construction.

It is useful in commissioning to consider the Common Mistakes in Fishway Design listed in Section 1.4.7. These should, however, have already all been considered during the Design Phases.

Final payment to the fishway builder should only be done after any identified faults are rectified and commissioning has been successful.

Once all defects are rectified and the fishway is complete, a “handover” of the fishway to the owner/operator can occur. In the handover the full operation of the fishway and weir is explained (see 0 for further explanation).

### 2.7. Defects Liability Period

A defects liability period is written into the tender documents and construction contract. It is the period after construction is complete, when the builder (also called contractor or constructor) is fully responsible to correct any identified defects that occur in the fishway. The defects liability period is typically 52 weeks, and it helps prevents low quality construction work, as it is expensive for the builder to return to the site.
Defects also need to be corrected within a specific period, which needs to be included in the tender documents and contract. That period is also typically 52 weeks. If a defect occurs and is fixed, the *defects liability period* is reset to 52 weeks and starts again, to cover the new work.

Independent inspections need to occur within the *defects liability period* to identify defects. These should preferably occur at different flows, so the fishway is observed operating in different conditions. After the *defect’s liability period*, any further modifications required to the fishway are the responsibility of the weir/sluice gate owner. Within the project budget it is prudent to also provide funds to pay for any adjustments required after the *defect’s liability period*, particularly where there are higher risk design elements or assumptions.
STEP 3: FISHWAY OPERATION

The fishway should provide passage for fish upstream and downstream throughout the year, and especially during the migration season. However, inappropriate operation of the weir and gates can block fish migration despite an excellent fishway installation. A full Operations Plan will be provided to operators, and they will be engaged in a handover at the end of commissioning. Operators will then be responsible for the fishway, and gate operation on the weir to ensure *fish attraction* to the fishway entrance and downstream fish passage.

Operation will have been considered in concept and detailed design, in consultation with owner and operator of the structure. Most of the key features used in *Fishway Entrance (attraction) Design*, as explained in Section 1.4.3, are used in operation:

### 3.1. Upstream migration

**Setting the fishway entrance at the upstream limit of migration**

The upstream limit of migration would have been defined/estimated during the design phase, but it also depends on operation of the weir/sluice gates, and this operation changes at different flows in the dry and rainy seasons.

**Low flows**

During low river flows from a weir, operators should open only a gate adjacent to the fishway entrance. The gate discharge will attract fish, which assists them to find the fishway entrance (Figure 39). When only a gate farther from the entrance remains open, fish are attracted to a zone far from the fishway (Figure 40).

![Figure 39: At low river flows an open gate next to the fishway to attract fish.](image)

![Figure 40: If a gate is opened away from the fishway, fish will be attracted away from the entrance.](image)
**Medium flows**

In medium river flows, the fishway entrance is set at the *upstream limit of migration* by releasing small amounts of water from a gate adjacent to the fishway, while greater amounts of water are released from other gates (Figure 41). This tapers the *upstream limit of migration* to the fishway entrance. Gate operations that guide fish away from the fishway are to be avoided. For example, using a gate far from the entrance to release little water while other gates release large amounts of water - as a result, fish move to the *upstream limit of migration* that is on the opposite bank to the fishway (Figure 42).

![Figure 41: Flow pattern created with the upstream limit of migration guiding fish to the fishway entrance.](image1)

![Figure 42: Gate operation to be avoided, with little attraction of fish to fishway.](image2)

**High flows**

During high river flows it is important to have the same taper of the *limit of migration* as described for medium flows, but further adjustment is also likely to ensure the fishway entrance is protected from turbulence and the fishway flow is not masked.
**Avoid competing flows**

As explained earlier, flow from the fishway entrance needs to be distinct and easily detectable by fish. High discharge released adjacent to a fishway entrance is the main cause of confusing flows, that disrupt flow from the fishway.

**Avoid recirculating flows**

Recirculating flows can be caused by the shape of banks and abutments, which should be addressed in concept and detailed design (see Section 1.4.3), but it is also caused by operation of gates on one side (Figure 14). It is important to release water evenly from gates to ensure that a static water zone is not created next to larger water flows (O’Connor et.al., 2015). Figure 14 shows an example of a center gate of a weir closed which creates a static zone where the upstream limit is at the center gate; fish then accumulate in the middle of the weir.

**Use exit gate fully open**

The hydraulic design of a fishway is calculated on the exit gate being fully open. If the exit gate is partially open, it creates a high velocity under the gate that fish cannot pass through; hence, they accumulate in the exit pool of the fishway, but cannot complete their migration.
3.2. Downstream migration and gate operation

Downstream migration can occur via fishways but if there is more flow passing through weir gates - as in the rainy season - fish are more likely to pass through the gates. Hence, gate operation is important for downstream fish passage. Gate design and downstream passage is considered in concept and detailed design, with the preferred option being overshot gates and plunge pools. If these are included in the structure they should be used before any other gates, making sure that attraction flows for upstream passage are also effective.

If a fishway has been built on an existing weir with undershot gates then these should be used fully open, when possible, as partially open undershot gates can injure fish. If this is not practical, due to the loss of water, a small overshot gate should be considered, which can be included in existing under shot gates.

Downstream-migrating fish can accumulate in the static water on the upstream side of a weir. They may be reluctant to pass through an undershot gate, or there may be very little flow. There may be small fish in this static water, as well as large fish preying on them. Therefore, it is desirable to sometimes open gates for short periods to release these small fish and predators downstream.
Gate operation should also try to guide downstream-migrating fish away from irrigation offtakes.

Figure 45: Opening one or more gates enables fish to migrate downstream.
STEP 4: FISHWAY MAINTENANCE AND INSPECTION

Maintenance is needed on all fishways, and the frequency and extent vary between sites and fishway designs. Inspections occur at specific intervals which identify issues for maintenance, refurbishment and optimizing operation. Monitoring evaluates the biological performance the fishway, through direct sampling of the fishway, sampling of fish populations and abundance upstream and downstream, and socioeconomic sampling.

4.1. Fishway functions

A fishway has three functions: providing fish passage, environmental flow, and being structurally stable. The fishway function relies on clear Key Performance Indicators (KPIs) that can be easily measured. These KPIs are developed in the Maintenance Plan and include many of the key design criteria (e.g., pool head loss). They underpin the Maintenance Plan and Maintenance Cycle and ensures the fishway fulfills its function. Figure 46 shows the relationship between KPIs, problems in the fishway and fishway function.

![Figure 46: Relationship of Key Performance Indicators (KPIs), fishway problems and function deterioration.](image)

4.2. Maintenance Cycle and Plan

The fishways described in this guideline are effectively channels of water that require regular maintenance. They commonly get blocked by plants, woody debris, sand, gravels, and other
sediment (Figure 47). These blockages change the hydraulics of the fishway – often causing high head losses and water velocities – and creating behavioral and physical barriers to migrating fish. Sediment can also accumulate in front of the fishway exit or entrance (Figure 48).

![Figure 47: Cleaning debris from a fishway.](image)

![Figure 48: Sedimentation in fishway and at entrance (red circle).](image)

![Fishway entrance](image)

![Figure 49: Sedimentation of gravels and stones near fishway entrance (red circle).](image)

Developing a fishway design with minimal maintenance is an important aspect of design. During the Design Phase there is ongoing engagement with the owner and operator of the weir to ensure their inputs and advice are considered regarding maintenance. In the Detailed Design phase (Phase 6, page 10) a Maintenance Plan is developed, which details the required maintenance and frequency. Nevertheless, it is difficult to predict the extent of maintenance
needed. Local engagement and ownership of the fishway project, combined with training, is then important to identify unforeseen issues and solutions to refine the Maintenance Plan.

The Maintenance Plan is the initial step of a Fishway Maintenance Cycle (Figure 50). The plan describes the inspection points, performance criteria and procedures for rehabilitation. *Regular maintenance* occurs on a short time frame, which could be every week if debris (logs and plant material) or sediment loads are high. This maintenance can be conducted by the weir operator or government staff; or local people and fishers if no other staff are present. The local commitment for maintenance can be done under the framework of the Participatory Irrigation Management (PIM).

![Fishway Maintenance Cycle](image)

**Figure 50:** Fishway Maintenance Cycle showing the links between Inspection, Monitoring and Step 6 Adjustment.

*Inspections* are less frequent, more detailed, and use staff that understand all aspects of the fishway design. Recommendations from the inspection can inform maintenance or may suggest more substantial *adjustment* (Figure 50).

Once maintenance and inspections have started the Maintenance Plan should be reviewed and adjusted as needed after each cycle. In the lower Mekong Basin, inspections are required every month for the first 12 months, which aligns with the *defects liability period* (see Section 2.7) - followed by inspections every three months: in the middle of the dry season, before the rainy season, mid rainy-season and end of the rainy-season. Operators and maintenance staff should also inspect the fishway immediately after any floods.
4.3. Regular inspection and maintenance

The key aspects to investigate in regular inspections are:

i) blockages due to debris and sediment near entrance (same as regular maintenance),
ii) upstream and downstream water levels
iii) internal fishway hydraulics (water levels, head losses),
iv) operation of fishway exit gate (to ensure it is fully open or fully closed)
v) weir operation for attraction flows,
vi) operation of gates for downstream fish passage, and
vii) structural integrity and defects of fishway and surrounding area

During the inspection it is useful to consider the Common Mistakes in Fishway Design listed in Section 1.4.7. These mistakes are mostly included in the five categories above. Detailed inspections are particularly important in the first year of operation to detect: i) issues that are not compliant with the design - and which can be fixed by the contractor within the defects liability period; and ii) issues overlooked in the Design Phases. Inspections should be conducted during low, moderate, and high flows.

Inspections are in addition to Monitoring, which assesses biological function and socio-economic benefits. Monitoring can frequently detect issues not picked up in inspections and can lead to Adjustment (Step 6) of the fishway.

The following sections briefly describe the key aspects and issues, while some further solutions are described in Step 6 Adjustment.

4.3.1. Upstream and downstream water levels

Two fundamental design criteria used in fishway design are: i) the upstream water level, which sets the minimum depth for the entire fishway channel; and ii) the difference in upstream and downstream water levels, which determines the total length of the fishway.

The upstream and downstream water levels need to be checked against the Design Report and engineering drawings. An inspection is a spot check on water levels on a single day, so it is highly advisable to collect water level data daily, if possible.

Upstream water levels may vary and be outside the design range because operation of the weir changes or streamflow changes (e.g., extreme drought). Downstream levels can vary because there is erosion of the streambed downstream or because streamflow changes.

4.3.2. Internal fishway hydraulics

Pool head loss (difference in upstream and downstream water levels in adjacent fishway pools) and depth are the two key hydraulic measurements of a fishway that are used to diagnose
problems in fishways. As explained earlier in this guideline, the pool head loss determines the maximum water velocity in the fishway, which also influences turbulence. If the pool head is more than 10-20% above the design specification, then this indicates a blockage or change in structural integrity of the fishway (e.g., baffle or floor movement). Loss of depth is caused by low headwater level, blockages, sediment, or change in structural integrity with loss of flow.

4.3.3. Operation of fishway exit gate

As discussed earlier the fishway exit must be either fully open, to allow fish through, or fully closed for dewatering or maintenance.

4.3.4. Weir operation for attraction flows

Inspections provide the opportunity to refine the weir operation to provide suitable attraction flows. Operation follows the principles outlined earlier in Section 1.4.3 on Fishway Entrance (attraction) Design:

- Setting the fishway entrance at the upstream limit of migration
- Avoid recirculating flows
- Avoid masking flows

These aspects are assessed by visual inspection. Fish monitoring can also inform weir operation.

4.3.5. Operation of gates for downstream fish passage

The inspection needs to check that any specific gates installed for downstream passage are being used.

4.3.6. Structural integrity of fishway and surrounding area

The integrity and quality of all constructed work (concrete, stability of rocks, fishway baffles) needs to be inspected by someone familiar with the fishway design and engineering standards. Inspections after floods are particularly important to detect structural issues and defects.

Inspection of the surrounding area is important to detect: i) erosion or subsidence, which would affect structural support of the fishway, and ii) erosion of the downstream riverbed, leading to a lower tailwater. The latter would also be detected when measuring water levels.
STEP 5: MONITORING

Fishways have three objectives:

i) restore migratory pathways,
ii) improve fish populations and biodiversity,
iii) provide improved ecosystem services (e.g., socio-economic benefits, resilience to climate change).

Monitoring is structured around these objectives, with monitoring of:

i) fish migration in the fishway (passage efficiency) and at the weir (attraction efficiency and downstream passage),
ii) fish populations in the area or region, upstream and downstream of the barrier,
iii) ecosystem services, usually socio-economic benefits.

Even though there are generic designs of fishways, all applications at a site are unique – varying in length, layout, specific dimensions, length – and each site has a unique combination of characteristics including river flow, fish species and sizes, and flow patterns downstream and upstream. Hence, all fishways need to be monitored to confirm they are passing fish and meeting the three key objectives of migration, populations, and ecosystem services. Monitoring is also an essential tool to optimize fishways, with the results providing feedback to Step 6 Adjustment (Figure 50).

As described earlier, a Monitoring Plan should be developed in the Design Phase by the design team as well as fish biologists, irrigation engineers, hydrologists, and local fishers. The monitoring program will vary with the fishway size and complexity. Larger structures or larger catchments require more detailed monitoring of all three objectives. Small structures carrying a reduced risk of inadequate operation may only require a limited monitoring program of passage efficiency with visual assessment of attraction efficiency and downstream passage.

5.1. Fishway sampling – passage efficiency

In passage efficiency, monitoring is assessing whether all fish that enter the fishway can ascend. Therefore, there is sampling:

i) downstream of the fishway entrance (to have a sample of migrating fish approaching the fishway),
ii) in the fishway entrance (a sample of fish that can enter the fishway), and
iii) at the fishway exit (a sample of fish that can ascend the fishway).

A range of methods can be used to sample downstream of the fishway - including nets, electrofishing, and surveys of fishers - with the objective of sampling the full range of sizes and species of fish. These samples generally provide a qualitative comparison with samples in the fishway, but direct samples of abundance immediately downstream of the fishway may be possible in some circumstances.
The fishway itself is sampled by trapping with a cage (Figure 52) or funnel net (Figure 52) - both have a cone or funnel that allows fish entry and limits escapement of fish. The traps should be designed to capture all fish species and size classes; sometimes separate traps might be needed for small fish and large fish.

Using these at the fishway exit and entrance (Figure 53) provides two quantitative samples to compare size, species, and abundance of fish. Some escapement from these traps is expected, but if it is the same between the entrance and exit samples a quantitative comparison is valid.

**Figure 51**: Example of a cage trap.

**Figure 52**: Fixed net sampling a fishway exit. (Source: MAFF, Japan)

**Figure 53**: Fishway traps in a) exit and b) entrance

If species or sizes are present in the downstream samples but not the fishway entrance, it may indicate that these fish cannot enter the fishway or they cannot locate the fishway entrance. If the size range or species composition varies between the entrance and exit samples, this may indicate that some fish are unable to ascend the fishway and it is operating sub-optimally.
In fishway designs that are difficult to trap, such as rock ramp fishways, alternative methods such as electrofishing or cast netting at the entrance and exit of the fishway may be used in place of the traps.

These trapping techniques provide a useful measure of the diversity of fish and size of fish ascending a fishway. Other monitoring techniques that track individual fish - such as PIT tags, radio tags and acoustic tags – provide additional data on fish passage and a more holistic view of fish passage efficiency.

**Methods of entrance and exit trapping:**

The general method of sampling is:

1. Set traps at the fishway entrance and exit, and sample downstream of the fishway on separate days
2. Trap day and night to account for different species
3. Follow the same protocol with the same trap and same mesh etc. to avoid biased results
4. Sample fish in different flows (high and low flows) and seasons.

**Data recording**

The sampling team needs to record the species, size (length) and weight of individual fish (Table 2). This will also provide the total number of captured fish for each species. The ways of measuring captured fish are indicted in the FADM guideline (MRC, 2018). If there are high numbers of fish, only a subsample of 200 fish of each species needs to be measured for length; and the remaining fish counted, or the total weighed by species (weight can be used to extrapolate numbers if a subsample is weighed and counted). The data is then summarized (Table 3).

**Table 2.** A sample datasheet for recording individual lengths of fish.
Table 3. Sampling of a summary recording sheet.

<table>
<thead>
<tr>
<th>Sampling date</th>
<th>Sampling location (downstream trap, entrance trap exit trap)</th>
<th>Fish species</th>
<th>Total number of fish captured</th>
<th>Size of captured fish</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>S (0-10mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>M (10-50mm)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>L (&lt;50mm)</td>
</tr>
</tbody>
</table>

Analysis

Analysis for *passage efficiency* needs to evaluate:

- If the same species are observed at the exit and entrance of the fishway.
- If the target size range of fish are passing the fishway, by comparison of length/frequency distributions from the exit and entrance. Note that fish length is also a useful for swimming ability, as large fish are better swimmers than small fish.

Timing of sampling

It is desirable to monitor more than one year for obtaining reliable monitoring data. The number of fish and species vary both seasonally and annually. In addition, monitoring should be conducted over a wide range of flows (high and low) throughout the migration season, especially during months when peak numbers of fish are likely to be migrating. However, fishway monitoring during high flow, especially flood, can be dangerous for team members and should only be undertaken if the sampling locations at the top and bottom of the fishway can be safe (Annex 9).

Sampling methodologies including data analysis are indicated in the FADM guideline (MARC 2018).

5.2. Assessing attraction efficiency

*Attraction efficiency* is a measure of the fish that migrate up to the structure and locate the fishway entrance. It can be assessed using:

i) observations, by examining flow patterns downstream of the weir and around the fishway, using the three principles described earlier of: setting the fishway entrance at the upstream limit of migration, avoid recirculating and masking flows,

ii) netting or fisher samples below the weir and further downstream. If there is a high relative abundance of fish below the weir but not downstream, it suggests that fish are accumulating below the weir and fishway, either unable to find the entrance or unable to ascend the fishway.
iii) electrofishing samples below the weir and further downstream. As for netting and fisher samples, the difference in abundance between sites indicates attraction efficiency.
iv) Passive Integrated Transponder (PIT) tags
v) Radio or acoustic tags
vi) DiDSON sonar camera

**Electrofishing:**

Electrofishing in large rivers is done with a specialist boat. They can be tuned to stun most fish within proximity of the boat. Fish can then be identified, measured, and released with high survival. Quantitative samples can be taken by ensuring consistency of electrofishing time. These can provide relative abundance of fish and would be useful to assess fish accumulation in a fishway downstream and provide an independent sample of migrating fish to compare with fishway samples. The main limitations are that capture of fish is poor, which can remain stunned on the bottom of the river, and efficiency in deep water (> 2 m) is poor (MRC 2019).

![Electric fishing equipment](Source of Photo: “Joint Environment Monitoring of Mekong Mainstream Hydropower Projects”).

(Source: MRC (2019))

**Passive Integrated Transponder (PIT) tags:**

These is a small, lifetime (i.e., no battery) tag that has an individual code. The tag is identified and automatically logged into a computer when it passes within 20-40 cm of a specialist reader. These characteristics make it ideal for assessing fish passing through confined spaces in fishways (MRC 2019).
Radio or acoustic tags:
These are much larger than a PIT tag – varying in size from a very small finger to a large finger, depending on battery life and range of signal. The range is usually hundreds of meters and so they are ideal for monitoring fish as they approach or leave a fishway. Note: up to 40% of tags can be lost to mortality or fishing, so the sample size needs to accommodate this. At least 50-60 fish of one species would be required to understand the variation in behavior, hence, 100 tags would be required (MRC,2019).

DIDSON sonar camera:
DIDSON or ARIS cameras use sonar technology to produce clear video images in water with almost any turbidity. Their limitations are they operate poorly in highly aerated water, which would be near spillways, and have a narrow beam which cannot view a large wide river with a
complex bed, such as the Mekong. The DIDSON or ARIS cameras are particularly useful to assess fish attraction in the tailwater, fish entry into the upstream or downstream fishway, and fish impingement on trash screens. Because fish are not handled or captured, the data represents a reliable view of fish behavior (MRC, 2019).

![Image of DIDSON camera (left) and typical screen shot of DIDSON image (right) *Source of Photo: “Joint Environment Monitoring of Mekong Mainstream Hydropower Projects”.

Figure 57. Image of DIDSON camera (left) and typical screen shot of DIDSON image (right) *Source of Photo: “Joint Environment Monitoring of Mekong Mainstream Hydropower Projects”.

(Source: MRC (2019))

5.3. Assessing downstream passage

*Downstream passage* can be assessed using:

i) observations, by examining flow patterns, plunge pools, gate usage  
ii) sampling fish as they pass through the weir  
iii) Passive Integrated Transponder (PIT) tags (return journeys show survival)  
iv) Radio or acoustic tags  
v) DIDSON sonar camera

5.4. Assessing fish populations in the region

Monitoring fish in the region provides an assessment of whether the fishway is contributing to broader improvements in fish populations. Several sites are needed upstream and downstream of the structure, before and after construction of the fishway. The presence upstream of more fish or fish species not found prior to fishway operation demonstrates that the fishway is positively impacting the fish community. This fish community data can be collected using a variety of methods including nets, electrofishing, or fish traps (Annex 9).
5.5. Socio-economic monitoring

Socio-economic monitoring is to evaluate the benefits which local people obtain from a constructed fishway. Socio-economic monitoring should be conducted at three main levels i.e., village, household and individual fisheries and be also undertaken both before and after fishway construction, over a minimum of two wet seasons.

The Socio-economic surveys should focus on four key metrics:

- Determine the baseline degree of fish harvest and consumption upstream and downstream of the structure.
- Monitor local markets and other fish marketing pathways (fish trade) affected by the structure.
- Identify the origin of fish from upstream and downstream of the structure to household incomes; if fishers are travelling long distances from upstream to downstream to fish, then a good fishway will allow the fish to move upstream and benefit more people.
- Quantify the arrangement of local fish-based economies by determining where people fish, when they fish, how much money they make from each species, seasonal market variations. These can all influence household income and a fishway can help.

The study should focus on local villages near a fishway. Village sample surveys should involve interviews with village chiefs and experienced fishers with a general knowledge of fishing practices in their region. Fish markets within each village and fish traders should be monitored to determine any fluctuations in fish prices both seasonally, and before/after structure modification. Several villages should be surveyed in the study region to gauge the degree of spatial variation in fishing rates.

Household surveys, within each village, should be undertaken to determine overall consumption and catch of fish at a household level. Surveys should be undertaken several times annually, both before and after structure modification, to determine seasonal changes in catch and consumption rates. This information can be correlated with seasonal fish migrations to determine if there is a link between the two factors. Information should be obtained through a face-to-face survey with the head of house, and some houses should be surveyed in each village.

Individual surveys are then required to obtain information on individual fishing practices. This is necessary to determine the range of fishing techniques and target species. Any variation in fishing effort and sampling method must be considered when analyzing data at the village or household level because effort can greatly bias results. This method will involve surveying both male and female fishing activities. A clear picture of group fishing activities and expedition fishing both into and away from the study area will also be developed. Villages should be presented with the results of the study to provide a basis for improving community-based fisheries management. Metrics describing fisheries production should be refined once structure modification has been completed.

It is desirable for the team to conduct the socio-economic monitoring in the villages identified for analyzing Attribute 14 so that it will be able to confirm the validity of the prioritization. Sample questions of socio-economic survey is shown in Annex 11.
Benefit-cost analysis

Benefit-cost analysis can be utilized for estimating the effectiveness of the constructed fishway in monetary base. In the benefit-cost analysis, the total cost of a fishway is estimated based on all the expected cost, i.e., construction and maintenance, for the lifespan of the project. On the other hand, the total benefit of the fishway comprise the direct benefits of the fishway over the lifespan of the project (Cooper et al., 2019). The benefit is estimated from the additional fish yield.

In general, the benefit-cost analysis is conducted before construction. However, it can be also done during fishway operation to evaluate the effectiveness of the post-construction. The analysis of the post construction will be able to provide more reliable result than the pre-construction analysis because it can be estimated based on the actual construction and maintenance costs and the additional fish yield. The benefit-cost analysis during operation is expected to make decision more transparent for additional fishway installation in the LMB.

University of South Australia and Charles Sturt University developed the Lower Mekong Fishway Support Tool (LMFST) and utilized it in Laos PDR to analyze the benefit-cost of a fishway. Once data e.g., fishway structure, type, target species, lifespan, discount rate and fish price, are inputted, the LMFST analyzes the benefit-cost of a fishway (Cooper et al, 2019). The LMFST can be utilized to evaluate the effectiveness of a fishway.
STEP 6: FISHWAY ADJUSTMENT

Fishway adjustment can follow commissioning, inspection, and monitoring. As listed in Section 4.3 Inspection, the most common issues for adjustment are related to the Common Mistakes in Fishway Design (see Section 1.4.7) and are listed here, with solutions:

i) blockages due to debris,
   \textit{Solution:} increase maintenance; add trash rack, debris boom.

ii) upstream and downstream water levels
    \textit{Solution:} adjust weir operation, redesign fishway.

iii) internal fishway hydraulics (water levels, head losses),
    \textit{Solution:} adjust weir operation, redesign fishway

iv) operation of fishway exit gate
    \textit{Solution:} operate fully open or fully closed

v) weir operation for attraction flows,
   - Setting the fishway entrance at the upstream limit of migration
   - Avoid recirculating flows
   - Avoid masking flows
   \textit{Solution:} adjust operation of gates; modify abutments and fishway entrance.

vi) operation of gates for downstream fish passage,
   \textit{Solution:} adjust operation of gates

vii) structural integrity and defects of fishway and surrounding area
    - structural integrity of fishway
      \textit{Solution:} repair fishway
    - erosion of stream bed and lower tailwater
      \textit{Solution:} install rock protection downstream to raise tailwater level; extend fishway to riverbed

In addition to these issues, monitoring may find that:

i) design water velocity or turbulence is too high for fish passage
   \textit{Solution:} Redesign baffles or fishway.

ii) unintended loss of fish in irrigation offtakes
    \textit{Solution:} Screen offtake or extend fishway exit away from offtake.

iii) downstream passage mortalities
    \textit{Solution:} Add overshot gate and plunge pool.

iv) fish stay in a static water area in the upstream side of a weir or gates
    \textit{Solution:} Adjust operation of gates; add overshot gate for downstream passage.

Most of these issues are addressed in \textit{Step 1 Fishway Design} and \textit{Step 2 Fishway Operation}. Annex 12 and 13 provides further information on fishway inspection, problems, and adjustments.
CONCLUSION

This Guideline aims at providing professionals in the Lower Mekong Basin with insights about fishway design and construction, structured around six steps.

- Step 1. Fishway design
- Step 2. Fishway construction
- Step 3. Fishway operation
- Step 4. Fishway maintenance and inspection
- Step 5. Fishway monitoring
- Step 6. Fishway adjustment

Fishways have a history of not performing as expected, with inadequate passage of fish and no improvement in fish populations. The underlying reason is not considering and linking all six steps. Continuity between these steps is emphasized in the guideline. For example, upstream fish passage has two components in design: attraction (fish finding the entrance) and passage (fish passing up the fishway). These two themes continue through design, commissioning, inspection, monitoring and adjustment (Steps 1, 3, 4 and 5). Equally downstream passage, which is often overlooked, is also considered in the same steps.

Fishways in the past have been designed and constructed, but the process has often had a narrow focus on engineering. This guideline emphasizes a multidisciplinary approach (biology, hydrology, hydraulics, engineering) and early engagement with stakeholders (structure owner, operator, local community), so that design objectives and assumptions are transparent. Fishways are a balance of cost and function, as well between initial cost (capital) and ongoing cost (operation and maintenance). These decisions need to be made jointly.

In Step 2 Construction quality control is emphasized, along with maintaining safety and environmental standards. Quality control is maintained through independent inspections and continuity with the Design Team- this helps the contractor because it minimizes costly changes at the end of construction. Wet commissioning is a crucial last step of construction followed by a 12 month’s Defects Liability Period, when the contractor is responsible for any defects.

Once the fishway is open, the operation of the weir and gates is important to guide fish to the fishway entrance (i.e., provide effective attraction), and to provide safe downstream passage. Engagement with operators early in the design process enables their inputs to be part of the final fishway and weir operation.

Inadequate maintenance of fishways is one of the most common causes of fishways not functioning well. This guideline incorporates a Maintenance Plan from Step 1 Fishway Design and outlines a Maintenance Cycle that acknowledges that this is an ongoing responsibility for the life of the fishway. The Maintenance Cycle links with Inspections, Monitoring and Adjustment; within these steps there is continuity where the design criteria from Step 1 become Key Performance Indicators (KPIs) for inspection and adjustment.
Monitoring is essential to evaluate the effectiveness of a fishway: in passing fish, improving fish populations, and providing socio-economic benefits to the local community. This Guideline introduces methods to monitor the numbers of fish, species, size, and weight; and to survey incomes for analyzing the economic benefits to local community. If the number and species of fish passing a fishway is less than expected, there might be failures in design or construction, which need to be fixed.

Inspections and Monitoring provide input to Adjustment. Although there are generic designs of fishways it is important to note that each application at a site is unique and adjustments are likely and should not be considered a failure of the design process. If all the steps in this guideline are followed adjustments should be minimized.

**RECOMMENDATIONS**

The MRC expects this Guideline to be widely utilized to reduce the negative impact of irrigation structures on fish migration and facilitate fishway installation in the LMB. The MRC hopes the guideline will motivate governments and developers to install fishways in irrigation structures.

Therefore, it is essential to translate this Guideline into the four riparian languages i.e., Khmer, Lao, Thai, and Vietnamese, so that not only central government officers, but also local government ones will be able to utilize it well.

Capacity building of the experts in the LMB is also necessary to enhance their understanding of the Guideline. Regional and national workshops for the experts in the LMB need to be organized to train additional agency staff. In addition, it is necessary for more experts to participate in onsite trainings on remote assessments, field appraisal and fishway construction and monitoring.

This Guideline mentions little about the removal of unused irrigation structures which significantly block fish migration. However, the removal of those structures is the most effective and cost-effective way to provide fish passages and restore migration. Therefore, it is recommended that the governments survey the locations of unused structures using GIS identification and evaluate their impact on fish migration. The unused structures should then be prioritized for removal in terms of impact on fish biology in the river and cost of removal.
**GLOSSARY**

**Annual Exceedance Probability (AEP):** The probability of a flood event occurring in any year. The probability is expressed as a percentage.

**Barrier:** Any structure across a waterway that inhibits the movement of fish up and down the waterway.

**Dam:** A barrier across a waterway that has a separate spillway structure, they are large structures, usually greater than 5m high.

**Fish Friendly:** A structure that provides easy access for fish to upstream habitats through the design of the structure or inclusion of a fishway.

**Fish Passage:** The movement of fish in both upstream and downstream directions past an obstruction in the waterway.

**Fishway:** An engineered structure that provides fish passage past a barrier.

**Floodgate:** A structure that prevents floodwaters from entering the floodplain, usually consists of steel flaps that can let water out of the floodplain, but not let water in.

**Head loss:** Difference in upstream and downstream water levels at a fishway baffle.

**Head differential:** Total difference in upstream and downstream water levels at a barrier.

**Orifice:** An opening, such as a vent, mouth, or hole, through which something may pass. Orifice controls water flow in a fishway, and fish pass it to move from a pool to the next.

**Potamodromous:** Fish species whose migrations occur wholly within freshwater for breeding and other purposes.

**Regulator:** A gated structure that regulates the flow of water, usually into off-stream channels.

**Rehabilitation:** The process of restoring a structure, habitat, or stream back to a condition of good condition or operation.

**Road Crossing:** Any structure that crosses a waterway to enable traffic to cross the waterway.

**Spillway:** A structure on a barrier that conveys water past the barrier.

**Stream order:** Stream ordering is a method of assigning a numeric order to links in a stream network. This order is a method for identifying and classifying types of streams based on their numbers of tributaries.

**Waterway:** A river, stream, creek, or channel.

**Weir:** A barrier across a waterway that incorporates the spillway into the main body of the structure.
REFERENCES


FAO (2020). *The State of World Fisheries and Aquaculture 2020*. Available at: https://doi.org/10.4060/ca9229en


ANNEXES

Annex 1: Necessary information for data collection

Fish biology
- Fish assemblages, e.g., species and sizes at the site(s) and up and downstream of the site(s) and any relevant movement and other behavioral data, e.g., migration size and timing, swimming capability (swimming velocity)

Barrier structure and operation
- Construction year
- Structure type (e.g., weir, reservoir, gate, regulator, or culvert)
- Barrier size (length, height, and width), construction material and design plan
- Irrigation offtake conditions e.g., offtake location, water-intake period for irrigation, intake water quantity and water intake level
- Water levels in the upstream and downstream sides throughout all year
- Operation rules for the structure e.g., operation frequency, operation period, water discharge volume, management water level, maintenance method and water discharge rule
- Access for operators to maintain the fishway

Flow condition
- Existing and or modelled hydrological data on the river or stream (e.g., flow duration curves, annual exceedance probabilities, daily flow data across a range of rainfall years, flow event curves, local knowledge of flow peaks)
- Known or projected headwater/tailwater levels and rate of rise/fall at a range of flows as witnessed by locals or recorded by irrigation officials
- Volume and entry pathway of drifted wood and trash into the barrier (to create prevention measures against fish pass blockage.)
- Details of downstream tailwater control and how stable the tailwater level is over an extended period. This detail is critical as the tailwater level that changes overtime can leave the fishway stranded and nonfunctioning.

Riverbed condition
- Geotechnical information (riverbed material, bedrock depth etc.) of the site, as this will affect the potential design and the construction cost.
- Sediment volume at upper and lower course of the barrier
- Riverbed scour in the lower course of the barrier
- Riverbed gradient

Construction methods and materials
- Construction methods used by local contractors should be examined to determine if they are suitable for the construction at the site.
- Information on the construction materials of the existing barrier.

During site inspections, the team needs to understand the complexities of the site and how the fishway can be incorporated into the site. The site inspection also allows the team to interview local operators and communities onsite to gain further insight into the operation of the structure. The site inspection should:
- Inspect the barrier site with local officials and operators
- Inspect tide lines remaining on the barrier to examine high and low water levels
- Determine how access to the fishway will be provided for construction, monitoring, operating and maintenance purposes
- Identify how the hydrological data relates to the barrier and the abutments of the structure
<table>
<thead>
<tr>
<th>Migratory Guild and number</th>
<th>Typical characteristics</th>
<th>Relative impact of mainstream dams on migration</th>
<th>Relative effect of change in flow regime on fish production</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 - Rhithron resident guild</td>
<td>• Resident in rapids torrents, rocky areas, and pools in the rhithron.</td>
<td>Little or no impact from mainstream dams (but note, potentially high in upland storage dams)</td>
<td>Little or no impact from mainstream dams (But note potentially high in upland storage dams due to possible exposure of riffle areas and inundation of habitats upstream)</td>
</tr>
<tr>
<td>2 - Migratory main channel (and tributaries) resident guild</td>
<td>• Long distance migrants spawning in the main channel (sometimes in upper zone of the Mekong (Figure 6-1) upstream of adult feeding habitat in the main channel. • May migrate to refuges (deep pools) in the main channel during the dry season. • Palaeophytic members have drifting pelagic egg or larval stages returning to adult habitat using backwaters and slacks as nurseries. • Adults do not enter floodplain and may be piscivorous.</td>
<td>Very high</td>
<td>High: flow variation may affect the pass ability at Khone falls and other natural barriers and delayed flooding disrupt migratory cues</td>
</tr>
<tr>
<td>3 - Migratory main channel spawner guild</td>
<td>• Spawn in the main channel, tributaries, or margins upstream of floodplain feeding and nursery habitat often with pelagic egg or larval stages. • Adults and drifting larvae return to floodplains to feed. • May migrate to refuges (deep pools) in the main channel during the dry season.</td>
<td>Very high</td>
<td>Very high: loss of connectivity and flooding of spawning and nursery habitat</td>
</tr>
<tr>
<td>4 - Migratory main channel refuge seeker guild</td>
<td>• Migrates from floodplain feeding and spawning habitat to refuges (deep pools) in the main channel during the dry season. • Spawning occurs on the floodplain and main channel used as refuge during dry season.</td>
<td>Medium</td>
<td>High: loss of connectivity and flooding of spawning and nursery habitat</td>
</tr>
<tr>
<td>5 - Generalist guild</td>
<td>• Limited non-critical migrations in mainstream. • Highly adaptable, mobile, and static elements in their genome make them highly adaptable to habitat modification.</td>
<td>Little or no impact</td>
<td>Medium: loss of connectivity and reduced flooding of floodplain</td>
</tr>
<tr>
<td>6 - Floodplain resident guild (Blackfish)</td>
<td>• Limited migrations between floodplains pools, river margins, swamps, and inundated floodplains. • Tolerant to low oxygen concentrations or complete anoxia.</td>
<td>Little or no impact</td>
<td>Medium: loss of connectivity and reduced flooding of floodplain</td>
</tr>
</tbody>
</table>
### Migratory Guild and number

<table>
<thead>
<tr>
<th>Migratory Guild and number</th>
<th>Typical characteristics</th>
<th>Relative impact of mainstream dams on migration</th>
<th>Relative effect of change in flow regime on fish production</th>
</tr>
</thead>
<tbody>
<tr>
<td>7 - Estuarine resident guild</td>
<td>Limited migrations within the estuary in response to daily and seasonal variations in salinity.</td>
<td>Little impact (if dam is upstream of estuary and does not influence salinity dynamics in estuary).</td>
<td>Little or no impact</td>
</tr>
<tr>
<td>8 - Anadromous guild</td>
<td>Enters fresh/brackish waters to breed. Enters freshwaters as larvae/juveniles to use the area as a nursery, either obligate or opportunistic.</td>
<td>High (for dams located in river mouths or lower putamen).</td>
<td>Little or no impact</td>
</tr>
<tr>
<td>9 - Catadromous guild</td>
<td>Reproduction, early feeding, and growth at sea. Juvenile or sub-adult migration to freshwater habitat, often penetrating far upstream.</td>
<td>Very high</td>
<td>Very high: loss of connectivity to feeding and nursery habitat</td>
</tr>
<tr>
<td>10 - Marine visitor guild</td>
<td>Enters estuaries opportunistically</td>
<td>Little or no impact</td>
<td>Little or no impact</td>
</tr>
</tbody>
</table>

### Indicator species for Mekong fish guilds (MRC, 2020)

( DT = Delta; PP = Phnom Penh; TS = Tonle Sap)

**Guild 1 - Rhithron resident guild:**

- **Notopteridae:** Chitala blanci (main channel with rocky only).
- **Cyprinidae:** Gara spp., Brachydanio spp., Devario spp., Poropuntius spp., Tor spp., Neolissocheilus spp., Osteochilus waandersii, Raiamas guttatus, Opsarius spp., Lobocheiros spp., Onychostoma spp. (Laos), Scaphidonuchthys acantheropterus (Laos), Mekongina erythrospila (Stuntreng-3S, Laos), Mystacoleucus spp.
- **Balitoridae:** all species (e.g., Homaloptera spp., Balitora spp.).
- **Nemacheilidae:** all species (e.g. Nemacheilus spp., Schistura spp.).
- **Akysidae:** all species (e.g., Akysis spp., Pseudobagarius spp.).
- **Sisoridae:** Cryptothorax spp., Bagarius spp. (main channel).
- **Datnioididae:** Datnioides undecimradiatus (main channel only).
- **Channidae:** Channa gachua,
- **Osphronemidae:** Osphronemus exodon,
- **Gobiidae:** Rhinogobius mekongianus (above Stuntreng).
- **Tetraodontidae:** Pao baileyi (main channel only), P. turgidus

**Guild 2 - Migratory main channel (and tributaries) resident guild:**

- **Cyprinidae:** Cirrhinus microlepis, Cyclocheilos enoplos, Cosmochirus harmandi, Probarbus jullieni;
- **Pangasiidae:** Pangasianodon hypophthalmus (all places), Pangasius larnardii (all places), P. mekongensis, P. bocourti (except TS system), P. concophilus (except TS system)

**Guild 3 – Migratory main channel spawner guild:**

- **Clupeidae:** Clupeichthys aesarnensis (all places), Clupeoides borneensis (all places), Corica laciniata (DT-PP-TS).
Cyprinidae: Cirrhinus prosemion, C. jullieni, Hypsibarbus spp., Puntioplites falcifer (above Kratie), P. proctozysron (below Kratie to DT), Labeo chrysophkeadion, L. pierrei, Sikukia spp., Incisilabeo behri, Scaphognathops spp. (above Kratie), Barbihtys laevis, Leptobarbus rubripinna, Amblyrynchichthys micracanthus,

Botiidae: all species (Synccrossus spp., Yasuhikotakia spp.).

Pangasiidae: Pangasius macronema, Pseudolais pleurotaenia, Helicophagus leptorhynchus,

Siluridae: Walago attu, Phalacronotus spp., Kryptopterus spp.

Bagridae: Hemibagrus spp.

Cobitidae: Acanotopsis spp., Acanthopsoides spp. (prefers sandy bottom).

Gyrinocheilidae: all species.

Tetraodontidae: Auriglobus nefastus

Guild 4 - Migratory main channel refuge seeker guild:

Cyprinidae: Barbonymus altus, B. Schwenkfeldian, Cyclocheilichthys spp., Rasbora spp., Paralaubuca spp., Parachela spp., Thynnichthys thynnoides; Cobitidae: Pangio spp.; Siluridae: Ompok siluroides; Bagridae: Mystus spp.; Pseudolepidiidae: Pseudolepis fasciata; Ambassidae: Parambassis wolfii, P. apogonoides; Sciadidae: Boesemania microlepis (d/s Stuntreng common, above Khone Falls very rare now); Tetraodontidae: Pao cambodgiensis, P. suvattii (above Khone Falls only)

Guild 5 - Generalist guild: Notopteriidae: Notopterus notopterus, Chitala ornata; Cyprinidae: Gymnomostomus (Henichorynchus) spp., Barbonymus gonionotus, Syntomus orphoides, Crossocheirus spp. Osteochirus vittatus, O. microcephalus, Hampala spp., Labiobarbus spp., Cyclocheilichthys spp.; Syngnathidae: Doryichthys boisjoli (below Kratie to DT-TP), D. dekhotoides (below Kratie to DT-TP), D. contiguus (confirmed between Vientiane-Ubonratitchanathai, does not exist below Khone Falls), Mastacembelidae: Mastacembelus spp. (e.g. M. favus, M. armatus); Ambassidae: Parambassis siamensis; Eleotridae: Oxyleotris marmanrata

Guild 6 - Floodplain resident guild (Blackfish): Cyprinidae: Esomus spp.; Cobitidae: Lepidocephalichthys hasselti; Claridae: all species (e.g., C. macrocephalus, C. cf batrachus); Chiclidae: all species except C. trachurus, C. cf batrachus; Adrianichthidae: Oryzias siamensis, O. minutillus; Hemiramphidae: Dermogenys siamensis; Channidae: Channa striata, C. lucius; Anabantidae: Anabas testudineus; Osphronemidae: Trichopodus spp., Trichopsis spp; Synbranchidae: Monopterus albus; Mastacembelidae: Macrognathus spp.; Tetraodontidae: Pao cochichinensis

Guild 7 - Estuarine resident guild:

_Protocidae: Plotosus canius_ (DT); Ariidae: all species (DT); Adrianichthidae: Oryzias haugiangensis (DT); Gobiidae: Glossopteris spp. (DT-PP); Polynemidae: Polynemus spp. (DT-PP); Cynoglossidae: all species (DT-PP-TP); Soleidae: Brachirus spp. except B. harmandi and B. siamensis

Guild 8 - Anadromous guild:

Pangasiidae: Pangasius krempfi, P. elongates (mainstream only); Ariidae: all species (DT-PP)

Guild 9 - Catadromous guild:

Anguillidae: Anguilla marmorata, A. bicolor (all nodes); Ophichthidae: Pisodonophis boro (DT-PP-TP)

Guild 10 - Marine visitor guild:

Scombridae: Scomberomorus sinensis (DT-PP), Gerreidae: all species (DT); Ambassidae: all species except Parambassis spp. (DT); Terapontidae: Terapon jarbua; Sciadidae: all species except Boesemania; Gobiidae: Pseudapocryptes elongatus, Periopthalmodon schlosseri

Non-native: Cyprinidae: Labeo rohita, Cyprinus carpio, Cirrhinus cirrosus, Cyprinus rubripinna; Serrasalmidae: Piaractus brachypomus; Cichlidae: Claris gariepinus, Loricariidae: Pterygoplichthys spp.; Cichlidae: Oreochromis spp.
Annex 3: Additional information on design criteria of fishways

1) Hydraulic Formulae

Maximum water velocity

Vertical slot fishways

The maximum velocity in a vertical slot fishway occurs in the slot of the baffle as water constricts through the slot (Figure A3.1) and is. Water velocity is determined by head loss which is water level difference between a pool to the next.

![Vertical slot fishway showing maximum water velocity.](image)

Figure A3.1. Vertical slot fishway showing maximum water velocity.

Maximum water velocity is calculated using the following formula:

\[ V = \sqrt{(2gh\Delta h)} \]

\( V = \) water velocity (m/s)
g = acceleration due to gravity (9.8 m/s)
\( \Delta h = \) head loss between pools (m) (Figure A3.2)

![Figure A3.2: Head loss (difference in water level between adjacent fishway pools)](image)

The same formula can be used to approximate maximum water velocity for submerged-orifice fishways, pool-type fishways with discrete drops (cone, rock-concrete hybrid). It can also be used in rock-ramp fishways with discrete drops, but there are often multiple pathways through rock-ramp fishways so it should only be used as a guide.

**Denil fishways**

Design velocity in channel fishway is calculated by the Manning formula:

\[
V = \frac{1}{n} R^{2/3} I^{1/2}
\]

- \( V = \) water velocity (m/s)
- \( n = \) Gackle-Manning coefficient
- \( R = \) Hydraulic radius (m)
- \( I = \) Slope of the hydraulic grade line

**Turbulence**

Turbulence is calculated by the following formula:

\[
P = \frac{Q \Delta h r}{v} \quad \text{Turbulence is measured as units of energy per water volume}
\]

- \( P = \) Power, Watts/m³ (W/m³)
- \( Q = \) discharge (m³/s)
- \( \Delta h = \) head loss between pools (m)
- \( \Gamma = \) the weight density of water
- \( V = \) pool volume (m³) (calculated from length x width x depth)

**Fishway discharge**

Formulae of design flow volume are as follows:

**Vertical slot**

\[
Q = Cd b y \sqrt{(2g\Delta h)}
\]

- \( Q = \) coefficient of flow
b = width of a slot (m)
y = depth of a slot (m)
g = acceleration due to gravity (9.8 m/s)
Δh= head loss between pools (m)

Denil

Q = AV
A = Cross sectional area of flow (m²)
V = Design velocity (m/s): \( V = \frac{1}{n} R^{\frac{2}{3}} I^{\frac{1}{2}} \) (Manning formula)

Rock-ramp

Q = BdV
B= Width of a fishway (m)
d= Depth (m)
V= Mean velocity (m/s)

2) Fishway layouts to optimize entrance location

Three types of layouts are commonly used to optimize the entrance location for the *upstream limit migration*:

U-shaped fishway (also “dog-leg”, or switchback) (Figure A3.3)

The layout of the fishways doubles back to form a U-shape or “dog-leg” entrance is located downstream of the upstream limit and the fish accumulation zone because the fishway is switched back to the weir. A resting pool is also set at the switch-back point for fish to rest before moving up the fishway.
Recessed Fishway (Figure A3.4)

The fishway is recessed into the weir; the entrance is placed upstream of the *upstream limit of migration* and the fish accumulation zone.

![Figure A3.3: U-shaped fishway](image)

![Figure A3.4: Recessed fishway.](image)

Barrier Weir (Figure A3.5)

A barrier weir is located at the same horizontal line as the fishway entrance, blocking fish migration and in the river and creating an *upstream limit* and fish accumulation zone in front of the fishway entrance. It is not commonly used and is only applicable for sites with fish passage at low flows, because at high flows fish pass directly over the barrier weir and miss the fishway entrance.

![Figure A3.5: Small crest adjacent to the entrance](image)

3) Multiple entrances

If the *upstream limit of migration* changes substantially with changes in flow during the migration period, multiple entrances may be needed for low and high flows. When the tailwater and flow is low in the beginning or late rainy season, the *upstream limit* is close to the weir or gate (Figure A3.6). When the tailwater is high in the middle of the rainy season, the limit is far away from the weir or gate (Figure A3.7). If only one fishway entrance is set near the *upstream limit* of the low tailwater, fish cannot enter the entrance when high tailwater because the upstream limit shifts downstream. Therefore, two entrances enable fish migration during changes in river flow.
4) **Location of the fishway exit**

The fishway exit should be located: i) as far as possible from the weir crest and gates to prevent fish being swept back downstream, ii) away from offtake channel (Figure A3.8) to prevent fish.

Figure A3.8: Options for fishway exit recessed away from the crest and gates (left), or offtake channel passing flow under fishway to prevent loss of fish.

Fishway exits can also have an extended corridor and walls to lead fish area from the weir crest or gates (Figure A3.9)
Figure A3.9: Extension of a fishway exit corridor and walls

*Source of Figure: Department of Fisheries of Thailand (2020). Country Paper on Results of Fish Passage Barrier Inventory and Construction in Haui Luang Catchment and Recommendations for Finalizing the Guideline to Prioritizing Fish Passage Barriers and Creating Fish Friendly Irrigation Structure

Figure A3.10: Extension of a fishway exit corridor and walls

*Source of Photo: Department of Fisheries of Thailand (2020). Country Paper on Results of Fish Passage Barrier Inventory and Construction in Haui Luang Catchment and Recommendations for Finalizing the Guideline to Prioritizing Fish Passage Barriers and Creating Fish Friendly Irrigation Structure

5) Offtake Screens
Where there is a risk of fish being drawn into an irrigation channel, or where the fishway exit cannot be sited away from an offtake channel, a fish screen should be incorporated into the offtake to prevent fish from entering it (Figure A3.11):

Figure A3.11: Screens on offtakes

*Source of Photo: “Masterclass in Fish Passage Engineering Design, Construction, Ecology and Monitoring”. (Martin Mallen-Cooper November 2018)
# Annex 4: Fishway types and characteristic

<table>
<thead>
<tr>
<th>Fishway Type</th>
<th>Description</th>
<th>Source of Photo: MAFF/Japan</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full-width overflow (Pool)</td>
<td>Designed for specific structures: * Full-width overflow is a class model of a fishway. Many types of fishways were developed based on it. Designed for specific structures: Installed in high-head facilities such as dams or a long fishway course.</td>
<td>*Source of Photo: MAFF/Japan</td>
</tr>
<tr>
<td>Ice Harbors (Pool)</td>
<td>Structure: A baffle, or partition wall, separates one pool from the next. All water overflows the partition wall to the next pool. Hydrological characteristics: Flow velocity depends on the overflow depth (head loss) from the top of partition walls. Flow volume depends on overflow depth and width. Adaptivity to swimming characteristics: Suitable: Large, middle, and small fish. Unsuitable: Demersal fish, Crustaceans. Adaptivity to water level change: Water level change on the upstream side of the weir directly affects the velocity and volume of water flow in the fishway. Maintenance: Easy to clear floating trash. Sediments in pool are drained from submerged orifices. Benefits: Easy to construct.</td>
<td>*Source of Photo: MAFF/Japan</td>
</tr>
<tr>
<td>Sloping weir (Pool)</td>
<td>Structure: Composed of a non-overflow central baffle, two overflow sections and two submerged orifices. Large fish pass each pool from overflow sections, and small fish pass submerged orifices. Hydrological characteristics: A baffle and submerged orifices reduce turbulence in pools. Same as Full-width overflow. Adaptivity to swimming characteristics: Suitable: Large, middle, and small fish. Unsuitable: Demersal fish, Crustaceans. Adaptivity to water level change: Same as Full-width overflow. Maintenance: Easy to clear floating trash in the fishway by draining from submerged orifices. Benefits: Debris and trash in pools are easily discharged. Generates varied flows similar to mountain streams.</td>
<td>*Source of Photo: MAFF/Japan</td>
</tr>
</tbody>
</table>

*Deeper the overflow depth and wider overflow width, the more water flows. The steeper the slope gradient is, the more turbulence in the pools.*
<p>| Limitations  | Fishway cannot function well under large flow fluctuations. High turbulence is generated by large overflow into pools. Fish cannot swim up the fishway when the top corner of a partition wall is at right angle. (Water does not flow along the block and is apart from a partition.) | As water flow increases in the fishway, more air bubbles and turbulence are generated in pools. Rectangular overflow impedes demersal fish and crustaceans in ascending between pools. Gravels easily accumulate in pools. Never been tried in the Mekong before | Does not function well under high flow fluctuation conditions. Large overflow conditions generate high turbulence, impeding small fish and demersal fish and crustaceans. |</p>
<table>
<thead>
<tr>
<th>Fishway type</th>
<th>Cone (Pool type)</th>
<th>Vertical slot (Pool type)</th>
<th>Trapezoidal (Pool type)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed for specific structures</td>
<td>Low-head barriers (&lt;3m) High water level is less than ridge crest level.</td>
<td>Functions well under low gradient. Can be installed in high-head barriers when keeping low gradient by extending length.</td>
<td>Low-head barriers (&lt;3 m)</td>
</tr>
<tr>
<td>Structure</td>
<td>A series of ridges with cone shaped baffles designed to pass a broad size range of fish.</td>
<td>Water flows through vertical slot to the next pool.</td>
<td>Combination of pools, weirs, and vertical slots</td>
</tr>
<tr>
<td>Hydrological characteristics</td>
<td>Cone shaped baffles generate conservative hydraulics. Low flow results in low velocity and turbulence so that small fish can pass. High flow increases velocity and turbulence levels and allows larger fish to pass.</td>
<td>Water velocity at slot depends on the difference in water level between one pool and the next. Water volume is derived from the velocity of water flow at a slot and the cross-sectional area of slot.</td>
<td>Creates a central high flow zone and low flow zones on both sides where fish can rest. Large fish swim in the central zone. Small fish swim in low flow zones.</td>
</tr>
<tr>
<td>Adaptivity to swimming characteristics</td>
<td>Suitable: Large, middle, and small fish, Demersal fish, Crustaceans</td>
<td>Suitable: Large, middle/ small size fish, Demersal fish, Unsuitable: Crustaceans</td>
<td>Suitable: Large, middle, and small fish, Demersal fish, Crustaceans</td>
</tr>
<tr>
<td>Adaptivity to water level changes</td>
<td>Water level change on upstream side of weir directly affects the velocity and volume of flow in fishway.</td>
<td>Flow velocity at slot is less likely to be affected by water level changes on the downstream and upstream sides.</td>
<td>Same as cone type</td>
</tr>
<tr>
<td>Benefits</td>
<td>Easy to construct. Generates high attraction flow.</td>
<td>Vertical-slot functions over very wide range of water levels. Slot can be adjusted to different fish and river systems</td>
<td>Easy to construct (simple, flat transportable baffle) Generates very high attraction flow.</td>
</tr>
<tr>
<td>Limitations</td>
<td>Headwater range is more limited than vertical slot (1.0 m max.) Less effective for small fish under high flows.</td>
<td>Construction cost is relatively high. Can be installed in low gradients. Attraction flow is less than other designs. Water velocity at a slot can be too fast for small fish to swim up when water level in the downstream side is too low. Gravels and debris are easily accumulated in a pool.</td>
<td>Headwater range is more limited than vertical slot. Need large space to be installed Little data available on this uncommon design.</td>
</tr>
<tr>
<td>------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>-----------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Fishway type</td>
<td>Denil (Channel)</td>
<td>Full-width rock ramp (Rock ramp)</td>
<td>Partial-width rock ramp (Rock ramp)</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>-------------------------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Designed for specific structures</td>
<td>Suitable for long and narrow space and low-head barriers.</td>
<td>Appropriate for relatively low-head barriers. Commonly used for low barriers (&lt;2m).</td>
<td>Same as Full-width rock ramp</td>
</tr>
<tr>
<td>Structure</td>
<td>Consists of a series of narrow flumes with U-shaped baffles at short intervals to generate varied flow velocities.</td>
<td>Rocks are used to construct pools and small falls that mimic natural structures of a river or a stream.</td>
<td>Same as Full-width rock ramp</td>
</tr>
<tr>
<td>Hydrological characteristics</td>
<td>Water flow velocity at the bottom is slow and increases as it approaches the surface of the water.</td>
<td>Creates varied water flow velocities with low turbulence. Rocks provide roughness that generates low water velocity zones.</td>
<td>Same as Full-width rock ramp</td>
</tr>
<tr>
<td>Adaptivity to swimming characteristics</td>
<td>Suitable; Large and middle size fish</td>
<td>Suitable; Large, middle, and small size fish, Demersal fish, Crustaceans</td>
<td>Suitable; Large, middle, and small size fish, Demersal fish, Crustaceans</td>
</tr>
<tr>
<td></td>
<td>Moderate: Small size</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Unsuitable: Demersal fish, Crustaceans</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Adaptivity to water level changes</td>
<td>Water flow velocity and volume depend on water level on upstream side.</td>
<td>Water flow velocity and volume depend on water levels on upstream side.</td>
<td>Same as Full-width rock ramp</td>
</tr>
<tr>
<td>Benefits</td>
<td>Can be installed in long-narrow space and on steeper slope as compared with pool type.</td>
<td>No attraction flow needed because of a full-width entrance. Provides riverine habitat for many species including fish and mussels. Low construction cost. Effective in most vertical water ranges and discharges</td>
<td>Provides riverine habitat for many species including fish and mussels. Low construction cost</td>
</tr>
</tbody>
</table>

*Source of Photo: MAFF/Japan

Photo: "Masterclass in Fish Passage Engineering Design, Construction, Ecology and Monitoring" (Wayne Stancil)
<p>| Limitations | Generates turbulence in narrow fishways. Trash, debris, and gravels accumulate in fishway. Resting pools are necessary when the course is long. | Needs high quality large rocks (Rocks should be sized to withstand flood events.) Need regular maintenance, (Removal of debris, encroachment of weeds and movement of rocks) Roughness is decreased when rocks are submerged due to high water. | Needs high quality large rocks (Rocks should be sized to withstand flood events.) Needs regular maintenance, (removal of debris, encroachment of weeds and movement of rocks) Roughness is decreased when rocks are submerged due to high water. Limited vertical water range (Less effective at high flows) |</p>
<table>
<thead>
<tr>
<th>Fishway type</th>
<th>Bypass</th>
<th>Fish lift (Operation)</th>
<th>Fish locks (Operation)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Designed for specific structures</td>
<td>Weir height does not limit bypass type installation. However, this fishway type requires access to adjacent land.</td>
<td>Most suited to large and high dams</td>
<td>Most suited to medium/high dams (e.g., 5-14 m). Has also been used at low head (e.g., 3 m) structures.</td>
</tr>
<tr>
<td>Structure</td>
<td>Detour to connect upstream side with the downstream one. Uses natural materials such as rocks and stones to mimic natural river characteristics</td>
<td>After a specified period, the hopper is lifted over the wall and lowered into the water upstream of the dam. Fish are then released from the hopper.</td>
<td>Provides passage upstream through a series of hydraulically operated gates that regulate the water levels within the lock. Fish enter the lower section of the lock while the water level in the lock is equal to the downstream water level. After a set period, the fish lock is closed, and the water level is raised to be equal to the headwater storage level.</td>
</tr>
<tr>
<td>Hydrological characteristics</td>
<td>Creates varied water flow velocities (However, the hydrological situation depends on head water level and weir operation.)</td>
<td>–</td>
<td>–</td>
</tr>
<tr>
<td>Adaptivity to swimming characteristics</td>
<td>Suitable: Large, middle, and small fish, Demersal fish, Crustaceans</td>
<td>Suitable: Large, middle, and small fish, Demersal fish, Crustaceans</td>
<td>Suitable: Large, middle, and small fish, Demersal fish, Crustaceans</td>
</tr>
<tr>
<td>Adaptivity to water level changes</td>
<td>Water levels on upstream side of weir directly affect the velocity and volume of water flow in fishway</td>
<td>Does not depend on water level changes on upstream and downstream sides.</td>
<td>Same as fish lift.</td>
</tr>
<tr>
<td>Benefits</td>
<td>Simulates a natural channel and creates varied flows. Induces fish to swim downstream by increasing water flow. (Can prevent fish from entering irrigation offtakes or staying in reservoir.)</td>
<td>Attraction flow is not always required. Fish can move to the upstream side even though a dam is large and high.</td>
<td>Same as fish lift</td>
</tr>
<tr>
<td>Limitations</td>
<td>Fish easily detected by predators under low water velocity conditions. Requires large area of land adjacent to weir or reservoir.</td>
<td>Large construction and maintenance cost.</td>
<td>Large construction and maintenance cost</td>
</tr>
</tbody>
</table>
Annex 5: Culvert design

Barriers to fish migration
Culverts may create barriers to fish migration due to:
(1) High drop between the culvert exits and water surface
(2) Shallow water depth in front of the culvert entrance
(3) Lack of resting areas in culvert with excessive water velocity

(1) High drop between the culvert exits and water surface
Fish cannot enter culverts with excessive drop between the culvert exit and the water surface. Excessive water velocity in the culvert may also exceed fish swim capability.

(2) Shallow water depth in front of the culvert entrance
Steep culvert gradient, low head and tailwater and wide culvert outlets also block fish migration by generating shallow water depths on the downstream side of the culvert (Figure A5.2).

(3) Bank erosion at around the culvert exist and entrance
As the culvert width is less than full channel width, bank erosion may occur around the inlet or outlet (Figure A5.3).
Figure A5.3: Narrow culverts may increase bank erosion.

(4) Lack of resting areas and excessive water velocity
Excessive water velocity and turbulence are generated at high gradient culverts and at those providing low hydraulic roughness. High water velocity and turbulence may also erode stream banks and the stream bed downstream of the culvert outlet.

Remediation of culvert barriers
Measures to remediate existing culverts that are barriers to fish migration include:
(1) Install culvert below stream bed level
(2) Replace culvert to match stream or channel width
(3) Install fishways
(4) Add roughness (baffles or rocks)

(1) Installing culvert below ground level
Culverts should be placed below ground level for fish to smoothly pass without jumping (Figure A5.4)

![Culvert placed below ground level](image)

Figure A5.4: A culvert placed below ground level

(1) Replace culvert to match stream width
Culverts need to be sized to minimize bank erosion. Culverts closer in width to channel width will reduce erosion (Figure A5.5).

![Culvert matched to stream width](image)

Figure A5.5: Culvert replacement matches the stream width
(3) **Install fishways**

Fishways may also be installed downstream of culverts to reduce erosion and water velocity. In Lao PDR, a cone fishway is placed downstream of a culvert (Figure A5.6).

![Figure A5.6: Cone fishway downstream of a culvert in Lao PDR](source)

*Source of Photo (left): “Masterclass in Fish Passage Engineering Design, Construction, Ecology and Monitoring” (Tim Marsden)*

(2) **Add baffles or rocks**

Culvert baffles consist of a set of vertical protrusions from side walls that reduce water flow and velocity adjacent to the culvert walls and provide resting areas and migration pathways for fish (Figure A5.7). They are most suitable for application at floodgates where culverts are often used in association with gates.

![Figure A5.7: Culvert baffle fishway constructed on Marion Creek, Queensland, Australia.](source)
Rock can be placed in the bottom of a culvert to reduce water flow velocity and create resting areas for fish (Figure A5.8).

*Source of Photo: "Masterclass in Fish Passage Engineering Design, Construction, Ecology and Monitoring" (William Rice)

Figure A5.8: Rocks in a culvert
Annex 6: Temporary work (Dewatering and prevention of soil erosion and water contamination)

Dewatering
Dewatering keeps the work area dry and can be accomplished by pumping, partially closing the river or stream with large sandbags, or by diverting flow around the construction site through a bypass channel. Pumping is suitable for a small work area. Pumps should be sized in accordance with an amount of predicted dewatering, and a backup pump should be installed on site. Soil excavation during construction results in turbid water, impacting aquatic fauna. Pumps should be placed in clear or surface waters to minimize sediment transport (Figure A6.1).

Large sandbags can be employed to separate work areas from the river or stream. However, damaged sandbags result in sand entering the water body (Figure A6.2). The contractor should take special care not to damage sandbags during placement or removal.

A bypass channel is also suitable to dry a work area (Figure A6.3). If the contractor blocks the entire river or stream for fishway construction, a bypass channels needed to detour water around the site. The contractor should ensure that scour does not occur at the point of an outflow from the channel and soil erosion from banks of the channel does not generate (Figure A6.4). In a large work area, a bypass channel is also utilized to drain pumped-up water from a work area.
Prevention of soil erosion and water contamination

Site excavation may cause soil erosion, particularly under rainy or windy conditions. (Figure A6.6). Three steps may be taken to curb soil erosion at the construction site:

- Prevention of soil erosion on the construction site
  Vinyl sheets, fiber mats, or blown seeds can be placed on steep slopes. (Figure A6.7 and A6.8).

- Prevention of turbid water outflow
  The contractor must prevent outside effluent from entering the construction site and prevent turbid water from the site from entering the river or stream.
Prevention measures against turbid water are as follows:

- **Small berm**
  A small berm enclosing the construction site, blocking turbid water outflow to the outside and effluent to the site (Figure A6.9).

  ![Figure A6.9: Small berm *Source of Photo: MAFF/Japan](image)

- **Drainage channels**
  Drainage channels (Figure A6.10) can be used to route rainwater and minimize erosion.

  ![Figure A6.10: Drainage channel for temporary work *Source of Photo: MAFF/Japan](image)

- **Sedimentation ponds**
  Sedimentation ponds may be used to allow soil particles to separate from outflow water (Figure A6.11; the contractor must check the quality of water in the pond before releasing it to the river or stream).

  ![Figure A6.11: Sedimentation Pond *Source of Photo: MAFF/Japan](image)
- **Floating boom**

Floating booms are placed at the construction site to block eroded materials and trash being transported from the upstream side (Figure A6.12). Floating booms may also be placed on the downstream side of the construction site to reduce transport of eroded materials and trash (Figure A6.13).

*Source of Photo: “Masterclass in Fish Passage Engineering Design, Construction, Ecology and Monitoring” (Wayne Stancil)*
### Annex 7: Design tolerances for vertical-slot cone and rock-ramp Fishways

<table>
<thead>
<tr>
<th>Design item</th>
<th>Vertical slot &amp; cone tolerance</th>
<th>Rock-ramp tolerance</th>
</tr>
</thead>
<tbody>
<tr>
<td>Invert of hydraulic control point</td>
<td>±2mm for design</td>
<td>±5 mm from design</td>
</tr>
<tr>
<td>Variation in slot width</td>
<td>±1.5% for adjacent baffles</td>
<td>Match cross-sectional area of flow pathways throughout the fishway</td>
</tr>
<tr>
<td></td>
<td>±3% along full length of fishway</td>
<td></td>
</tr>
<tr>
<td>Hydraulic head loss</td>
<td>±5% from design per baffle</td>
<td>No head loss is to exceed 20% of design (e.g., no head loss &gt; 120 mm in a fishway designed for 100 mm)</td>
</tr>
<tr>
<td>Baffle and rock angle</td>
<td>Angle of water jet conforms to design standard without water jet turning directly downward, creating “Carryover” water velocity at next slot</td>
<td>In lateral-ridge-rock fishways, the rocks in adjacent pools should not be aligned to limit carryover water velocity</td>
</tr>
</tbody>
</table>


## Annex 8: Summary of Potential Impacts of fishway construction and solutions

<table>
<thead>
<tr>
<th>Impacts</th>
<th>Impact reduction tools</th>
<th>Solutions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fishway construction could affect fish migration and damage environmental conditions in water bodies. (Step 2.4)</td>
<td>Construction timing</td>
<td>- Restrict construction works to months of the least fish movement and low flows to minimize impacts on fish and water quality.</td>
</tr>
<tr>
<td>Wet conditions at construction site delay construction work and lower construction quality. (Step 2.4)</td>
<td>Dewatering</td>
<td>- Pump water out of work area (Pump should be elevated to remove surface water only.)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Partially block construction site with large sandbags (Monitor for loss of sand into water)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Divert flow around construction site through a bypass channel (Monitor for scour at outflow from channel and install erosion control materials)</td>
</tr>
<tr>
<td>Excavation in construction site erodes soil and causes sediment flow into water body (Step 2.4)</td>
<td>Prevention of soil erosion and water contamination</td>
<td>- Line vinyl sheets or fiber mats or blow seeds on slopes etc. to curb soil erosion.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Enclose construction site with small berms to block turbid water outflow and inflow.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Construct drainage channels to drain rainwater and spring water from construction site to the outside.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Construct a sedimentation pond to reduce outflow water turbidity.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>- Place floating booms to block eroded materials and trash transport from upstream to downstream sides.</td>
</tr>
<tr>
<td>Water is contaminated by construction equipment. (Step 2.4)</td>
<td>Wash equipment</td>
<td>- Wash construction equipment daily after use.</td>
</tr>
<tr>
<td>Structure inspection (Step 2.5)</td>
<td>Site inspection</td>
<td>- Obtain structure blueprints and inspect a construction site.</td>
</tr>
<tr>
<td>Riverbeds and banks are damaged by construction. (This impacts fish habitat as well as flow.) (Step 2.4)</td>
<td>Restore waterway bed and banks</td>
<td>- Restore riverbeds and banks to original profile and stability after construction</td>
</tr>
</tbody>
</table>
Annex 9: Trap setting and sampling

Traps should be set as paired replicates of the fishway exit versus its entrance. The required period for the sampling will vary, depending on the size and complexity of the site being studied. The sampling should be conducted for 8-10 days in both the rainy and dry seasons respectively. The minimum sampling that could be undertaken would consist of five days for each sampling occasion if there is limited budget or labor for monitoring. This five-day monitoring period is suitable for small structures.

A typical five-day sampling would be conducted in the morning, afternoon, and nighttime because the number of fish and species are different in each time frame. For example, Catfish and Sheatfish are active in the nighttime. The recommended sampling period and times per day are two hours and eight times as indicated in the following table (Table A9.1). After the two-hour sampling, the number of fish, species, sizes, and weights should be recorded.

The total quantity of replicates will be proportional to the size and complexity of the fish passage. Larger structures may require many replicates over the entire migration season.

<table>
<thead>
<tr>
<th>Table A9.1: Trap locations for an example five-day sampling regime of the entrance and exit of a low level fishway</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Period</strong></td>
</tr>
<tr>
<td>------------</td>
</tr>
<tr>
<td>Morning</td>
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<td></td>
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<td>Afternoon</td>
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<td>Nighttime</td>
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</tbody>
</table>

Traps used in fishway sampling are of a mesh aperture suitable to capture all species and size classes likely to ascend the fishway. The traps collect fish from the full width of the fishway and are set either directly at the entrance to the fishway or directly above the exit of the fishway. These traps should be constructed using a steel frame covered by fine mesh netting, suitable to trap small, bodied fish (Figure A9.1).

Figure A9.1: Fish tap with a steel frame covered by mesh netting.

The trap must be set upstream of the fishway under full operating conditions to determine if the fishway is working correctly.
Cones at the entrance of the trap should extend the whole height of the trap. The cones taper into the body of the trap and are used to reduce fish escapement back out of the entrance of the trap once the fish have entered the trap. Electrofishing/cast netting, if used, will collect fish from directly below the fishway in place of the bottom trap if it is not feasible to use a trap e.g., due to shallow water depths at the locations. Electrofishing sampling consists of sweeps across the pool below the fishway with the electro fisher unit, while cast netting requires ten casts into the waters across the width of the fishway entrance.

All fish collected with traps, electrofishing or cast netting should be identified to species level, measured for length, and recorded on data sheets. Water conditions such as quality and flow should also be recorded each day. All fish species counts and length data, together with water quality data, flow and fishway function observations should then be entered into a computerized database. The biological data collected is analyzed to look at any differences between fish caught entering the fishway and those successfully exiting the fishway. Once analysis has been completed a technical report outlining the results of the monitoring and success of the fishway at passing fish and any modifications required to improve the fishway is completed.
Annex 10: Methods of fish community sampling

This fish community data can be collected in a variety of ways, gill, seine or drum nets, electrofishing or fish traps would all be suitable techniques. The sampling may also collect fisheries data from local fisher persons who fish in the vicinity of the fishway. All data, however, should be collected in a manner that is easily compared over the life of the sampling program. As such the method for data collection should be fixed at the commencement of the sampling program.

A minimum direct sampling program could consist of gill net sampling with a range of mesh sizes from 1” to 6”, at 4 locations downstream and 4 locations upstream of the fishway twice per year in each season, i.e., the rainy season and dry season, over three years (Table A10.1, Figure A10.2 and A10.3). Gill nets are set for a standard period at all locations (e.g., three hours per net per and per day site) in a closely spaced (from 5 to 10 km) sampling run (i.e., over 4 days). Much like the fishway sampling, depending on the size of the system and complexity of the fishway and fisheries this sampling program may need to be extended to more sites, or a longer period. Each site needs to have a monitoring program developed that is suitable for these factors and will vary from the options presented here. This survey can be also utilized to confirm the results of Attribute 13 “Productivity Benefits of Constructing a Fishway”.

Table A10.1: Gill net locations over a typical four-day sampling run.

<table>
<thead>
<tr>
<th>Time</th>
<th>Day 1</th>
<th>Day 2</th>
<th>Day 3</th>
<th>Day 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morning</td>
<td>Site 1</td>
<td>Site 3</td>
<td>Site 5</td>
<td>Site 7</td>
</tr>
<tr>
<td></td>
<td>Site 2</td>
<td>Site 4</td>
<td>Site 6</td>
<td>Site 8</td>
</tr>
<tr>
<td>Afternoon</td>
<td>Site 1</td>
<td>Site 3</td>
<td>Site 5</td>
<td>Site 7</td>
</tr>
<tr>
<td></td>
<td>Site 2</td>
<td>Site 4</td>
<td>Site 6</td>
<td>Site 8</td>
</tr>
<tr>
<td>Nighttime</td>
<td>Site 1</td>
<td>Site 3</td>
<td>Site 5</td>
<td>Site 7</td>
</tr>
<tr>
<td></td>
<td>Site 2</td>
<td>Site 4</td>
<td>Site 6</td>
<td>Site 8</td>
</tr>
</tbody>
</table>
Figure A10.2: Image of gill net sampling *Source of Photo: “Joint Environment Monitoring of Mekong Mainstream Hydropower Projects”. (MRC.2018)

Figure A10.3: Typical sampling locations associated with the construction of a new fishway. Sites are located upstream and downstream of the fishway location.

All fish collected in the fish community sampling are identified to species level, measured for length, and recorded on data sheets. Water conditions such as quality and flow are recorded at each sampling location. All fish species counts and length data, together with water quality data, flow and fishway function observations should then be entered into a computerized database. The biological data collected is then analyzed to look at any differences between fish caught upstream and downstream of the fishway before and after construction. In general, sampling should show that there are more fish and species accumulating below the barrier prior to fishway construction and that these accumulations reduce after construction so that fish numbers are more evenly spread across sites (Figure A10.4).
Figure A10.4: Idealized sampling results from sites downstream (left) and upstream (right) of a fishway before (top) and after (bottom) construction. After the successful construction of the fishway the number of species able to move into the upstream waters increases, improving productivity in the system.
Annex 11: Sample questions of socio-economic survey

Here are sample questions on differences before and after a fishway installation:

✔ Is there difference in the number of fish captured by fishers?
✔ Is there difference in the captured species?
✔ Is there difference in the weights of captured fish?
✔ Is there difference in the observed fish population at around a barrier?
✔ Do fishers increase their income?
✔ Is there any difference in fish migration pattern?
✔ Is there difference in time spent fishing?
✔ Is there difference in use of captured fish? Are fish sold in a market, consumed in house, gifted to relatives or friends?

Table A11.1: Sample of a record table for socio-economic survey

<table>
<thead>
<tr>
<th>Fishing location</th>
<th>Species name</th>
<th>Number of captured fish</th>
<th>Total weight (Kg)</th>
<th>Weight of eaten fish in house (Kg)</th>
<th>Weight of gifted or given fish (Kg)</th>
<th>Fish weight sold in a market (kg)</th>
<th>Fish price sold (USD/kg)</th>
</tr>
</thead>
<tbody>
<tr>
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</tbody>
</table>
## Annex 12: Key Performance Indicators (KPIs) for Inspection, with common problems and adjustment

<table>
<thead>
<tr>
<th>KPI</th>
<th>Problem</th>
<th>Cause of problem</th>
<th>Adjustment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Structural stability</strong></td>
<td>Any structural failure or damage</td>
<td>Fish cannot enter, ascend, or descend fishway.</td>
<td>Design or construction failure. Flood damage.</td>
</tr>
<tr>
<td></td>
<td>Erosion and undermining of fishway channel and/or entrance</td>
<td>Potential failure of fishway channel</td>
<td>Design or construction failure. Unforeseen flow patterns after construction.</td>
</tr>
<tr>
<td></td>
<td>Erosion of streambed downstream, with drop in downstream water level.</td>
<td>Fish cannot enter fishway because it is elevated above downstream water level.</td>
<td>Inadequate protection of riverbed and banks during construction. Flood damage. New weir captures sediment, creating erosion downstream as river regains suspended sediment load. Natural erosion.</td>
</tr>
<tr>
<td><strong>Regular Maintenance</strong></td>
<td>Assess floating debris and trash rack in fishway channel, especially upstream exit. Measure head losses at exit, entrance, and all baffles.</td>
<td>Fish cannot enter, ascend, or descend in a fishway.</td>
<td>Unexpectedly high debris loads. Lack of trash rack/debris boom.</td>
</tr>
<tr>
<td></td>
<td>Assess sediment (sand and gravels) accumulation in the fishway.</td>
<td>Fish cannot enter, ascend, or descend fishway.</td>
<td>Unexpected sediment load. Lack of fishway maintenance.</td>
</tr>
<tr>
<td>KPI</td>
<td>Problem</td>
<td>Cause of problem</td>
<td>Adjustment</td>
</tr>
<tr>
<td>-----</td>
<td>---------</td>
<td>------------------</td>
<td>------------</td>
</tr>
<tr>
<td>Measure depths at exit, entrance, and all fishway pools.</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Fishway Channel</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Excessive turbulence</td>
<td>Fish fail to ascend fishway.</td>
<td>Hydraulic design incorrect. Unexpected additional discharge enters fishway from the side (Figure 11.1). High turbulence used in design criteria. Construction error.</td>
<td>Redesign/modify baffles to reduce discharge. Redesign fishway with larger pools and lower gradient. Modify fishway channel to prevent extra discharge from entering Correct in defects liability period</td>
</tr>
<tr>
<td><strong>Fish Entrance and Attraction</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fish cannot locate fishway entrance and remain downstream of the weir and fishway.</td>
<td>Migration and life cycle not completed.</td>
<td>Insufficient or badly managed attraction flow.</td>
<td>Increase discharge from gates adjacent to fishway. Relocate fishway entrance to the fish accumulation zone. Add auxiliary water to fishway entrance with modification of entrance size and shape.</td>
</tr>
<tr>
<td>Turbulence masks fishway entrance.</td>
<td>Strong flow from a gate or weir crests adjacent to fishway entrance.</td>
<td></td>
<td>Adjust gate operation to reduce flow adjacent to fishway; or modify weir crest with a protection block.</td>
</tr>
<tr>
<td>Recirculation flows direct fish away from fishway entrance.</td>
<td>Operation of gates creates recirculation. Not examined sufficiently in design, with large spaces included downstream of fishway, generating recirculation flow.</td>
<td></td>
<td>Modify gate operation. Fill spaces near banks in.</td>
</tr>
<tr>
<td>KPI</td>
<td>Problem</td>
<td>Cause of problem</td>
<td>Adjustment</td>
</tr>
<tr>
<td>----------------------------------</td>
<td>-------------------------------------------------------------------------</td>
<td>----------------------------------------------------------------------------------</td>
<td>---------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Downstream migration</td>
<td>Fish survival though weir. Fish are injured or die either: i) passing through an undershot gate, or ii) passing onto a shallow downstream apron.</td>
<td>Use of undershot gate. Downstream depth on apron is too shallow.</td>
<td>Install overshot gates. Increase tailwater (full-width rock-ramp is one solution)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Few fish passing downstream</td>
<td>Fish staying in the static water in the upstream pool.</td>
<td>No flow patterns to guide fish downstream. Insufficient flow passing downstream.</td>
<td>Increase water flow to gate designed to pass fish or flow toward fishway. Open gates to release fish.</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Loss of fish into upstream offtakes</td>
<td>Data on fish entry into offtakes Fish enter offtakes on the upstream side of a fishway. Migration and life cycle not completed.</td>
<td>Offtake entrance is too close to fishway exit. Unscreened offtakes.</td>
<td>Place fishway entrance far from an offtake. Screen offtake entrance.</td>
</tr>
</tbody>
</table>

Figure A12.1: Example of unexpected additional discharge entering a fishway from the side potentially causing increased turbulence. A higher side wall would fix this problem.
Annex 13: Downstream erosion

Downstream erosion can cause two issues:

1. Erosion under and around the fishway channel, especially the downstream section, and
2. Erosion of riverbed and loss of tailwater.

The solution to the first problem is localized refurbishment. There are two solutions to a loss of tailwater:

i) Extend the fishway channel (Figure A13.1),
ii) Rehabilitate and secure the riverbed and raise tailwater to original (design level).

Figure A13.1: Extension of a fishway to a riverbed

Figure A13.2: Fish cannot ascend due to subsidence

*Source of Photo: MAFF/Japan

Figure A13.3: Extend fishway to fill gap (Rehabilitation)

*Source of Photo: MAFF/Japan

Figure A13.4: Fill a gap by blocks

Figure A13.5: Fill a gap by blocks

Source of Photo: MAFF/Japan
Protection blocks functioning as a fishway can be installed in the entire riverbed downstream of the weir in the case of subsidence of the entire riverbed in front of the weir (Figure A13.7 and A13.7).

![Figure A13.6: Riverbed before rehabilitation](source) ![Figure A13.7: Riverbed protection](source)  
*Source of Photo: MAFF/Japan*  

When the water level of a river decreases too much, riverbed protection blocks may emerge on the surface of the water, which prevents fish from accessing the fishway entrance. In this case, passage should be placed between the apron and riverbed protection blocks to induce fish to the fishway entrance (Figure A13.8).

![Figure A13.8: A passage between the apron and riverbed protection](source)