Mekong River Commission
Initiative for Sustainable Hydropower

Review of Existing Knowledge on the Effectiveness and Economics of Fish-Friendly Turbines

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Executive Summary

This document reviews existing knowledge on the effectiveness and economics of fish-friendly turbines (FFT) by providing current information on:

- FFT technologies and research at different scales, deploying different designs and approaches.
- Ways that FFTs influence fish injury and survival under different riverine environments and in systems with varying fish biodiversity.
- Economic trade-offs for different types and scales of turbines at different hydropower projects.
- Applicability of FFT technologies and the trade-offs for deploying different designs and approaches at hydropower projects on the main stem of the Lower Mekong River

Mekong River Environment

Continued hydropower development is planned for the Lower Mekong Basin (LMB). Eleven hydropower projects are proposed for the main stem of the river, with seven in Lao PDR, two in Cambodia, and two shared between Lao PDR and Thailand.

The LMB supports the world's largest inland fishery, essential for the livelihood, nutrition, and food security for a large population. Indigenous fish species are numerous, variable and part of an important bio-diversity. Migratory behaviour is complex, with three distinct, but inter-connected, general fish migration life histories evident, each involving multiple species and movements between the main river, tributaries and floodplains. Downstream fish passage will need to address these system characteristics as well as the wide diversity of fish species, ranging from the very large fish, like the iconic giant Mekong catfish to very small fish eggs and larvae

Creating barriers to flow on the Mekong River will cause disruptions to fish migration behaviours and could seriously impact the associated ecosystem. Establishing facilities that enable the upstream and downstream passage of fish past hydropower projects is important in order to manage the overall migration effectively. Historically, much research has been undertaken on upstream fish passage and many such facilities are in place globally, but there is much less understanding of the effects on fish passing downstream. This report is focused primarily on *downstream* fish passage through hydraulic turbines. Upstream fish passage is the subject of a related report for the MRC by Schmutz (2014, in press).

Downstream Fish Passage

Downstream passage of fish, over, around or through a barrier to flow (dam, weir or diversion), poses challenges as hydrologic, hydraulic and geomorphologic conditions vary considerably from natural river systems. Even when alternate routes are available, some fish will likely pass through the turbines and be subject to potential injury mechanisms such as rapid pressure decreases, strike, cavitation, and turbulence.

A holistic approach to the downstream passage of fish should be a component of the environmental assessment for any new hydropower projects on the Mekong River, with the outcomes being part of the mitigation strategy for the identified impact. The approach should cover all relevant fish species, all temporal variations in migration and flow characteristics and all reasonable means to pass fish downstream through the structure, including, but not necessarily limited to the turbines.

However, because of the wide diversity and number of fish species in the LMB, it will be challenging to identify particular species of interest for turbine design. In other words, it may be difficult to design a turbine that will provide improved fish passage for all species. A design that will provide improved fish passage for a few key species or functional group(s) may be more attainable.

Experiences from other Regions and River Systems

Much of the research to date on downstream fish passage has been focused on North American and European fish species. On this basis significant research and testing would be required to support the specification and design of FFTs that would minimize damage to fish in the LMB. This is compounded by the LMB supporting such a very large number of species, most of which are dissimilar to species that have been studied to date in these other locations.

Fish Passage through Hydraulic Turbines

Nearly all the significant research to date covering turbine design to improve fish passage has been undertaken based on juvenile salmon in the USA. This has led to the development of sophisticated equipment and methodologies, as well as extensive field and laboratory experience to understand fish behaviour. It has also provided the impetus for improved materials and technology in turbine engineering and manufacture. These advancements will be most useful in studying the issues and improving the performance of fish passage through hydraulic turbines in the LMB.

Effectiveness of Fish Friendly Turbines – Minimum Gap Runner (MGR) Turbines

Four projects on the Columbia River and its tributaries with large MGR turbines have shown improved survival rates for juvenile salmon and improved power output compared to conventional designs. The majority of the proposed hydropower projects along the Lower Mekong River include Kaplan turbines and these could be modified as MGR units or the more advanced Ice Harbor designs.

Effectiveness of Fish Friendly Turbines - Ice Harbor Turbines

The Ice Harbor Hydropower Project is undergoing refurbishment and provided an excellent opportunity to design and test large turbine runners with an emphasis on fish passage. The entire water passageway has been investigated for fish passage improvement.

The technical results to date have advanced understanding of the relationship between strike and flow quality and how leading-edge strike probability is governed by blade number, rotational speed and fish length. Considerable testing has already been undertaken, and is continuing, to examine the performance of these turbines in regards to fish passage. Results from turbine physical modelling to date suggest that a collaborative approach, between research scientists and engineers, and between the project owner and the equipment manufacturer, is effective in the design of turbine runners for safer fish passage and increased efficiency.

Effectiveness of Fish Friendly Turbines - Bulb Turbines

A few of the units presently proposed for the hydropower projects on the Lower Mekong River are or could incorporate Bulb turbine technology. Bulb units are considered to be intrinsically fish-friendly, having a horizontal axis arrangement providing reasonably linear flow, low turbine rotational speed and a minimum number of turbine blades. It is expected that modifications derived from studies for the MGR or Ice Harbor turbine designs to improve their fish-friendly attributes would generally be transferrable to Bulb units.

Effectiveness of Fish Friendly Turbines - Alden Turbines

The Alden turbine has not been yet been proven at a prototype level and is not ready for commercial deployment. Presently, the unit is only applicable for small scale hydro.

Significant levels of research indicate that fish survivability rates for the Alden Turbine exceed 97% due to improvement in strike and shear forces under certain conditions. However, it is unclear what the level of barotrauma may be expected in a full-scale deployment.

Economic Considerations

There is little published information on costs of the different types and scales of FFTs.

The supply and installation costs of large MGR Kaplan turbines and the Ice Harbor designs for new powerplants on the Lower Mekong River would be expected to be similar to those of a conventional design. However, there may be extra costs during the study, design and testing phases. A significant economic benefit has been found as they are generally more efficient than conventional designs.

While there are no examples of Bulb turbine units being specifically designed to improve their fish friendly attributes, cost and performance outcomes are expected to be similar to standard designs.

The supply and installation costs of an Alden turbine are reportedly significantly higher than for Kaplan and Bulb turbine units, however, these could be balanced with consideration of a life-cycle cost analysis.

Applicability of Fish-Friendly Turbines for Hydropower Projects in the Lower Mekong River

Global studies have shown that FFTs can improve fish passage survivability rates, mainly for juvenile salmonid of about 200mm length. These studies have been supported by detailed analysis, sophisticated model testing and major monitoring programs, over a number of years, costing many millions of dollars. Focused research work is required before applying lessons learned from this significant levels of global investment in turbine technology and fish passage research, study and testing, to the LMB environment.

Kaplan or Bulb turbines are currently proposed for the hydropower projects on the mainstream of the Lower Mekong River. To enhance fish-friendly attributes, their application would need to incorporate appropriate design parameters based on migrating fish and site conditions. These designs would need to include the full water passage from intake to tailwater and be based on laboratory studies, computational fluid dynamic (CFD) analysis and possibly physical model testing.

Selecting fish-friendly attributes to incorporate into the turbine designs for hydropower projects on the Lower Mekong River will be a challenge. Designs will have to take into account the large variety of species and their respective migratory life histories, leading to improved performance with respect to survivability rates.

Research Requirements

Knowledge gaps and uncertainties around the need and potential for installing FFTs in hydropower units on the Lower Mekong River have been identified and suggestions made to address these issues.

The knowledge gaps and uncertainties relating to migrating fish species in the LMB include:

- Baseline information on the fish species that would be affected at each proposed hydropower plant during their migration, together with their characteristics and behaviours. (Obtained through field programs, monitoring and laboratory testing/research)
- Baseline information on the migration cycles of the fish species that would be affected at each proposed hydroplant. (Obtained through field programs and monitoring)
- Understanding the potential impacts on these fish species as a result of passing through turbines. (Obtained through laboratory testing/research)

Closing these gaps and reducing uncertainties will be a very significant task, requiring both considerable study and research effort. The MRC could play a role in scoping and sponsoring this research on behalf of all Member Countries.

The key to selecting FFTs for the Lower Mekong River hydropower plant is to prove their performance with respect to survivability rates for the respective migratory fish species. In terms of research, including the barotrauma effect of the turbines, the main areas to study cover:

- Applications of Sensor Fish technology at dams currently present within the region to characterize turbine passage conditions

- Laboratory studies investigating the influence of turbine passage conditions on fish. This includes examining damage such as barotrauma, strike and shear forces from:
  - Fish ecology and behaviour;
  - Pressures (rate and range) fish are exposed to when passing through the turbines
  - The rate of injury and mortality and the range and rate of exposures to rapid pressure changes, turbine strike, exposure to shear and turbulence for different species
- CFD and hydraulic modelling to improve turbine and water passage design

In general it is not feasible to measure the turbine-passage survival of every species of fish in every hydroelectric turbine design. To support the research activities two analytical approaches should be considered:

- Research that relates the traits and physiology of fish to the conditions they could be exposed to during turbine passage. An example of this is the Traits Based Assessment (TBA) process.
- The use of models that include input from several sources. An example of this is the Hydro Turbine Biological Performance Assessment (BioPA) Tool

However, because of the complexity, costs and timelines required to undertake research and studies, considerations should also be given to a process that focuses on key issues, and prioritizes them based on their importance to both environmental and social factors and to bio-diversity.

Other Downstream Passage Options

FFT are not the only way to help fish pass downstream. Other facilities that can be used in combination with, or as viable alternatives to, passage through turbines. The proven options fall into three main categories:

- Passing fish through or over discharge facilities, such as outlets, sluices, locks and spillways.
- Diverting fish to surface collection devices with physical transfer downstream via trucks or barges.
- Diverting fish to bypass channels or pipes.

All alternatives should be considered for Lower Mekong River migrating fish species, and it is equally important that estimates of survival rates be considered for each.

Guidelines

Guidelines are an important means to help hydropower developers comply with environmental standards and, in the Mekong and MRC context, with the agreed Preliminary Design Guidance (PDG) for mainstream dams. A Guide covering fish friendly turbine would support the PDG by providing considerations that developers and Member Countries may need to take into account when striving for sustainable hydropower.

1 Background

1.1 Overview of Fish-Friendly Turbines

Dams and other barriers to river flow can alter the natural migration of fish. Where hydropower plant are associated with dams, migrating fish may pass downstream through the hydraulic turbines, unless prevented by intake screens or similar devices, although these may not be effective for guiding larval fish. As fish pass through operating turbines of various types, the complexity of the structures, flows and pressure change can result in injury and mortality. Providing safe passage for downstream migrating fish is an important consideration in the study, design, construction and operation of hydropower plant.

There are alternative ways to pass fish downstream that avoid the hydraulic turbines and these should be investigated as part of the project environmental studies. Fish can often be routed away from the turbines by passing water over spillways or diversion through bypass systems. However, these methods may not be effective if the spillway design is inappropriate or the hydroplant operates near continuously. During peak migration periods, alternative fish passage methods may be used to pass fish downstream.

In response to concern about the effects on fish passing through turbines, some countries have funded special programs to identify options for passing fish with minimal negative impact. In the USA, the Department of Energy (USDOE) Advanced Hydropower Turbine Systems (AHTS) program was funded from 1995 to 2005 and restarted as the Water Power Program in 2009. Together with the US Army Corps of Engineers (USACE) Turbine Survival Program, the focus was on better understanding turbine hydraulic conditions and the mechanical and hydrodynamic factors that could cause injury and mortality to fish. This R&D was primarily focused on juvenile salmon in the NW of the USA, and in turn led to new turbine designs that are likely to improve fish survival rates (Čada Čada2001; Dauble 2007). The starting of similar programs in the Mekong region could provide similar insight into the expected damage that Mekong species may incur when exposed to passage through hydro projects, and specifically hydraulic turbines. This may help guide selection, design and operation of turbines that would be fish-friendly to Mekong specific species.

Research efforts in the USA have been exploring modifications to axial flow turbines, such as the Kaplan turbine, that are prevalent in hydropower dams on the Columbia and Snake Rivers. This research has led to a few “fish-friendly” designed turbine units, such as the minimum gap runner (MGR), being deployed as part of equipment refurbishment programs. Research on these MGR turbines has shown an improved passage environment than the units they replaced (Dauble 2007). Design modifications are continuing on units to replace ageing Kaplan turbines over the next few years. However, to date, no turbines with specific “fish-friendly” attributes have been installed as part of a new hydroplant development.

While research into new, more fish-friendly turbine designs continues, information on the vulnerability of non-salmonid fish species to turbine passage is very limited. Research is also needed to ensure minimal damage to fish during the entire passage from intake to tailrace, and not just through the turbine, as well as covering different species of fish and the full range of life stages. Improvements in turbine design and operation, as well as the techniques used to understand the turbine environment and the damage to fish during turbine passage, will all contribute toward fish passage survival during downstream migration. However, as this review clearly indicates, there is an urgent need for a better understanding of how Mekong basin fish species will be influenced by the construction of hydropower dams.

1.2 Objectives of the Review

This review was designed to address the objectives provided in the MRC Terms of Reference (ToR):

- Provide documentation of available fish friendly turbine (FFT) technologies and research at different scales and types.
- Provide an understanding of the possible influence of FFT on fish injury and survival under different riverine environments and in systems with varying fish biodiversity.
- Document case studies on economic trade-offs for different types and scales of turbines at different types of hydro projects.
- Provide documentation, with clear graphics, of FFT technologies and the trade-offs for deploying different designs and approaches.

1.3 Methodological Approach

The methodological approach followed to meet the objectives of this review, included:

- Collecting and analysing existing knowledge and research on FFT's for their effectiveness and economics.
- Analysis of the applicability of internationally gathered experience to the fish fauna of the Mekong River Basin and the economic situation of hydropower development.
- Identifying knowledge gaps and uncertainties concerning FFTs in the Mekong River Basin.
- Engaging with Mekong River Commission (MRC) staff and stakeholders and discussing the findings of the study.

1.4 Outputs of the Review

This Review Paper provides the following outputs:

- A literature review including information gathered from equipment suppliers and research groups.
- Documents and information from interviews with project owner/operators and research groups.
- Information from regions similar to the Mekong River Basin to determine if information from those regions may be applicable.
- Case histories and comparative analysis of the biological and economic effectiveness of FFTs for different scales and types.
- The results of the review, with graphical presentations of biological and economic trade-offs for different scales of the FFTs
- A presentation to line agencies and consultants and developers/operators in a designated MRC workshop or event (as required by MRC)

2 Mekong River Hydropower Development

2.1 Introduction

The Mekong River rises in China and flows through Yunnan Province into Lao PDR, Cambodia and the Delta in Vietnam. The Mekong is the twelfth longest river in the world (4,350 km) and the seventh longest in Asia, and is reported to have a biological diversity comparable to that the Amazon (Figure 1). The Mekong River and its tributaries play a very important role in terms of water resources and fisheries source for rural people of the Mekong River Basin.

Figure 1: Mekong Subregion

It is well documented that dams and barriers to natural river flow affect river ecosystems, which in turn will affect fish species and fisheries. For the Mekong River this will include:

- Creating barriers to fish migrations, which could threaten species and fisheries.
- Interrupting natural flood cycles.
- Impounding sediments behind the dams.
- Changing water temperatures throughout the water column, and that of released water.
- Changing the total dissolved gas content, as well as oxygen levels of the rivers.
- Changing compositions of river bed materials, which affects habitat.

2.2 Hydropower on the Mekong River Mainstream

Continued hydropower development is planned for the Mekong River Basin (MRB). China completed the first dam across the mainstream in 1995, followed by two others completed in 2003 and 2008. China also plans to build a further five hydro plants in the future. Downstream, more than one hundred new projects are proposed in the lower basin including Lao PDR, Thailand, Cambodia and Vietnam. Of these, eleven are planned for the mainstream of the river (Table 1), with seven in Lao PDR, two in Cambodia, and two shared between Lao PDR and Thailand. The mainstream of the Lower Mekong Basin (LMB) has a potential to produce over 13,000 MW of hydropower.

The potential of hydropower in the MRB is about 53 GW consisting of 23 GW in the Upper Mekong Basin (China) and 30 GW in Lower Mekong Basin (Lao PDR, Thailand, Cambodia and Vietnam).

Project name	Installed Capacity (MW)	Dam Height (m)	Live Storage (106m3)	Inundated Area (km2)	Rated Head (m)	Turbine Type (number)
Pak Beng	1230	62	442	110	31	Kaplan (10)
Luang Prabang	1410	68	734	110	40	Kaplan (10)
Xayabouri	1260	53	224	30	24	Kaplan (10)
Pak Lay	1320	54	385	110	26	Kaplan (10)
Sanakham	1200	38	106	N/A	25	Kaplan (6)
Pak Chom	1079	55	12	N/A	22	
Ban Koum	1872	53	0	158	19	Kaplan (20)
Lat Sua	800	27	NA	N/A	10	
Don Sahong	360	10.6	115	1.6	N/A	Bulb (4)
Stung Treng	980	22	70	N/A	15	Kaplan (16)
Sambor	3300	35	2000	880	33	Kaplan (26)

Table 1 Key Features of the 11 Proposed Mainstream Hydropower Dams in the LMB. (Halls 2009)

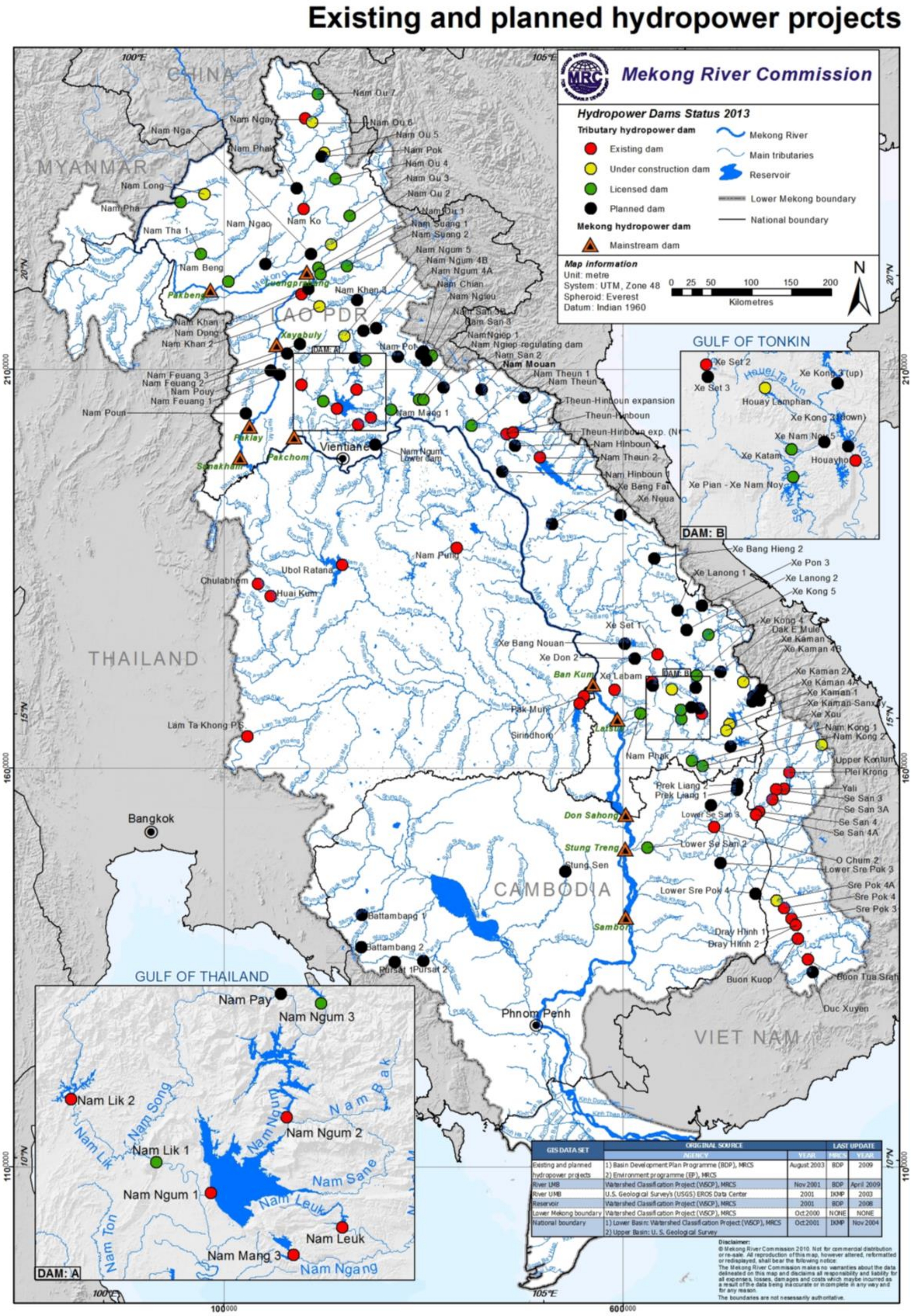


Figure 2: Locations of the 11 Proposed Hydropower Dams on the Mekong River

2.3 Hydropower on Mekong River Tributaries

Some hydropower has already been developed along the tributaries in the LMB and a significant construction program is underway. Thailand is reported to have developed all of its hydropower potential and Vietnam has built, or is currently constructing, most of its potential along the tributaries. Lao PDR has the largest remaining potential for hydropower development along the Mekong River tributaries, with many projects under construction or already licensed.

COUNTRY	HYDROPOWER PROJECTS SUMMARY	Project Update Status 2014				
		OPERATION	UNDER CONST.	LICENSE	PLANNED	TOTAL
Cambodia	Project	1	1	0	18	20
	Capacity (MW)	1	400	0	4,739	5,140
	Annual Energy (GWh)	3	1,954	0	22,400	24,356
	Investment (Million US$ 2014)	7	943	0	17,106	18,056
Lao PDR	Project	21	25	16	38	100
	Capacity (MW)	2,970	4,765	2,885	6,760	17,380
	Annual Energy (GWh)	14,282	19,564	14,870	31,159	79,875
	Investment (Million US$ 2014)	3,869	7,967	7,288	18,692	37,816
Thailand	Project	7	0	0	0	7
	Capacity (MW)	745	0	0	0	745
	Annual Energy (GWh)	904	0	0	0	904
	Investment (Million US$ 2014)	1,940	0	0	0	1,940
Viet Nam	Project	13	1	0	1	15
	Capacity (MW)	2,357	250	0	58	2,665
	Annual Energy (GWh)	11,184	1,056	0	181	12,422
	Investment (Million US$ 2014)	2,948	304	0	97	3,349
Lao-Thai	Project	0	0	1	1	2
	Capacity (MW)	0	0	660	1,079	1,739
	Annual Energy (GWh)	0	0	5,015	5,318	10,333
	Investment (Million US$ 2014)	0	0	1,788	2,452	4,240
Total	Project	42	27	17	58	144
	Capacity (MW)	6,072	5,415	3,545	12,636	27,668
	Annual Energy (GWh)	26,373	22,574	19,885	59,057	127,890
	Investment (Million US$ 2014)	8,764	9,213	9,076	38,347	65,401

Table 2: Project Status of Hydropower in LMB (MRC 2009a)

3 Mekong River Fish Migration

3.1 Introduction

Hydropower schemes and the selection of plant type should be designed to facilitate as far as possible the upstream and downstream migration of relevant fish species in order to avoid, minimise or mitigate impacts on fish. This is also a requirement of the MRC's *Preliminary Design Guidance for Mainstream Dams* (MRC 2009b). A sound understanding of the fish migration patterns is needed to best determine these design criteria.

There have been several studies on fish migration along the Mekong River, confirming that many fish species in the basin are migratory (Poulsen 2002). Many migrate long distances on a seasonal basis, often across international borders. Throughout the basin, the local population depends on migrating fish for food and livelihood. Water management projects such as hydroelectric dams could adversely impact migrations and negatively affect the livelihoods of a large number of people. MRC 2009b identifies key features of the Mekong River ecosystem that are important for the sustainability of migratory fish populations and their habitats, as well as ways in which available information about migratory fish can be incorporated into planning and environmental assessments.

3.2 Fish Migration

Three distinct, but inter-connected, general migratory life histories have been identified in the Lower Mekong River Basin, each involving multiple species (Poulsen 2002). These have been described as the lower (LMS), middle (MMS) and upper (UMS) Mekong migration systems, each of which have evolved in response to variations in hydrological and morphological characteristics. Within complex, multi-species ecosystems, such as the Mekong River Basin, management based on a single or small number of species would not be sufficient. Instead, a more holistic ecosystem approach is required for management and planning.

Poulsen (2002) details the important ecological, or ecosystem, attributes of migratory fish for each migration system. There is also an emphasis on maintaining critical habitats, the connectivity between them and the annual hydrological pattern responsible for the creation of seasonal floodplain habitats.

As part of the ecological system of the Mekong River, Singhanouvong (2012) describes the life cycle of many migrating fish as spawning, feeding, refuge and back to spawning. After spawning and early life, juveniles travel down into the Mekong River. Once within the mainstream, juveniles and adult fish migrate to find feeding and refuge habitat (deep pools). In due course, adult fish migrate back to the spawning areas. A schematic representation of potential fish migrations between critical habitats is shown on Figure 3 (Halls 2009)

Life cycles and the use of different critical habitats are often strongly associated with the hydrological cycle within the Mekong Basin. Migrating fishes respond to hydrological changes and use hydrological events as triggers for the initiation of their migrations. Many species initiate their migrations at the start of annual flooding and later initiate return migrations at the end of the flood, thus producing two peaks (Poulsen 2002). The spawning season is also tuned to river hydrology, with many species spawning at the onset of the monsoon season.

Appropriate design of hydropower facilities and fish-friendly turbines will be critical to maintaining fish species having these varied life history characteristics. While this review focuses primarily on fish-friendly turbine evaluation, details of fish migratory behaviours and habitats in the Mekong River Basin can be found in other reports (Poulsen 2002, Schmutz 2014).

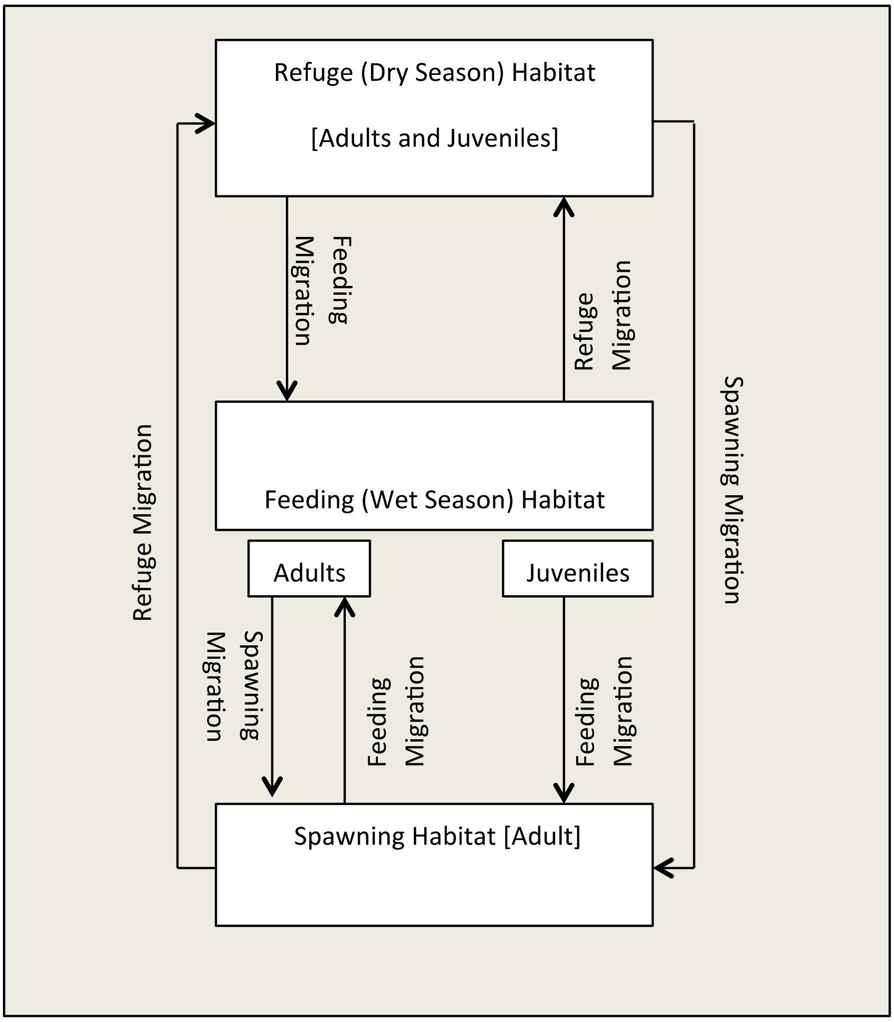


Figure 3: A Schematic Representation of Potential Fish Migrations among Critical Habitats (Halls 2009)

3.3 Migratory Fish Species

Mekong River fish species have been broadly classified into black-fishes and white-fishes (Poulsen 2002, Schmutz 2014, in press), based on their different life history strategies:

Black-fishes spend most of their life in lakes and wetlands on the floodplains adjacent to river channels and move into seasonally flooded areas. They are physiologically adapted to withstand adverse environmental conditions, such as low dissolved oxygen levels, which enable them to survive in wetlands and small floodplain lakes during the dry season. They are normally referred to as non-migratory, although they perform short seasonal movements between permanent and seasonally available habitats.

White-fishes, on the other hand, depend on habitats within the main river channels for the majority of the year. In the Mekong Basin, most white-fish species move into flooded areas during the monsoon season, returning to their mainstream river habitats when floodwaters retreat.

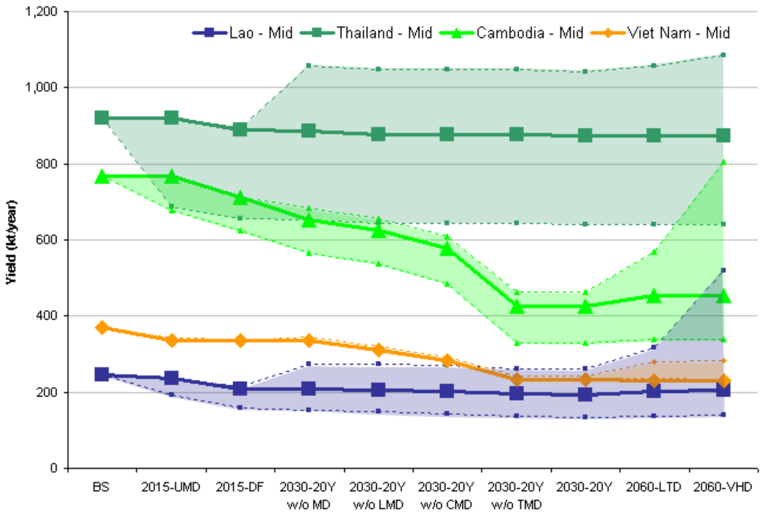
An additional, intermediate group has recently been classified as **grey-fishes**. Species of this group undertake only short migrations between floodplains and adjacent rivers and/or between permanent and seasonal water bodies within the floodplain.

3.4 Hydropower Impacts on Fish Migration

Due to the importance of migratory fish in the Mekong River Basin, there have been a number of assessments made of the potential impact of hydropower development on the river's mainstream (Dugan 2010, MRC 2011, ICEM 2010). These assessments were based on ecological and population characteristics of important fish species in the Mekong and comparable rivers, as well as experience designing and operating hydroelectric dams to minimize impacts on migratory fish populations.

Dugan (2010) concluded that dams currently planned for the Mekong River would likely have a major impact on the fisheries of the basin, primarily through disruption of upstream spawning migrations. Downstream drift of fish eggs and larvae that sustain fisheries recruitment would also be compromised. Dugan (2010) suggested that dams in the middle and lower reaches of the Lower Mekong Basin, and in the major tributaries would disrupt the longest migrations and recruitment to the lower reaches of the river. Although the impacts of dams higher in the basin and on individual tributaries would be restrictive to fish populations that use these reaches, these populations contribute substantially to fish production along large stretches of the river (Figure 4).

Figure 4: Estimated Reduction in Fish Productivity under different Mekong Development Scenarios (MRC 2011)



There are a number of examples of the potential impacts of hydropower on the Mekong River environment, which have concluded that their effect on migratory fish stocks could be significant (Poulsen 2002). Conditions that could change include:

- Hydrology and water levels for a significant distance upstream and downstream of proposed dam sites, including any deep pool stretches that would likely fill with sediment.
- Migration corridors between floodplain and refuge habitats.
- Passageways for larval drift, causing increased direct and indirect mortality.

To maintain fish diversity and limit social and economic impacts, research is needed to guide the design and management of hydropower facilities and other water infrastructure in the LMB.

3.5 Summary

The Mekong River Basin supports the world's largest inland fishery, essential for the livelihood, nutrition, and food security for its large population. In addition, the indigenous fish species are numerous, variable and part of important bio-diversity. Migratory behaviour among many species is complex. Creating barriers to flow on the Mekong River would cause disruptions to fish migration behaviours and could seriously impact the associated ecosystem. Establishing structures, systems and facilities that would enable successful downstream migration of fish is considered essential for maintaining the ecosystem and fisheries resources.

There are three relatively distinct fish migrating systems in the LMB, and the proposed hydropower plant will each influence at least one of these systems. Requirements for downstream fish passage will need to consider these system characteristics as well as the wide diversity of fish species, ranging from the very large fish, like the iconic giant Mekong catfish to very small fish eggs and larvae. Guidelines and design criteria that cover downstream fish passage with minimum damage to fish are necessary, and these should include considerations for fish-friendly turbines.

4 Downstream Fish Passage

4.1 Introduction

The downstream passage of fish, over, around or through a barrier to flow (e.g., dam, weir, water diversion structure), pose challenges as hydrologic, hydraulic and geomorphologic conditions vary considerably from natural river systems. Key effects include:

- Reservoirs create storages with slow moving water.
- Spawning and feeding areas can be inundated by reservoirs.
- Discharges from dams are drawn from varying depths, potentially affecting temperature and water quality.
- Areas upstream and downstream of barriers host numerous predators which target the fish entering and exiting bypass channels, discharge facilities and powerhouses.

Čada (2012a) notes the need for an improved understanding of the relative importance of causative factors that contribute to turbine passage mortality, so that turbine design efforts can focus on mitigating the most damaging components. It is further noted that present knowledge is based on studies of only a few species (mainly salmon and American shad) and that these data may not be representative of turbine passage effects for the hundreds of other fish species that are susceptible to downstream passage at hydroelectric projects. Tests of advanced hydropower turbines have been limited to seven species – Chinook and coho salmon, rainbow trout, alewife, eel, smallmouth bass, and white sturgeon. It is also noted that thirty species of fish have also been tested in conventional turbines in the USA (Čada 2012). This should be taken into perspective with the approximately 900 species of freshwater fish in the USA and over 14,000 globally.

4.2 Alternative Downstream Fish Passage Options

While FFTs are the prime focus of this review paper, it is important to appreciate that there are other fish passage options that have been developed to minimize the impact of hydropower plant on fish populations. These should be considered in any study and their design and operation should specifically accommodate the characteristics of the fish species, including their life-cycle form, physiology and hardiness. The various alternative approaches that have been developed, tested and implemented fall into the main categories of:

- Passing fish through or over discharge facilities, such as outlets, sluices, locks and spillways.
- Diverting fish to surface collection devices with physical transfer downstream via trucks or barges.
- Diverting fish to bypass channels or pipes.

Spillways, gates and other discharge facilities: During operation of the discharge facilities, flows pass over the spillway crest, under the gates, or through pipes, conduits or other outlets. This allows fish to pass downstream, but can result in detrimental impacts, similar in nature to those that can affect fish passing through turbines (i.e., fish may be exposed to a rapid decrease in pressure, collisions with structures, turbulence, and shear forces). In addition, discharge flows can increase levels of total dissolved gas levels in the tailrace, and river segment far downstream from dam. Exposure to these elevated gas levels can lead to gas bubble disease).

Surface water collectors: located in the reservoir, ideally create flow conditions that attract the fish, which in turn can be transferred to holding tanks on shore. Following monitoring of some fish to determine species and size metrics, the fish can then be trucked or barged downstream, often past the final barrier to river flow. This method is considered expensive as it requires significant on-going operation costs.

Fish diversion screens: come in a number of forms, including some patented devices. Some are external to the powerhouse intake, while others are within the water passages. Typically, they divert fish into a bypass channel. Where predominately near-surface swimming fish are to be diverted, partial screens may be installed. These are only effective for fish in the upper levels of the water column and some fish may pass under the screens and through the turbines. Screening of intakes can result in both head loss for power generation and unsteady flow conditions through the water passages, as well as considerable mortality to species which can become impinged on the screens (Moursund 2003). Screen systems also require significant ongoing maintenance costs.

These alternative approaches may require structural enablers such as physical barriers (screens), and structural and behavioural guidance systems as part of the design, however, it is noted that:

- There is no optimum solution for downstream fish passage. The approach needs to be site and species specific, based on accepted good practice developed by engineers and fish biologists.
- Physical barriers (screens) are often used to keep fish away from powerhouse intakes. However, these are expensive, need regular maintenance and affect power production. They may also not be fully effective especially for drifting eggs and larvae or fish that are deep in the water column. Many fish can also be impinged on the screens, for example, this is common among juvenile lamprey.
- Structural guidance has been shown to work well in some applications, though the science is not well understood for many species and regions.
- Behavioural guidance systems (sound, light, electrical etc.) have been shown to be effective for some species, but not all.

Overall, while there are alternative means of passing fish downstream other than through turbines, it is not uncommon for some fish to be unguided and passed through operating turbines. Among the different downstream passage routes available at hydropower dams, (i.e. spillways, turbines and bypass systems), estimates of survival through turbines are typically the lowest (Trumbo 2013).

4.3 Turbine Passage

It has long been the assumption that mortality rates for fish passing through turbines are greater than those taking other routes for downstream passage. While this may be justified for small-scale hydro or projects with high hydraulic heads, having Francis and Pelton units, mortality rates are typically lower for highly efficient, medium to large-scale axial flow units. Improved survival rates are now being achieved through modifications to existing turbine types, such as Kaplan and Bulb units. Recent studies have shown that survival estimates of juvenile salmonids that pass downstream through the lower eight dams on the lower Snake and Columbia rivers in the Pacific Northwest of the United States can be greater than 93% (Weiland 2012, Skalski 2013).

Meanwhile, other turbine designs such as the Alden, and advanced modifications such as at Ice Harbor may also lead to better passage conditions. Continuing development of “fish-friendly” turbines and criteria for the design and operation of such turbines is critical for sustaining fisheries resources.

4.4 General Impacts of Hydropower Turbines on Fish

The impacts of fish passing through hydropower waterways and turbines have long been recognized, but it was the Advanced Hydropower Turbine Systems (AHTS) Program in the USA, funded by the USDOE, that initiated significant levels of research and development in this area. This R&D was specifically focused towards turbine designs that could lead to reducing negative impacts in this area of fish passage (Čada 2001). Over the years, this has led to a better understanding of turbine hydraulic conditions, as well as the mechanical, hydrodynamic and operational factors that cause fish injury and mortality.

To optimize the fish passage environment through the turbines, the flow characteristics and potential damage mechanisms within the water passage must be understood (Figure 5). As fish pass through hydropower intakes and approach the turbines, the hydrostatic pressures increase and the presence of stay vanes and wicket gates can obstruct the flow path and cause fish strike, grinding or pinching (Deng 2010b). As the fish reach the runner, several potential damage mechanisms exist, including blade strike, grinding, and shear forces, turbulence, and rapid decompression (Brown 2012b). Within the draft tube, fish can also be influenced by the shear forces and turbulence, which can disorient fish, increasing the potential for predation in the tailrace (Deng 2011).

Impacts on fish arising from the operation of hydropower plant are discussed in the following sections as dependant on mechanical, hydrodynamic and operational factors. These impacts are affected by the turbine features, hydraulic conditions, and the characteristics and physiology of the fish, such as the species, life-stage, size, state of buoyancy and behaviour (Brown 2014). For example, it is generally understood that turbine mortality associated with strike increases with fish length.

This understanding of the general impacts of the operation of hydropower plant on fish has led to important research into the ways that fish injury and mortality can be reduced (Katopodis 2013). Modifying the number of turbine blades, eliminating gaps, sharp edges and rough surfaces in the turbine and throughout the entire water passage can help to reduce fish injury and mortality. Selecting a higher number of blades may in some cases lead to a lower likelihood of barotrauma but may also increase the occurrence of blade strike. It is also important to minimize shear and turbulence throughout the entire water passage from the intake to the tailrace under the full unit operating range (Deng 2007b). Keeping the lowest pressure that fish may experience (nadir) close to or above surface pressure (101 kPa) may also help to reduce the likelihood of barotrauma (Brown 2014). Reducing the rate of pressure change may also decrease the likelihood of barotrauma, but more research is needed to understand this phenomenon (Brown 2012).

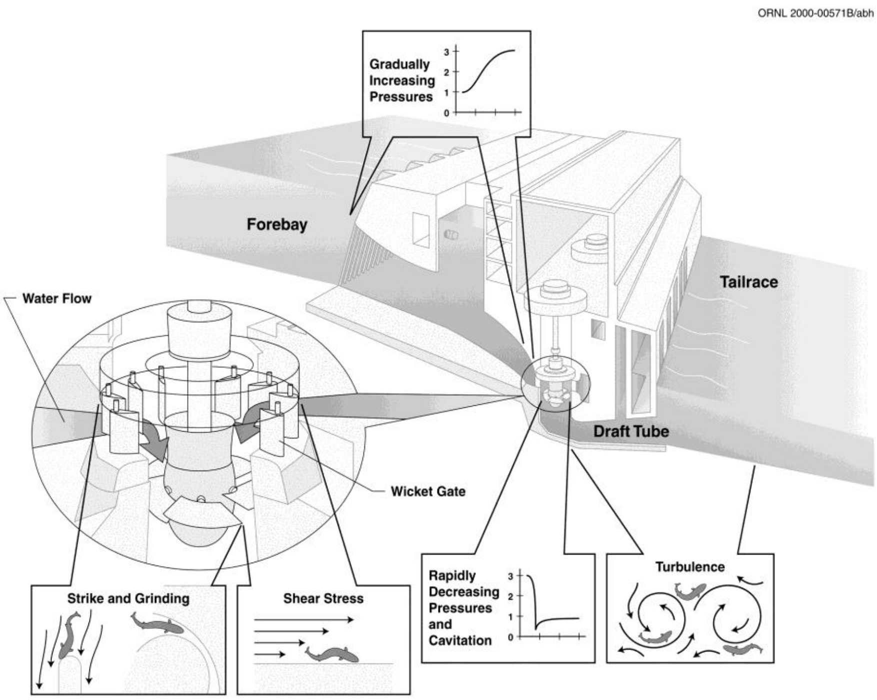


Figure 5: Turbine Passage Injury Mechanisms (Cada 2001)

4.5 Hydrodynamic Factors

The hydrodynamic conditions that fish encounter during turbine passage may involve: (Katopodis 2013):

- Shear forces: turbulence caused by high velocity gradients, curvilinear flow and eddies.
- Rapid decompression: rapid pressure fluctuations across the turbine blades.
- Cavitation: bubble formation and implosion associated with rapid pressure changes to vapour pressure (0 kPa) when all gases are brought out of solution in the water column.

Shear stresses are compounded by any structural gaps within the water passages, such as between stay vane trailing edges and wicket gate leading edges, as well as between turbine blade extremities and the hub and the discharge ring. Turbulence, including vortices, wakes and backflows, can lead to fish striking fixed objects or becoming disoriented, and should be minimized. Recent improvements in testing and design can deliver technologies that meet these challenges (Trumbo 2013).

Fish passing through turbines are exposed to rapid decompression and barotrauma. Barotraumas that result from exposure to rapid changes in pressures can include swim bladder rupture, haemorrhaging and emboli in the fins, gills, eyes and blood vessels. These injuries can result in immediate or delayed mortality, and may also contribute to other sources of indirect mortality (i.e., predation). The severity of barotrauma is dependent on the ratio of pressure change that fish experience as they pass through a turbine (Brown 2012b). This ratio is simply the pressure that a fish is acclimated (neutrally buoyant prior to entering the turbine) divided by the minimum pressure a fish experiences. The higher the ratio, the greater the likelihood that a fish will die as a result of exposure. Turbine design can incorporate modifications that increase the minimum pressure a fish experiences (Trumbo 2013a). However, the depth of fish acclimation, prior to passing through the turbine is very important and must also be considered.

Recent studies suggest that the turbine pressure cycling ratio is very useful in predicting the effect on smolt survival. The USACE and the Pacific Northwest National Laboratory (PNNL) released Sensor Fish (the latest generation 6-degree-of-freedom version of this device is an autonomous sensor package, consisting of three rate gyros, three acceleration sensors, a pressure sensor, and a temperature sensor [Deng 2007a]) into turbine passageways along the Lower Snake and Columbia Rivers to determine the magnitude and rate of pressure change fish might experience (Trumbo 2013b). Recorded pressures were applied to simulated turbine passage in laboratory studies to determine the effect of rapid decompression on juvenile Chinook salmon (Brown 2012). It was concluded that designing new turbines with higher nadir pressure criteria is likely to provide safer passage for salmonids passing through turbines.

Physiological, behavioural or life history trait affecting susceptibility to barotrauma		Presence or absence	Susceptibility to barotrauma	Example species or project
The amount of free (undissolved) gas in the body				
	Presence of a swim bladder			
		Yes	High	Chinook salmon
		No	Low	Pacific lamprey
	Type of swim bladder			
		Open (physostomous)	Low	Chinook salmon
		Closed (physoclistous)	High	Bluegill
	Ability to expel gas out of the swim bladder through pneumatic duct			
		Better	Low	Large rainbow trout
		Poorer	High	Small rainbow trout

Physiological, behavioural or life history trait affecting susceptibility to barotrauma		Presence or absence	Susceptibility to barotrauma	Example species or project
	Ability to fill the swim bladder with vasculature (rete)			
		Better	High	Bluegill
		Poorer	Low	Chinook salmon
	Acclimation depth ability			
		Better	High	Burbot, rainbow trout
		Poorer	Low	Chinook salmon
Pressure exposure				
	Acclimation depth			
		Deeper	High	Burbot
		Shallower	Low	Chinook salmon
	Exposure pressure			
		Higher	Low	Irrigation weirs/spillways
		Lower	High	High head dams
	Ratio of pressure change (acclimation pressure/exposure pressure)			
		Higher	High	Hydroturbine
		Lower	Low	Bypass system
	Rate of ratio pressure change			
		Higher	High	Hydroturbine
		Lower	Low	Angling
Life history				
	Migration patterns			
		More migratory	High	Murray cod, salmonids
		More sedentary	Low	Trout perch (*Percopsis omiscomaycus)*
	Larval or juvenile drift stage			
		Yes	High	Sturgeon, Murray cod
		No	Low	Salmonids
Structural integrity				
	High		Low	Adult fish
	Low		High	Larval or juvenile fish or eggs

Table 3: Various Traits that can Influence the Susceptibility of Fish to Barotrauma along with Example Species. (Brown 2014)

4.6 Mechanical Factors

The mechanical conditions that fish encounter during turbine passage may involve (Čada 2001):

a) Strike: hitting stationary or moving mechanical components such as the leading edges of runner blades, stay vanes, wicket gates, and draft tube piers.
b) Grinding: squeezing, pinching and trapping in narrow spaces (gaps) between fixed and moving components.

c) Abrasion: physical damage through impact with rough surfaces

Fish passing through the turbine waterways can strike obstacles such as the leading edges of stay vanes, wickets gates and runner blades as well as draft tube piers. The number of structures in the turbine wetted passage that are exposed to flow should be minimized and stay vane and runner blade leading edges rounded. During fish passage, unit operation should have wicket gate leading edges positioned in the shadow of the stay vane trailing edge (Figure 6).

Strike probability during fish passage through the runner is related to several factors, including the rotational speed of the runner, number of blades, fish length, flow angle and velocity through the blades. Over the years, researchers have studied the influence of fish strike on mortality and found that obstacle geometry and the relative velocity of the fish influences injury associate with strike. To optimize the fish passage environment within the turbine, geometry and velocity criteria should be considered when defining modifications to turbine components that may strike passing fish.

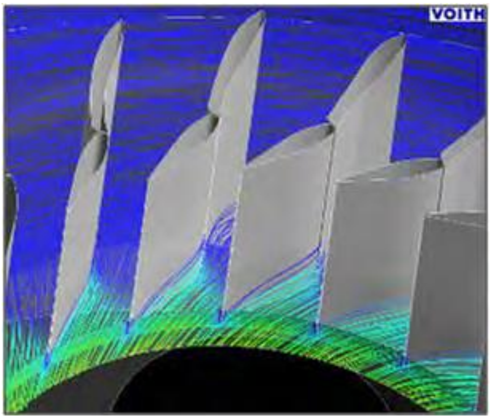


Figure 6: Stay Vane - Wicket Gate Alignment Design Analysis for Mechanical Strike and Shear (Voith)

In regard to shear, gaps found within the water passages are hazardous in terms of grinding or pinching. Axial-flow turbines have gaps between the blade tip and the discharge ring. Adjustable blade Kaplan turbines also have gaps between the blade inner periphery and the hub. Gaps also occur between the stay vanes and wicket gates. In conventional designs, these gaps can become quite large, representing locations where fish can be trapped or pinched.

4.7 Operational Factors

Hydrodynamic conditions within the entire water passage appear to be smoother and less turbulent at discharges near the optimum operating point of the turbine. In this range, peak turbine efficiency coincides with optimum hydraulic conditions wherein the stay vanes and wicket gates are aligned and flow is streamlined throughout the passage, without regions of turbulence, reverse flow and flow separation. On the other hand, flows are notably more turbulent at lower discharges, suggesting that there is a higher risk of injury to fish when passing through the turbine passages at flows less than the optimum operating range.

4.8 Summary

The downstream passage of fish, over, around or through a barrier to flow (e.g., dam, weir, water diversion structure), pose challenges as hydrologic, hydraulic and geomorphologic conditions vary considerably from natural river systems. Even when alternate routes are available, it is likely that some fish will pass through turbines and be affected by hydrodynamic, mechanical and operational factors

Fish passing through the turbine water passages are subject to specific sources of potential injury such as rapid decreases in pressure, strike, cavitation, and turbulence. Despite these risks, information from laboratory and field studies has provided guidance on ways to improve turbine design and operation. This has the purpose of minimizing potential sources of injury that fish may be exposed to during downstream passage. However, much more research is needed, especially among fish types found in the Mekong drainage.

While much of the study and research to date on downstream fish passage has been focused on North American and European fish species, there will be significant challenges in specifying and designing turbines that could minimize damage to fish in the Mekong Basin. This is compounded by the Mekong Basin containing such a very large number of species, most of which are dissimilar to species that have been studied to date.

5 Experiences from other Regions and River Systems

5.1 Introduction

Information from regions similar to the Mekong Basin was gathered, based on its applicability to the Mekong River Basin. Specifically, this focused on fish passage through turbines, the development of any potentially fish-friendly devices and the impacts of hydropower on fish species and fisheries. The review identified that:

- The USA, and to a lesser extent some countries in Europe, have undertaken research and developed facilities to improve downstream fish passage through turbines. However, this has been limited to only a few fish species.
- Within most countries in the world, hydro plants do not include facilities for either upstream or downstream fish passage. In many instances, the barriers to flow, as well as other factors, have led to a severe depletion of fisheries resources.
- Where fish passage facilities have been built, they are primarily only aimed at upstream passage. In many cases, designs are ineffective and the facilities are poorly maintained.
- Where downstream fish passage is considered, it is usually based on avoiding passage through the turbines.

Fish passage in the Pacific Northwest of North America tends to be focused on passing pre-spawning salmonid adults upstream to spawning habitat, and successfully passing juveniles downstream to the ocean. Driven by legislation, research aimed at developing and deploying structures and techniques to improve passage survival through turbines have been actively pursued for over a decade at significant cost.

However, to put this into context, it is estimated that while there are over 900 species of fish in the United States, Brazil has an estimated 3,000 freshwater species, of which 30% are believed to be migratory and worldwide there are some 14,000 freshwater species (Čada 2012) of which significant numbers are reported as susceptible to hydropower impacts. By contrast, the Lower Mekong Basin has over 850 known fish species but is home to the highest fish biodiversity in the world after the Amazon River. The Mekong area is also characterised by very intensive fish migrations. At least a third of Mekong fish species need to migrate between downstream floodplains where they feed and upstream tributaries where they breed (ICEM 2010, Schmutz 2014).

In general, very little information is published specifically on fish-friendly turbines in parts of the world other than North America. A more modest effort has been underway in some European countries and Australia, and has included alternative downstream passage options. One case history will be summarized covering downstream migration of eels in France through Kaplan and Bulb units. Another case history will cover the selection process for turbines in Manitoba, Canada to minimize the risk of injury and mortality to fish passing downstream.

5.2 Experience from France (Baran 2011)

A study was undertaken in France (2009 and 2010) on survival rates for eels migrating downstream through large Kaplan and Bulb turbine units, the type used extensively on the Rhine and Rhône rivers. The Kaplan turbines, one with four blades, and one with five, are installed on EDF projects along the Rhine. The Bulb turbine, with four blades, is installed on a CNR project along the Rhône.

A group of 350 large eels (600 to 900 mm) was released at different points just upstream of the turbines and a control group of 50 was injected downstream. Hi-Z tagging techniques using inflatable balloons allowed fish to be captured downstream, where they were examined and held for 48 hours to check for any delayed mortalities. High recapture rates (over 95% on each of the three sites) allowed a strong degree of confidence in the results noted in Table 4.

At the two sites with four-bladed Kaplan and Bulb turbines, survival rates were reported higher than expected given similar tests carried out in North America and other countries in Europe. However, the survival rates for the five-bladed Kaplan were reported as significantly lower. It is possible that the particular shape and profile of the runner and blades may be responsible for this result, but this has not been confirmed.

Hydroplant Type	*Runner Diameter (m)*	*Rotational Speed (rpm)*	*Hydraulic Head (m)*	*Survival Rate (1 hour)*	*Survival Rate (48 hour)*
Kaplan 4 blade	*6.66*	*88.2*	*15.7*	*93.2*	*92.4*
Kaplan 5 blade	*6.25*	*93.7*	*15.5*	*82.6*	*78.6*
Bulb 4 blade	*6.24*	*94*	*16*	*95.6*	*92.3*

Table 4: Survival rates in large turbines.

Based on the high expense and time to undertake tests such as this on a broad scale, other ways to estimate survival rates were investigated. It was noted that approximate estimates could be obtained through extrapolation of test results from similar turbines, and it is believed that more accurate estimates can be achieved by using predictive models with input of results obtained at other sites. Following analysis, the research team produced equations to predict survivability as a function of eel size, rotor diameter, the nominal flow rate and the rotational speed (Baran 2011).

5.3 Experience from Canada (Manitoba Hydro 2012)

In a supporting document to the Keeyask GS Environmental Impact Statement, Manitoba Hydro identified the parameters considered for the selection and development of turbines to increase fish passage survival (Manitoba Hydro 2012). The general objective of selection was to achieve a minimum survival rate of 90% for fish as large as 50mm. To achieve this target, a number of variables were considered, including:

- Number, alignment and shape of wicket gates and guide vanes
- Number, size and geometry of runner blades
- Rate of turbine rotation
- Absolute lowest pressure (nadir)

Many variables were considered beyond those specifically relevant for fish passage survival, particularly efficiency, performance and cost. A fixed-blade vertical-axis turbine unit (propeller) was selected as having several overall advantages compared to other types.

5.4 Summary

Most research to date on downstream fish passage through turbines has focused on juvenile salmon in the Pacific NW of the USA. This is summarized in Sections 7 through 11. There are other major river systems in the world supporting a diverse range of species and life history stages that undertake migrations and are therefore at risk if dams or barriers have been constructed. However, in general, little research has been undertaken or documented relating to project design that could be considered fish friendly.

The present state of technology development would allow the initiation of research on downstream passage through turbines for a range of Mekong species using standardized approaches. Such an approach could provide a more rapid advancement of science and engineering while minimizing duplication of effort (Brown 2014).

6 Fish Passage through Hydraulic Turbines

6.1 Introduction to Hydraulic Turbines

The choice of hydraulic turbines for any hydropower project is normally determined by optimizing their expected performance against cost. This technical determination has to take into consideration the operating range of the equipment for the specific site, in terms of hydraulic head and flow characteristics as well as required operational flexibility. Figure 7 shows the generally accepted operating ranges for the most common types of turbines, with axial comprising Kaplan, Bulb and Alden units

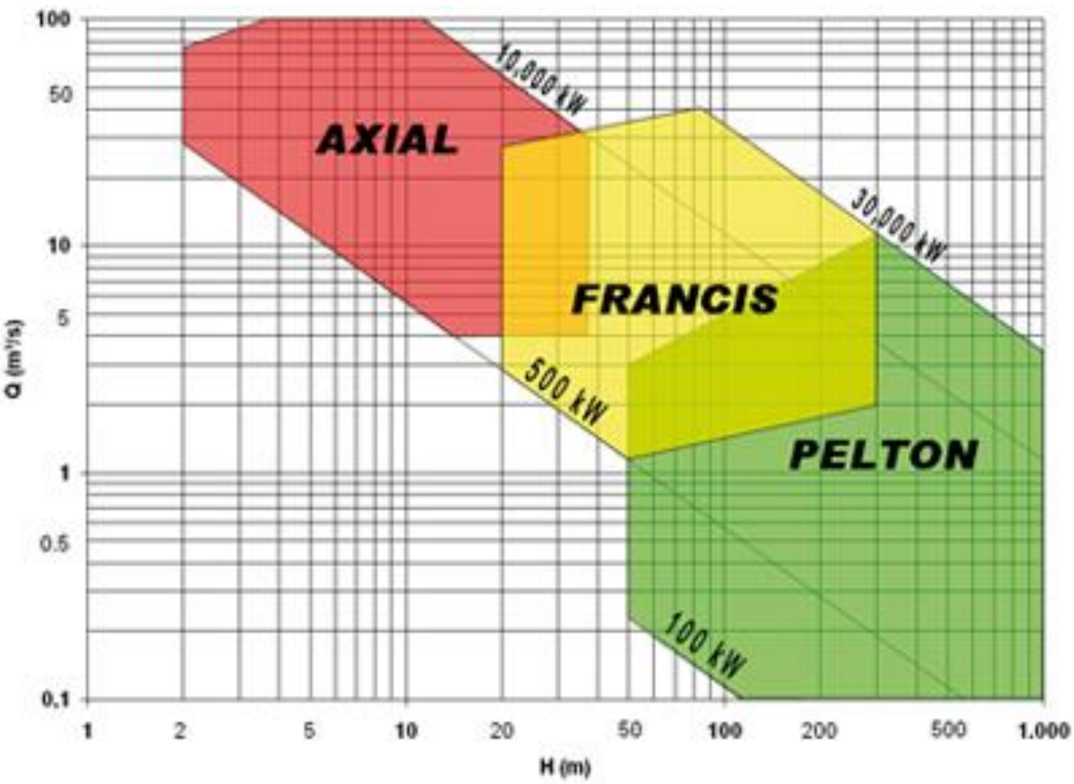


Figure 7: Range of Application of Turbine Type; Hydraulic head (H) m. vs. Flow (Q) cms

The types of hydraulic turbines presently envisioned for the eleven projects on the mainstream of the Mekong River have been identified (Table 1 in Section 2.2) as eight Kaplan and one Bulb, with two not presently specified. Of these, one would likely have Kaplan units, while the other could have either Kaplan or Bulb equipment. The proposed Mekong River project with the highest hydraulic head across the units is noted to be about 40m and the one with the lowest hydraulic head, less than 10m. A section of a typical Kaplan unit is shown on Figure 8.

However, in addition to hydraulic turbine and water passage designs based on technical and operational performance, there will be environmental performance criteria that need to be considered, including those relating to fish passage. These aspects will be covered in greater depth in Section 11 and summarized in Section 12.

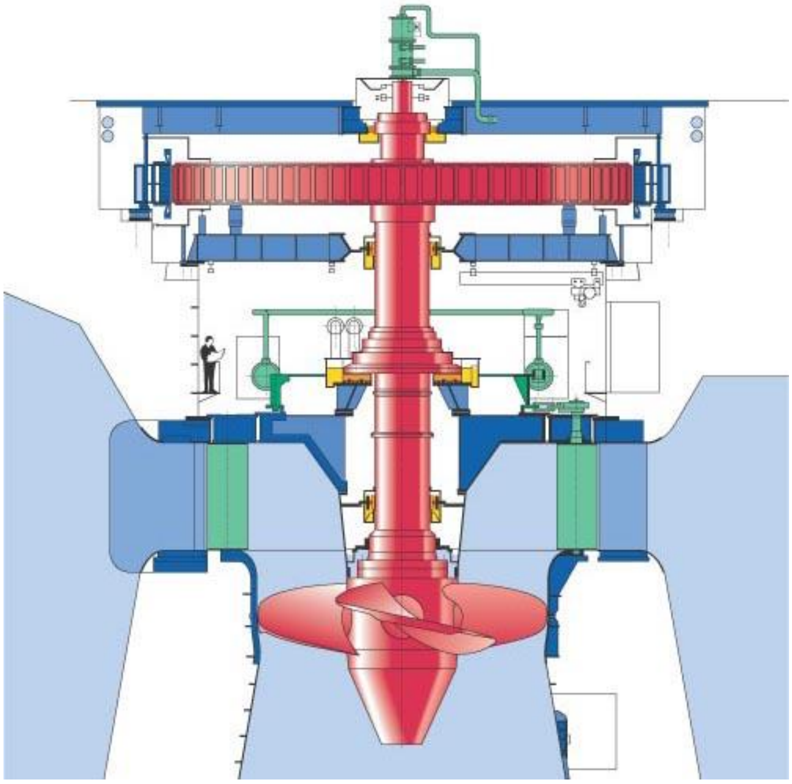


Figure 8: Cross-section of a Kaplan Turbine.

6.2 Development of Fish-Friendly Turbines

As set out in the preceding sections, an important issue for the hydroelectric industry is to ensure safe downstream passage of migrating fish. Also it is important to understand the link between fish injuries and hydraulic characteristics associated with turbine passage. As noted in Section 1.1, the USDOE funded the AHTS starting in 1995 to better understand the link between turbine flow characteristics and fish survival, primarily for juvenile salmon. Two concepts emerged for further development; the Minimum Gap Runner (MGR) turbine design and the Alden Turbine design. Voith Pty Ltd, an International Turbine Manufacturer (Voith) developed and patented the Minimum Gap Runner (MGR) Kaplan turbine and soon after, Alden Research Laboratory developed and patented the Alden Turbine.

MGR Kaplan turbines have been installed at the Wanapum and Bonneville dams on the Columbia River. Within the last few years, Voith and USACE have also undertaken significant research to create two improved MGR type turbines for installation at the Ice Harbor project on the Snake River. Installation and testing of these turbines (one fixed blade and one adjustable blade) are scheduled over the next few years. While the Alden turbine has been tested as a scale model (EPRI and USDOE 2011) it has not been deployed in a power plant.

Passage of fish through axial-type turbines, (Kaplan, fixed blade propeller, MGR Kaplan and Bulb) is normally considered to result in less damage to fish than passage through Francis turbines. For this reason and because Francis turbines are not presently considered for any of the proposed hydropower projects on the Mekong River and they will not be considered in this review. The following sections of this review will focus on axial-flow turbine types, as follows:

- Minimum Gap Runner (MGR) a modified Kaplan unit with fish-friendly credentials.
- Bulb turbine.
- Ice Harbor turbine, a further improvement of the MGR and the fixed-blade propeller runner.
- Alden turbine.

The general principle of FFT design is to maximize downstream fish passage survival rates whilst maintaining power generation performance at minimal extra cost. A key consideration in any design process is to tailor the FFT characteristics and performance to the specific types of fish that will pass through the turbine. Some considerations to be taken into account include:

- Careful environmental research to determine which fish will pass through the turbines, in what life stage and in what season or seasons (reference Section 3.2 of this report).
- Seasonal changes in head and tail water elevation and water temperature, river discharge, etc., are likely to influence environmental factors like predation and stress, (i.e. indirect injury and mortality associated with turbine passage).
- Selection of a slower rotational speed and optimal number of blades. This may require a larger radius machine, while many modern designs tend to favour higher speeds and smaller size. Design trade-offs exist where fewer blades may reduce strike, but also lowers nadir pressure.
- Optimizing thickness, spacing, and orientation of turbine blades, wicket gates and stay vanes.
- Reduction of the gap between the runner blades and hub and the outer discharge ring on Kaplan units.
- Adopting a fixed blade Kaplan or propeller turbine may ensure the smallest gap at the tip of the blades.
- Including fish-friendly attributes for the design, testing and monitoring of the entire water way from the intake to the tailrace.

6.3 Physical and Biological Considerations

As noted in section 6.2, there are several characteristics that are important to consider when designing turbines having fish-friendly attributes. As an example, Dixon (2012) provided a comparison of the physical attributes of three turbines. These were the Alden, Francis and MGR Kaplan each with 13.6 MW of power output (Table 5). The information was used to support modelling for the placement of a FFT at the School Street Hydro PowerStation that is owned and operated by Brookfield Renewable Power.

	Alden	Conventional Francis	MGR Kaplan
Hub diameter (m)	3.9	2.5	2.7
Rotational speed (rpm)	120	190	277
# of runner blades	3	13	5
# of wicket gates	14	20	24

Table 5: Turbine Comparisons

A similar comparison was made for estimates of fish survivability across the three turbines with results shown in Table 6. While this particular project has not been upgraded using turbines with specific fish-friendly attributes, the comparisons are considered useful.

	Alden	Conventional Francis	MGR Kaplan
Survival rate for a fish of 200mm, based on strike	98%	< 50%	86%

Table 6: Comparison of Various Turbines for Fish Survivability (based on a 13.6MW unit)

A comparison was made for the three types of turbines (fixed-blade propeller, adjustable-blade Kaplan, and bulb) at the Rock Island Dam on the Columbia River using balloon-tagged juvenile Chinook salmon (Normandeau & Skalski 1996, reviewed by Čada 2001). The turbines were operated at a constant efficiency (normal peak efficiency) and fish were released into the turbines at two depths. The estimated survival 48 h after the fish were recaptured is shown in Table 7. There was no significant difference in survival among the turbine types or the depth at which the fish were injected into the turbine. Most injuries from the fixed blade and Kaplan turbines were attributed to strike and grinding, whereas injuries from the bulb turbine were believed to be pressure related.

	Fixed-blade Propeller	Variable-blade Kaplan	Bulb
Survival rate for juvenile Chinook salmon	93%	96%	96%

Table 7: Comparison of Various Turbines for Fish Survivability (Rock Island Dam)

While balloon tag studies have provided a large amount of valuable data on the effects on fish passing through turbines, the information related to barotrauma is likely a best case scenario and should be viewed with caution. This is because the fish are injected into turbine entrances from surface pressure. Thus, the fish would not be injured by barotrauma as much as fish which are acclimated (neutrally buoyant) to greater depths and have more gas in their swim bladder (Brown 2012). It can be shown that barotrauma-related mortality and injury can be up to ten times higher for fish (juvenile Chinook salmon used in their study) neutrally buoyant at 10m of water depth compared to fish neutrally buoyant at surface pressure [101 kPa]).

A study on the application of FFT's was provided by Voith (2012) and compares ranges of hydraulic head and power output, and including indicative results of fish survival studies based on strike for a 200mm juvenile salmonid (Figure 9). While the survival information in this Figure may be very approximate, relationships between various turbine types and their application ranges is of interest.

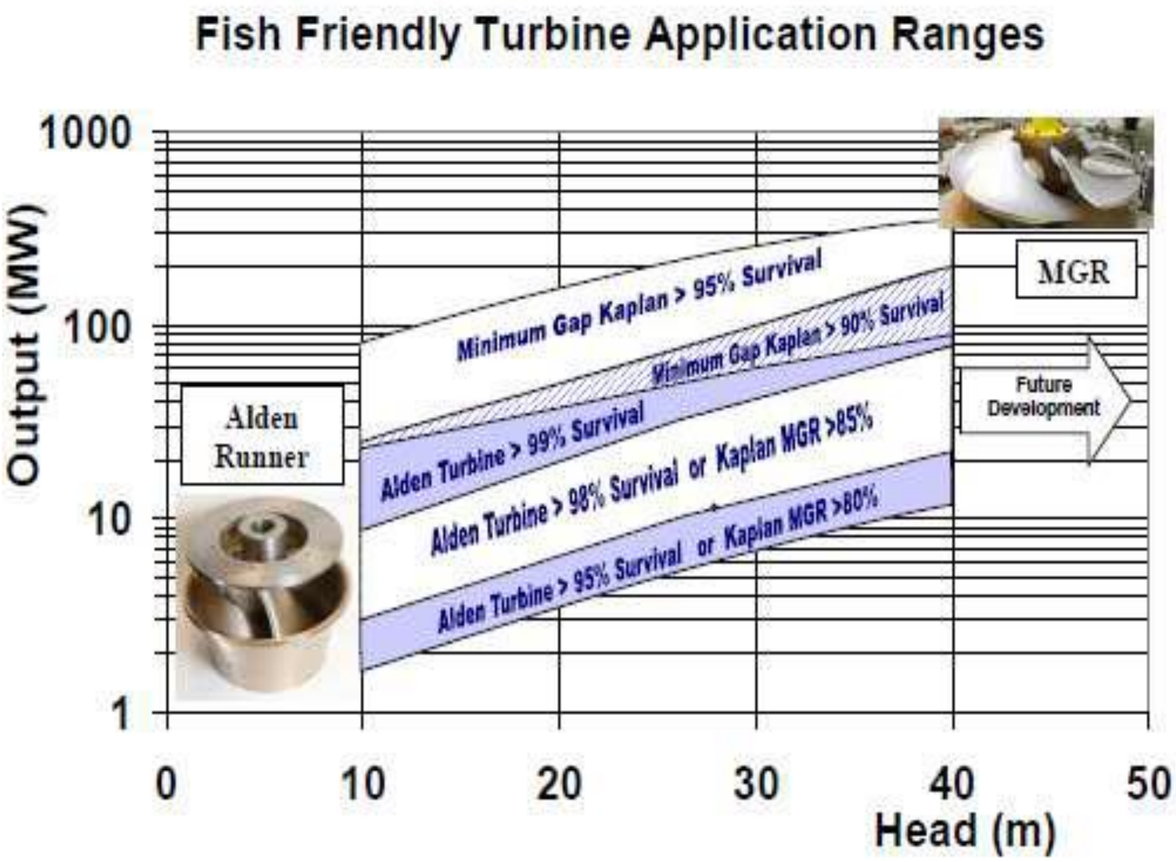


Figure 9: Fish-friendly Turbine Application Ranges (Voith 2012)

While Bulb units are not included in Figure 9, their range of hydraulic head is from under 10m to about 25m, with power output up to about 70MW. Based on very limited information, fish survival rates are expected to be similar to Kaplan or MGR units. One of the reasons that fish survival information on Bulb turbines is rather sparse is that they have traditionally been considered relatively fish-friendly. With fish survival quite dependant on low rotational speed and a low number of turbine blades, Bulb units can generally be expected to perform well in this regard.

6.4 Summary

Most of the turbines currently planned for installation into dams on the mainstream of the Mekong River are Kaplan or bulb units. New research should be conducted to determine what type of fish injury and survival rates would be anticipated if these types of units were to be deployed or if they were modified to be more similar to the MGR or Ice Harbor designs.

The Alden turbine, based on its limited development to date and the application range provided in Figure 9 is generally considered not suitable for application on these Mekong River projects. The one exception could possibly be the Stung Treng Project. While this project is within the noted application range of the Alden turbine, it is well beyond the experience of the unit's development to date.

The Bulb units presently proposed for the Mekong River projects are within the normal operating range for this type of unit. Based on the given site parameters given in Table 1, maybe three or four of the total eleven projects could be developed using Bulb units if environmental and cost considerations were favourable.

In all cases, the application of these types of units at the Mekong River sites would need to incorporate appropriate design parameters based both on the migrating fish requirements and site conditions. These designs would also need to include the full water passageways from intake to tail water.

It is noted that nearly all the significant research to date covering turbine design to improve fish passage, has been undertaken based on juvenile salmon in the USA. This has led to the development of sophisticated equipment and methodology, as well as extensive field and laboratory experience to understand fish behaviour. It has also provided the impetus for improved materials and technology in turbine engineering and manufacture. These advancements will be most useful in studying the issues and improving the performance of fish passage through hydraulic turbine in other parts of the world, including the Mekong River Basin.

However, there are limitations in the research undertaken to date from a global perspective, in that it is very fish species and size specific. There is very little documented research on the performance of other species of fish and of different shapes, sizes and life stages passing through hydraulic turbines. The next steps in closing this gap, as it relates to the Mekong River, is discussed in Section 11 and summarized in Section 12.

7 Minimum Gap Runner (MGR)

7.1 Introduction and Development History

Voith developed the Minimum Gap Runner (MGR) technology from a standard axial-flow Kaplan unit, as part of the USDOE's AHPT Program. The goal of this development was to reduce any gaps between the turbine and its housing. Conventional Kaplan turbines can have large gaps at the hub and periphery of the blades and these can cause fish pinching, decreased pressure, increased shear forces and result in fish becoming disoriented. These also allow the establishment of vortices, which together with higher flow velocities, pressure variations, and shear, could reduce fish survival. MGR Units have been installed at the USACE's Bonneville (1999) and Grant County PUD's Wanapum (2005) power stations. Kaplan turbines modified to minimize gaps have also been installed at Chelan County PUD's Rock Island hydro plant and at Pend Oreille County PUD's Box Canyon Dam. All these projects are located on the Columbia River or its main tributaries.

7.2 Description and Physical Characteristics

The principle of the MGR is to reduce gaps by contouring the blades to the fully spherical hub and peripheral discharge ring geometry. The gap is thus minimized and remains constant across the full range of blade pitch with the objective of reducing injury and mortality. In addition, the reduction of gaps and improved geometry of the MGR technology is expected to help improve turbine operating efficiency. An MGR with the key areas where the gap has been minimized is shown on Figure 10.

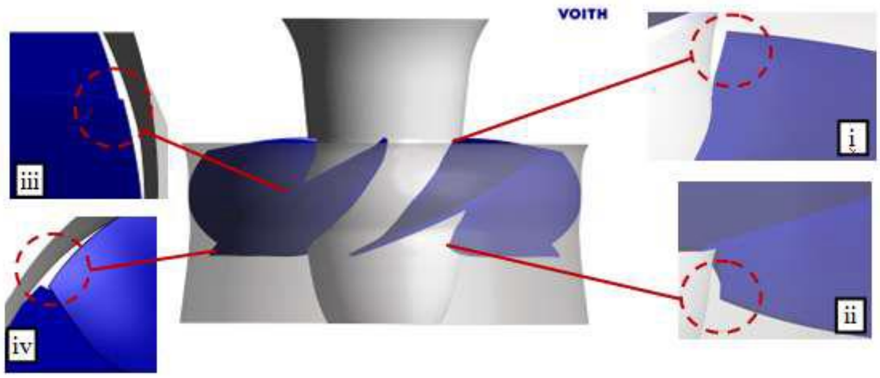


Figure 10: Voith Hydro's Minimum Gap Runner with gaps

In addition to reducing the gaps in the runner, it is also important to reduce the gaps between the stay and guide vanes and ensure that they are reshaped and well aligned in the most important range of operation. The alignment can be achieved by using an asymmetric guide vane profile to get the leading edge in the shadow of the stay vane and keeping the flow angle on the trailing edge for the relevant operating points (Nichtawitz 2000). If possible, the number of wicket gates and stay vanes should also be reduced.

In addition to Voith, Alstom have introduced a version of the MGR, with also has the prime purpose of improving survival rates of fish passing through low head turbines. Only limited information was found through the Alstom website.

7.3 Generation Performance

The MGR, being very similar in design and manufacture to a standard Kaplan turbine, is expected to have the same operating range in terms of dimensions, power output, flow capacity and hydraulic head. Based on the substantial testing carried out and extensive experience and successful track-record of the equipment designers and manufacturers, expectations are that performance will also be similar to the standard Kaplan unit.

To reach optimum performance in terms of both energy production and fish survival, it could be crucial to operate the units close to their peak operating range. At the ends of the range, the pressure changes, shear stresses, and turbulence become very severe, and cavitation can occur. Because these are all sources of injury to fish, it is expected that survival will be reduced under conditions of low operating efficiency.

For projects where selections of multiple units are proposed, this could include some MGR Kaplans and some fixed-blade propeller units. From an economic perspective, propeller units have lower supply and construction costs, as well as lower operating costs. They are normally selected for projects with stable reservoir and tail water levels and operation in a base load mode. On the other hand Kaplan units, while more expensive than propeller units, provide greater operational flexibility. However, it is possible that both types of units can be included in a powerhouse similar to the plans for turbine replacement at Ice Harbor dam.

From the perspective of biological effectiveness in terms of maximizing fish passage survival rates, the propeller can be operated within a range that provides a fish passage benefit, although this range is greatly reduced relative to that of a Kaplan runner and may reduce overall facility operation flexibility (Trumbo 2014). During periods of fish migration, it may be possible to operate a powerhouse such that downstream migrating fish may be directed into these units if a mix of propeller and Kaplan units is installed in the same powerhouse. The converse is also true should operating flexibility be important or required.

7.4 Economic Parameters

The costs for the MGR Kaplan as part of a hydropower plant unit refurbishment or upgrade would include the design and fabrication of the new unit as well as any modifications necessary to the wicket gates, stay vanes or embedded steelwork. Thus replacing a standard Kaplan with a MGR Kaplan would incur higher costs than than an in-kind (identical) replacement. However, the costs for supply and installation of a MGR Kaplan for a new development should not be any higher than for a standard Kaplan. In addition, the full-scale demonstrations have verified the performance of Voith Hydro's minimum gap runner turbine, which maintains high survival rates for fish while producing more power than conventional designs (Hogan 2014).

7.5 Biological Performance

Preliminary analyses from the Bonneville hydropower plant suggest that the MGR unit had superior performance in terms of survival to the conventional Kaplan unit and there is good reason to expect that reducing gaps will in general, improve survival rates. For example, the absolute survival of balloon-tagged fish released at the blade tip in the MGR unit was up to 3% higher than for those passing near the blade tip in an adjacent Unit of the old turbine design (Normandeau Associates 2000). Implementation of MGR units is expected to reduce the chance of grinding, cavitation, shear stress, and turbulence over that associated with the hub and blade-tip gaps on conventional Kaplan runners (Čada 2001).

7.6 Case History

7.6.1 Case History #1 – Bonneville Dam (Normandeau Associates 2000, Fisher 2000)

As part of the USACE's Turbine Survival Program (TSP), survival probabilities were estimated for hatchery-reared Chinook salmon, (av. length 166 mm), passing through Unit 5 (existing Kaplan) and Unit 6 (upgraded MGR) at Bonneville Dam from November 1999 through January 2000. The powerhouse has a nameplate capacity of 1189 MW, a head of 18.3m, and a total hydraulic capacity of 8,155 m3/s

The prime objective was to compare the performance of Units 5 and 6 in terms of fish survival rates, as measured by sensor fish. Secondary objectives included:

- Correlating peak turbine operating efficiency with turbine passage survival;
- Assessing the effectiveness of gap minimization; and
- Identifying injury mechanisms and in-turbine areas where fish injuries occur.

The study released balloon tagged fish to pass near the blade tip, mid-blade, and hub regions in each turbine at four discrete power levels. Analyses based on the results of sensor fish testing, suggest that the MGR tests could yield higher survival rates overall than the adjacent conventional Kaplan, and could be particularly beneficial for improving survival of fish that would pass near the runner blade tips. While there was some variation in the results obtained, the initial review found that balloon tagged fish passing through the MGR unit experienced less injury and had higher survival rates than fish passing through the conventional Kaplan runner (Figure 11). Injury was reduced by 40%, with most injuries at both turbines inflicted by shear and mechanical forces. No statistically significant correlation was found between fish passage survival and turbine operating efficiency for either unit. As has been mentioned previously, it should be kept in mind that use of surface released balloon tagged fish would only provide a best case scenario for barotrauma injuries.

It was also noted that the absolute efficiency of the MGR was greater than or equal to that of the existing unit at all test points.

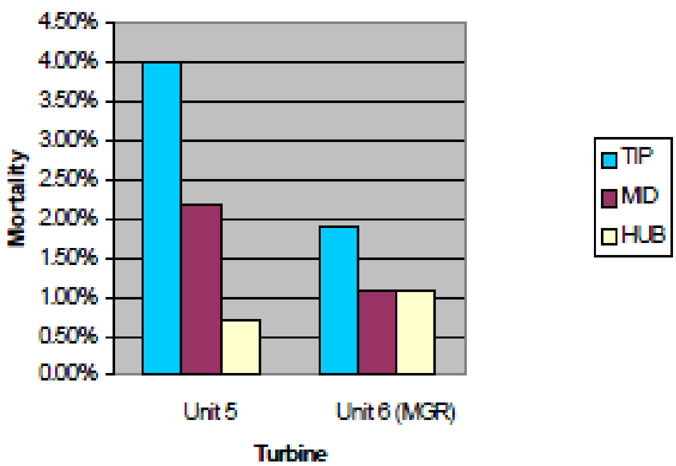


Figure 11: Comparison of Injury Rates for MGR and Kaplan units

7.6.2 Case History #2 – Rock Island – Columbia River (Grafenberger 2006).

Chelan County PUD has two powerhouses at the Rock Island Hydro project on the Colombia River with a nameplate capacity of 624MW. The original powerhouse includes six Kaplan units which were recently rehabilitated by VA Tech Hydro. As part of the rehabilitation, special attention was given to fish friendly attributes throughout the design process. These included

- Reducing the gap between the stay and guide vanes and improving the alignment.
- Sharpening the overhanging trailing edge of the guide vanes to reduce shear stresses.
- Reducing the runner blades from five to four, while maintaining speed of 100 rpm.
- Reducing runner gaps where economically possible with a semi-spherical discharge ring,
- Stabilizing draft tube flow with a horizontal splitter vane

Studies on fish passage prior to rehabilitation showed survival estimates for juvenile salmonids of between 93 and 94%, however, there was no separation of results between the powerhouse with Kaplans and fixed blade propellers and the one with Bulb units. Analyses conducted by Skalski (2012) found that juvenile salmonid survival at Rock Island met set standards suggesting that the rehabilitated turbine units provided a fish passage benefit.

7.6.3 Case History #3 – Wanapum Dam – Columbia River (Normandeau 2005).

As part of the Grant Co. PUD turbine upgrade program at Wanapum Dam powerhouses (1040 MW) on the Columbia River, a new turbine featuring many elements of the Advanced Hydro Turbine System (AHTS) was installed in Unit 8 in 2004. As part of the program, a study compared balloon tagged fish passage survival between this unit and an existing turbine. Results showed a 48 hr. survival rate for Unit 8 of 97%, compared with 97.5% for the existing turbine, which was considered statistically insignificant.

7.7 Summary of MGR Turbine

Four projects have been identified where modifications to Kaplan units have been specifically designed with fish friendly attributes on the primary basis of reducing gaps. These installations of the MGR turbine have been replacement units in existing power plants at large hydropower plant on the Columbia River and its tributaries. To support these installations, the MGR has only been tested in the Pacific NW of the USA, particularly for the salmonids of the Lower / mid-Columbia and Lower Snake Rivers. Reaching improved survival rates for juvenile salmon, by replacing older Kaplan units with MGR's should be readily achievable in this region as well as producing more power than conventional designs.

The application of the MGR design is an important development for new projects in many parts of the world, and its design features appear suitable to provide improved survival performance for many fish species. However, for the MGR technology to be helpful to improve survival in projects proposed for development on the Mekong River it will require a significant level of effort, both in research of fish behaviour and impacts and in technology development.

In addition, to maximize fish survival passing through the MGR it is important that all new designs incorporate a holistic approach to the entire water passages from intake to tailrace and include assessments at various plant operation zones (this is the basis for the "Ice Harbor turbine" described in Section 8).

The supply and installation costs of a MGR Kaplan turbine in a new power plant are expected to be similar to those for a conventional design. However, there may be extra costs for the study, design and testing phase. One possible economic benefit has been the performance results of MGR turbines, which have maintained high survival rates for fish while producing more power than conventional designs.

8 Ice Harbor Turbine (MGR-Modification)

8.1 Introduction and Development History

The US Army Corps of Engineers (USACE) Turbine Survival Program (TSP) was developed in 1997 to help improve fish passage survival within the Federal Columbia River Power System on the Lower Snake and Columbia Rivers (USACE 2004). Biological studies in the early to mid-2000's estimated survival of juvenile salmon passing through turbines to be as low as approximately 78 – 89% (Trumbo 2013b) indicating the potential for improvements in turbine runner design.

The purpose of the TSP was to evaluate the turbine passage environment and to develop an understanding of the effects of that environment on juvenile fish. The TSP was then tasked to develop improved operational guidelines for the existing hydro turbines and new design criteria and guidelines for replacement turbines that would provide for safer fish passage.

A new design approach was developed by the TSP that incorporates USACE turbine modelling expertise with Industry standard design processes. This enabled the design and evaluation of new turbine runner alternatives that meet targeted fish passage criteria while maintaining high turbine efficiencies. This new approach has been used to design new turbine runners for the Ice Harbor Lock and Dam Powerhouse (IHR) located on the Lower Snake River in the State of Washington. Several turbine runners in the Ice Harbor Powerhouse have a history of cracked blades and oil leaks. The Unit 2 runner developed a significant oil leak in the early 2000s which required the hub to be drained and blades welded in a fixed position (USACE 2010). Both fixed-blade propeller and adjustable-blade Kaplan runners will replace the failing Kaplan runners and will be designed to minimize risk of injury to fish resulting from blade strike and severe pressure differentials. Other improvements within the turbine passage environment such as draft tube and stay vane modifications will also be implemented. The turbine runners are currently being manufactured and will be installed and tested for fish passage survival in 2017 and 2018.

Design and model testing of the IHR units was a combined effort by Voith Hydro and USACE. For both fixed-blade and Kaplan runners, model testing was performed following the CFD analysis in both the Voith Laboratories in York, Pa and the USACE's Engineer Research and Development Centre (ERDC) in Vicksburg, Ms. Both the performance model testing carried out by Voith and the ERDC model testing were conducted using physical hydraulic models at a 1:25 scale.

8.2 Project Description

Presently the Ice Harbor powerhouse (603 MW) holds six Allis Chalmers Kaplan hydropower turbine units numbered 1-6 from south to north, although Unit 2 is currently fixed at 29 degrees as a temporary repair from mechanical failure. Units 1-3 and 4-6 have different spiral cases and runner designs and are capable of producing 90 and 111MW, respectively. Each unit intake has three bays and is equipped with a standard-length submersible traveling screen which diverts juvenile out-migrants into a bypass system.

The ICH reservoir (Lake Sacajawea) has an area of 1447.2 hectares. Specifications for each of Units 1-3 are:

- Runner diameter 7.1 m
- 6 blades runner
- Rotational speed 90 rpm
- Hydraulic head between 25.6 m and 31.4 m

8.3 Biological Performance

The replacement of the Ice Harbor units was primarily driven by the need to repair and replace the existing turbine runners. However, this opportunity was taken to improve the turbine runner performance for juvenile salmonids as they out-migrate from the Snake River Basin to the ocean. Turbine survival estimates for the existing units were derived from three series of study (Table 8). It should be noted that the fish introduced directly into the turbine flow were held and released at near atmospheric pressure and thus were not necessarily susceptible to barotrauma to the extent that naturally migrating fish may be. It should also be noted that although some survival estimates are relatively high, these estimates are likely biased by small sample size where few fish pass through the turbine. Conversely, low survival estimates (e.g. 78 – 89%) indicate a significant potential for improvement.

Species	Study Method	Survival Estimate	Reference
Yearling Chinook salmon	radio telemetry studies	94% to 98%	(Axel 2007,2010)
Sub-yearling Chinook salmon	radio telemetry studies	78% to 89%	(Absolon 2005, Axel 2010
Yearling Chinook salmon	direct introduction to turbine unit	93% to 99%	(Normandeau 2008)

Table 8: Turbine Survival Estimates for Chinook Salmon at existing Ice Harbor Units

Each turbine unit intake has a fish guidance screen that intercepts the majority of downstream migrating fish. Screens are installed between 1st April and 15th December on an annual basis and these guide fish into the gate well and through the powerhouse bypass system where they may be collected for studies or released back into the river. With screens installed, less than 10% of downstream migrating fish pass through the turbines (Trumbo 2013b). While guidance screens have been important for improving juvenile fish passage, consideration may be given to screen removal in the future if the new turbine runners significantly improve fish survival.

8.4 Design Approach

There are a number of causes that result in fish mortality following downstream passage through turbines. The IHR design incorporated criteria covering the following areas: (USACE 2011)

- Mechanical Strike: reduce number of structures and round edges.
- Shear: minimize gaps between the runner hub and blades, blade tips and discharge ring, etc.
- Turbulence: reduce vortices, wakes and backflows throughout the turbine unit.
- Pressure: minimum acceptable pressure of 10 psia, while targeting a design pressure equal to or greater than 1 atmosphere.
- Optimum operation: operate at best geometry (stay vane – wicket gate – blade alignment) and within 1% of peak efficiency during the fish passage/migration season.

As part of the TSP, the USACE undertook a number of studies to develop design criteria as well as methods to design and evaluate alternatives for fish passage. These are summarized by Trumbo (2013a). Information provided from PNNL barotrauma studies was incorporated to develop new differential pressure limits for the Ice Harbor turbines (Brown 2012). A design goal was to:

- Keep minimum turbine pressures at or above atmospheric pressure.
- Minimize risk of blade strike and exposures to shear.
- Maintain high turbine efficiencies.

Figure 12 shows how pressure changes throughout the turbine runner and illustrates the magnitude of difference in pressure in the intake before turbine passage relative to nadir pressure. Keeping nadir pressures high will not only provide fish passage survival benefits, but will eliminate turbine cavitation risks.

The IHR turbine design process with Voith and USACE was iterative with hydraulic modifications developed, evaluated and refined during a three-step process, Foust (2011):

- Computational Fluid Dynamic (CFD) analysis: modelling to evaluate potential runner designs and modifications to existing hydraulic components.
- Performance model testing: traditional Reynolds scale model turbine testing, by Voith to establish power performance and operational parameters.
- Observational model testing: open flume 1:25 scale physical model, with Froude similitude by USACE, with majority of model being transparent acrylic for visual observation and laser Doppler velocity measurements. Used to evaluate the fish passage environment.

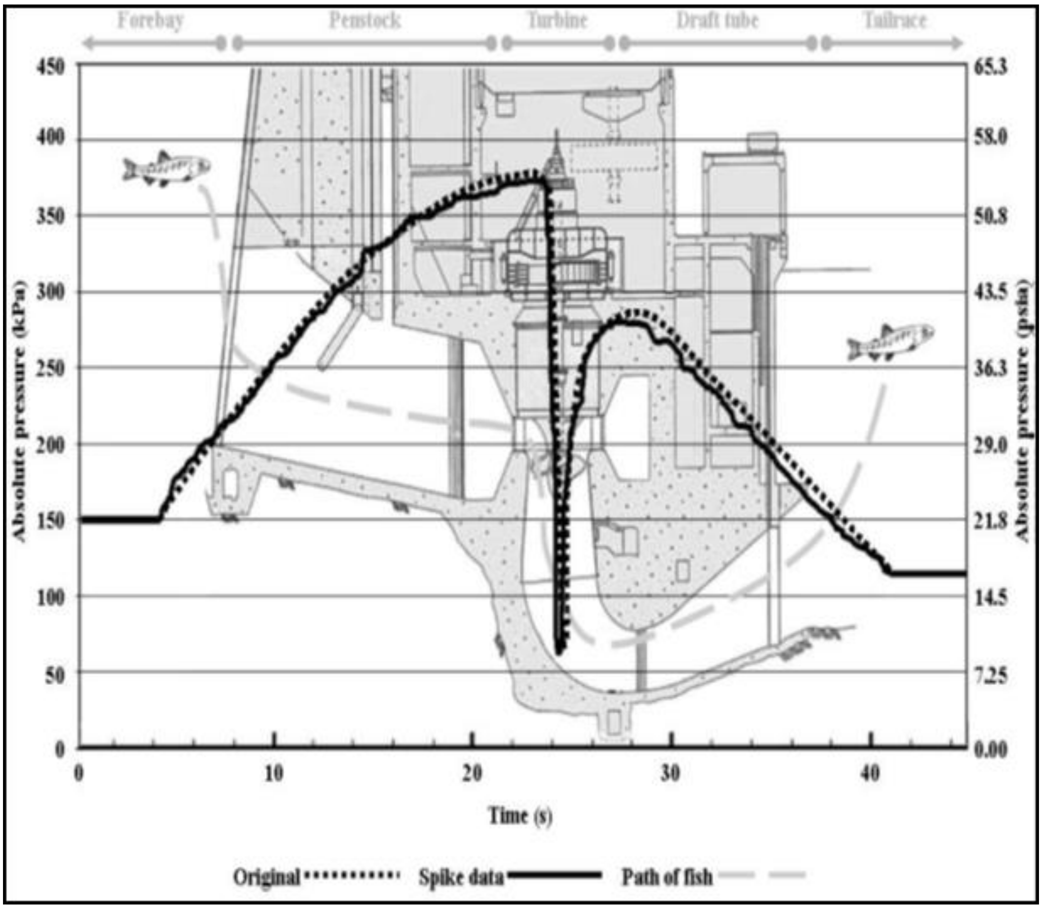


Figure 12: Turbine pressure-time profile experienced by fish passing through a Kaplan turbine (Stephenson 2010)

8.5 Turbine Model Studies and Testing

A 1:25 scale model of the existing Ice Harbor turbines (Units 1-3) was constructed at the USACE Engineer Research and Development Centre (ERDC) to evaluate their hydraulic and biological performance (Figure 13 courtesy of the USACE, ERDC). Operations and structural modifications to the unit and runner intended to improve fish passage were modelled. Hydraulic conditions within the runner and draft tube were tested using a laser Doppler velocimeter, die injections and high speed imaging of neutrally buoyant beads released into the flow path. In the existing configuration, the stay vanes were found to be poorly aligned with flows and the wicket gates poorly aligned with the stay vanes. This causes separation of flows with increased risk of injury to fish from strike and hydraulic shear. The poor alignment also creates a gap opening between the stay vane and wicket gates, which increases the risk of strike and exposure to shear forces. The existing draft tube design is also problematic for fish passage, with non-uniform flows and areas of turbulence and reverse flow (USACE 2011).

A number of alternatives were investigated in the model to improve the flow conditions through the turbine runner and overall turbine unit. Stay vane alignment was improved by extending and reshaping both the leading and trailing edges. Draft tube improvements were achieved by restricting flow expansion by elevating the floors or lowering the ceilings of each draft tube barrel.

Figure 13: The Ice Harbor turbine 1:25 scale model used to evaluate fish passage conditions

8.6 Generation Parameters

The new turbine runners were designed to operate within the same head range and flow range as the existing units. The modified designs of turbine (fixed blade and adjustable blade) stay vanes and draft tubes have resulted in increased turbine efficiencies while improving the fish passage environment.

8.7 Economic Considerations

Replacement of the Ice Harbor Unit 2 runner was driven by an opportunity to test the TSP design process and design criteria. The success of this effort will support the future rehabilitation and runner replacement of the aging turbine units within the FCRPS Hydro-Projects on the lower Snake and Columbia Rivers. This effort has since led to the replacement turbine the Ice Harbor Units 1 and 3. The Economics of this effort are justified by improving project reliability, increased turbine efficiency, and opportunity for future project operation flexibility resulting from turbines providing a safer fish passage environment. Although the total cost for the design, supply and installation of the fixed and adjustable blade turbine units are not yet available, fixed-blade units are normally lower cost than adjustable blade units, both for supply and installation of the turbine, as well as for operation and maintenance. Another consideration is that operating flexibility is reduced with the selection of a fixed-blade runner. Although it was reported that the efficiency of the new unit is better than the existing runner, no specific quantitative information is available. Not included in this economic consideration are the large costs associated with study, modelling, design and testing.

8.8 Summary of Ice Harbor Turbine

Fish passage through turbines and water passages has been studied at several Snake River and Columbia River Dams using various methodologies including sensor fish and live specimens (telemetry and balloon tag studies). Laboratory testing (pressure studies) and observational modelling have been performed as well. Study results have led to the development of improved turbine runner design criteria for fish passage. This encompasses nadir pressures, improving flow quality, decreasing shear and turbulence, and minimizing the potential for mechanical strike.

A collaborative and iterative design, approach has been developed for the Ice Harbor Dam turbine replacement project. This allowed the key criteria and general knowledge on fish friendly attributes to be incorporated into the design while taking full advantage of industries' turbine runner design expertise. The replacement of Ice Harbor Units 1 to 3 will provide an excellent opportunity to install and test large turbine runners designed for safer fish passage. Testing will include both a fixed blade and Kaplan runner and encompass the entire water way for fish passage improvement.

Results from turbine physical modelling to date suggest that the collaborative design approach between research scientists and engineers is effective in designing turbine runners for safer fish passage and increased efficiency. The Ice Harbor design effort has advanced the USACE understanding of the relationship between pressure, probability of strike and flow quality with respect to runner blade shape and design. The IHR turbine replacement project has provided the most thorough investigation and design criteria for fish passage to date. While biological testing has yet to be completed, physical model results are encouraging. Although the turbine runners design for Ice Harbor may not be applicable to other facilities as designed, the design process and criteria may be fully applicable.

To date, the study and design of the Ice Harbor Turbines has been as replacements for units at the existing power plant. However, the application of this design to new developments is considered to be fully appropriate.

9 Bulb Turbines

9.1 Introduction

Bulb turbines are often selected for low head projects with high flows. They cover the range of hydraulic head from under 10m to over 25m and maximum capacity to about 80MW. Axial-flow Bulb units are mounted in a horizontal shaft and this helps to reduce the size and depth of the powerhouse excavation, and hence cost, compared to vertical shaft arrangements. From the reservoir, flows pass through the intake structure, around the bulb housing and are regulated by the wicket gates located just before the runners. Flows then exit the draft tube to the tailrace. The generator and auxiliary equipment is housed in the watertight unit (Figure 14). Bulb units normally have higher full-load efficiency and higher flow capacities than vertical Kaplan turbines, primarily because of their linear waterway. This can lead to higher annual energy output and lower relative construction costs.

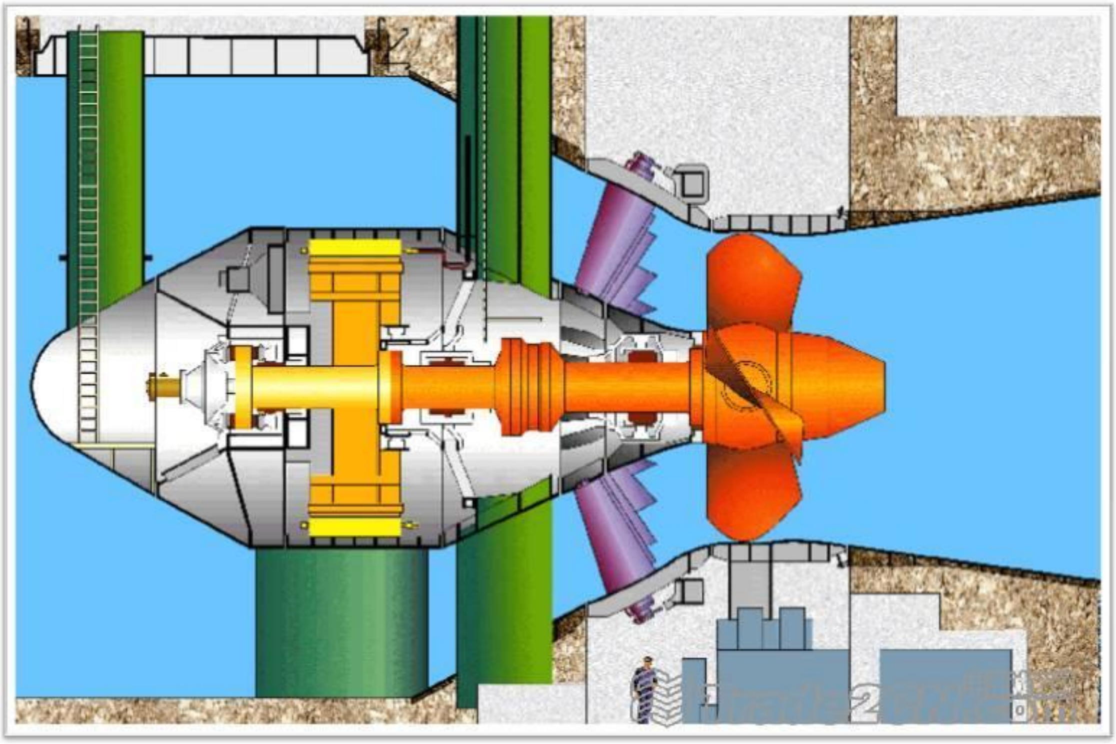


Figure 14: Schematic of a Bulb turbine

9.2 Generation Performance Considerations

Bulb units are an established hydropower turbine technology and have been used worldwide on many low-head hydropower projects. Normally they are selected for sites having a combination of large flows, low hydraulic heads and often challenging foundation conditions, which limit the feasible depth of excavation. They can also be the lowest cost alternative in such cases.

Bulb units can have fixed or variable-pitch runner blades (like vertical axis Kaplan runners). Presumably, if required, the variable pitch runner blades could be modified in a similar manner to the MGR designs. The relatively linear water passageway could presumably also be modified to enhance any fish friendly features, as determined by CFD studies and testing. It is believed that any appropriate modifications to the turbine and water passages, to enhance fish passage, could enhance, but would not adversely affect generation performance.

9.3 Biological Performance

In general there has been little study, testing and documentation on fish passage through Bulb units for a number of reasons:

- Bulb turbine units through their design concept have features that could be considered as fish-friendly, such as linear pathways, slow rotational speed and few blades.
- Research and development on fish-friendly turbines in the USA is mainly focused on projects in the Pacific NW, where there is only one significant powerplant with Bulb units installed
- Europe has a large number of Bulb units on major rivers. However, legislation and; regulations have not driven R&D on fish-friendly turbines, including bulb units, and there are only limited numbers of published reports on fish passage survival rates.

Compared to a vertical axis turbine, there are numerous paths that a fish could take passing through a horizontal axis bulb unit, each with different time-pressure histories. The most extreme pressure changes would occur if the fish were to enter near the ceiling of the turbine intake and exit near the floor of the draft tube, or vice versa. The pressure changes could be estimated from such a pathway, and compared to pressure sensitivities of the fish species of interest.

9.4 Case History

9.4.1 Case History #1 – Rock Island Hydroplant – Columbia River (624 MW)

The Rock Island Hydro project on the Colombia River has two powerhouses, with the newest (circa late 70's) having eight Bulb units with a hydraulic head of about 13m and capacity of over 50MW each. The original powerhouse includes Kaplan and propeller units.

A comparison was made of fish passage statistics for the three types of turbines (fixed-blade propeller, adjustable-blade Kaplan, and bulb) at the Rock Island Dam on the Columbia River using balloon-tagged juvenile Chinook salmon. This is documented in Section 6.3 and Table 7 and showed that the estimated survival probabilities were 93, 96 and 96% for the three unit types respectively, with no significant difference between either turbine types or entrainment depth.

9.4.2 Case History #2 - Beaucaire Power Station - Rhone River (210MW)

The Beaucaire Power Station on the Rhone River in France has 6 bulb units, each with an installed capacity of 35MW at a head of 13.5m. A study was undertaken to determine survival probabilities (1- and 48-hour) of balloon-tagged adult European eels passing through a 4 bladed bulb turbine (Normandeau 2011). The eels ranged in length from 570 mm to 1040 mm with an average of 686 mm. A total of 275 eels were introduced at two release depths (0.5 m below the intake invert and 3.5 m below the intake invert, while 50 eels were released into the discharge as controls). The released fish were projected to pass near the turbine blade tip and mid blade, respectively. Recapture rates were high for all releases (95.1 to 96.4%) and most specimens were recaptured within 10 minutes of release.

The 1-hour direct survival was 95.5% (tip) and 95.7% (mid) with a pooled value of 95.6%. Survival at 48-hour was 93.7 and 91.4% for tip and mid releases, with a pooled value of 92.3%. The primary injury was bruising on head and body, attributed to mechanical causes resulting from blade strikes or direct contact with other structural components during turbine passage. The direct survival and injury-free rates at the Beaucaire turbine were similar to those obtained for similar sized adult eels passed through a 4 bladed Kaplan turbine at the Fessenheim Hydroplant. The bulb turbines at Beaucaire appear to be friendlier to large fish than most other Kaplan/propeller type turbines evaluated. However, caution should be used when interpreting these results. Since the eels were released from surface pressure, the damage due to pressure could be much higher if fish were acclimated to depth. This is especially the case for eels which have a very active bed of vasculature on their swim bladder (Fange 1983), which could lead to high rates of barotrauma (Brown 2014). This could lead to relatively high mortality of eels during turbine passage, but this has not been confirmed by research.

The Beaucaire hydro plant owners are continuing in their efforts to restore the circulation of migrating fish (shad, eel, and lamprey) in the middle Rhone and between the Rhone Valley and its tributaries in line with regional planning objectives.

9.5 Summary of Bulb turbines

Bulb turbine units cover a range of hydraulic head from under 10m to over 25m and maximum capacity to about 80MW and are presently under consideration for some of the units in the proposed development of Mekong River hydropower projects. Based on very limited information, fish survival rates for Bulb units are expected to be similar or better than the MGR units. As with other unit types, research is lacking to determine expected levels of survival for Mekong Basin fish passing through bulb turbines.

While there is little data available on the performance of bulb units with regards to fish passage, there are some useful interpretations that can be made. Naturally, these would need to be supported by the appropriate level of testing prior to consideration of any application.

- The layout of a bulb turbine having a horizontal axis could be considered intrinsically more favourable to fish passage than a unit aligned along a vertical axis.
- Similarly design features, such as low rotational speed and reduced number of blades could be considered favourable in terms of strike, and a low-head setting favourable in terms of pressure change.
- Modifications made or considered for a vertical axis Kaplan or propeller turbine, to improve fish-friendly attributes, should be transferrable to bulb units.

Overall, it is suggested that any assessment of fish-friendly turbines for the Mekong River projects include the consideration of Bulb turbine units, where they meet site development criteria.

10 Alden Turbine

10.1 Introduction and Development History

The specific objective in the development of the Alden turbine concept was to minimize damage to fish. Alden Research Laboratory developed and patented the Alden Turbine in the early 2000's, with an initial arrangement as a three-bladed runner for smaller radial flow machines. Over the years the design has been modified and model tested based on funding from EPRI, USDOE and industry sources. However, to date no full-scale prototype has been implemented. (Dixon 2013).

A one-third scale model was built and over 40,000 fish passed through the unit. Species included American eel, white sturgeon, coho salmon, rainbow trout, smallmouth bass and alewife. Based on the favourable results, a full-scale survival rate of between 97 and 100% was predicted (Perkins 2013a). However, as noted previously, when examining results from studies such as this one where fish are injected into turbines from the surface these very high survival estimates should be viewed with some caution. Conducting laboratory research with appropriately acclimated fish could improve the confidence that this turbine would be fish-friendly when deployed.

By 2008/9 Alden was collaborating with Voith to refine the hydraulic design and thereafter Voith modified the original Alden geometry with the goal of minimizing damage to fish, reducing manufacturing costs and improving efficiency. Refinements were conducted using Computational Fluid Dynamics (CFD) with key goals of:

- Low collision-induced fish mortality.
- Optimum number of turbine blades and guide vanes.
- Improved hydraulic profile of individual components.
- Reduced rotation speed.
- Excellent water flow geometry, supporting downstream fish passages.

A performance model was built and testing in Voith's facilities was conducted in October 2010, and following the tests, Voith and Alden refined their scope definition for commercial installation.

Although no full scale prototype has not yet been developed, it is noted that a pilot project was considered for the Brookfield Renewable Power's School Street Hydro PowerStation, in which one Alden turbine was proposed (Voith 2013). Part of the development study included comparison with two other types of turbine, which are summarized in Section 6.3. More information from this development study is included in Section 10.5

10.2 Description and Physical Characteristics

The Alden turbine design parameters, selected to enhance fish-friendliness, include:

- A large hub diameter
- Slow rotational speed
- Three turbine blades
- Minimal gaps between the blades and the hub
- Thick leading edges on blades
- Thick leading edges on stay vanes and wicket gates
- Biological design criteria to minimize damaging shear and pressure drops

The 1:8.71 physical model of the Alden turbine is shown on Figure 15 . This model runner was tested by Voith Hydro and provided peak efficiency of 91.9% (which translates to a maximum calculated prototype efficiency of 93.6%).

Figure 15: Photograph of the Alden Turbine used in Physical Model

10.3 Performance Parameters

Information provided by EPRI (2011) and Murtha, (2011) indicates that, based on a mechanical design review, the Alden turbine could be implemented for a range of applications. However, at present, physical size limitations translate into hydraulic head (H) and power flows (Q) for individual units as shown in Table 9. The review also indicated that peak efficiency would be higher than conventional turbines at design operating conditions, though lower when operating on either side of this optimum.

Development Status	Hydraulic Head, H (m)	Power Flows Q (m3/s)	Comments
Current application	22 to 30	28 to 50	Based on physical size limitations
Modified application	10 to 40	17 to 325	10m is lowest practical hydraulic head
Future development	>40	17 to 325	Following successful prototype

Table 9: Range of Alden Turbine Development

10.4 Economic Considerations

A comparison was made of the equipment supply and construction costs of three similarly rated turbines; the Alden, Conventional Francis and MGR Kaplan (Perkins 2013b). It was estimated that the Alden turbine would cost 39% more than a conventional Francis turbine and 35% more than a MGR Kaplan unit. Perkins notes that full life-cycle costing provides more relevance to any comparison. It is therefore suggested that any cost comparison includes all relevant cost parameters, such as;

equipment supply and installation, powerhouse construction, costs of alternate fish mitigation measures and any lost energy through spill. Some life-cycle cost parameters include:

- Additional energy could be gained by greater equipment and water passage efficiencies and optimized unit operations.
- Less powerhouse excavation (higher turbine setting), requiring about 17% less than a comparable Kaplan turbine.
- Overall civil works expected to be approximately 12% less than a comparable Kaplan turbine
- Fish bypass systems may no longer be needed if further testing determines that passage survival is high. This could allow more flows for generation.
- Possible avoided O&M and capital costs if downstream fish bypass systems no longer required.

This life-cycle cost comparison should be taken into account as well as the inherent value of the selected turbine in providing an improved rate of downstream migrating fish survival.

10.5 Case History

Although no full-scale prototype of the Alden turbine has yet been installed, it is an important technology for potential future applications of improved fish survival turbines. For that reason, two examples of studies have been considered as case histories.

10.5.1 Case #1 – Brookfield Renewable Power – School Street

A pilot project was considered at Brookfield Renewable Power's School Street Hydro PowerStation, in which one Alden turbine was proposed (Voith 2013), with the following parameters:

Turbine Design (to meet power production criteria):

- Net Head of 28 m,
- Power flow of 42.5 m^3/s,
- Rotational speed of 120 rpm, and
- Runner diameter of 3.9m

Hydraulic Design Parameters

- Pressure change rates ≤ 3.5 MPa/s,
- Velocity shear rate ≤ 360/s,
- Minimum pressure in the runner passage ≥ 51.0 kPa

10.5.2 Case History #2 – Columbia River

A project is being considered to install Alden turbines in the empty bays of a powerhouse on the Columbia River (Amaral 2014). The preliminary design parameters are

- Rated power flow for each unit: would be about 210 to 240 m^3/s.
- Hydraulic head: with a head of about 30.5 m
- Turbine runner diameter: 8.5 to 9 m
- Unit rotational speed: <60 rpm.

Based on this information, the capacity for each proposed unit is estimated to be about 14 to 17 MW.

10.6 Summary of Alden Turbine

To date, no full-scale prototypes of the Alden turbine have been built, so that despite the very large research and development effort that has been expended and the extensive experience of the developers, it cannot be considered as a commercially proven technology. Notwithstanding this present situation, it is considered to have significant future potential for the appropriate application. At this stage the technology is noted as being particularly suited for small hydro applications where costly fish bypass systems make hydro development possibly unfeasible. The design also could possibly provide passage of longer fish such as eels at a higher survival rate than Kaplan and bulb turbines due to a possible lower chance of strike. Eventually larger scale development is planned.

Tests of fish passed through a scaled model of the Alden Turbine indicate survival could be high. Modelling of the design suggests that survival due to strike and shear forces could be as high as 97-100%. These results reportedly could help provide a balance between fish passage and energy production considerations.

In terms of life-cycle cost comparison to other turbine designs, if fish survival is as high as the proponents of the Alden turbine suggest, less expense may be needed for downstream fish passage efforts such as bypass systems and trap and haul compared to other turbine designs. To determine the potential for use of this turbine in the Mekong Basin, further research would be needed. This could be done by exposing fish to conditions that are determined by modelling or putting Sensor Fish through the scaled model. This testing would need to take into account the physiological state of Mekong fish species that would be approaching and passing through the turbines.

11 Applicability of Fish-Friendly Turbines for Mekong River Hydropower plant

11.1 Introduction

A key issue in the development of hydropower plants in the LMB, as it relates to downstream fish passage, is to evaluate the applicability of fish-friendly turbines in providing effective mitigation. This can be accomplished through the transition from the present state of knowledge relating to fish and turbine interactions, to what needs to be done to broaden this knowledge to cover fish and turbine interaction for the migrating species of the LMB. Furthermore, it is most important that every effort be made to provide information and processes, based on best scientific and engineering knowledge, to support future hydropower developers in selecting and implementing FFT designs. This Section will provide a high level guide to the components that need to be addressed.

It is clear that the development of hydropower dams and power plants on the Lower Mekong River will present a barrier to migrating fish. This in turn will likely have significant social and environmental impacts. Fish-friendly turbines have the potential to be an important component of the mitigation framework. However their effectiveness in providing improvements to fish passage in the LMB context needs to be evaluated.

Studies to date on the applicability of FFTs to provide safe downstream fish passage have focused primarily on juvenile salmonids in the Pacific NW region of the USA. These studies have been supported by detailed analysis, sophisticated model testing and major monitoring programs, with many millions of dollars spent over a number of years. The outcome has been advancement in knowledge of the behaviour of the fish passing downstream and the mechanisms that influence their survival when interacting with hydro projects.

Studies have been undertaken on other species, in other regions, and by different organizations, but these have also been of limited scope. Studies are ongoing for some South American and South-East Asian fish, and non-salmonids in North America, but at a much lower level of research effort. They have generally covered only a limited number of species, and those studied normally had predictable behaviours in terms of their life stage and time of year for migration, while this is not necessarily the case for fish species in the LMB.

Research and development activity has mostly been focused on existing hydro plants and the replacement of turbine units with designs intended to be more fish-friendly. However, there will be limits to the direct applicability of these studies to guide new hydropower development in the LMB with its large number and variety of fish species.

One very significant positive in terms of applicability is that nearly all documented research which provides successful examples of FFTs is based on axial-flow units. These include Kaplan and Bulb type turbines which are presently being considered for the eleven projects on the Mekong River.

Notwithstanding these limitations, significant advancements in FFT technology have been achieved, through research, study and testing. This provides confidence that turbines with fish-friendly attributes could provide benefits in terms of applicability in the LMB. However, much research, study and testing needs to be undertaken to investigate and define these benefits.

11.2 Research needs on Mekong River fish species.

Section 4.4 discussed the general impacts associated with the operation of hydropower turbines on fish and noted that impacts can be linked to mechanical, hydrodynamic and operational factors. These in turn are affected by the turbine features, hydraulic conditions, and the characteristics and physiology of the fish, such as the species, life-stage, size, state of buoyancy and behaviour.

Mekong River fish species have many differences in characteristics and behaviours to those studied to guide current FFT designs. To support the selection of turbines with fish-friendly attributes for the proposed hydropower dams on the Mekong River, a significant program of focused research, analysis and testing on relevant migrating species will be required.

Clearly, a research program to test the applicability of FFTs for the LMB would need to cover all the potential impacts emanating from mechanical, hydrodynamic and operational factors. One key component that is discussed in the following sections covers a program on barotrauma research, based on a logical and staged approach (Brown 2014). Such a program would start with field or desktop investigations necessary to determine which species and life history stages could be good bio-indicators to guide FFT design in the LMB (Figure 16).

Other key turbine passage injury mechanisms, such as strike, shear, etc., would need to be addressed in similar fashion. This is research that is ongoing in the USA and Europe by research laboratories and turbine manufacturers and could generally be applicable in the LMB.

The research needs to transition from the present state of knowledge relating to fish and turbine interactions, to what needs to be done to broaden this knowledge to cover fish and turbine interaction for the migrating species of the LMB, will undoubtedly be a daunting task. Considerations therefore need to be developed that focus on key issues, and prioritize them based on their importance to both environmental and social factors and to bio-diversity.

11.2.1 Fish Ecology and Behaviour Research

The survival of fish passing downstream through turbines depends on a variety of parameters for both the hydropower plant (type and size of turbines, environmental settings, and modes of operation) and the entrained fish (species, size, physiology, condition and migration patterns). Looking specifically at FFT's, the challenge is to apply the knowledge gathered from the broad range of international experience to the conditions within the LMB. This includes the range of issues associated with the various migrating fish species and the planned hydropower development scenarios on the mainstream of the river. Topics that need to be considered include:

- The characteristics and behaviours of the specific fish species at that site, and their migratory patterns.
- The migration patterns of the various fish species along a range of life stages from larvae to large adults.
- Understanding how a range of migrating fish species could be affected during downstream migration through the turbines and how this could vary among numerous hydro projects that are currently being planned for the LMB.

It will be difficult to prioritize which species of fish to focus research on since there is a large number of species in the LMB of greatly varying sizes. Considerations of the many factors affecting susceptibility to barotrauma, for instance, including ecological and biological parameters, would be helpful in this regard (see Section 3.4).

A first step would be grouping fish based on vulnerability to barotrauma and other stressors, starting with species and considering their life history stages at which they may have the highest vulnerability. Combining a field, laboratory and modelling approach can allow an understanding of the fish species acclimation depths and the expected range of pressures they may be exposed to when passing through the turbine. This would provide a range of pressure changes that fish could be subjected to in experimental pressure chambers and from this, injury or mortality relationships can be modelled.

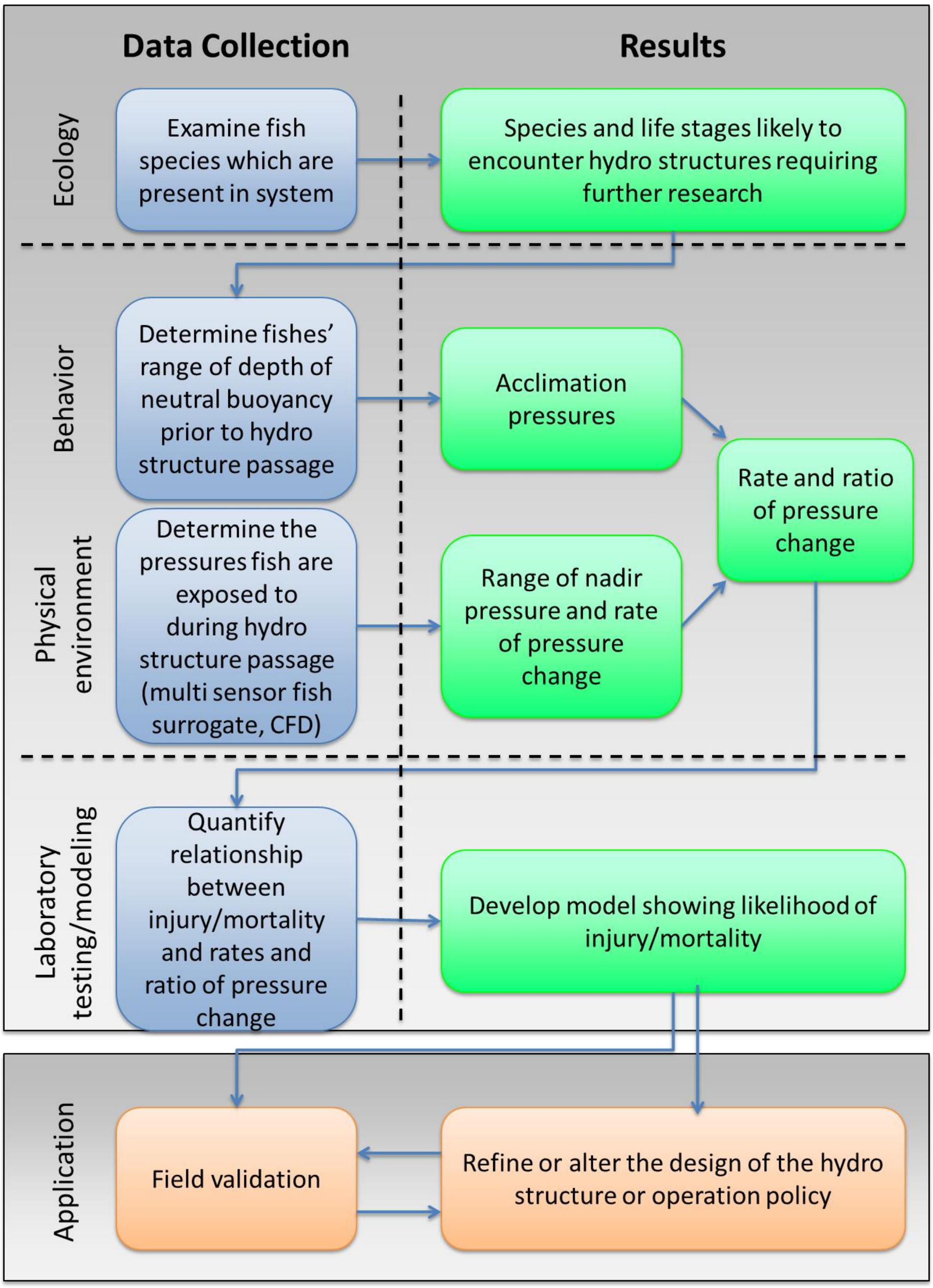


Figure 16: A recommended Barotrauma Research Framework (Brown 2014)

An important challenge for understanding any linkage between technological development and research done to date in the USA and Europe and that which is applicable to the Mekong River Basin is the sheer numbers and differences in the fish species to be found in either environment. This is compounded by the research efforts to date based only on a small fraction of the overall number of species.

Ways that could improve the efficiency of turbine survival evaluations include assessments based on fish characteristics such as the Traits-Based Assessment (TBA) process (Čada 2012a,b. Hogan 2014) and others (Brown 2014). Since it is not likely that funds are available to determine an all-inclusive understanding of the relationship between turbine-passage conditions and the survival and injury of fish for every species found in the LMB, identifying the most likely to be damaged, as indicator species, is important.

Such processes are geared towards predicting fish mortality based on an improved understanding of the characteristics (pressure, shear stress, turbulence, strike) and information about the morphological, behavioural and physiological characteristics of different fish that make them vulnerable to turbine passage characteristics. Important traits may be classified as ecological – environmental preferences, behaviours, and biological – body size, shape, physiology and life history characteristics. The concept of the assessment process is that similar traits may lead to similar risks associated with turbine passage and similar turbine passage survival rates. Such processes are designed to identify species that have traits that could make their species relatively vulnerable to the effects of turbine-passage and the appropriate structural and operational mitigation measures. Improved flow release regimes could speed the passage of downstream-migrating fish through the reservoir at critical times, and advanced turbines may reduce mortality among turbine-passed fish.

11.2.2 Research in the Pressures Fish are Exposed to when passing through the Turbine.

a) Characterize physical conditions fish are exposed to during turbine passage

It is well understood that as fish move through the low pressure region below the turbine runner, rapid decompression can lead to barotrauma (Trumbo 2013). The USACE and PNNL have, over the last two decades, released Sensor Fish into turbines within powerhouses along the Lower Snake and Columbia Rivers. Simulated turbine passage (STP) studies were designed to evaluate barotrauma experienced by fish passing though turbines under a wide range of pressure scenarios. This was achieved by exposing fish, in a laboratory setting, to pressures that they are likely to experience during turbine passage and has greatly increased the understanding of how rapid decompression affects fish passing through turbines (Brown 2012a, b, c). Research has been conducted using a series of pressure testing devices that have evolved from the early 2000’s to the much more complex equipment currently used (Stephenson 2010).

This research, which more accurately simulates the conditions that fish are exposed to, has been fundamental in understanding how injuries to fish are linked to the conditions experienced during turbine passage. This methodology can provide basic information on the types of barotraumas that would occur during passage of fish through turbines in hydropower plants in the LMB.

b) CFD and Physical Models

The use of CFD and physical models can be very helpful to refine infrastructure design. These models use input from laboratory research, monitoring of 3D acoustic telemetry tags, and data from Sensor Fish that have been passed through turbines. This type of modelling can be validated during field trials, with this field validation and testing being a critical link in an adaptive management loop. Scientists and engineers can keep the research and development applied and ultimately targeted on the goal of promoting sustainable water resource development and improving fish passage in the complex turbine environment.

Another approach that has been developed by PNNL and which may be applicable for the LMB design process is a hydro turbine biological performance assessment (BioPA) tool. This tool could bridge the gap between field and laboratory studies on fish injury and turbine engineering design (Richmond 2013). The BioPA tool can combine input from laboratory-based fish-response criteria (Brown 2012a, b) with CFD models and can be used to determine how fish are influenced by exposure to the hydro turbine passage environment. This approach can use data inputs such as stream traces from CFD models to understand how fluid conditions and the probabilities of such exposures could negatively influence fish. However, the tool will require measurements of physical conditions (typically through Sensor Fish) and live fish experiments (in both laboratory and field) for validation.

11.3 Selecting FFTs for the Mekong River developments

Research, development and deployment initiatives on FFT's to date have indicated that, mainly for juvenile salmonids, such designs show promise for improving fish passage survival rates. This is particularly the case for the modified MGR Kaplan turbine (with improvements driven by the Ice Harbor project). Similar improvements could also be expected through appropriate modifications to the four-blade Bulb turbine units. Kaplan and Bulb units are the types presently being considered for hydro-mechanical equipment at the eleven proposed hydro projects on the Mekong River. Use of Alden turbines, which could possibly provide relatively low levels of shear and blade strike, are presently only in the development phase and have not yet realized a full-scale prototype.

As noted in Section 3, there are three relatively distinct fish migrating systems in the LMB, and there is at least one of the eleven proposed hydropower plants located within each system in areas where these fish could be influenced. It is thus suggested that requirements for downstream fish passage be considered within each of these migratory pathways. This should be reflected in designs of any installed turbine, to ensure that appropriate fish-friendly attributes are incorporated.

The key to selecting FFTs for the Mekong River hydropower plants is to prove their performance with respect to survival rates for the respective Mekong River migratory fish species. This will be a challenging task based on the wide diversity and numbers of fish species in the LMB to be considered and the time and cost that is needed to undertake the necessary research. It will also be challenging to identify which particular species should be examined to minimize damage due to different turbine designs. In other words, it may be difficult to design a turbine that will provide improved fish passage for all species. A design that will provide improved fish passage for a few key species or functional group(s) may be more attainable.

Based on information available, and unless significant changes to design were required to accommodate Mekong River species, the overall costs for supply and installation of FFTs is expected to be very similar to that of standard equipment. There would be extra costs during the design phase which would require sophisticated CFD analysis and model testing to cover fish related issues; however, these would be undertaken in conjunction with optimizing generation performance. One possible economic benefit has been the performance results of MGR turbines, which have maintained relatively high passage survival rates for fish, while producing more power than many of the designs that area currently being employed (Section 7.4). This information should be considered when selecting and designing FFTs for deployment in the LMB.

11.4 Selecting FFTs for Hydropower plant on Mekong River Tributaries

The main purpose of this review was to gather currently available information on the effectiveness and application of FFT's. This was done to guide the acquisition of knowledge required for the selection of turbine technologies that could minimize damage to fish interacting with hydropower projects on the mainstream of the Mekong River.

The tributaries of the LMB are also an important component of the overall environmental health and are essential for many migrating species to complete their life histories. Many fish spawn in the flooded areas and tributaries that feed the Mekong River and it is imperative that their migration routes are maintained. It is therefore important that, as part of the process to retain fish migration routes, plans for proposed hydropower plants on the LMB tributaries should also be evaluated to determine if FFTs could minimize fish damage and maintain necessary migration behaviours. To this end, research should be conducted to evaluate the effectiveness and economics of FFTs at the scales to be expected for hydropower plant on the tributaries.

In general terms, the same issues need to be addressed for the tributaries, as for the hydropower dams proposed on the mainstream of the Mekong River. This will include a life-history approach to fish migration and a holistic approach to providing downstream passage routes which have minimal influence on fish, and to the design of the water passages, including FFTs.

In the lower reaches of LMB tributaries, where projects with low to medium hydraulic heads may be found, it may well be that selection of modified vertical-axis Kaplan turbines, fixed-blade propeller or horizontal-axis Bulb units could minimize fish mortality. For smaller hydroelectric projects, the Alden turbine, when it has been proven commercially and evaluated further (with fish acclimated to a range of depths, not just surface acclimated), may also facilitate lower fish mortality than other designs (Katopodis 2013). In the upper reaches of the tributaries, more often associated with projects with higher hydraulic heads, Francis or Pelton turbines are usually selected. While these units are outside the scope of this review, they are normally associated with low to negligible fish survival rates.

In addition, there are many new infrastructure projects proposed for thousands of small tributary streams throughout the LMB and it is important that these developments take advantage of available technology and science. Obtaining and applying this knowledge to new infrastructure projects, as a means to improve local ecosystems and fisheries is an important consideration (Baumgartner 2014).

A focused research and monitoring program should be used to support any decisions regarding the installation of FFTs on the LMB tributaries. This would include considerations of their mechanical and hydrodynamic characteristics to minimize sources of injury and mortality for fish. As for large units on the Mekong River, concerns should include:

- Minimizing all gaps and the number of wicket gates, stay vanes and under some circumstances minimizing the number of runner blades;
- Adopting rounded and wide leading-edge blade shapes;
- Offering adequate clearance for fish between solid boundaries;
- Providing smooth surfaces and streamlined hydrodynamics;
- Reducing the relative velocity of flow along solid surfaces;
- Avoiding highly curvilinear flow or eddies;
- Minimizing pressure changes and the rates of pressure change.

Research on FFTs should also include their suitability for passing fish safely through hydro plants generating power from in-stream flow releases and also where hydropower generation facilities are added to existing dams.

11.5 Summary

Focused research is required to transition the lessons learned from the significant levels of investment in turbine technology and fish passage research, study and testing, to the LMB environment.

Studies to date on the applicability of FFTs to provide safe downstream fish passage in regions other than the LMB, have shown that in most cases, with the latest developments, they can improve fish passage survival rates, mainly for juvenile salmonid. These studies have been supported by detailed analysis, sophisticated model testing and major monitoring programs, over a number of years and costing many millions of dollars. The outcome has been advancement in knowledge and a greater understanding of the behaviour and survivability of the fish passing downstream through turbine water passages and the mechanisms that contribute to their fate.

Kaplan and Bulb turbines units are the present choice for the proposed hydropower developments on the Mekong River. This approach may be guided by the technology advancements on FFTs, evaluations based on research from a small number of regions and species, and relatively lower mortality rates for fish passing through modified MGR Kaplan turbines than for other turbine types.

However, taking advantage of further turbine improvements, such as those expected from the Ice Harbor project, will be most beneficial.

The key to selecting FFTs for the Mekong River hydropower plants is to prove their performance with respect to survival rates for the respective LMB migratory fish species. It would be optimal if the relationships between fish survival and passage of FFTs within the LMB hydropower plants could be established. This is a daunting task based on the large variety of species that reside within the region and the time and cost that would be needed to undertake the necessary research. In terms of research, there are several main areas to study:

- Applications of Sensor Fish technology at dams currently present with in the region to characterize turbine passage conditions.
- Laboratory studies to investigate how turbine passage conditions could influence fish. This would include examining damage such as barotrauma, strike and shear forces on fish in association with:
  - Fish ecology and behaviour;
  - Pressures (rate and range) fish are exposed to when passing through the turbines
  - Relationships between the rate of injury and mortality and the range and rate of exposures to rapid pressure changes, turbine strike, exposure to shear and turbulence for different species
- CFD and hydraulic modelling to improve turbine and water passage design.

To support the research activities two analytical approaches should be considered.

- Research that relates the traits and physiology of fish to the conditions they could be exposed to during turbine passage. An example of this is the Traits Based Assessment (TBA) process.
- The use of models that include input from several sources. This includes detailed characterization of the turbine passage environment (using tools like the Sensor Fish) and models that relate turbine passage conditions to relationships between those conditions and the survival of fish such. An example of this is the Hydro Turbine Biological Performance Assessment (BioPA) Tool.

However, notwithstanding the complexity, costs and timelines required to undertake research and studies, considerations should also be given to a process that focuses on key issues, and prioritizes them based on their importance to both environmental and social factors and to bio-diversity.

Based on information available, the overall costs for supply and installation of FFTs is expected to be very similar for Mekong River projects to that of standard equipment, notwithstanding extra costs during the planning and design phases. However, these could be offset by the expected improvements in turbine performance.

While the assessment of FFTs for the Mekong River tributaries is outside the scope of this review, safe downstream passage of fish throughout the basin is an important component of the life history of migrating species and should be studied appropriately.

12 Summary of Findings

This section will summarize the applicability of the internationally gathered experience to the fish fauna of the Mekong River and the economic development of hydropower along the Mekong River.

12.1 Overall findings

A holistic approach to the downstream passage of fish should be a component of the environmental assessment for any new hydropower projects on the Mekong River, with the outcomes being part of the mitigation strategy for the design studies. The approach should cover all relevant fish species, all temporal variations in migration and flow characteristics and all reasonable means to pass fish downstream, including, but not necessarily limited to the turbines.

However, because of the wide diversity and numbers of fish species in the LMB, it will be challenging to identify particular species of interest for turbine design. In other words, it may be difficult to design a turbine that will provide improved fish passage for all species. A design that will provide improved fish passage for a few key species or functional group(s) may be more attainable.

It is most important that the approach to providing downstream fish passage be holistic, based on best practice and consider all factors, rather than be solely focused on FFTs.

12.2 Mekong River Fish

Summaries of Sections 3 through 5 provide the following key points.

12.2.1 Section 3: Mekong River Fish Migration

- The Mekong River Basin supports the world’s largest inland fishery, essential for the livelihood, nutrition, and food security for a large population. Indigenous fish species are numerous, variable and part of an important bio-diversity. Migratory behaviour is complex.
- Creating barriers to flow on the Mekong River will cause disruptions to fish migration behaviours and could seriously impact the associated ecosystem. Establishing structures and facilities that enable the downstream migrations of fish is an important component of processes to manage the overall migration effectively.
- There are three relatively distinct fish migrating systems in the LMB, with at least one of the eleven proposed hydropower plant located in each. Requirements for downstream fish passage might have variations for each system, and would need to be reflected in FFT design.

12.2.2 Section 4: Downstream Fish Passage

- The downstream passage of fish, over, around or through a dam (hydropower or otherwise) or other barrier to flow, poses challenges as hydrologic, hydraulic and geomorphologic conditions vary considerably from a natural river system.
- Downstream passage has impacts on fish, from various hydrodynamic, mechanical and operational Factors.

12.2.3 Section 5: Experiences from other Regions and River Systems

- Most research to date on downstream fish passage through turbines has focused on juvenile salmonids in the Pacific NW of the USA.
- Other major river systems in the world support a diverse range of species and within their life history undertake migrations and are therefore at risk if dams or barriers have been constructed.

- Minimizing risks to fish passing downstream as part of their migration cycle is a project issue, but also has river basin and regional implications. Significant investment is needed to study the issues and develop the technologies to overcome the hurdles. Because many of the species of fish in the basin have drifting larvae, that could cover relatively long distances, as part of their life cycle, the implications of even a single project could reach far beyond the location of the dam and reservoir.

There would be great benefit in encouraging international cooperation for future research efforts. There are many similarities in fish species among different regions of the world, and international collaboration would greatly reduce redundancy.

There are a number of reports that cover fish species and migration along the Mekong River in general terms, but do not provide background information for the analysis of likely impacts from barriers to downstream passage and the effect of FFTs.

12.3 Comparative Analysis of FFT's

In terms of the applicability of FFTs for Mekong River hydropower plant, it is noteworthy that of the eleven proposed hydropower developments on the Lower Mekong River, eight are presently nominated to include Kaplan units, with one to include Bulb units. Of the two that presently do not show a preferred type of unit, one Kaplan and one Bulb would appear most likely, based on hydraulic head, size and flow parameters. Most recent FFT research has been focused on Kaplan units (with Bulb units being similar in concept). However, most of this research has been focused on salmonids. Verification of biological effects on all units is recommended.

Summaries of Sections 6 through 10 provide the following key points.

12.3.1 Section 6: Fish Passage through Hydraulic Turbines

Methods to evaluate the performance of new turbine designs are readily available and continually improved:

- Kaplan units presently proposed for the Mekong River projects could be modified to MGR or the more advanced Ice Harbor designs.
- Three or four of the total eleven projects presently proposed for the Mekong River projects are within the normal operating range of Bulb units and could be developed with this technology if environmental and cost considerations were favourable.
- Despite significant levels of research, the Alden turbine has not been yet been proven at a prototype level and is not ready for commercial deployment. In addition, based on its nominal application range, it would not be applicable for Mekong River projects, with the possible exception of Stung Treng.
- FFT selection for Mekong River projects would require appropriate design parameters to meet migrating fish requirements and site conditions, and include the full water passageways from intake to tail-water.

It is noted that nearly all the significant research to date supporting turbine designs to improve fish passage, has been undertaken based on juvenile salmon in the USA. This has led to the development of sophisticated equipment and methodology, as well as extensive field and laboratory experience to understand fish behaviour. It has also provided the impetus for improved materials and technology in turbine engineering and manufacture. These advancements will be most useful in studying the issues and improving the performance of fish passage through hydraulic turbine in other parts of the world, including the Mekong River Basin.

Based on experience to date, future analysis and designs of FFTs will be a sophisticated approach, taking into account the characteristic of the entire water passage as they relate to the fish species under study. Research, testing and design will be based on laboratory studies, CFD analysis and possibly model testing.

While research on physical and biological parameters is continuing, it is at a relatively low pace. A far higher rate and extent of research is needed for there to be any confidence in fully understanding the interactions between hydro projects and fish in the LMB.

12.3.2 Section 7: Minimum Gap Runner Turbines

- Four projects have had large MGR turbines installed as replacement units in existing power plants on the Columbia River and its tributaries. To support these installations, the MGR has only been tested in the Pacific NW of the USA, particularly for the salmonids of this region.
- The majority of units presently proposed for the Mekong River projects are Kaplan and could be modified to MGR or the more advanced Ice Harbor designs.
- The MGR design is an important development and has potential for new projects. Overall, its design features have provided similar or better results in some aspects of fish passage survival.
- The supply and installation costs of a MGR Kaplan turbine in a new powerplant are expected to be similar to those for a conventional design. However, there may be extra costs for the study, design and testing phase.
- One possible economic benefit has been the performance results of MGR turbines, which have maintained high survival rates for fish passage while producing more power than conventional designs.

12.3.3 Section 8: Ice Harbor Turbines

- The refurbishment of turbine units at Ice Harbor (IHR) has provided an excellent opportunity to design and test large turbine runners with emphasis on fish passage. This will cover the entire water passageway for fish passage improvement.
- The technical results to date have shown advances in:
  - Understanding the relationship between strike and flow quality.
  - How leading edge strike probability is governed by blade number, rotational speed and fish length.
- The development of the Ice Harbor Turbines has been as replacements for units at the existing power plant. Considerable testing has already been undertaken and is continuing to examine the performance of these turbines in regard to fish passage.
- Based on preliminary assessments, the application of the ICH design to new developments is considered to be fully appropriate.
- Results from turbine physical modelling to date suggest that the collaborative design approach between research scientists and engineers, and between the project owner and the equipment manufacturer is effective in designing turbine runners for safer fish passage and increased efficiency.

12.3.4 Section 9: Bulb Turbines

- Application ranges for Bulb units vary between about 10m and 25m for hydraulic head, with power outputs up to about 70MW.
- Fish passage survival rates are generally considered to be quite dependant on low turbine rotational speed and a minimum number of turbine blades, which are attributes of Bulb units.
- Horizontal-axis Bulb units have the potential to have fish passage survival rates as good or better than vertical axis axial-flow units. However, very little research and testing has been carried out to verify their performance.

- Modifications made or considered for a vertical axis Kaplan or propeller turbine, to improve fish-friendly attributes, should be transferrable to bulb units.

12.3.5 Section 10: Alden Turbines

- The Alden turbine has not yet been proven at a prototype level and is not ready for commercial deployment. Presently, the unit is only applicable for small scale hydro.
- Based on significant levels of research, fish survival rates for the Alden Turbine were reported by the technology developers to exceed 97% due to strike and sheer forces under certain conditions, although it is unclear what the level of barotrauma may be in a full scale deployment.
- While the supply and installation costs of an Alden turbine are reportedly significantly higher than for Kaplan and Bulb turbine units, the technology developers report that costs would be comparable based on a full of life-cycle cost analysis.

12.4 Economic Hydropower Development

Decisions on hydropower development by government agencies tend to be based on maximizing the use of the resource and considering multi-purpose services, while ensuring an economically and financially viable project. On the other hand, private hydropower development tends to be based on optimizing the use of the resource, valuing multi-purpose benefits and generally making decisions that garner maximum financial returns.

Hydropower development along the Mekong River will likely be financed through a combination of private equity and national/multi-lateral bank loans, under the regulatory auspices of a national government. Any guidance or requirements to include considerations for passage of migratory fish species will need to be properly researched and appropriately promulgated based on best practice and cost effectiveness covering environmental and social issues.

While an economic assessment is beyond the scope of this Review, this is an important consideration in determining future activities relating to fish passage and fish-friendly turbines. A number of factors will need to be covered, including:

- Undertaking the necessary studies of migration fish species that need to pass the dam.
- Evaluating fish friendly turbine options that are appropriate for the Mekong River species.
- Determining the most effective and economic combination of downstream passage facilities to ensure the highest overall fish survival rates. This may include, but likely not be limited to turbine water way passage.
- Once passage through turbines is selected as part of the optimum solution, any extra costs for supply, installation and operation of FFTs should be balanced against the overall project costs of the alternatives based on a life-cycle economic analysis.

12.5 Applicability of Fish-Friendly Turbines for Mekong River Hydropower plants

It will be a long journey to extrapolate the lessons learned from the significant levels of investment in turbine technology and fish passage research, study and testing, to the LMB environment.

Studies to date on the applicability of FFTs to provide safe downstream fish passage have shown their ability to improve fish passage survival rates, mainly for juvenile salmonid. These studies have been supported by detail analysis, sophisticated model testing and major monitoring programs, over a number of years and costing many millions of dollars. The outcome has been advancement in knowledge of the behaviour of the fish passing downstream through turbine water passages and the mechanisms that contribute to their fate.

Kaplan and Bulb turbines units are the present choice for the proposed hydropower developments on the Mekong River. This is in line with most of the technology advancements on FFTs, such as the modified MGR Kaplan turbine (with further improvements expected from the Ice Harbor project).

The key to selecting FFTs for the Mekong River hydropower plants is to prove their performance with respect to survival rates for the respective Mekong River migratory fish species. This will be a challenging task based on the large variety of species to be considered and the time and cost that will be required to undertake the necessary work activities. In terms of research, there are three main areas to study:

- Applications of Sensor Fish technology at dams currently present with in the region to characterize turbine passage conditions.
- Laboratory studies to investigate the effects of barotrauma and other stressors on fish.
- CFD and hydraulic modelling to improve turbine and water passage design.

To support the research activities are two analytical approaches that should be considered.

- Models that include detailed characterization of the turbine passage environment and relate passage conditions to the survival of fish, such as the BioPA Tool.
- Research that relates the traits and physiology of fish to the conditions they could be exposed to during turbine passage, such as the TPA process.

However, notwithstanding the complexity, costs and timelines required to undertake research and studies, considerations should also be given to a process that focuses on key issues, and prioritizes them based on their importance to both environmental and social factors and to bio-diversity.

While the assessment of FFTs for the Mekong River tributaries is outside the scope of this review, safe downstream passage of fish throughout the basin is an important component of the life history of migrating species and should be studied appropriately. The basic conclusions from this Review are similar for those developments having low to medium heads and selecting Kaplan or Bulb turbines. Higher head projects using Francis or Pelton turbines are normally associated with low to negligible fish survival rates.

13 Next Steps

This section will summarize the knowledge gaps and uncertainties concerning the need and potential for installing FFTs in the Mekong River and provide suggestions on how best to address these in terms of advocating best practice for future hydropower selection and development.

13.1 Identification of Knowledge Gaps and Uncertainties

There are significant limitations in fish passage research undertaken to date from a global perspective, in that existing information is very fish species and size specific. There is very little documented research on the performance of other species of fish and of different shapes, sizes and life stages passing through hydraulic turbines. Thus present knowledge on fish passage is not fully representative of the potential effects on the hundreds of fish species prevalent in the LMB. A number of reports cover fish species and migration life histories along the Mekong River in general terms. However, they do not provide sufficient background information for the analysis of likely impacts from barriers to downstream fish passage and the contribution that FFTs could make in providing certain levels of mitigation.

The knowledge gaps and uncertainties relating to migrating fish species in the LMB include:

- Baseline information on the fish species that would be affected at each proposed hydroplant during their migration, together with their characteristics and behaviours. Obtained through field programs, monitoring and laboratory testing/research.
- Baseline information on the migration cycles of the fish species that would be affected at each proposed hydroplant. Obtained through field programs and monitoring.
- Understanding the potential impacts on these fish species as a result of passing through turbines. Obtained through laboratory testing/research.

The knowledge gaps and uncertainties relating to FFT performance include:

- Baseline information for survival estimates for key fish species passing through Kaplan and Bulb units (appropriately modified).
- Optimum design parameters for key fish species passing through the turbines. Obtained through CFD analysis and model testing.

Closing the gaps and reducing uncertainties will be a very significant task, requiring both considerable effort and commitment by the regulating authorities.

Sections 13.2 through 13.7 will cover some suggested approaches, though the development of a full program is beyond the scope of this Review.

13.2 Research, Testing and Monitoring

The key to selecting FFTs for the Mekong River hydropower plants is to prove their performance with respect to survival rates for the respective Mekong River migratory fish species. This will be a challenging task based on the large variety of species to be considered and the time and cost that is needed to undertake the necessary research. In terms of research, there are three main areas to study:

- Applications of Sensor Fish technology at dams currently present within the region to characterize turbine passage conditions.
- Laboratory studies to investigate how turbine passage conditions could influence fish. This would include examining damage such as barotrauma, strike and shear forces on fish in association with:
    - Fish ecology and behaviour;

  - Pressures (rate and range) fish are exposed to when passing through the turbines
  - Relationships between the rate of injury and mortality and the range and rate of exposures to rapid pressure changes, turbine strike, exposure to shear and turbulence for different species
- CFD and hydraulic modelling to improve turbine and water passage design

A key area for additional research is to investigate ways to better correlate the survival rates that can be expected through the turbines following their installation, with the results of model tests and CFD analysis.

Another key area for research is to determine any common factors between fish species and whether this can enable extrapolation of results from model tests, CFD modelling and actual monitoring programs from one species to another. A program of testing with sensor fish, followed by laboratory analysis would be advantageous. There is great uncertainty about the impact of hydropower on fish in the LMB, and fish passage testing needs to be carried out to reduce that uncertainty.

However, because of the complexity, costs and timelines required to undertake research and studies, considerations should also be given to a process that focuses on key issues, and prioritizes them based on their importance to both environmental and social factors and to bio-diversity.

13.3 Study and Analysis

A full scale research, laboratory testing and monitoring program for the Mekong River will be a very significant task based on the large variety of species to be considered. In general it is not feasible to measure the turbine-passage survival of every species of fish in every hydroelectric turbine design. To support the research activities detailed above, two analytical approaches should also be considered:

- Research that relates the traits and physiology of fish to the conditions they could be exposed to during turbine passage. An example of this is the Traits Based Assessment (TBA) process.
- The use of models that include input from several sources. This includes detailed characterization of the turbine passage environment (using tools like the Sensor Fish) and models that relate turbine passage conditions to relationships between those conditions and the survival of fish such. An example of this is the Hydro Turbine Biological Performance Assessment (BioPA) Tool.

13.4 Pilot Projects

These would be benefits if a fish-friendly turbine was installed on a hydro projects in the LMB as a pilot project. This would both allow research to be carried out and raise the profile of this approach to improving survival rates for downstream fish passage.

An initial step of such a beneficial approach could be through the installation of a FFT in a hydroplant on a carefully selected Mekong River tributary. This would enable a better understanding of the impacts on migratory fish species passing through the turbines. As a means to support this research and provide some baseline data, an existing project on a Mekong River tributary with Kaplan units could be used. A program of testing with sensor fish, followed by laboratory analysis would be advantageous.

Another possible approach would be to install an Alden turbine in a hydro plant on a tributary of the Mekong River. This would be a step to the eventual development and production of Alden turbines of a size suitable eventually for the mainstream Mekong River plants. However, prior to such an application, fish passage testing, including the effects of barotrauma, needs to be carried out at a suitable prototype site.

While a prototype application in the LMB is preferable, prototypes developed anywhere would add value to the knowledge base. One specific example would be the development and thorough testing of a Bulb turbine developed with fish friendly considerations. This could then be compared with the performance of a vertical axis Kaplan units, with or without MGR modifications.

13.5 Classification System for Fish-Friendly Turbines

Classification systems normally try and advocate a numerical approach to categories. However, the use of universal numbers for such matrices as acceptable survival rates for downstream passage is not considered advisable. It is well understood that there are many complexities that have to be addressed relating to the characteristics of specific fish species, as well as variability in the performance of turbines, including type, size, speed of rotation, etc. For this reason the classification of whether a turbine unit can be considered as “fish friendly” is extremely difficult. With so many variables, such an approach could be subject to challenge. One example of a quantitative approach to fish-friendly classification is to answer the question “What makes a turbine Fish-Friendly?”

- Larger rotating diameter
- Slower rotational speed
- Reductions in number of turbine blades
- Reductions in gaps between moving and fixed parts
- Thick leading edges on blades, vanes and gates
- Determining biological design criteria such as:
    - Damaging shear
    - Pressure decreases
    - Depth acclimation

13.6 Alternatives to Turbine Passage

As noted in Section 4.2, there could be viable alternatives for the downstream passage of fish in addition to through turbines (although many fish, such as drifting larvae cannot be screened and diverted) and these should be considered in any study. A study of these alternatives is available (EPRI 1998) and includes passage through or by:

- Spillways, gates, weirs and other discharge facilities
- Fish bypasses
- Screening of intakes and diversions to other fish passage facilities
- Shutting down units at peak migration times
- Selected operation of more fish-friendlier units during migrations
- Collect and transport by truck or barge and release downstream of lowest dam or barrier on the river

These alternatives should be considered for Mekong River migrating fish species, and it is equally important that estimates of survival rates should be considered for each alternative.

13.7 Guidelines for Downstream Fish Passage

Guidelines are an important means to help hydropower developers comply with environmental standards and, in the Mekong and MRC context, with the agreed Preliminary Design Guidance (PDG) for mainstream dams (MRC 2009b). The PDG is a central Guideline agreed by all MRC Member Countries under the ISH banner to provide overall guidance to project developers and the LMB countries regarding Mekong mainstream hydropower schemes in the form of performance targets, design and operating principles for mitigation measures, as well as compliance monitoring and adaptive management.

A Guide covering fish friendly turbine would support the PDG by providing considerations that developers and Member Countries may need to take into account when striving for sustainable hydropower. These may include the processes and parameters that hydraulic turbine design and testing should follow to ensure downstream passage with minimum damage to fish. Such a Guide would outline the requirements that developers may need to include in a full assessment of downstream fish passage options.

A set of Guidelines exist that cover downstream fish passage (Halls 2009), but these need to be updated taking into account the current state of the science, strengthened in terms of coverage, focused specifically on downstream fish passage, and focussed on hard science.

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