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# Mitigation of the impacts of dams on fisheries —

## A primer



Mekong River Commission

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Front cover photos (from left to right): Runner of a typical Kaplan turbine, top-down radial water gates at Huai Luang Dam in Thailand and a nature-like bypass fish pass at a small weir blocking a stream between Reinsvatnet and Mellsjoen Lakes in Norway (first photo by Rolf Süssbrich, other photos by Kent Hortle)

Back cover photos (from left to right): Nam Houm Dam and reservoir near Vientiane in Lao PDR, a vertical-slot fish pass on the Murray River in Australia and a pool-and-weir fish pass at the Huay Siet Weir in Lao PDR (all photos by Kent Hortle)

# Foreword

The Mekong River Commission supports sustainable development, utilisation, conservation and management of the Mekong River Basin water and related resources, within a framework of cooperation under the 1995 Mekong Agreement. The MRC supports the Mekong countries in their efforts to derive the maximum benefits from management of their water resources while at the same time avoiding, minimising and mitigating negative impacts.

The Mekong Basin's fisheries are a vital resource, providing food security and livelihoods for millions of people, many of whom have limited opportunities to increase their food production or income. About two million tonnes of fish and other aquatic animals are caught in the Lower Mekong Basin each year, making the Mekong one of the world's most productive river basins.

With a growing population of over 60 million people, development of the Lower Mekong Basin is essential to provide access to reliable supplies of water, electricity and food. Many dams have already been built to support irrigated agriculture and hydropower, and more dams are planned or under construction. Dams inevitably alter the natural environment and affect existing users of natural resources, including wild capture fisheries.

While dams bring many benefits, this report is a timely introduction to some of the possible negative impacts of dams on fisheries, and some of the approaches that may be taken to mitigation. Ideally, negative impacts would be avoided to the extent possible at the design stage, and mitigation would be fully incorporated during planning and construction.
The report also introduces the concepts of offsets or compensation for impacts, and enhancement and intensification of reservoir fisheries, positive outcomes from many dam projects.

The report only touches on what can be highly technical issues as it is intended for a general audience. The MRC supports wider consideration of the possibilities for mitigation of impacts of new projects as well as improving existing dams through retrofit in the interests of sustainable development and for the benefit of the people of the Mekong Basin.

Dr Pham Tuan Phan
Chief Executive Officer
Mekong River Commission

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# Glossary and acronyms

| | |
|---|---|
| Active storage | The total volume of water that may be discharged from a reservoir, which equals total storage minus dead storage. |
| AIFP | Agriculture, Irrigation and Forestry Programme of the MRC. |
| Anadromous | Refers to animals that spend most of their life in brackish or marine waters, but must migrate upstream to breed in rivers. |
| Barotrauma | Damage to an animal’s body tissues caused by a difference in pressure between a gas space inside, or in contact with its body and the surrounding fluid. Barotrauma may be caused by the pressure changes experienced by a fish as it passes through a hydroelectric turbine. |
| Catadromous | Refers to animals that spend most of their life in fresh water, but must migrate downstream to breed in estuaries or the sea. |
| Colmatage system | An irrigation system which diverts water laterally from a river into low-lying floodplains during high river levels (i.e. no dam is involved). |
| Compensation | A term synonymous with ‘offset’ in EIA terminology. Actions taken to compensate for some negative impact of a development, which may be distant from the impact site. |
| Dam | A barrier which obstructs the flow of water. An irrigation or hydropower dam is typically built across a watercourse, raising the water level upstream and creating an impoundment. Dams may also be walls constructed around a depression to store water. |
| Dead storage | The volume of water held in a reservoir below the lowest offtake. |
| Diadromous | Refers to animals that must migrate between the river and the sea to reproduce. |
| DMFPF | Demonstration of the Multi-Functionality of Paddy Fields project of the MRC’s Agriculture, Irrigation and Forestry Programme. |
| Effect | A change resulting from some action, used synonymously with ‘impact’ in EIA, but in common usage covers all kinds of changes. |
| EIA | Environmental Impact Assessment, a procedure for assessing environmental impacts, and also the document which results from the procedure. |

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|---|---|
| Endemic | Occurring only within a defined area. |
| Enhancement | Altering conditions within a reservoir to increase or stabilise the catch of desirable species. |
| Euryhaline | Refers to animals that can tolerate a wide range of salinity, including diadromous animals. |
| Fish passage | Movement of fish, usually referring to actions taken to assist movement past barriers such as dams. Passage may be upstream or downstream, and may be active (by swimming) or passive (by drifting). |
| Fish ladder | An everyday term for an upstream fish pass; usually refers to a ‘pool’ type of fish pass. |
| Fish pass | A device which assists fish to pass a barrier. A synonym of fishway. |
| Fishway | A device which assists fish to pass a barrier. A synonym of fish pass. |
| FSL | Full supply level of a reservoir; the surface water level when the reservoir is full. The maximum level at the invert of fixed spillways or at the top of spillway gates when closed. The water level of a reservoir may exceed its FSL during floods. |
| GBT | Gas bubble trauma, a result of fish exposure to supersaturated water. |
| Impact | A change resulting from some action, used synonymously with ‘effect’ in EIA, but tends to refer to short-term and negative effects. |
| Impoundment | A body of water formed behind a dam; an artificial reservoir. |
| Intensification | To increase the productivity of reservoir fisheries and aquaculture by increasing inputs such as nutrients, habitat, fish, fish food and/or by enclosing parts of the reservoir for aquaculture. |
| LMB | Lower Mekong Basin, the portion of the Mekong Basin which is downstream of China, falling within Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam. |
| MASL | Metres above sea level |
| Migration | Cyclic and predictable movements of large numbers of animals in synchrony. Fish and other animals migrate because the habitats that they require for breeding, feeding, or to provide shelter or refuge are separated in space. |

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| Mitigation | To reduce the negative impacts of a development project. Mitigation in the direct sense means to maintain within an altered system some pre-existing function or use of the system, but at a reduced level. In the broader sense, mitigation can refer to any measures which may increase the benefits from a development project, including offsets. |
| Offset | Synonymous with compensation in EIA terminology. Offsets are actions taken to compensate for some negative impact of a development, which may be distant from the impact site. |
| Pondage | A relatively small reservoir, typically formed by a run-of-river dam. |
| Primer | An introductory text which covers the basic elements of a subject. |
| Reservoir | A water storage, which may be a natural water body, or an artificial lake formed by a dam. |
| Rheophilic | ‘Flow-loving’, refers to organisms adapted to life in running waters. |
| Rheotaxis | Movement in response to a current of water or air; positive rheotaxis refers to movement towards or orientation into a current. |
| Runner | The rotating part of a turbine to which blades or vanes are attached. |
| Run-of-river dam | A dam which creates only small impoundment or pondage upstream. There is no universally accepted definition, but such dams typically store water for a day or two, in contrast to a storage dam. Run-of-river dams (weirs, barrages and diversion dams) raise the level of water upstream to create hydraulic head, typically to supply irrigation canals or power stations. |
| Spillway | A structure for controlled release of flows from a dam. |
| Stratification | Separation of water into stable layers or strata, usually referring to lakes or reservoirs where an oxygenated upper layer (epilimnion) overlies an anoxic bottom layer (hypolimnion). An intermediate layer is the metalimnion. |
| Storage dam | A dam which impounds a reservoir to store a significant amount of water, often for months or years, in contrast to a run-of-river dam. In the LMB, such dams typically store wet-season water for release during the dry season. |
| Supersaturation | Dissolution of gases into water so their concentrations are higher than they would be at equilibrium. |

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| Total storage | The volume of water held in a reservoir at full supply level (FSL). |
| TDG | Total dissolved gases. |
| Turbine | A device in which moving fluids spin a runner, which is attached to a rotating shaft that may be used to directly power machines (as in a mill) or to turn the rotor of a generator to produce electricity (as in a hydroelectric plant). |
| WCD | World Commission on Dams. |
| Weir | A low dam, usually a run-of-river dam designed to raise the water level for diversion or to create a barrier, e.g. between salt and fresh water. |

# Summary

The Lower Mekong Basin (LMB) in Cambodia, Lao PDR, Thailand and Viet Nam supports one of the world's largest and most diverse capture fisheries, which provides food and livelihoods for many of the basin's more than 60 million inhabitants. The Mekong's fisheries are based largely upon catches from rivers and floodplains, which continue to provide excellent aquatic habitats and an annual flood pulse, the basis for much of the fisheries production. To support the needs of a growing population, many dams were built in the 20th century, especially for irrigation, and more are under construction or planned, including several very large dams for hydropower. Dams are designed to modify the environment and in the process may cause various negative impacts which can lead to loss of fisheries productivity and biodiversity, which is of particular concern in the Mekong Basin. This report explains in general terms some of the impacts of dams on fisheries and outlines some approaches to mitigation. The report aims to inform discussion on mitigation of impacts of new dams as well as to encourage mitigation of impacts caused by existing dams.

Dams cause two main kinds of impacts: (1) a barrier impact, where a dam blocks a river or stream, and (2) alterations to flow patterns, which then lead to other changes. Such impacts are a result of the normal operation of dams. The impacts of dam construction, other developments around a dam, or unplanned events, are not considered in detail in this report.

Much of the research on fisheries mitigation refers to barrier effects on migrating fish and ways to facilitate fish passage past a dam. Many types of fish passes have been developed over the last few decades to allow fish to move upstream past a dam, and the basic features of some common types of fish pass are described in this report. However only a few fish passes have been built in the LMB, so there is a long-standing need to retrofit many dams as well as to properly consider fish pass design for Mekong species in new dams. There has been almost no attention to the need to facilitate downstream fish passage past dams, which requires better design of water gates, spillways and turbines, as well as measures to divert fish past intakes, as discussed in this report. As well as improving fish passage, mitigation of impacts on river fisheries may include propagation and stocking of fish, but maintenance of productive fisheries usually requires more attention to addressing the various other impacts of dams.

As well as blocking a river or stream, a dam alters flow patterns, causing direct impacts on fish and fisheries, as well as many other environmental changes – loss of water through abstraction, trapping of sediment and organic material, stratification and changes to water quality and others. Such flow-related impacts are briefly reviewed in this report with an overview of some approaches to mitigation, which could include destratification or aeration of released water, re-regulation of downstream flows, as well as measures to limit sedimentation in reservoirs. While there has been very little attention to these problems,

they are well understood and can be addressed technically, which would increase the overall benefits from existing and planned dams for a range of users in the LMB.

Upstream of a dam, water is impounded in a reservoir, an artificial environment which may support fish production which can indirectly mitigate losses from the river fishery. Reservoirs may require various other interventions to enhance their fisheries as mentioned briefly in this report. In the LMB many reservoirs have been stocked with fish and there has been some degree of fisheries management applied at some LMB reservoirs. The results from these endeavours need to be documented. Maintaining productive reservoir fisheries also requires environmental management, both in reservoirs and their catchments as discussed in the report.

The impacts of large dams on fisheries are difficult to mitigate, but efforts at other locations may be more successful in ‘offsetting’ the impacts of a dam. For example, rather than constructing a fish pass at a large dam where it may be ineffective, for the same expenditure several fish passes could be built elsewhere at low barriers, such as irrigation weirs, where they may be more efficient at passing fish and more effective for maintaining productive fish populations. Such environmental offsets or compensation are becoming common, but have yet to be applied in the Mekong Basin.

While this report briefly covers some of the main issues arising from the impacts of dams on fisheries, it is far from exhaustive, and mitigation approaches are continually improving. Each river and dam is unique, requiring an individual appraisal taking into account local conditions, including aquatic ecology, fish biology and fisheries, and the particular socioeconomic context and costs and benefits of mitigation at each site when deciding how best to proceed. Therefore any discussion on mitigation cannot be overly prescriptive, rather an adaptive approach is recommended. It is hoped that this report will be useful in introducing some general concepts and ideas to inform further discussion, as well as providing some supporting references for the interested reader.

The lessons learned from existing LMB dams, and especially the few dams where some mitigation measures for fisheries have been incorporated, should be documented as a guide to improving approaches in the region. Technical capacity needs to be developed and regional institutional frameworks and approaches need improvement to facilitate the application of mitigation measures. These and some other recommendations are covered in the conclusions of this report.

# 1. Introduction

Dams have been built for thousands of years, for irrigation, domestic water supply, hydropower, flood control, navigation, recreation, and fisheries; dams are also used as barriers to separate fresh from salt water. Dams are therefore an integral element in the development of river basins for human use, and with increasing human population and improved technology the rate of dam building accelerated in the 20th century, when most existing dams were built. There are now about 50,000 large dams in the world, with most being in China and the USA, and there are also millions of small or very small dams (Box 1). Large dams are the largest structures ever built by humans, and they are designed to cause major changes to river systems and the surrounding landscapes, including their environmental, social, and economic systems. Recent discourse on environmental and social impacts has focussed on large dams, and in particular some very large dams (WCD, 2000), but impacts from small or very small dams may also be significant, depending upon their location and characteristics. For example, smaller dams may be used to divert water, and they may create shallow reservoirs which trap nutrients and sediment and allow significant evaporation of water. The combined effect of many small dams can be as significant as those of a single large dam on a river basin, so size alone should not limit efforts to assess, manage and mitigate impacts of dam projects.

In the Mekong Basin, traditionally many small dams were built to divert water locally to rice fields, but the scale and pace of dam building increased during the late 20th century, particularly in northeast Thailand. Many Mekong Basin dams have been designed to store wet-season inflows for release during the dry season, and such storage dams even out seasonal variations in flows. By raising the level upstream, dams also allow water to be diverted for irrigation and used for hydropower generation. Some of these dams store relatively little water so may be termed ‘run-of-river’ during the wet season, but during the dry season run-of-river dams may store water for extended periods. In the Mekong Basin there are now thousands of dams, the vast majority supplying water for irrigation, whereas there are relatively few hydropower dams, but they tend to be larger, and in aggregate they store most of the impounded water in the basin (Box 2, Tables 1 and 2, and Figures 1 and 2). About 100 more hydropower dams are planned in the LMB, as well as numerous irrigation dams (Piman *et al*., 2013).

Since the 1990s there has been an increasing debate over the costs and benefits of dams in the Mekong region, particularly regarding the environmental and social impacts of large hydroelectric dams. One prominent element in this debate is the impacts of dams on riverine ecosystems and their fisheries. In their natural state, rivers and their floodplains provide many services; among these in the Lower Mekong Basin, fisheries are of particular importance for livelihoods and nutrition for millions of people (MRC, 2010). The total catch from the Lower Mekong Basin (LMB) has been estimated at about 2.3 million tonnes per year of fish and other aquatic animals, which supports millions of people’s livelihoods as well as providing a significant part of the food supply across the entire basin (Hortle, 2009a). There are about 850 species of fish in the LMB (Hortle, 2009b) as well as many other kinds of aquatic animals which are eaten by people. The natural flood pulse through a diversity of aquatic habitats is the driver for much of the fish production. Because fish and

# Box 1: Size of dams

The International Commission on Large Dams (ICOLD, 2011) defines a 'large dam' based on its height or volume of water impounded as having:

- a height of 15 m or more from its foundations, or
- a height 10 -15 m, and one or more of:
    - a reservoir volume of more than 3 million $m^3$,
    - a dam crest length of more than 500 m,
    - a spillway capacity of at least 2,000 $m^3/s$.

This definition derives primarily from considerations of dam safety and has been widely used, e.g. by the World Commission on Dams (WCD, 2000). Under the ICOLD definition, there are now about 50,000 large dams on Earth, the majority being in China and the USA (www.icold-cigb.org). In the LMB, ICOLD's large dam database currently lists 218 large dams in Thailand and 51 in Viet Nam, with several large dams in Lao PDR and Cambodia yet to be listed. According to Lempérière (2006), within the 50,000 dams defined as 'large', 5,000 'very large' dams store 90 percent of the all of the water impounded in reservoirs worldwide. A 'very large dam', is defined as having:

- a height of 60 m or more from its foundations, and/or
- a reservoir volume of more than 100 million $m^3$, and/or
- a spillway capacity of at least 5,000 $m^3/s$.

Thus very large dams have a disproportionate effect on the flow of water within the world's river systems, despite the fact that smaller dams are much more numerous. ICOLD (2011) has proposed a definition of a small dam as being 2.5 m to 15 m in height and having a low to moderate potential hazard classification, based on a factor which is calculated from dam height and impoundment volume; under this definition there are believed to be about 500,000 'small' dams on Earth. There are no estimates of 'very small' dams (i.e. smaller than 'small') but they would certainly number in the millions.

Various other definitions have been proposed for dam size based on volume or height, e.g. Graf (2005). From a fisheries perspective it is also useful to classify dams based on their likely impacts on a river system or by the size of their reservoir. The surface area of a reservoir is a more important parameter than its depth or volume in predicting total fish catches. While fish catches tend to be higher in large reservoirs, catch per unit area tends to be higher in small reservoirs (Figure 12 in Hortle and Bamrungrach, 2015).

**The world's largest dams**

The tallest dams in the world include the Jinping-I Dam on the Yalong River, China at 305 m, the Nurek Dam in Tajikistan on the Vaksh River at 300 m, and the Xiaowan Dam on the Upper Mekong (Lancang) River at 292 m. The largest reservoirs in the world include Lake Kariba on the Zambezi River, which holds about 181 $km^3$ of water, Bratsk Reservoir on the Angara River in Russia which holds 169 $km^3$ of water and Lake Nasser on the Nile River which holds 157 $km^3$ of water. The entire storage of the 37 largest completed dams in the Mekong Basin by 2013 was about 75 $km^3$, or about 16 percent of the annual flow of the Mekong which is about 475 $km^3$ (Table 1).

# Box 2: How many dams are there in the Lower Mekong Basin?

As is usual worldwide, most dams in the LMB were built to provide water for irrigation. There are about 12,000 irrigation projects in the LMB registered in MRC databases by the AIFP (Table 2), and of these about 8,000 include a reservoir and/or dam (Figure 2), but there is limited information on the size and other characteristics of irrigation dams; furthermore many small irrigation dams, especially those made of local materials, are not registered.

In Thailand, as summarized by Virapat and Mattson (2001), in 1996, the Thai Department of Fisheries (DOF) collected statistics on 27,799 standing water bodies, with surface areas from 0.01 to 41,000 ha. Most were small ponds or communal reservoirs, and 3,241 (12 percent) were classed as reservoirs, of which 1,872 or 58 percent were in the Thai Mekong Basin, and these had a total FSL surface area of 2,120 km$^2$. The MRC AIFP database lists over 6,000 reservoirs or weirs in the LMB in Thailand, but details of most are incomplete. A 1999 database of 453 LMB Thai reservoirs larger than 100 ha in surface area indicated their total FSL surface area was 2,657 km$^2$ (Virapat *et al*., 2000)[1]. The reservoirs are used primarily for irrigation (288), domestic water supply (157), hydropower (6) and fisheries (2). However, irrespective of primary use, all Thai LMB dams are in fact multi-purpose, supporting domestic water supply, irrigation, livestock watering and fishing. Under the ICOLD criteria (Box 1), 71 of the Thai LMB dams would be classed as ‘large’. All major Mekong tributaries in the Thai LMB have been substantially modified by dams, which have brought many benefits, but at the expense of highly modifying their river systems.

In Cambodia, there are relatively few large dams. A database compiled by the Department of Fisheries (DOF, 1999) listed 666 irrigation reservoirs, with a total FSL surface area of about 287 km$^2$. Most (92 percent) of these reservoirs were less than 1000 ha in area and 37 percent were less than 100 ha. Many of the Cambodian dams were built during the Khmer Rouge era as long, low earth walls across small rivers and many did not function well. Currently there are efforts to rebuild or redesign irrigation systems across the country and two large dams have been recently rebuilt (Table 1 and Figure 2). The MRC AIFP database lists 907 reservoirs or weirs in Cambodia but information is incomplete for most of them.

The AIFP irrigation database also lists 1189 registered weirs or reservoirs in Lao PDR, and 96 in Viet Nam; but these are clearly underestimates. For example, Ly *et al.* (2006) state that in just one of the Viet Nam highland provinces (Dak Lak) there are about 500 reservoirs, and in Lao PDR there are many small locally built schemes which are not registered. As well as existing dams and weirs, the AIFP database includes location details for 2,752 proposed new dams or weirs, most of them in Lao PDR.

Information on hydropower dams is relatively complete compared with dams built for irrigation and other purposes. MRC-registered data up to end-2013 include 42 completed hydropower dams on Mekong tributaries with another 17 tributary dams under construction, together with one mainstream dam, Xayaburi. A further 91 dams on tributaries and 10 mainstream dams are licensed or planned (Figure 1). As is usual worldwide (Lempérière, 2006), the largest Mekong Basin reservoirs are for hydropower and store (or will store) a disproportionate amount of the total water impounded in Mekong Basin reservoirs (Table 1).

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[1] The database was audited against Google Earth images and corrections to many areas were made. Some areas were apparently reported in rai rather than km$^2$, leading to an overestimate of total area by Virapat and Mattson (2001).

other aquatic animals evolve and adapt over long periods to survive, grow and reproduce within natural environments, any changes, such as those caused by damming a river, affect fish and fisheries and the people that depend upon them. The potential losses of fisheries productivity and biodiversity as a result of ongoing dam building have been highlighted by many authors (e.g. Barlow *et al.*, 2008; Ziv *et al.*, 2012) and freshwater fish are considered to be particularly at risk from habitat alteration.

Only about 0.01 percent of the Earth's water is fresh, but freshwaters support a disproportionate share - about 40 percent - of the Earth's 33,000 fish species (Lundberg *et al.*, 2000). Most species of freshwater fish are adapted to live in rivers and streams, so it is not surprising that changes caused by dams have affected many freshwater fish species (Dudgeon, 2005; Dudgeon *et al.* 2006; Brown *et al.*, 2013b), with populations of riverine fish in severe decline in many countries (Dudgeon *et al.*, 2006; Williams, 2008). For fishes whose status has been assessed by the IUCN, about one quarter are considered threatened, the majority being freshwater species, and a further 60 freshwater fishes are known to have become extinct recently, in contrast to marine fishes, for which there have been no recent extinctions.

Despite the importance of inland fisheries production and high fish diversity in the region, only a few of the many thousands of LMB dams have incorporated any measures to mitigate impacts on riverine ecosystems and fisheries. This report is a step towards improving the situation by describing for a general audience some of the impacts of dams on fisheries, and outlining some of the mitigation measures that may be taken.

The World Commission on Dams (WCD, 2000) considered that dams under normal operating conditions cause two main types of impacts: (1) a barrier effect and (ii) alterations to flow, or some combination of these effects, with various other impacts caused by these primary impacts. However, some other types of impacts arise during dam construction, such as site clearance and development of roads and other infrastructure; dams may also generate various wastes that cause pollution, and they may lead to increased population and other activities in their vicinity. Such generic development impacts are not considered in detail in this report, nor are the effects of unplanned events or catastrophes, such as in the worst case, dam collapse.

The main kinds of dam impacts and their mitigation are summarised in Table 3, grouped by stages of a project. This report covers only some of the main impacts and their mitigation as highlighted in the table.

Mitigation in the direct sense (as discussed in Section 2 of this report) means to reduce the negative impacts of dams by maintaining some existing function or use of an aquatic system prior to its alteration, but at a reduced level; mitigation rarely eliminates negative effects entirely. For example, installing a fish pass usually only reduces the impacts of a dam on migrating fish. In the broader sense, mitigation can refer to any measures which may increase the benefits from a dam project, as a way of balancing negative impacts. These may include enhancement of reservoir fisheries and aquaculture (Section 3) and offsets or compensation (Section 4).

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[2] www.redlist.org

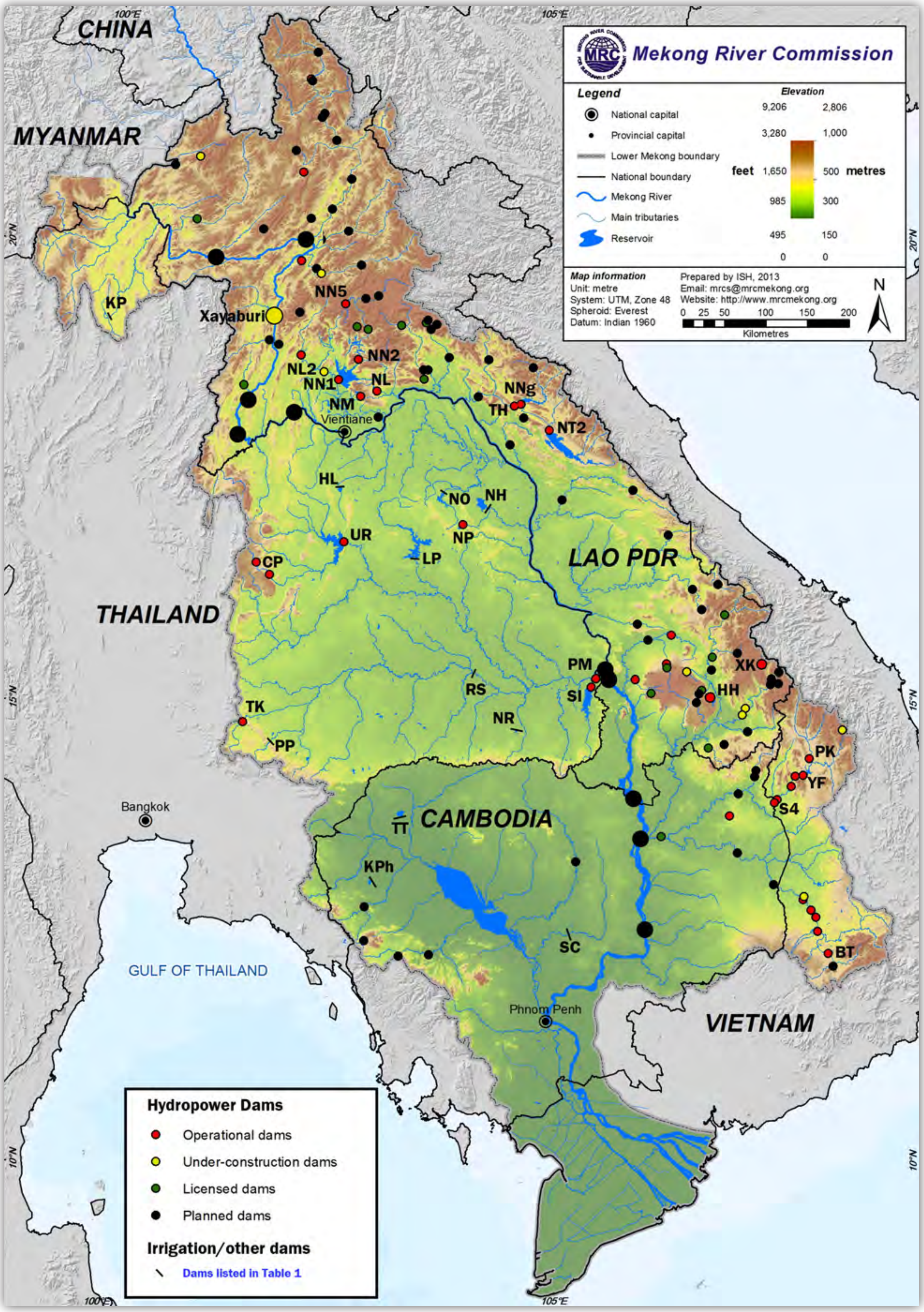


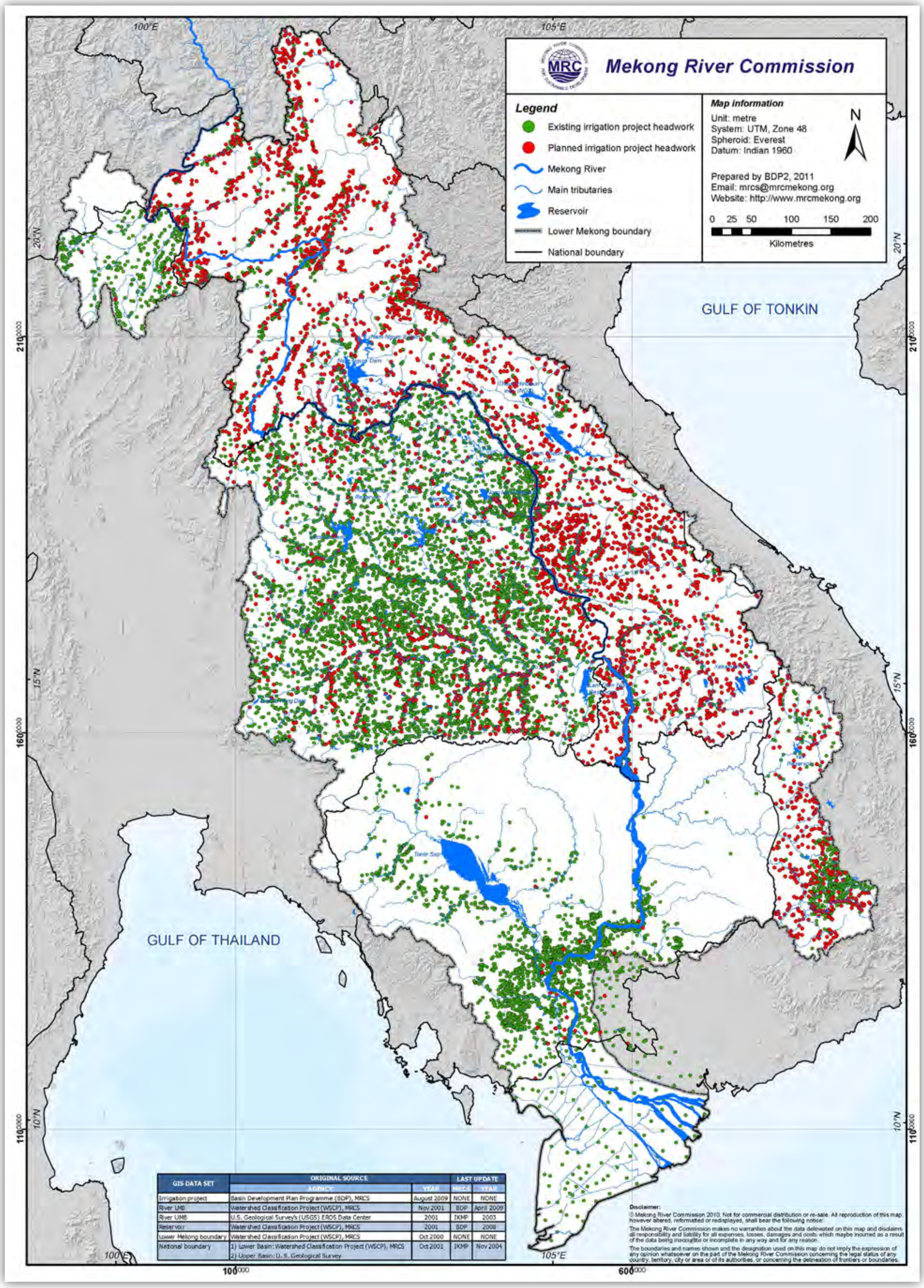
**Figure 1:** Hydropower dams and other large dams in the Lower Mekong Basin in 2013

The map shows all hydropower dams and other large dams labelled as in Table 1. Mekong mainstream dams are shown as large symbols; note that there are many smaller dams which are not shown (see Figure 2).

Table 1: **The largest dams in the Mekong Basin in late 2013**

LMB dams are shown on Figure 1; dams in China are upstream of Figure 1. FSL - full supply level
Dams with reservoirs whose surface area is greater than 20 km$^2$ or volume is greater than 150 million m$^3$

| Country | Dam | Code | River System | Completed | Purpose | Elevation (masl) | Wall Height (m) | Wall Length (m) | Reservoir Area at FSL (km$^2$) | Reservoir Volume at FSL (Mm$^3$) | Mean Depth at FSL (m) | Catchment Area (km$^2$) | Mean Inflow (m$^3$/s) | Installed Capacity (MW) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| China | Gongguoqiao | | Mekong (Lancang) | 2008 | Hydropower | 1,319 | 130 | 356 | 11 | 510 | 45.0 | 97,200 | 984 | 750 |
| China | Xiaowan | | Mekong (Lancang) | 2010 | Hydropower | 1,236 | 292 | 902 | 190 | 15,043 | 79.2 | 113,300 | 1,220 | 4,200 |
| China | Manwan | | Mekong (Lancang) | 1996 | Hydropower | 994 | 132 | 418 | 24 | 920 | 39.0 | 114,500 | 1,230 | 1,500 |
| China | Dachaoshan | | Mekong (Lancang) | 2003 | Hydropower | 906 | 111 | 460 | 83 | 940 | 11.4 | 121,000 | 1,330 | 1,350 |
| China | Nuozhadu | | Mekong (Lancang) | 2012 | Hydropower | 807 | 261 | 608 | 320 | 21,749 | 68.0 | 144,700 | 1,749 | 5,850 |
| China | Jinghong | | Mekong (Lancang) | 2010 | Hydropower | 602 | 108 | 705 | 51 | 1,233 | 24.2 | 149,100 | 1,839 | 1,750 |
| Lao PDR | Houay Ho | HH | Se Kong | 1999 | Hydropower | 883 | 79.5 | 400 | 42 | 620 | 14.8 | 192 | 9.5 | 152 |
| Lao PDR | Nam Leuk | NL | Leuk | 2000 | Hydropower | 405 | 45.5 | 800 | 13 | 185 | 14.2 | 274 | 16.4 | 60 |
| Lao PDR | Nam Lik 2 | NL2 | Nam Ngum | 2010 | Hydropower | 305 | 103 | 328 | 24.4 | 1,111 | 45.5 | 1,993 | 149 | 100 |
| Lao PDR | Nam Mang 3 | NM3 | Mang | 2004 | Hydropower | 770 | 28/19.9 | 151/436 | 18.5 | 141 | 7.6 | 82 | 3.9 | 40 |
| Lao PDR | Nam Ngum 2 | NN2 | Ngum | 2011 | Hydropower | 381 | 185 | 470 | 122.2 | 4,886 | 40.0 | 5,640 | 199 | 615 |
| Lao PDR | Nam Ngum 5 | NN5 | Ngum | 2012 | Hydropower | 1060 | 105 | 285 | 14.6 | 314 | 21.5 | 483 | 23 | 120 |
| Lao PDR | Xekaman 3 | XK3 | Se Kong | 2013 | Hydropower | 960 | 101.5 | 540 | 5.2 | 141.5 | 27.4 | 712 | 29.6 | 250 |
| Lao PDR | Nam Ngouang | NNg | Theun | 2012 | Multi-purpose | 455 | 67 | 486 | 105 | 2,450 | 23.3 | 2,942 | 175 | 60 |
| Lao PDR | Nam Ngum 1 | NN1 | Ngum | 1971/84 | Multi-purpose | 212 | 75 | 468 | 460 | 7,030 | 15.3 | 8,460 | 427 | 155 |
| Lao PDR | Nam Theun 2 | NT2 | Theun | 2010 | Multi-purpose | 538 | 45 | 48 | 450 | 3,680 | 8.2 | 4,013 | 245.3 | 1,070 |
| Thailand | Kwan Phayao | KP | Ing | 1941 | Fisheries | 405 | 5 | 10 | 24 | 11 | 0.5 | 1,161 | 10 | |
| Thailand | Nong Han | NH | Kam | 1953 | Fisheries | 157 | 5 | 200 | 135 | 64 | 0.5 | 1,653 | 10 | |
| Thailand | Huai Luang | HL | Huai Luang | 1973 | Irrigation | 198 | 12.5 | 1,400 | 31 | 113 | 3.6 | 666 | 5 | |
| Thailand | Lam Nam Rong | NR | Rong | 1991 | Irrigation | 143 | 23.5 | 1,500 | 25 | 218 | 8.7 | 453 | 5 | |
| Thailand | Lam Pao | LP | Pao | 1968 | Irrigation | 160 | 33 | 7,800 | 400 | 2,640 | 6.6 | 5,964 | 45 | |
| Thailand | Lam Ta Khong | TK | Ta Khong | 1969/2001 | Irrigation | 277 | 40.3 | 527 | 44 | 445 | 10.1 | 1,430 | 8 | 500 |
| Thailand | Nam Pra Phloeng | PP | Pra Phloeng | 1968 | Irrigation | 228 | 50 | 575 | 19 | 220 | 11.6 | 807 | 6 | |
| Thailand | Nam Un | NO | Oon | 1973 | Irrigation | 178 | 29.5 | 3,300 | 85 | 520 | 6.1 | 1,100 | 12 | |
| Thailand | Rasi Salai | RS | Mun | 1994 | Irrigation | 117 | 9 | nd | 110 | 440 | 4.0 | ~48,000 | ~310 | |
| Thailand | Chulaphorn | CP | Phrom | 1972 | Multi-purpose | 759 | 70 | 700 | 12 | 188 | 15.7 | 545 | 5 | 40 |
| Thailand | Nam Pung | NP | Pung | 1966 | Multi-purpose | 284 | 41 | 1,720 | 22 | 165 | 7.5 | 296 | 4 | 6.3 |
| Thailand | Pak Mun | PM | Mun | 1994 | Multi-purpose | 108 | 17 | 324 | 60 | 350 | 5.8 | 117,040 | 759 | 136 |
| Thailand | Sirindhorn | SI | Dom Noi | 1971 | Multi-purpose | 142 | 42 | 940 | 288 | 1,966 | 6.8 | 2,097 | 53 | 36 |
| Thailand | Ubolratana | UR | Pong | 1966 | Multi-purpose | 182 | 35.1 | 800 | 410 | 2,264 | 5.5 | 12,104 | 71 | 25.2 |
| Cambodia | Kamping Phuoy | KPh | Stung Mongkol Borey | 1977 | Irrigation | 22 | 2 | 12,000 | 30 | 110 | 3.7 | | | |
| Cambodia | Stung Chinit | SC | Stung Chinit | 2006 | Irrigation | 16 | 3 | 1,000 | 25 | 60 | 2.42 | 4,130 | 55 | |
| Cambodia | Trapeang Thmor | TT | Stung Mongkol Borey | 1977/2005 | Irrigation | 14 | 2 | 20,000 | 60 | 60 | 1 | | | |
| Viet Nam | Plei Krong | PK | Se San | 2006 | Hydropower | 570 | 71 | 495 | 53 | 1,049 | 19.8 | 3,216 | 128 | 100 |
| Viet Nam | Se San 4 | S4 | Se San | 2010 | Hydropower | 215 | 74 | 850 | 54 | 893 | 16.5 | 9,326 | 329 | 360 |
| Viet Nam | Buon Tua Srah | BT | Sre Pok | 2008? | Multi-purpose | 488 | 83 | 1,035 | 37 | 787 | 21.3 | 2,930 | 100 | 86 |
| Viet Nam | Yali Falls | YF | Se San | 2000 | Multi-purpose | 515 | 69 | 1,190 | 53 | 1,037 | 19.6 | 7,455 | 270 | 720 |



| GIS DATA SET | ORIGINAL SOURCE | | LAST UPDATE | |
|---|---|---|---|---|
| | AGENCY | YEAR | MRCS | YEAR |
| Irrigation project | Basin Development Plan Programme (BDP), MRCS | August 2009 | NONE | NONE |
| River LMB | Watershed Classification Project (WSCP), MRCS | Nov 2001 | BDP | April 2009 |
| River UMB | U.S. Geological Survey's (USGS) EROS Data Center | 2001 | IKMP | 2003 |
| Reservoir | Watershed Classification Project (WSCP), MRCS | 2001 | BDP | 2008 |
| Lower Mekong boundary | Watershed Classification Project (WSCP), MRCS | Oct 2000 | NONE | NONE |
| National boundary | 1) Lower Basin: Watershed Classification Project (WSCP), MRCS<br>2) Upper Basin: U. S. Geological Survey | Oct 2001 | IKMP | Nov 2004 |

**Disclaimer:**

The Mekong River Commission makes no warranties about the data delineated on this map and disclaims all responsibility and liability for all expenses, losses, damages and costs which maybe incurred as a result of the data being inaccurate or incomplete in any way and for any reason.

The boundaries and names shown and the designation used on this map do not imply the expression of any opinion whatsoever on the part of the Mekong River Commission concerning the legal status of any country, territory, city or area or of its authorities, or concerning the delineation of frontiers or boundaries.

**Figure 2:** Existing and planned irrigation projects in the LMB

Data are summarised in Table 2. Most projects include a dam or dams.

Table 2: **Irrigation projects in the Mekong Basin**

As registered on the DMFPF project of MRC's Agriculture, Irrigation and Forestry Project in 2003

| **Stage** | **Main component of irrigation system** | | | | | | | **Total** |
|---|---|---|---|---|---|---|---|---|
| | **Reservoirs** | **Weirs** | **Traditional Weirs** | **Sluices** | **Pumps** | **Colmatage Canals** | **Others, or Unknown** | |
| Cambodia | 25 | 47 | | 1 | 23 | 133 | 94 | 323 |
| Lao PDR | 175 | 1,014 | | 83 | 1,264 | | 9 | 2,545 |
| Thailand | 5,116 | 1,347 | 63 | 37 | 1,182 | | 1,004 | 8,749 |
| Viet Nam | 50 | 46 | | 157 | | 4 | 4 | 261 |
| **Total** | **5,366** | **2,454** | **63** | **278** | **2,469** | **137** | **1,111** | **11,878** |

The overall aim of preparing and disseminating this report is to maintain or improve environmental benefits from river systems. Specifically, the intention is that mitigation measures should be progressively applied to existing dams where appropriate, and should be considered, properly appraised and incorporated as appropriate in all new dams.

The objectives of this report are:

- to improve awareness and understanding of some of the possible negative impacts of dams on the physical environment, and thereby the effects on fish and other aquatic animals (OAAs), fisheries and people;
- to improve understanding of the basic concepts behind mitigation including enhancement measures, and the costs and benefits to fisheries;
- to introduce the concept of environmental compensation (or offsetting) as a possible alternative or supplement to mitigation;
- to provide readers with an overview to encourage dialogue on issues;
- to support discussion on further development of the MRC's Preliminary Design Guidance on Mainstream Dams; and
- to provide a list of key references which can be used to access more detailed information for assessing options and for design and costing purposes.

The document is a primer with rather limited scope. The efficiency or effectiveness of mitigation including enhancement measures can only be discussed in the most general terms. Detailed technical design information or advice on how to choose between options is beyond the scope of the document. Some measures that are commonplace in project design for large dams are not covered in this report; these include compensation, resettlement and social mitigation measures.

Technical measures for mitigating the negative impacts of dams on river fisheries have been applied at very few dams in the LMB. Therefore, as well as developing practical technical solutions as introduced in this report, there is a requirement for institutional frameworks and procedures which will support mitigation. These could include improved planning and EIA, with requirements for assessing environmental flows and environmental

Table 3: **Summary of the impacts of dams on fisheries and some mitigation measures**

Arranged by different stages of a dam project. The highlighted impacts are the subject of this report.

| Stage | Key Impacts | Description | Some Possible Mitigation Measures |
|---|---|---|---|
| Construction | Water Quality | Sediment effects from erosion of cleared surfaces. | Erosion and clearance controls. |
| | Habitat | Alteration of the channel and clearance. | Unavoidable. |
| Commissioning | Hydrology | Storage of water reduces total discharge for the period, severe impacts if filled during dry season. | Fill during the wet season, extend filling duration and maintain environmental flows. |
| Operation | Barrier effects on fish passage | Dams block movements of fish upstream and downstream. Fish moving downstream may pass a dam but be injured in the process by passage through water gates, over spillways or through turbines. Fish populations and fish catches decline. | Fish passes for upstream-migrating fish. For downstream migrating fish - screening and bypass, improved water gates, spillway and turbine designs. Trap and transport. Collection of wild fish and propagation for particular species. |
| | Flow pattern | Alteration of seasonal flow patterns, and diurnal variation for peak load hydroelectric generation. Inter-basin diversions and abstractions. Many ecosystem effects downstream and effects on fishing activities. | Environmental flows. Minimise abstraction and screen fish out of off-takes. Regulating ponds to minimise diurnal variation. For inter-basin schemes re-engineer receiving rivers. Manage irrigation usage to reduce abstraction. |
| | Trapping of sediment and other particulate material in reservoirs | Residual biomass on dam site, plus organic detritus input from catchment. Decomposition causes anoxia, and other water quality effects, which are exacerbated by stratification. May lead to initial pulse of organic material to river downstream, with later decline as biomass decays, leading to loss in system productivity downstream. May promote cyanobacteria blooms. | Catchment management, sediment routing through reservoirs, sediment removal. |
| | Stratification | Warm water overlies cold water, in which oxygen becomes depleted and toxic compounds and ions may form. Blue-green algae may be favoured. Reservoir productivity is reduced and the aquatic ecosystem is impacted downstream. | De-stratification, multi-level off-takes, oxygenation of discharges. |
| | Gas bubble trauma | Supersaturated water downstream of spillways can cause GBT in fish. | Spillway design and spill management. |
| | Reservoir fishery not productive, low fish catches | May be caused by various factors, including lack or excess nutrients, water quality problems, excess weed cover, poor spawning or recruitment of fish. | Enhancements of reservoir fisheries and aquaculture, catchment management, aquatic weed management. |
| | Food Chain Effects | Effects on invertebrates as above, including barrier effects. Lentic food chain replaces complex riverine food chain, and invertebrate assemblage modified downstream due to modified inputs and habitat. Change in food sources leads to change in fish species composition. | May be mitigated by measures above, but changes in invertebrate assemblages are inevitable. |
| | Exotic species | Dams facilitate introduction and invasion by exotic fish and weeds. | Various measures, including weed control and harvesting. |
| Closure | Multiple effects | Effects would include a gradual reversion to the original riverine conditions. | Rehabilitation of riverine habitat. Mitigation of impacts on fishers. |
| Catastrophic | Many effects | Dam failure directly affects the fishery and fishers downstream. | Normally subject of Engineering Risk Assessment, should include land-use management downstream to minimise consequences. |

offsets. As EIA only covers the largest new dams, new approaches are required to improve the environment and fisheries at other new and existing dams; these could cover guidelines for fish passage, water quality, and catchment and reservoir management.

**Figure 3:** Xiaowan Dam on the Lancang (Upper Mekong) River in China

Completed in 2007, Xiaowan is the tallest dam in the Mekong Basin at 292 m and impounds a reservoir which holds 15 $km^3$ of water. It is one of 13 hydropower dams that are planned, under construction or completed along the Upper Mekong or Lancang River, which now significantly regulate annual flows and trap sediment.

Photo: http://en.wikipedia.org/wiki/File:Xiaowan_Dam.jpg

**Figure 4:** Nam Ngum Dam and reservoir in Lao PDR

The dam created the largest Mekong reservoir in 1972. The powerhouse is at the centre and the large spillway is left of centre. Under normal operating conditions as shown here all water passes through the power station (centre) and none passes over the spillway. An additional turbine is being installed in the lower left foreground. Photographed in July, 2016.

Photo: Kent Hortle

**Figure 5:** Nam Lik 2 Dam and reservoir in Lao PDR

One of many new tributary hydropower dams, photographed in July, 2016.

Photo: Kent Hortle

**Figure 6:** Ba Lai Dam in the Mekong Delta, Viet Nam

Completed in 2001, this coastal barrage across a Mekong distributary separates fresh from saline water to support rice irrigation. Although only a few metres high, dams like this alter estuarine ecology and are significant barriers to passage for many species of fish that migrate between fresh and salt water.

Photo: Kent Hortle

**Figure 7:** Pak Mun Dam in Thailand, a 'run-of-river' hydroelectric dam

The photo is taken in the early dry season. The Mun River runs from the lower left into the Mekong (upper right). The Dom Noi River – clear as a result of trapping of sediment in Sirindhon Reservoir - joins the Mun River near the dam. The effect of Pak Mun Dam in storing water can be seen by comparing the levels upstream (foreground) and downstream.

Photo: Kent Hortle

**Figure 8:** One of several rubber weirs across the Mun River, Thailand

The weir is inflated with water during the dry season to create a temporary dam which blocks the river, raising the level upstream to facilitate pumped irrigation. There are many similar seasonal dams in the Mekong Basin.

Photo: Kent Hortle

**Figure 9:** Nam Souang, a typical shallow irrigation reservoir in the Mekong Basin in Lao PDR

The dam wall is earthen and the spillway is on the centre right. The irrigation canal is central and is piped under the spillway overflow. Most reservoirs in the Mekong Basin are small and shallow and can support productive fisheries, and there is ample scope for improving fish passage and for enhancing their fisheries.

Photo: Kent Hortle

**Figure 10:** Spillway of Stung Chinit, a large shallow irrigation reservoir in Cambodia

Photo: Kent Hortle

**Figure 11:** Boeng Chertrao, a typical small irrigation reservoir in Cambodia

The bed of the stream has been excavated, with the clay spoil used to make a dam wall.

Photo: Kent Hortle

**Figure 12:** A very small diversion weir in southern Lao PDR

In the LMB there are thousands of structures like this which could be readily modified to allow upstream fish migration.

Photo: Kent Hortle

**Figure 13:** Khuoi Cheua Weir on the Chi River in northeast Thailand

Looking upstream towards the six water gates, which are progressively opened as flows increase in the wet season. This is one of several large irrigation weirs in the Mun-Chi system, a major Mekong tributary.

Photo: Kent Hortle

# 2. Impacts and mitigation

This section deals with measures which aim to maintain within a dammed river the pre-existing fisheries, but at a reduced level; i.e. direct mitigation of impacts.

## 2.1 Barrier effects on fish passage

### Migrations and other movements

Fish and other aquatic animals move within their environment from day to day for many reasons: to find food, to breed, to seek shelter and escape predators, or to find water with characteristics (e.g. turbidity, salinity or oxygen content) within preferred ranges. River fish frequently attempt to swim upstream, a behaviour that is generally advantageous in an environment where they are often displaced downstream during high flows. Other animals such as shrimps and snails also often swim or crawl upstream, because such rheotactic behaviour is essential for the long-term survival of each species. As a result, fish and other aquatic animals can often be observed accumulating below dams and other barriers throughout the year.

As well as such local or general movements, migrations are usually considered to be cyclic and predictable movements of large numbers of animals in synchrony. Fish and other animals migrate primarily because the habitats that they require for reproduction, feeding or to provide refuge, are separated in space. In large monsoonal river systems such as the Mekong, aquatic habitats are also strongly affected by seasonality, expanding, contracting and changing as river flows vary and floodplains become inundated or dry out.

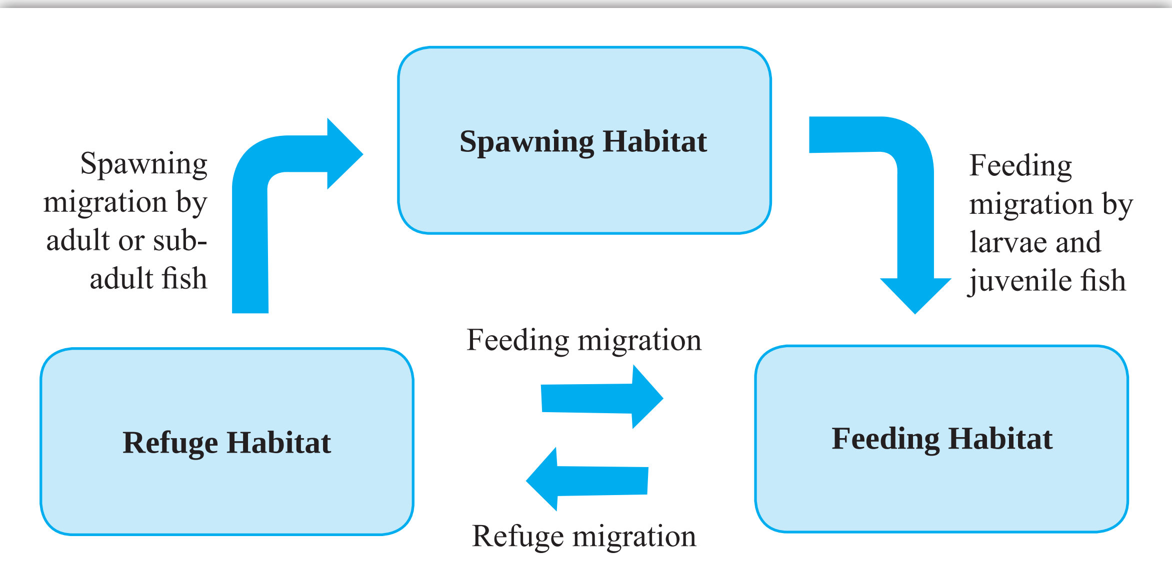


**Figure 14:** A general scheme of the main types of habitats and migration for river fish

In reality habitats usually support more than one of the main uses; e.g. some fish may spawn and also feed and grow on floodplains, before seeking dry-season refuge in a pool or river channel.

Illustration: redrawn from Northcote (1978)

Dams obstruct fish passage, both small-scale movements and large-scale migrations. The extent to which each fish species is affected depends partly upon its ecology; for example more sedentary species are likely to be less affected by barriers than highly migratory species. While river fish were formerly categorised as 'migratory' or 'resident', all freshwater fish are migratory to some extent (Lucas *et al*., 2001). About 850 fish species are found in the Mekong system (Hortle, 2009b), and of these about 200 species are important in lowland fisheries of the Mekong and its tributaries and floodplains. Most of these are purely freshwater species that can be grouped broadly as white fish, black fish or grey fish, categorisations based on their ecology, including propensity to migrate. The general characteristics of these groups are described below.

White fish typically inhabit rivers, where they are usually the most abundant fish in catches. They may migrate and breed entirely within river channels or may move onto flooded areas during the wet season to feed and/or to breed. The patterns of migration vary by species and locally, depending upon the position of habitats. White fishes' life-cycles may be more or less complex and variable, but within this group many fishes migrate long distances and are likely to be highly affected by barriers. In the LMB white fish are predominantly catfishes and cyprinids (carps and barbs), and include several of the world's largest freshwater fishes.

**Figure 15:** The mud carp *Cirrhinus molitorella,* a common white fish of the Mekong River system

Most white fish are migratory and require passage past barriers for breeding, feeding or to reach refuges

Photo: Kent Hortle

**Figure 16:** The Mekong giant catfish *Pangasianodon gigas,* one of the world's largest fishes

The giant catfish grows to about 350 kg, and like many large catfishes migrates long distances along the Mekong.

Photo: Kent Hortle

**Figure 17:** Black fish like this striped snakehead *Channa striata* are relatively sedentary and may live in reservoirs

Photo: Kent Hortle

Black fish are relatively sedentary fish that are typically found in still waters (such as on floodplains and in floodplain water bodies) or in slow-flowing waters (such as in river pools). They are air-breathing fish, with minimal or no requirement for dissolved oxygen. Several species can 'walk' over land and can bury themselves in mud where they aestivate through the dry season. Black fishes such as snakeheads, walking catfishes, climbing perch and swamp eels are among the most common fishes in the Mekong Basin in still or slow-flowing waters. In general, black fishes are likely to persist both upstream and downstream of a new dam, and some black fishes may thrive in impoundments, especially shallow impoundments with abundant aquatic plants.

**Figure 18:** A common Mekong grey fish, the bronze featherback *Notopterus notopterus*

Featherbacks migrate short distances, between floodplains, tributaries and the Mekong mainstream.

Photo: Kent Hortle

Grey fish have been defined as an intermediate group of fish that migrate short distances between floodplains and rivers and between permanent and seasonal waters on floodplains. They are also less affected by dams than white fish, with many grey fishes commonly found in impoundments.

Many black and grey fish are predators that become common in and immediately downstream of reservoirs, where they prey on fish that are attempting to swim past dams, so predation may exacerbate the direct effects of dams on migratory fish (e.g. Rieman 1999, Oldani *et al.*, 2007).

**Figure 19:** A giant snakehead *Channa micropeltes* feeding on migrating white fishes

Downstream of the Lower Chao Phraya Dam in Thailand.

Photos: Kent Hortle

As well as these three broad categories based on migration, the Mekong fish fauna includes diadromous fish, which migrate between the river and the sea; these are grouped as catadromous, living in fresh water, but migrating downstream to breed in the estuary or sea, and anadromous, spending most of their life in brackish or marine waters, but migrating upstream to breed in a river. The Mekong, especially in its lower reaches is also home to many fishes that move freely between marine and freshwaters (euryhaline species). There are also many species living primarily within tributaries about which relatively little is known, but for which some degree of seasonal migration along tributaries would be expected.

## The need for fish passage

Within the LMB, the Mekong is still fully connected to most of its tributaries and floodplains, allowing fish to move freely, as required for their survival. Dams restrict or prevent passage of many species, reduce spawning success, reduce survival and growth of larval and juvenile fish, and prevent fish moving to refuge habitats, which will ultimately reduce productivity and biodiversity upstream and downstream. Because many Mekong fish migrate long distances upstream, with their larvae and fry drifting downstream, barriers to migration may affect distant fisheries across national borders and such transboundary effects are a particular concern of the MRC.

In the LMB, three migration 'systems' have been proposed to describe general patterns of migration for large numbers of fish of many species along and near the mainstream (Figure 20). The Lower Mekong Migration System extends along the mainstream from the delta to Khone Falls and includes the Tonle Sap and the lower reaches of Mekong tributaries in Cambodia. Many fish within this system feed and grow during the wet season within the floodplains of the Tonle Sap and delta, the 'fish factory' of this system, migrating off flooded areas as water levels fall and then swimming to dry season refuges, particularly deep pools along the Mekong in upper Cambodia. At the beginning of the wet season, many fish spawn in upper Cambodia with their larvae subsequently drifting downstream to productive floodplains; others move onto floodplains to spawn, and many adult fish migrate downstream to access productive floodplains.

The Middle Mekong Migration System is partly separated from the lower system by Khone Falls, a natural barrier. Within the middle system, fish typically reside in deep pools in the mainstream during the dry season and migrate upstream to either spawn in the Mekong, tributaries or on floodplains at the start of the wet season. Fish move off floodplains as water levels fall and return back downstream to their dry season refuges in the Mekong.

The Upper Mekong Migration System encompasses the upland Mekong, from about the Loei River confluence upstream to and probably extending into China, and is separated from the middle system by long reaches of shallow sandy habitat near Vientiane. This upland reach of the Mekong is confined within a steep valley and lacks large floodplains, which are also relatively limited in extent along tributaries, so fish primarily migrate upstream within the main channel in the late dry season or early wet season, followed by spawning and downstream drift of larvae, with later return downstream migration of adults. More background information and details of the three migration systems are provided in Poulsen *et al*. (2002).

Dams on tributaries together with other barriers on smaller watercourses and floodplains have already interrupted these migration systems to some extent, and large dams on major tributaries or on the mainstream will further block fish migration. While all dams have some effects on fish passage, the most disruptive for fisheries will be the large dams proposed on the Lower Mekong mainstream (near productive floodplains) whereas smaller dams in headwaters are likely to have the least effect on productive lowland fisheries.
As well as effects on productivity, it should be noted that most of the Mekong's endemic species are small specialised fishes found in tributaries, with many confined to a one or a few rivers in the eastern part of its catchment along the Annamite range, so tributary dams

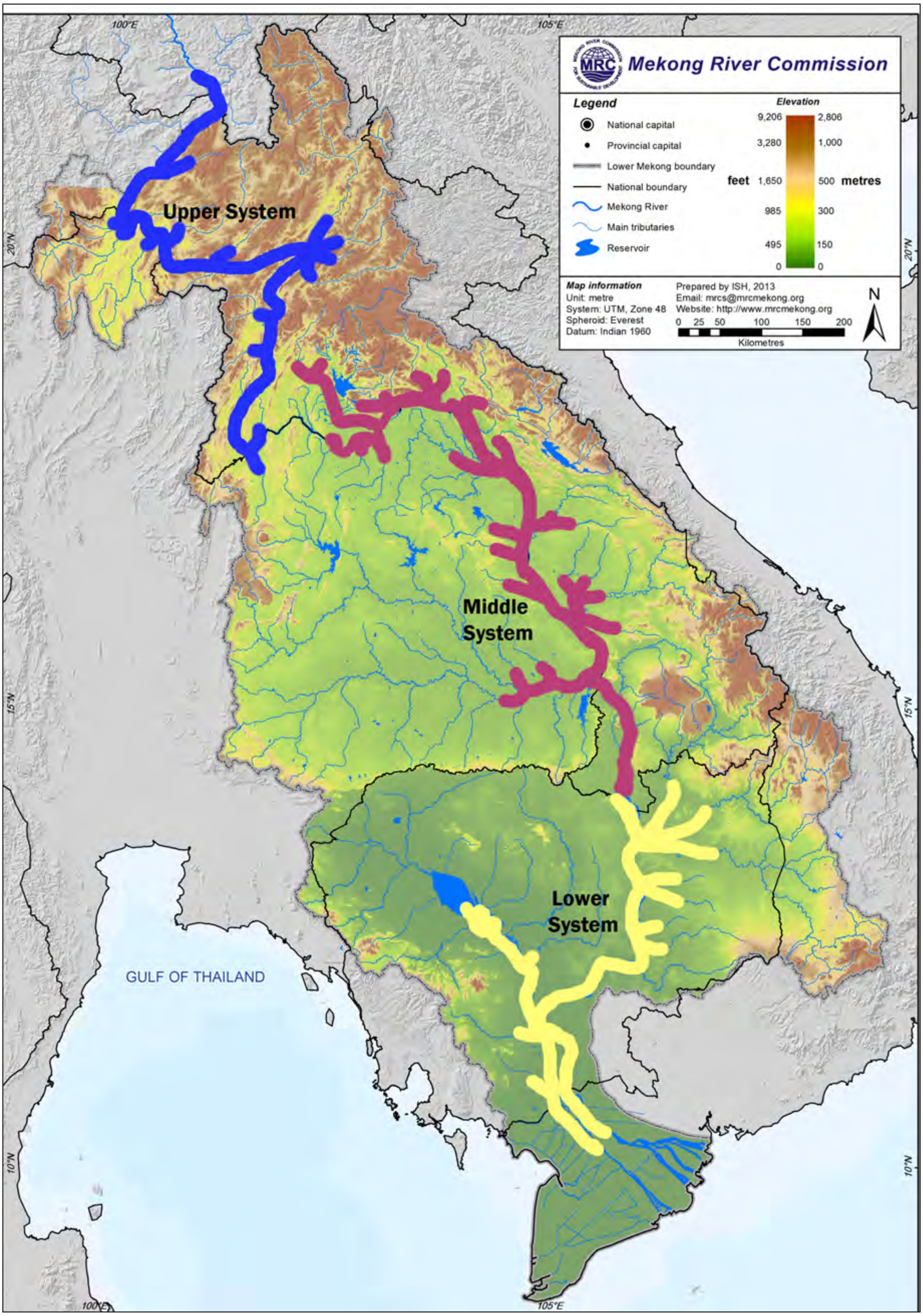


**Figure 20:** The main migration 'systems' of freshwater fishes of the Mekong mainstream in the LMB

Based on Poulsen *et al.* (2002). Many fish migrate between productive floodplains and rivers and along the mainstream; see text for explanation.

are likely to have a disproportionate effect on regional fish biodiversity (Ziv *et al.*, 2012).

While images of salmon leaping upstream over barriers are well known, to mitigate the barrier effect of a dam requires that both upstream and downstream passage are provided for, and that facilities allow for passage of large quantities of fish in a wide range of species and sizes. The basic elements of fish passage at a hypothetical hydroelectric dam are illustrated schematically in Figure 21, and discussed further below.

It should be noted that for fish passage to be effective, dam design must take account of many other impacts that also require mitigation, as discussed later in this report.

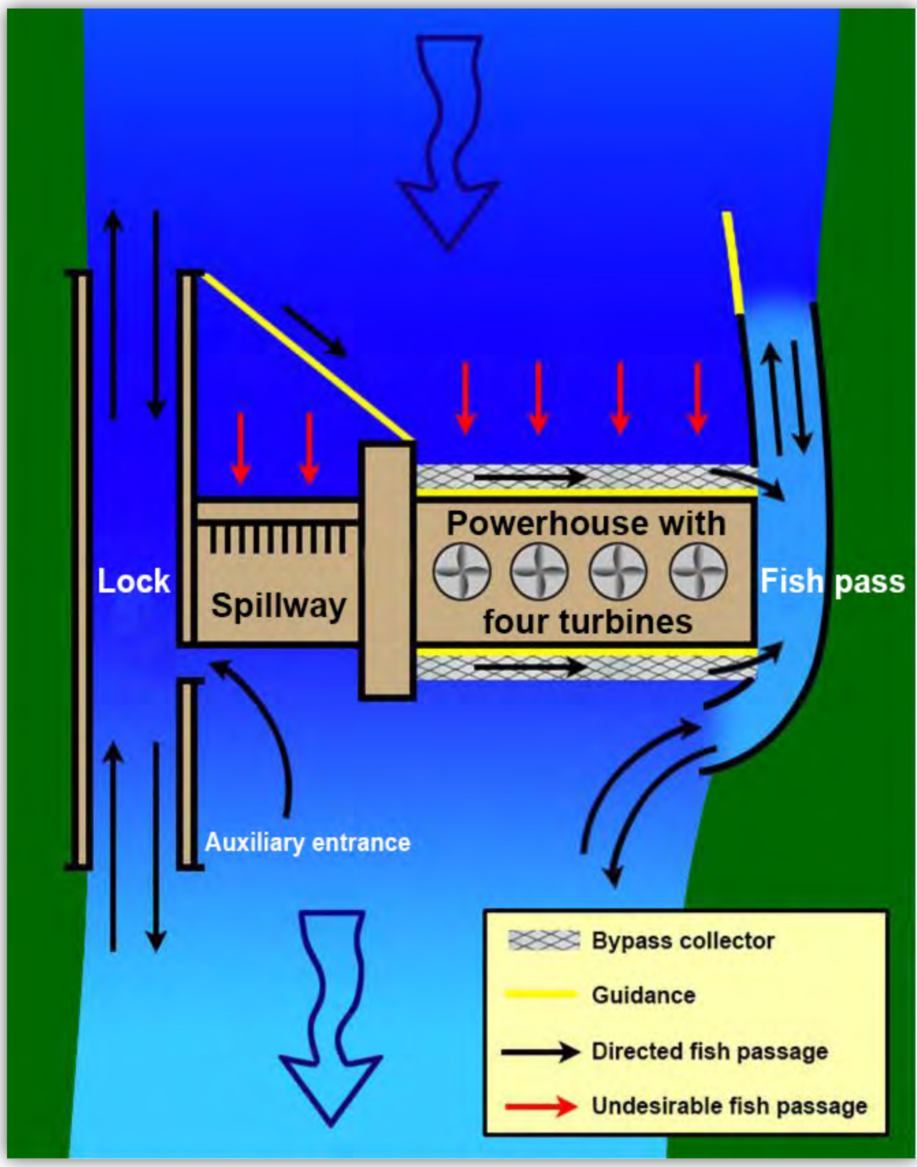


**Figure 21:** Schematic plan view of a hydropower dam showing upstream and downstream fish passage facilities

Guidance is by screens or behavioural barriers to divert fish away from spillways and turbines.

Illustration: Linden Hortle

## Upstream fish passage

Worldwide, most facilities for fish passage have been built for adult fish migrating upstream past dams or other barriers to reach spawning habitats. The first fish passes were built about 300 years ago in Europe for salmon, large and powerful fish that can leap over low barriers, and for many years fish pass design followed the approach used for salmon fish passes. Thousands of fish passes are now in place around the world, but it is only recently that designs have been improved so that they can efficiently pass a wide range of species, including smaller and slower species, many of which do not leap. Many improvements are still required, particularly in large monsoonal tropical rivers such as the Mekong, where the ecology of many species is poorly known and fish passes have only recently begun to be scientifically designed to pass a wide range of Mekong fishes of all sizes (Baumgartner *et al.* 2012).

Many types of fish pass could be constructed in the Mekong Basin to mitigate dam impacts on fish passage. The choice of fish pass and final design depend upon location and characteristics, the species and sizes of fish at the site, and the likely scale and timing of fish movements. Some common approaches discussed below are pool, lock, and bypass fish passes, as well as trap-and-transport systems, which may be applied singly or in combination. Fish pass design is constantly improving and being adapted, and readers are referred for further information to Bunt *et al.*, (2012), Clay (1995), Thorncraft and Harris (2000), Noonan *et al.*, (2012), Cowx, (2000), Gough *et al.*, (2012), Marmulla and Welcomme (2002) and Vigneux and Larinier (2002). A recent report provides detailed design guidance for fish passage relevant for the Mekong Basin (Schmutz and Mielach, 2015).

By convention, a fish pass's entrance is at the downstream end, where fish that are migrating upstream will enter, and its exit is at the upstream end where fish leave. The entrance of a fish pass must be in a location where fish will be likely to enter it. Fish migrating upstream that encounter a dam will approach a fish pass's entrance only if it is close to the main flow of water and if there is sufficient flow through it to attract the fish. Fish must be able to pass through the fish pass quickly – it cannot be too long – and exit from the fish pass where they will not be swept back downstream over spillways or through turbines. Fish passes must also be covered where there is a risk of people falling into them or poaching fish, and must be regularly maintained to remove debris or sediment. Many fish passes have been well designed hydraulically, but have failed because they have not adequately considered the optimal positions of the entrance and exit and the need to guide fish to safely enter and exit the fish pass.

## Pool fish passes

The most common fish passes comprise a series of pools and are often termed fish ladders. The simplest are 'pool-and-weir' fish passes, in which pools are separated by simple weirs, over which water flows. Early designs were a series of concrete boxes, as shown in Figure 22. Fish swimming upstream must leap between the pools, so simple pool-and-weir fish passes do not provide passage for fish that do not leap, including many tropical species. Pool fish passes are now usually constructed using a concrete channel or flume which is rectangular in cross section, with a series of baffles built into the channel to create the pools. Pool fish passes have been improved by adding orifices in the baffles, either at the surface or submerged, as can be seen at several fish passes on Mekong tributaries in Thailand (Figure 23) (Hortle *et al.*, 2003). Many pool fish passes now include orifices down the full depth of baffles as a 'vertical slot' (Figures 24-28). Vertical slots allow the levels in each pool to rise and fall as flows vary, without greatly altering the performance of the fish pass. Fish can swim upstream through the slots at any depth they choose. Vertical-slot fish passes are suitable for dams up to about 6 m high. The slope of a vertical-slot fish pass for tropical species is typically about 1:15 to 1:30, so for a dam 6-m high, a vertical-slot fish pass would need to be 90 m -180 m long. A steeper fish pass would be shorter and cheaper, but water would flow through it too fast for many types of fish. A less steep fish pass would be longer, would cost more, and fish that swim into it might tire and return down the fish pass. Recent research on Mekong fish has led to the use a gently sloping pool fish pass with multiple slots separated by adjustable concrete cones (Figure 29).

**Figure 22:** A simple pool-and-weir fish pass (right background) at the Huay Siet Weir in Lao PDR

This steep fish pass is not effective because many Mekong species will not leap, each step (weir) is too high (0.6 m) and fish are unlikely to find the fish pass. Rather they attempt unsuccessfully to ascend the spillway where they are attracted to the strong flow.

Photo: Kent Hortle

**Figure 23:** Inside a pool-and-weir fish pass at a dam on the Mae Nam Kham River Thailand

Photo taken during the dry season when there was little flow. Each baffle has a bottom orifice (right centre) which allows bottom-living fish to swim through the baffle, as well as a larger surface orifice (foreground and left centre) that can be fitted with removable gates to control water levels and flow. This design has been largely superseded by vertical-slot fishways which are less affected by variations in levels up and downstream.

Photo: Kent Hortle

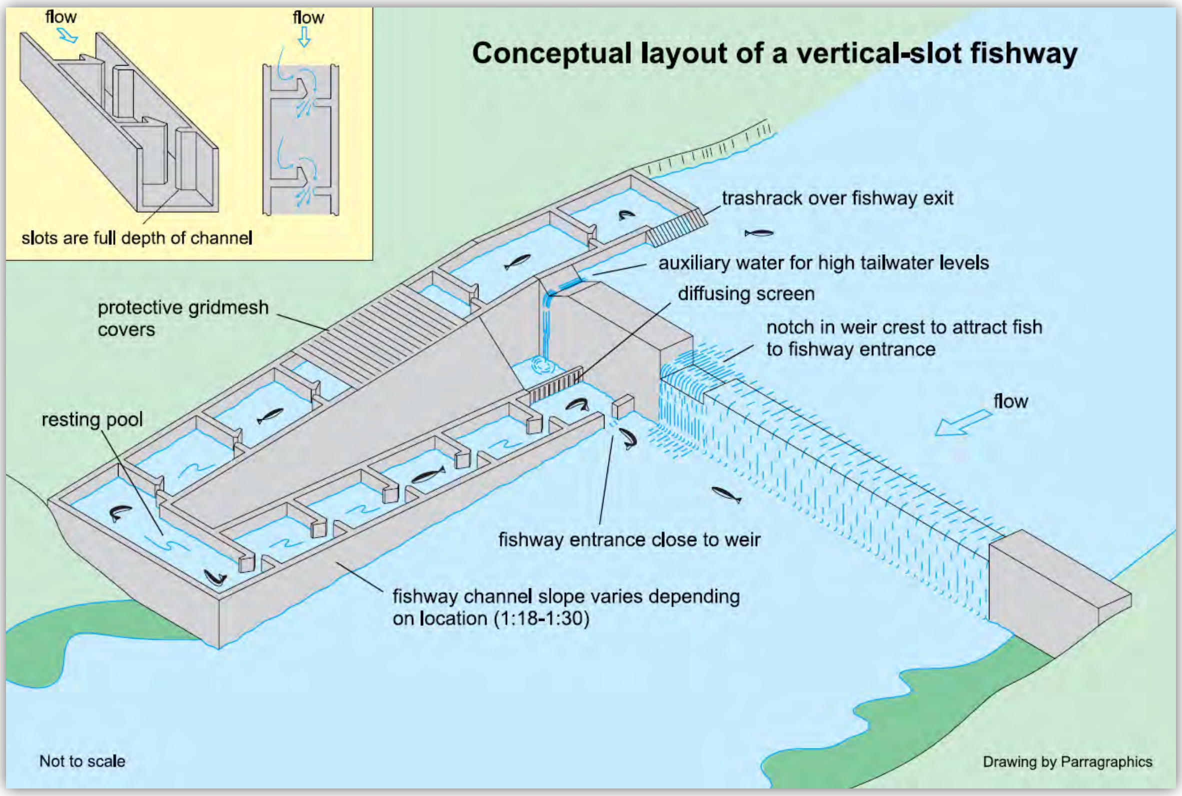


**Figure 24:** Conceptual layout of a vertical-slot fish pass

Illustration: Thorncraft and Harris (2000)

**Figure 25:** Stung Chinit Weir in Cambodia, downstream of the main dam wall

A water gate and flume (left centre) provide an environmental flow release, and a vertical-slot fish pass (right centre) supports fish passage upstream. This fish pass is a modern design that passes many fish, but the flow through it is small relative to both the environmental flow and the main dam overflow, which runs over a long spillway to the right of the photo. Most fish that are swimming upstream (left to right) would miss the fish pass entrance and continue towards the right where they are targeted by fishers.

Photo: Kent Hortle

**Figure 26:** Inside the vertical-slot fish pass at Stung Chinit Weir looking upstream

Fish swim upstream through each slot in the baffles, resting in the pools. The entire structure is covered by a steel mesh grid to prevent access. The photo was taken below the grid.

Photo: Kent Hortle

**Figure 27:** A typical vertical-slot fish pass looking downstream

This fish pass on the Schuylkill River, Philadelphia USA, was built to restore upstream migration of shad past Flat Rock Dam.

Photo: http://www.manayunkcanal.org/Fish-Ladders/71/

**Figure 28:** Vertical-slot fish pass at Lock 10 on the Murray River, Australia

The water is running from left to right. Space and materials are saved by zigzagging the structure down the slope.

Photo: Kent Hortle

**Figure 29:** A recently constructed cone fishway in Lao PDR

This fish pass in Lao PDR provides passage past a small floodplain regulator downstream of Pak Peung near Paksan. The design was developed from vertical-slot fish passes. The cones are removable. The presence of three tapering slots in each baffle allows the fish pass to continue to function if one slot is blocked by debris, and is also a safety feature; in a conventional vertical-slot fish pass (Figure 21) children may be trapped in the slot by water pressure. See Baumgartner *et al*. (2012) for background.

Photo: Kent Hortle

## Lock fish passes

Navigation locks are designed to allow vessels to pass dams, and fish may also swim upstream and downstream through locks. Working on the same principles as a navigation lock, water runs through a fish lock, attracting fish into it downstream of a dam (Figures 30, 31). When the downstream gates of the lock are closed, the water level in the lock rises to the same level as the water upstream, allowing fish to swim past the dam and into the reservoir. In practice, fish locks may need additional flows to attract fish to enter and exit, and may also need mobile screens to direct fish into and out of them. Fish locks are most suitable for high barriers (> 6 m), where conventional pool fish passes would be long and expensive and are also appropriate at sites where there is limited space. While a lock purely for fish passage may not be the optimal solution at a site, there is potential to modify existing navigation locks in the Mekong region to improve fish passage, and any new navigation locks should be designed with fish passage in mind as an added benefit.

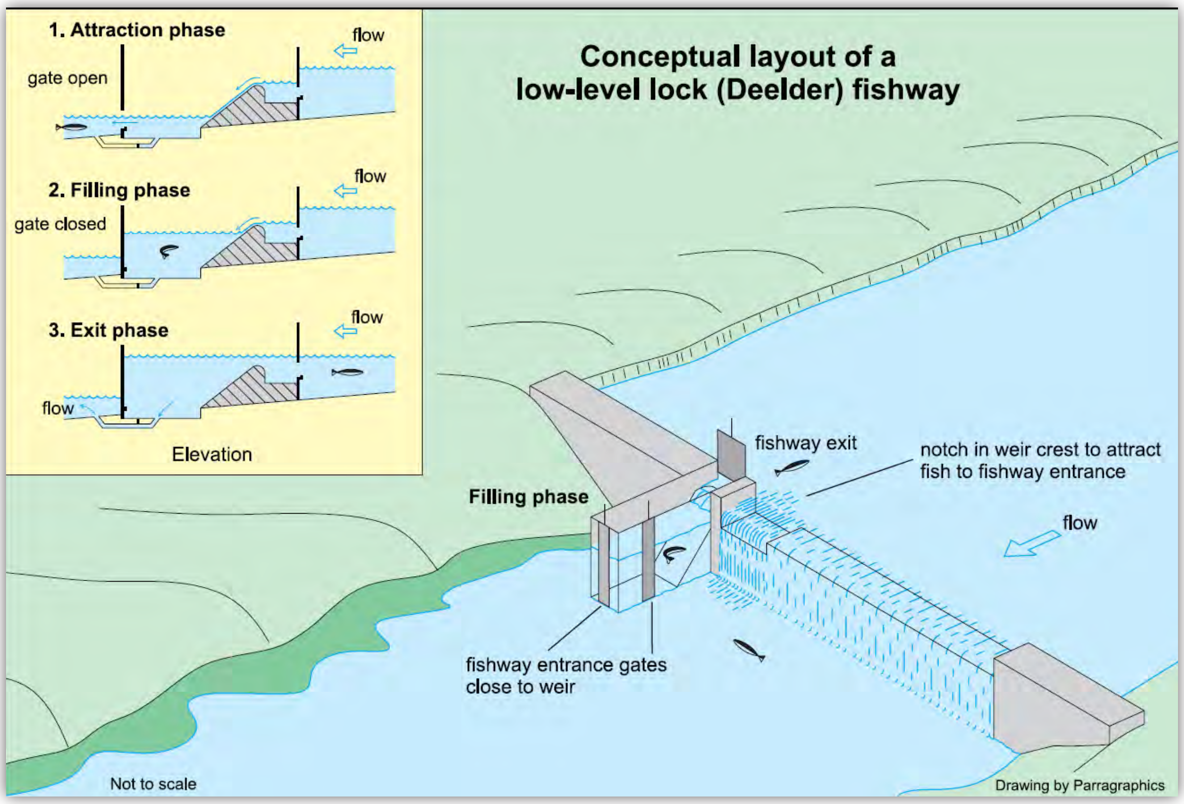


**Figure 30:** Conceptual layout of a lock fishway

Illustration: Thorncraft and Harris (2000)

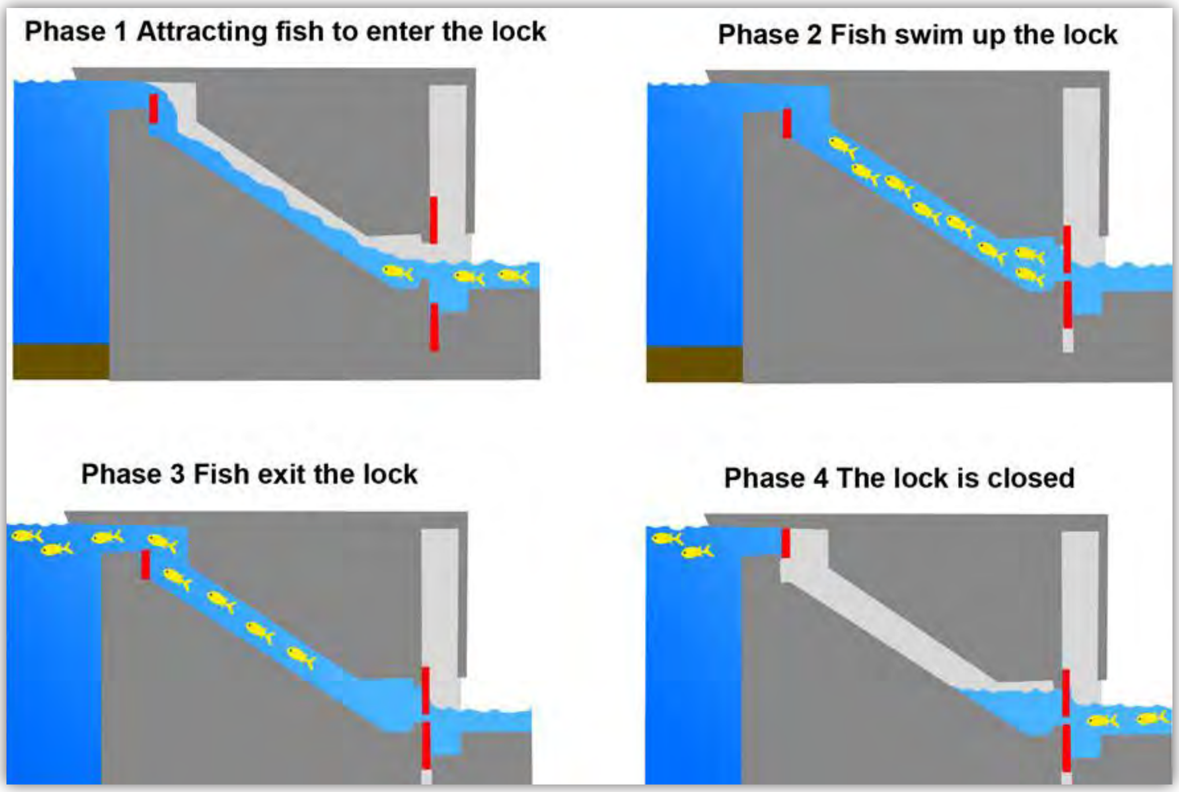


**Figure 31:** Simplified diagram of the operation of a Borland lock fish pass

Based on a lock at the Salto Grande Dam, Uruguay River, South America; such locks have various other elements such as a collection bay, which for clarity are not shown here.

Illustration: Linden Hortle

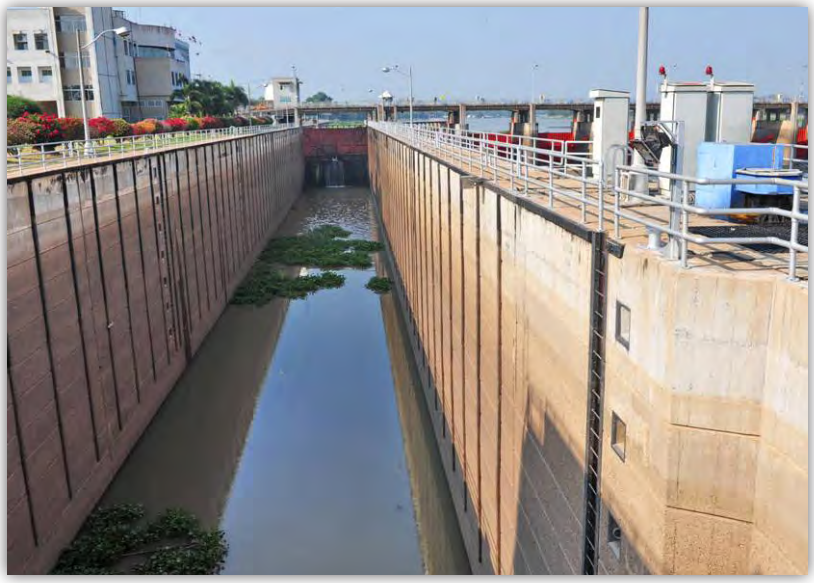


**Figure 32:** A navigation lock on the Lower Chao Phraya Dam, upstream of Bangkok

The view is looking upstream through the downstream chamber. Fish migrate upstream through this lock at certain times, but it could be modified to improve fish passage at this site. Spillway gates can be seen on the right.

Photo: Kent Hortle

**Figure 33:** Upstream of a navigation lock on the Erie Canal, USA

Photo: Kent Hortle

The large size of some navigation locks provides potential for passing fish, particularly species that are too large for pool fish passes.

## Bypass fish passes

Bypass fish passes are low-gradient earthen or rocky channels that mimic the structure of natural streams (Figure 34), and are often described as ‘nature-like’ fish passes. They are relatively cheap and aesthetically appealing, but require more space and may use significantly more water than other fish passes. Like any fish pass they also require maintenance, for example to ensure that flow-control structures do not block or wash out. A bypass fish pass has been built recently on the Phuc Hoa Dam, a tributary of the Saigon River in Viet Nam, and a similar long fish pass is being built as part of the fish passage facilities for the Xayaburi Dam in Lao PDR (Baumann and Stevanella, 2012). The world's longest fish pass allows fish to pass from the Parana River over Brazil's largest dam into the Itaipu Reservoir; it is 10 km long and includes a 6.7 km nature-like fish pass. Unfortunately the Itaipu fish pass and other fish passes at very large dams have been generally ineffective at maintaining migrating fish populations (Makrakis *et al.*, 2007).

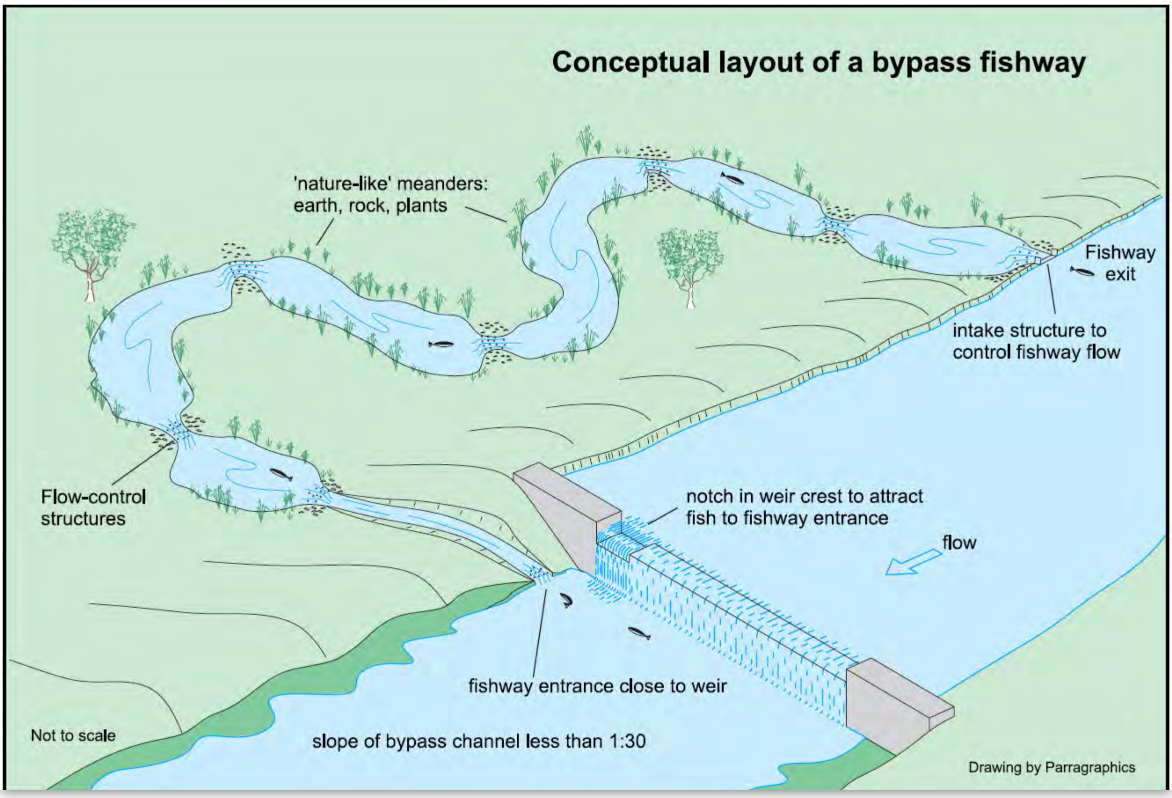


**Figure 34:** Conceptual layout of a nature-like bypass fishway

Illustration: Thorncraft and Harris (2000)

**Figure 35:** A nature-like bypass fish pass at a small weir

The weir blocks a stream between Reinsvatnet and Mellsjoen Lakes in Norway. Fish swim upstream from right to left.

Photo: Kent Hortle

## Trap and transport

Many river fish migrate upstream to seek habitats in flowing water where they spawn. A disadvantage of conventional fish passes is that fish which swim upstream through a fish pass may find themselves in a reservoir, where they may have to swim many kilometres to find suitable flowing water. While migrating through a reservoir, river fish expend additional energy and are exposed to lake-dwelling predators (e.g. Rieman, 1999).

Upstream-migrating fish can be trapped below a dam, (e.g. in a hopper) and then transported over the dam wall, in some cases using an elevator which lifts a hopper that contains water and fish. Such elevator fish passes are suitable for high barriers, and unlike fish locks, once in a hopper the fish do not need to swim but are simply transported over the dam. Fish can then be transported by road, rail or boat upstream to where there are suitable habitats, bypassing the reservoir. Trap and transport is also sometimes used for downstream migrating fish. However, trap and transport is expensive, has been applied at relatively few locations and is unsuitable for fish that are sensitive to damage during handling and transport.

On a Mekong tributary in Thailand a simple form of trap and transport was successfully trialled by paying local fishers to catch juvenile fish which were then transferred upstream past a dam (Hortle *et al.*, 2005).The main advantage of such an approach is that no capital works were required and relatively modest payments were made to fishers who would have otherwise killed and sold the juvenile fish. There was also no need to set up a system to prevent people fishing in or near a constructed fish pass.

**Figure 36:** A pool fish pass at a small hydroelectric weir

This photograph illustrates some of the complexities of upstream fish passage. The fishway connects to a bypass channel that runs along the downstream side of the power station; fish can enter at several points. The fishway ascends across a spillway and delivers the fish to the left and well upstream of the turbine intakes. At this time the spillway gates are closed, but when it is open fish that emerge from the fishway may be drawn into the spillway and pass downstream again.

Photo: Bunt (2009)

## Downstream fish passage

To pass a dam, fish may move downstream over spillways, through bottom outlets or through hydroelectric turbines. They may be killed or injured when they strike or are struck by objects or structures, or are subject to sudden pressure changes. They may also be diverted into offtakes for irrigation systems, which may be a dead end for river fish. Compared with upstream fish passage, facilitating downstream passage can be more difficult, because fish may be moving relatively rapidly with the flow so they have limited time to respond to cues, for example where flow and pressure change rapidly.

## Spillways

Passage over spillways may be safe for fish if there is no restriction on flow, the fish do not fall a long distance, and if they do not strike hard objects. In the Mekong Basin, the majority of spillways on dams and weirs unfortunately are fitted with top-down radial water gates (also termed Tainter gates) to regulate water levels upstream (Figure 37). Such gates are designed for hydraulic efficiency and cost, taking no account of fish passage. Fish passing under such gates are subject to impacts, shear stress and decompression, which may kill or injure them, in a similar way as fish passing through turbines, as discussed below.

**Figure 37:** Typical top-down radial water gates, Huai Luang Dam, Thailand

Fish cannot pass upstream. Any downstream-migrating fish must pass at high speed through a narrow gap where they are likely to be injured or killed by contact with the gate or sill, as well as suffering rapid decompression and shear stress. Note also the hanging nets that catch upstream-migrating fish that leap at the spillways, showing how spillways attract and aggregate fish that are easily caught if they cannot pass.

Photos: Kent Hortle

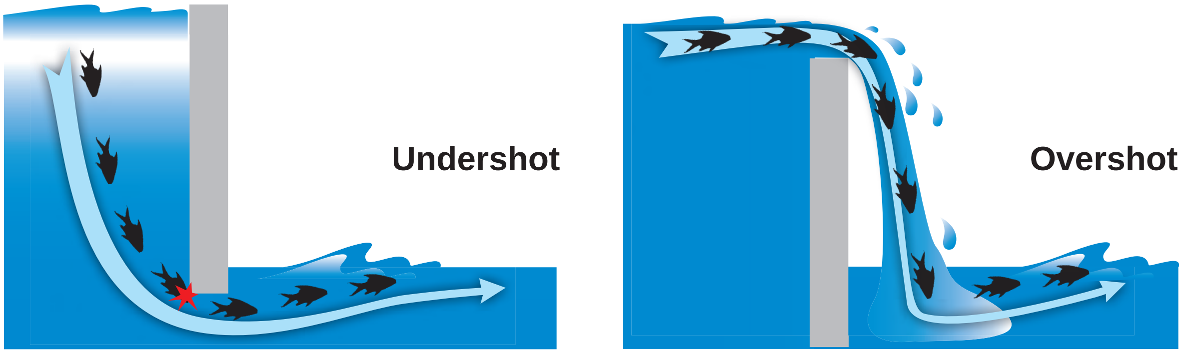


**Figure 38:** Bottom-up (left) and top-down (right) water gates

Pilot experiments in Australia and Lao PDR show that more fish are injured or killed by undershot weirs than overshot weirs. Overshot weirs are particularly effective if a deep plunge pool is maintained below the weir.

Illustration: Chhut Chheana

Top-down water gates also trap floating wood, debris and plants, which then tend to accumulate upstream in the reservoir, exacerbating problems of excessive plant growth. Water gates that rotate at the base and allow both fish and floating objects to pass have only been used at a few Mekong dams, where they provide benefits for operation of the dam, allowing debris to pass, and also allow fish passage downstream. Retrofit of bottom-up or lay-flat gates (Figure 38-39) is desirable at many reservoirs to improve downstream fish passage. Where the cost of complete replacement is prohibitive, another approach is to retrofit existing facilities with removable spillways (Figures 40-41) to provide safe passage past radial gates.

**Figure 39:** Tumnub Makak Dam, Kampong Thom, Cambodia

Lay-flat water gate in the centre of the spillway is open, allowing fish and floating weeds to pass. The photo was taken in 2013 in January - the dry season - so the other gates are closed.

Photo: Kent Hortle

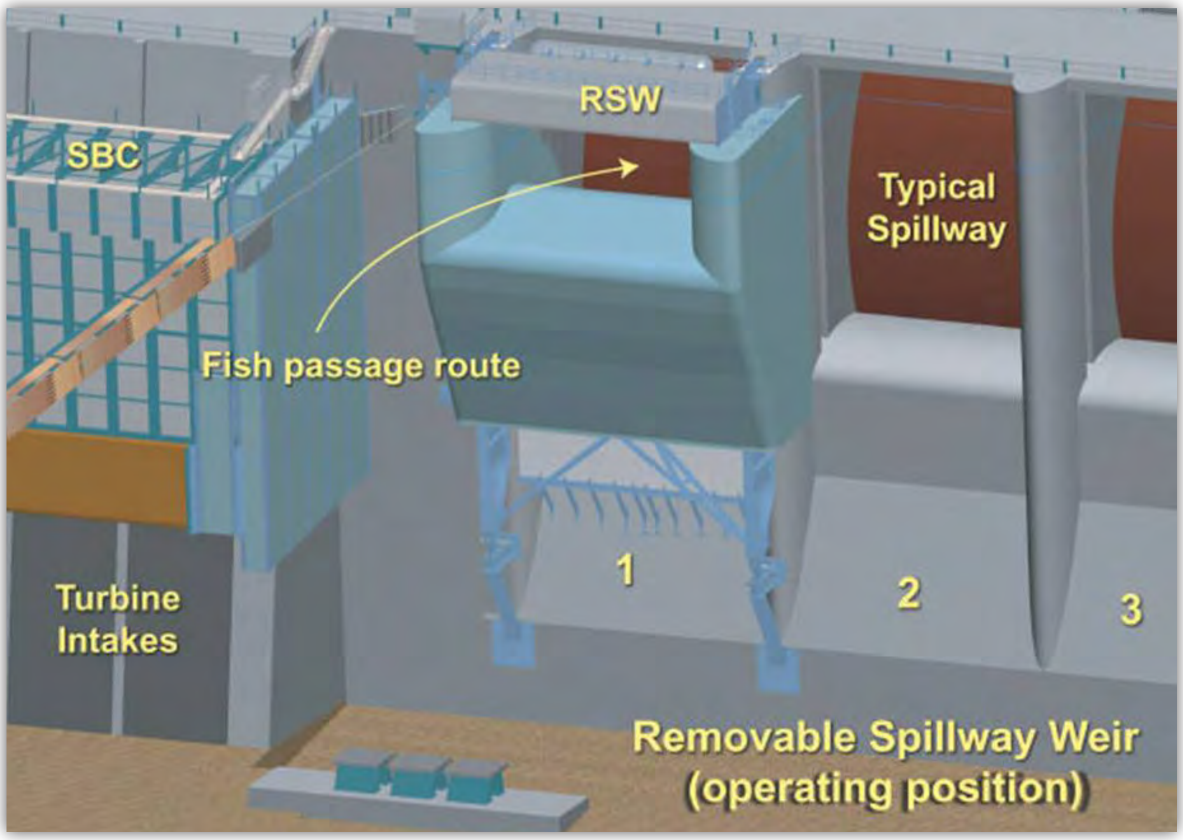


**Figure 40:** Removable spillway trialled on Columbia River dams for downstream fish passage

Illustration: http://www.salmonrecovery.gov/Files/Fact%20sheets/Surface%20Passage%20Systems%20and%20Removable%20Spillway%20Weirs.pdf

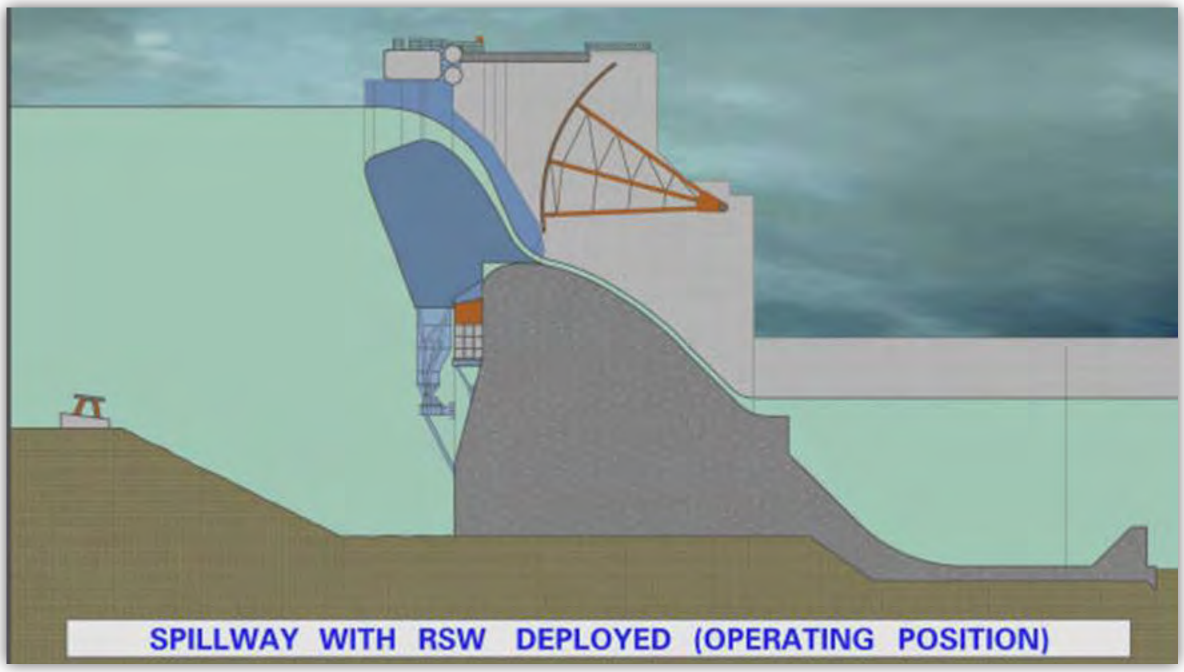


**Figure 41:** Operating position of removable spillway weir

Illustration: http://www.salmonrecovery.gov/Files/Fact%20sheets/Surface%20Passage%20Systems%20and%20Removable%20Spillway%20Weirs.pdf

## Turbines

A turbine is a device in which moving fluids spin a runner, which is attached to a rotating shaft that may be used to directly power machines (such as mills) or to turn the rotor of a generator to produce electricity, as in a hydroelectric plant. There are two main classes of turbines commonly used in hydropower plants: pressure and impulse turbines (Figure 42). The runners of pressure turbines are submerged and are driven by hydrostatic pressure; these include Francis, propeller and Kaplan turbines. The Kaplan turbine is a propeller turbine with blades whose angle can be varied to match flow rates. Francis turbines were invented in 1848 and are the most widely used turbine in hydropower plants. Kaplan turbines were invented in 1913 and allow efficient power production at high-flow low-head dams, for example so-called run-of-river dams. Impulse turbines are not submerged but are driven by kinetic energy in the same way as a waterwheel; the most common is the Pelton turbine. Impulse turbines are favoured in smaller plants where there is a high head but relatively low discharge, and they rotate rapidly, typically several times per second. Each type of turbine has certain advantages and disadvantages in terms of efficiency and reliability.

Francis Propeller Kaplan

Crossflow Turgo Pelton

**Figure 42:** The main types of turbine runners used to produce hydropower

The upper turbines are pressure turbines and the lower are impulse turbines.

Illustrations: www.publicresearchinstitute.org

Fish moving downstream past a dam are likely to enter turbine intakes in approximate proportion to the flow, which may comprise up to 100 percent of the total flow, especially during dry periods. Fish that pass through hydroelectric turbines may be killed or injured by physical contact with structures, by pressure changes, and by shear stress and turbulence (Figure 43). Different types of turbines pose different risks of damage to fish, and improving fish passage is becoming a significant consideration in turbine design.

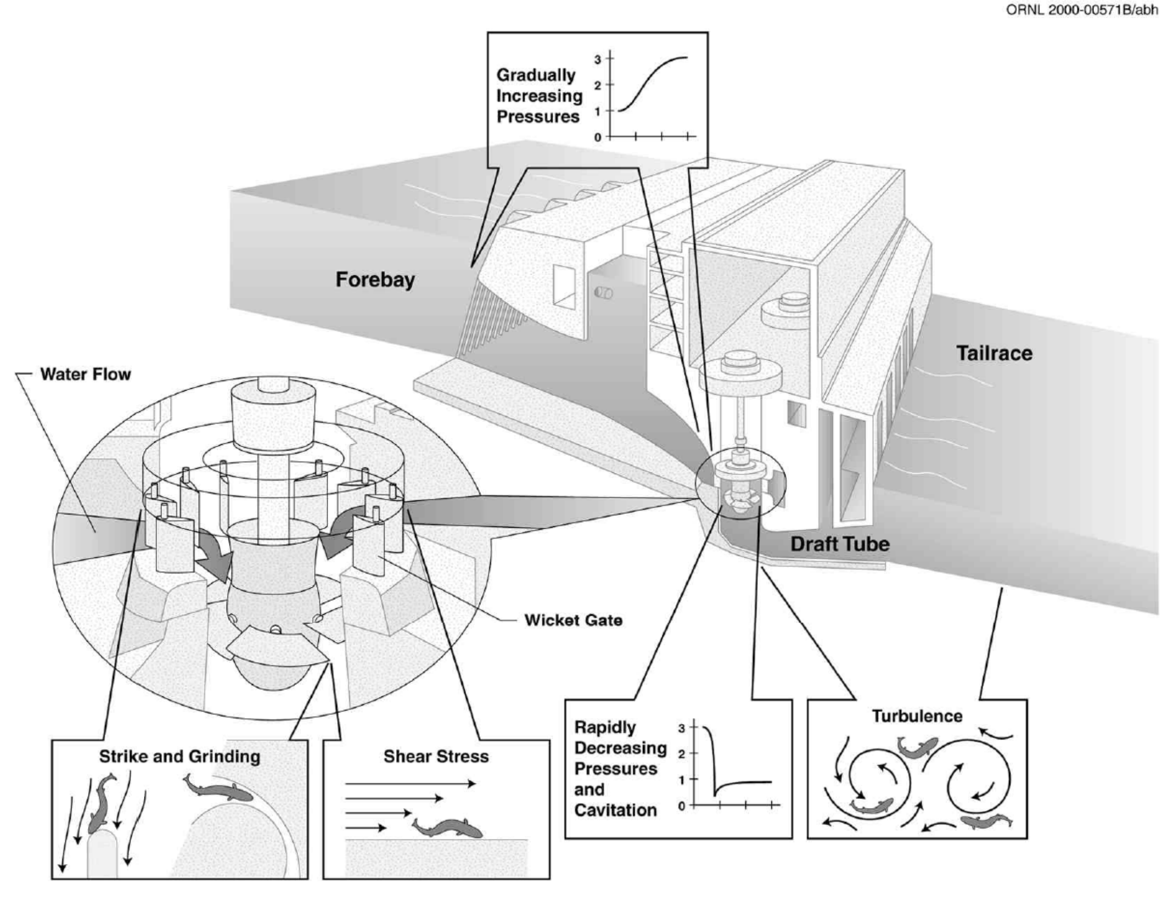


**Figure 43:** Cross-section through a powerhouse, showing a Kaplan turbine

The diagram illustrates where fish are likely to be injured.

Illustration: Cada (2001)

**Figure 44:** One of the eight original Francis turbine runners from Glen Canyon Dam, Colorado River, USA

The runner had 23 blades; it weighed about 42 tonnes and rotated at about 2.5 times per second. During its life between 1965 and 2008 this runner turned nearly 2 billion times.

Photo: Kent Hortle

**Figure 45:** The runner of a typical Kaplan turbine

The 4 blades are adjustable to improve efficiency at different flow rates. Kaplan turbines are more fish-friendly than the older Francis turbines, as they have fewer blades and rotate slower (1-2 times per second).

Photo: Rolf Süssbrich http://commons.wikimedia.org/wiki/File:KaplanTurbineLinzAustria.JPG

Physical contact with structures includes fish colliding with various parts of the turbine or being struck by the spinning blades, which can be several metres in diameter with edges moving at over 100 km/hr. Not surprisingly, larger fish passing through a turbine are more likely to be struck than smaller fish. There has been considerable research on making turbines safer for fish, particularly by reducing the speed of rotation and reducing the number of blades on the runner. Most of the older plants and plants on high dams use Francis turbines, which have up to 18 blades which spin up to three times per second (Figure 44); fish passing through such turbines are clearly at risk of being struck by the blades. Newer plants, especially those at low-head dams, mainly use Kaplan turbines which typically have 4-5 blades and spin at about 1-2 times per second (Figure 45). These and other improvements in design have greatly reduced the probability that the blades will strike fish passing through a turbine.

Pressure changes as water passes through a turbine. As fish enter a typical Kaplan turbine, the water pressure increases to a peak typically about 3-4 times surface pressure, and then rapidly falls for a short period (<1 second) to a pressure as low as half of that at the surface upstream of the plant (Figures 46). The initial compression causes little effect on fish, but rapid decompression causes gas spaces within a fish to expand proportionally – a halving of pressure will tend to cause a doubling of volume. Most fish can adjust the volume of their swim bladders, but the pressure change through a turbine is so fast that a fish cannot equalise in time to prevent a rapid expansion of its swim bladder, which may rupture, injuring or killing the fish. Such barotrauma may be more probable and more significant than physical impacts, which have been greatly reduced in modern turbines. Barotrauma is worse for fish that are drawn into the turbine from deeper water upstream of the turbine, as they experience a larger reduction in pressure when they pass through the turbine (Brown *et al.*, 2013a).

Currently, research is focusing on turbines that have only two or three blades, no gaps and are larger and rotate more slowly, which significantly reduces the chance of impact while preserving high efficiency and energy production. Some of the principles of an Archimedes screw (Figure 47) are being employed in new turbine designs (Figure 48).

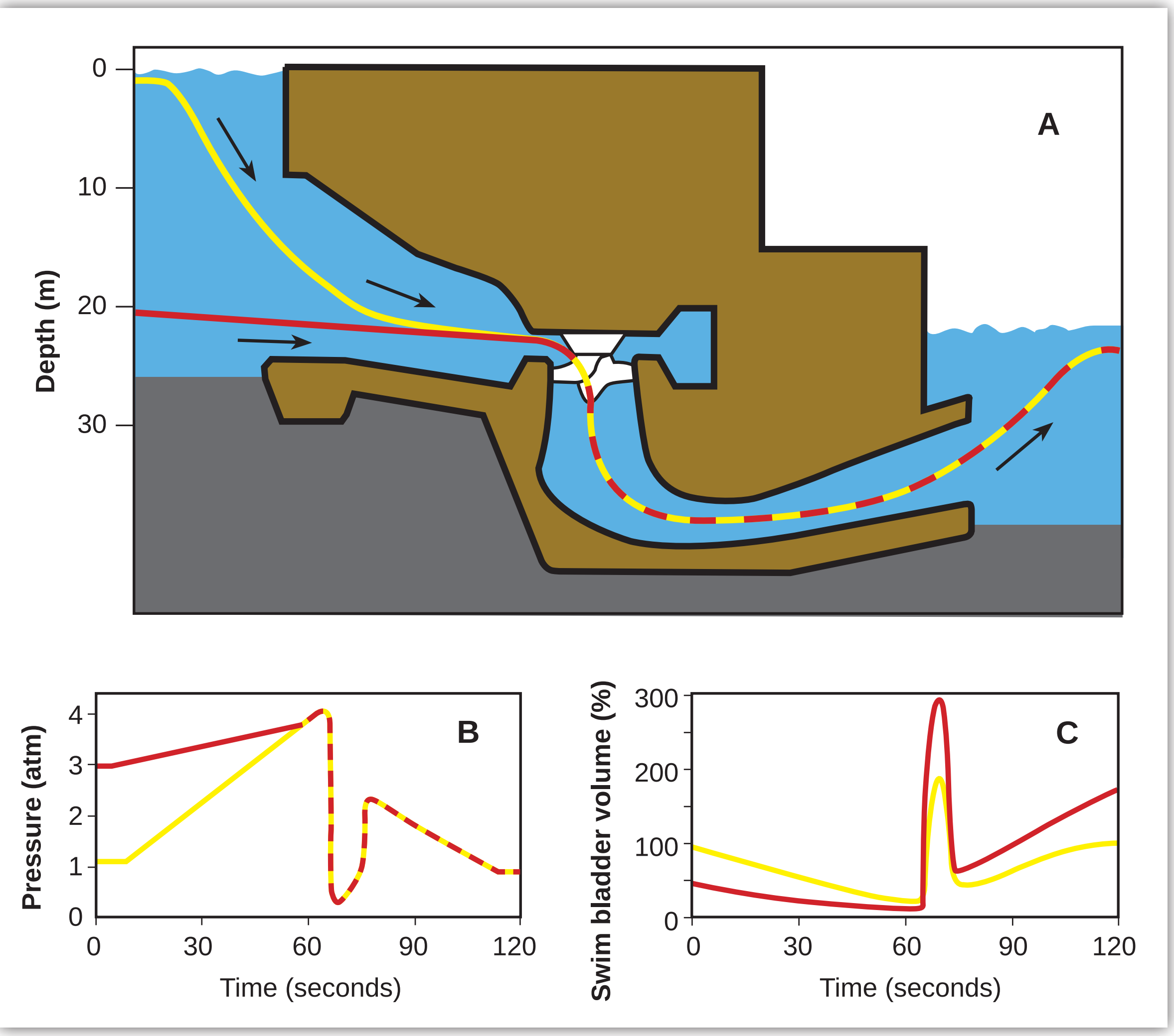


**Figure 46:** Pressure changes through a typical Kaplan turbine, from left to right

**A** – Passage from left to right of fish drawn from the surface (yellow) and the bottom (red) of the river.

**B** – Pressure rises within the turbine to as high as 4 atmospheres (atm) then rapidly falls after the runner.

**C** – Swim bladder of fish initially compresses than rapidly decompresses and expands in the zone of low pressure, potentially rupturing. A fish drawn in from 20 m depth will suffer a 6-fold pressure decrease, so its swim bladder may expand up to 6-fold, in this diagram from 50 percent inflation to 300 percent inflation.

Illustration: redrawn from Brown *et al*. (2013a)

Shear stress arises when layers of water flow rapidly in opposite directions, or when water flows past a boundary layer which is adjacent to stationary objects or turbine blades. If parts of a fish are within different layers of water, they may be torn or detached from the fish. Turbulence involves irregular motions of water which can cause localised injuries or disorientation. These effects are currently being intensively researched with the aim of making flow through turbines as smooth and efficient as possible to reduce injury to fish.

**Figure 47:** A hydropower turbine being run by an Archimedes screw, an ancient design

This is among the most fish-friendly of turbines, as it rotates slowly and there are is only one blade that can strike fish on entry or exit; fish move down through the screw with the water. The design is most suitable for small schemes.

Photo: http://allrivershydro.files.wordpress.com/2010/05/archimedes.jpg

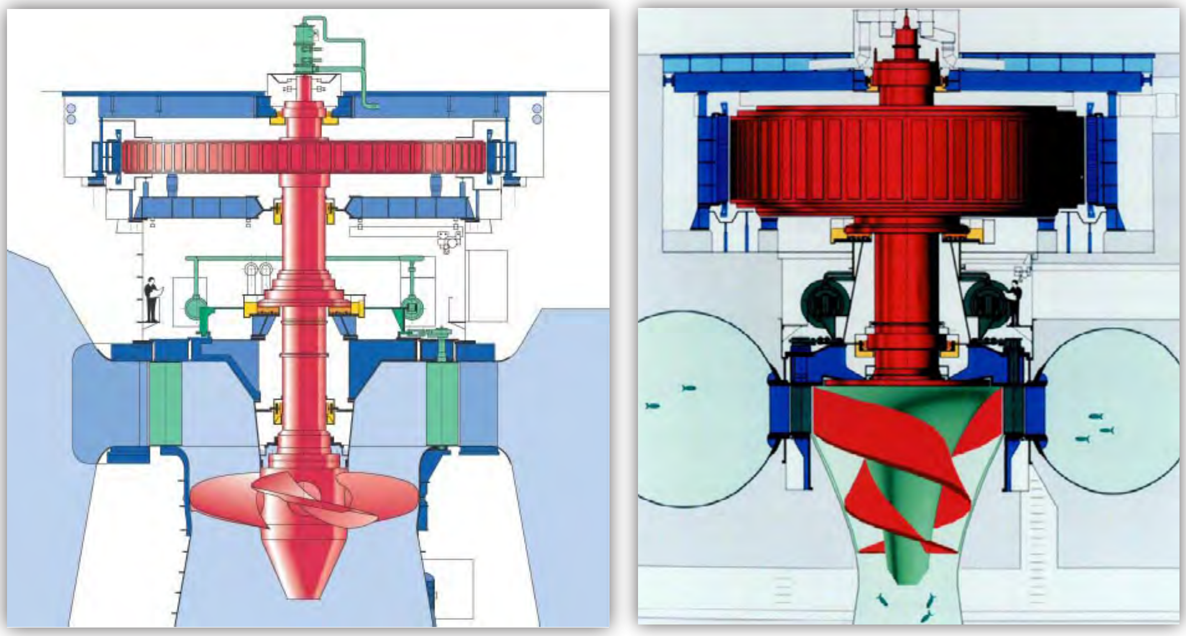


**Figure 48:** Evolution of hydroelectric turbines to improve efficiency and fish-friendliness

Kaplan turbine (left) and Alden turbine (right) - fewer blades, slower rotation, smoother shape.

Illustrations: Voith GmbH & Co and Odeh (1999)

The mortality of fish through modern Kaplan turbines from physical contact, shear stress and turbulence, is typically less than 10 percent, but is higher for large fish of breeding age, whose loss will have the most impact on fish populations (Halls and Kshatriya, 2009). The effects of pressure changes (barotrauma) are not fully understood, as they may be delayed for some time after turbine passage. Despite ongoing improvements in design, turbines will never be entirely fish friendly, and very large fish such as the adult Mekong giant catfish (Figure 7) could not pass safely through any turbines, so diverting fish around turbines is essential to mitigate downstream passage impacts.

## Diverting fish past turbines, spillways or offtakes

Fish that are migrating downstream may be diverted away from intakes by physical barriers, or by behavioural barriers; often it is necessary to create special structures or channels to allow the diverted fish to bypass a dam. There are many alternative approaches depending upon dam configuration.

Physical barriers usually incorporate screens, which must be carefully designed so that fish do not get held against them (impinged) or forced through them (entrained) by the force of the current. Drifting aquatic plants, detritus and sediment tend to clog screens, so provision must be made for periodic cleaning, which may require that screens are removed and flushed; alternatively screens may rotate or have airburst systems which periodically flush material off them. Growth of mussels and algae on screens may be inhibited by use of copper-nickel alloys.

**Figure 49:** A wire-mesh screen prevents fish passing into a diversion channel

The Sacramento River, California runs left to right in foreground of photo and the diversion channel runs to the upper right.

Photo: http://www.fws.gov/cno/fisheries/cvpia/Sutter%20picture-final-600.jpg

**Figure 50:** Fish screen at Iffezheim Dam, Rhine River looking downstream

The screens direct fish into a vertical-slot fish pass (centre), away from the turbine draft tubes (left and right).

Photo: Marmulla (2001)

**Figure 51:** Large screens on the intakes of the Theun-Hinboun hydropower plant in Lao PDR in 2001.

Workers were clearing an accumulation of logs, debris, sediment and a dense growth of mussels.

Photo: Kent Hortle

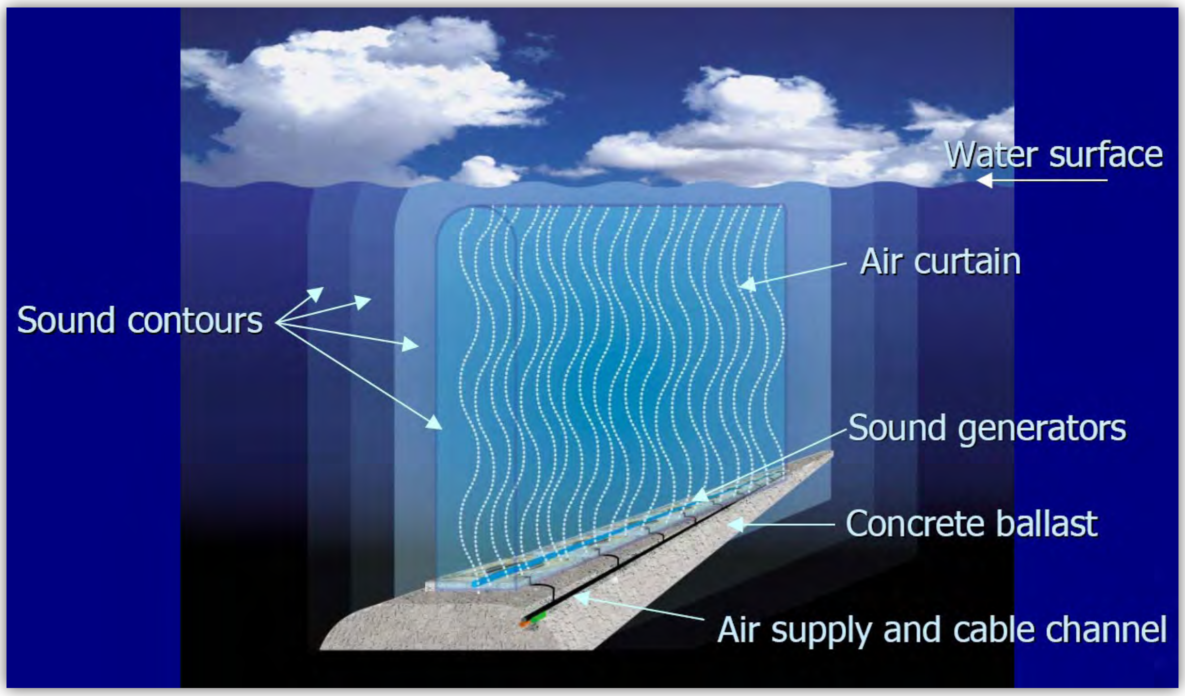


**Figure 52:** A behavioural barrier combining sound and an air curtain to repel fish

Illustration: O'Keeffe and Turnpenny (2005). The bioacoustics fish fence (BAFF™) is produced by Fish Guidance Systems UK.

Screen designs are still being actively developed with variable success rates; many fish are still killed or injured during turbine passage or when impinged on screens, so there is now considerable research on behavioural barriers to fish (Figure 52). Such barriers create conditions that fish avoid, such as noise, lights, air bubbles or electric currents, to repel them from intakes. Behavioural barriers are less likely to be affected by clogging and damage from suspended materials than screens.

Selection of the best option for screening, whether physical or behavioural, should take into account many site-specific factors and the range of species to be screened, as reviewed for example by O'Keeffe and Turnpenny (2005). As there is little or no field information about screening for Mekong fish, there is an urgent need for experimental studies to test the effectiveness of different approaches under a range of conditions for fish of a range of species and sizes, following a systematic approach as in a number of recent studies elsewhere (e.g. Boys *et al*., 2012; Flammang *et al*., 2014).

## Effectiveness and efficiency of fish passes

A fish pass has been defined in the MRC's Preliminary Design Guidance for Mainstream Dams (MRC, 2009) as effective if it provides safe passage for 95 percent of the target species under all flow conditions. Rather than 'effectiveness' the term 'efficiency' is more commonly used to refer to the proportions of fish actually passing a structure (Bunt *et al.*, 2012; Larinier, 2008; Odeh, 1999; Roscoe and Hinch, 2010). Efficiency depends upon biological characteristics of the fish, environmental conditions, and features of the fish pass (e.g. slope and length). Effectiveness has generally been used as a more qualitative term that refers to the potential of a fish pass to pass all target species (Larinier, 2008). Ultimately, the performance or success of a fish pass should be judged by the extent to which fish populations and fish production are maintained in the affected river. Fish passage is only one element in habitat compensation in Canada for example, where no nett loss (NNL) in fish producing capacity is the overall aim (Quigley and Harper, 2006). To be successful in maintaining fish populations, fish passage must not only provide close to 100 percent efficiency, but must also not affect long-term survival and reproductive success – there must be no migration delay, energetic cost, or any effects on fitness (stress, disease or injury). And as well as providing passage, other impacts affecting fish populations and production must be mitigated as discussed elsewhere in this report.

The effectiveness of any form of mitigation should be judged on biological grounds, and also in terms of the return on investment, which will tend to decline with incremental cost. Fish passes over low barriers have often been quite successful in maintaining or restoring populations of migratory fish, whereas fish passes over high dams have been much less successful, even being referred to as 'ecological traps' for the fish that ascend them into a large reservoir, a habitat for which they are not adapted and where they do not complete their life cycle. Where a large reservoir exists upstream of a dam, recent studies show that even if fish spawn in tributaries of the reservoir, there may be little or no return of downstream-migrating fish or their newly hatched larvae which are not adapted to reservoirs. It is very unlikely that fish passage efficiency at dams across the Mekong mainstream will ever approach 95 percent, given current passage efficiencies and experiences at dams in other large river basins, where many species either do not ascend, or they or their offspring do not descend past the dam (Agostinho *et al.*, 2007; Agostinho *et al.*, 2011; Noonan *et al.*, 2012; Oldani *et al.*, 2007; Pompeu *et al.*, 2012).

By changing conditions in their vicinity, dams tend to favour non-migratory fishes and species tolerant of altered hydrology, water quality and food chains downstream. Reservoirs are a benign environment for many non-native species that are competitors with or predators on native fishes (Waples *et al.*, 2008). Dams are also likely to harbour exotic species, and act as a continual source of their fry, which can then colonise downstream river reaches (e.g. Janáč *et al.*, 2013). In the long term, and even with fish passage measures in place, after a large dam is built the fish fauna at a site will usually change dramatically. Therefore, well as fish passage a good deal more attention needs to be paid to mitigating other impacts, and to consider whether expenditure on environmental offsets and/or enhancing reservoir fisheries might be more effective.

**Figure 53:** A challenge at dams is to pass large quantities of fish

This photo shows a catch in the Tonle Sap Dai net fishery of mainly small white fish which migrate down the Tonle Sap. Many small river fish are fragile, obviating consideration of trap-and-transport fish passage systems that require handling.

Photo: Ngor Pengbun

## Propagation of wild fish to mitigate fish passage impacts

Large adult fish in breeding condition often accumulate below dams, so fish passes are often built to assist them to migrate upstream. As a supplement or alternative to use of fish passes, wild fish in breeding condition may be caught and then bred in hatcheries, with their offspring released back into the wild. In the LMB there has been considerable testing of mobile hatcheries (e.g. Cacot and Phengarouni, 2006; Phanousith *et al*., 2006); which allow fish to be bred onsite, after which their fry stocked are in nearby ponds where they are grown prior to release. In the LMB there are now many permanent hatcheries producing fry for aquaculture or for stocking into reservoirs, but there has been very limited stocking of rivers.

**Figure 54:** Mobile hatchery at Paksan, Lao PDR

Photo: Anonymous, 2009

In most cases, hatchery propagation is unlikely to be the best approach for maintaining viable riverine fish populations in the Mekong, as it would be a poor substitute for natural spawning which produces billions of larvae each year (Hortle *et al*., 2015). Ensuring fish passage past barriers should in general be the priority for mitigating the barrier effects of dams, and reducing fishing pressure on spawning fish should also be a priority (Cacot, 2007). However captive breeding and stocking may be necessary for the long-term survival in the wild of some long-distance migratory species such as the Mekong giant catfish which is under particular threat from dams and fishing pressure (Halls and Kshatriya, 2009).

## 2.2 Flow changes

In the LMB, many large dams are designed to store wet-season water for release during the dry season, and some so-called run-of-river dams may store water for up to several weeks during the dry season (Figure 55). Downstream of a dam, the pattern of water release may be quite different to the natural seasonal pattern. Altering the seasonal pattern of flows may cause many ecological effects as riverine organisms are adapted to a natural flow regime. Altering flows may interfere with fish migrations or spawning and, reducing the extent and duration of annual flooding, will directly reduce fisheries production.

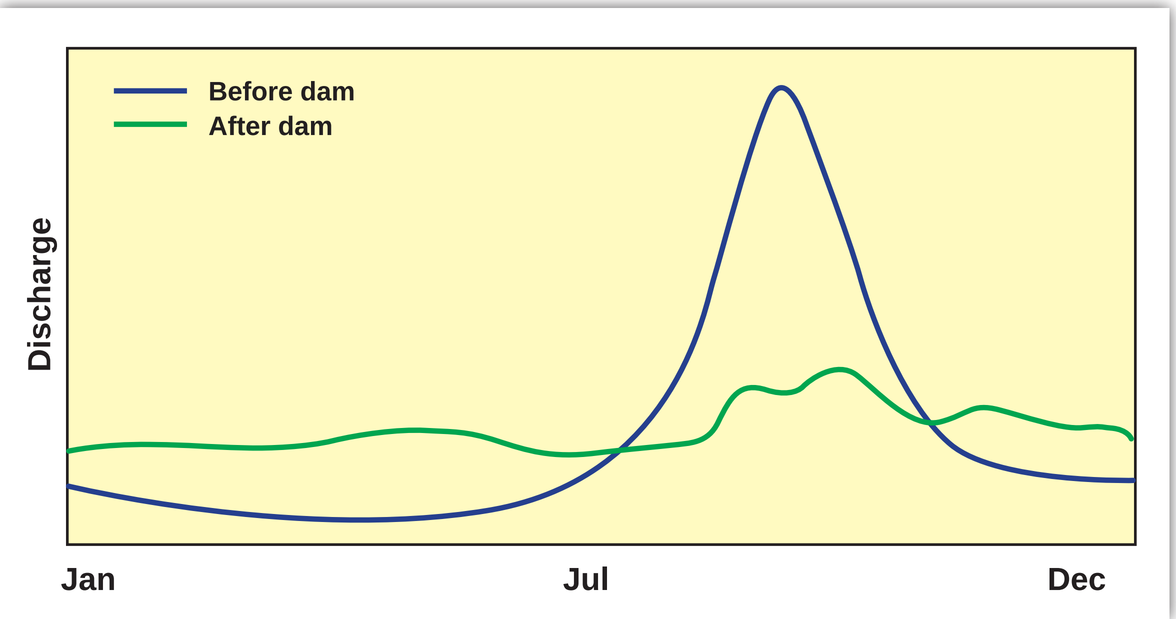


**Figure 55:** Schematic view of how a reservoir may even out seasonal variation

Under natural conditions, discharge in the Mekong system peaks in August-September each year.

Chart: Kent Hortle

Mitigating downstream impacts of river regulation often entails providing environmental flows, which may have varying objectives but generally seek to maintain some of the flow characteristics of a natural unregulated river, such as wet-dry seasonal variation, minimum dry-season flows, and artificial floods to flush deposited sediments and detritus through the system and to reconnect floodplain wetlands to the mainstream. Provision of environmental flows to support natural ecosystems and their fisheries needs to be traded off against some degree of loss of tangible benefits from the reservoir, such as irrigation or hydropower, so requires an extensive analysis and involvement of many stakeholders as discussed in detail by Acreman *et al.* (2014).

**Figure 56:** Storage of water in reservoirs can reduce the extent and duration of flooding

Floodplains shown here are along the Tonle Sap River in Cambodia; reducing flooding will have a direct effect on the Mekong's fish production.

Photo: Kent Hortle

As well as annual regulation of flows, most hydropower dams also cause short-term fluctuations in discharge when water is released to spin turbines to generate electricity during peak demand, typically for a few hours each day (Figure 57). Such short-term peaking flows creates highly variable conditions which many riverine organisms cannot cope with, may cause erosion and disturbance of the stream-bed, and also affect people's use of the river, including their fishing activities (Figure 58). Peaking flows can be limited by operating rules, which may however reduce the profitability of a plant. Another way to mitigate peaking flows is to build a smaller dam downstream of the main dam to create a re-regulating pondage (Figure 59). Peaking flows from the hydropower plant are stored in the re-regulating pondage and released in a steady flow.

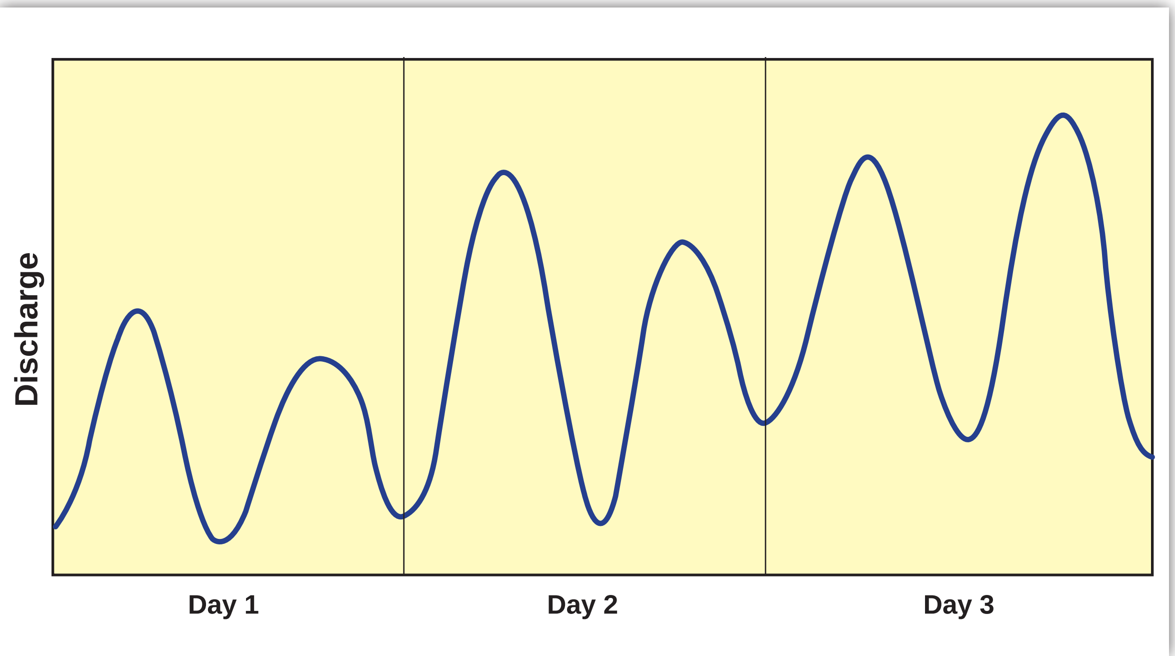


**Figure 57:** Schematic view of the effect of hydropower peaking on daily discharge patterns

Hydroelectric plants are often run to provide power for peak load electricity, often twice per day, as shown here.

Chart: Kent Hortle

**Figure 58:** Erosion of riverbanks along the Hai River, a tributary of the Hinboun River

Downstream of the Nam Theun-Hinboun dam in Lao PDR, additional water has been added from a diversion through a hydropower plant. Banks are slumping, deep pools have been filled by sediment, and pulsed flows interfere with fish migrations and fishing activities (Shoemaker, 2000).

Photo: Kent Hortle

**Figure 59:** Eildon Dam and its reservoir, Lake Eildon, on the right

A large re-regulating pondage is in the foreground, a road bridge is in the centre, and the pondage dam is to the left. Water flows to the left through the pondage to the Goulburn River. This multi-purpose gravity dam in Victoria, Australia provides water for irrigation, generates hydropower, and supports important recreational fisheries. The pondage evens out flows that are released to meet peak power demand, and is also stocked for put-and-take fishing of hatchery-reared fish.

Photo: Airview Aerial Photography with permission.

As well as these changes to seasonal and daily flow patterns, dams may be designed to divert water between river systems as do several hydropower dams in the LMB. Diversions deprive one river of some part of its flow while adding to the flow of the receiving river. The course of each river will have developed over many years in response to natural flow patterns, so the dammed river downstream of the diversion will tend to clog with sediment and debris while the receiving river will tend to scour out to accommodate the additional water (Figure 51). The river channels may take decades to adjust to the changed flows.

Mitigating such impacts would include re-engineering river channels and armouring banks during project development, using re-regulating ponds to limit extreme flows (Figure 52), providing environmental flows to the diverted river, and making use of some of the diverted water, for example in irrigation schemes.

Abstraction reduces the amount of water flowing down a river and will directly impact productivity; some avoidance can be achieved by improving irrigation efficiency to limit water usage. Intakes to irrigation canals and pumps may entrain aquatic animals, particularly small fish and fish larvae, which are likely to die during the passage or later in irrigation systems. Screening fish out of irrigation intakes is necessary to mitigate this impact (Figures 45 to 48).

## 2.3 Sediment and other particulate material

Small quantities of inorganic sediment generally have little effect on freshwater fish, but many species are affected at higher concentrations. Sediment irritates or abrades gills and is particularly damaging to fish eggs and larvae and also affects aquatic invertebrates such as caddis flies and mayflies, which are important food organisms. As rivers become more turbid, the fauna changes, favouring sediment-tolerant animals, and productivity in the channel generally decline. As well as inorganic sediment, large quantities of organic material from forests and farms are transported down rivers in the form of particles of various sizes and also associated with inorganic sediment. This particulate organic matter is one of the main food sources for invertebrates and some fish, and together with inorganic sediment is often simply termed ‘sediment’.

Like many large tropical rivers, the Mekong transports large quantities of sediment and other particulate materials towards the sea. Some estimates put the annual load of sediment as high as 140 million tonnes (Kummu *et al*., 2010), much of it originating from steep erosional uplands in China, where the Mekong is highly turbid for most of the year and where there is a relatively restricted aquatic fauna. As the Mekong flows downstream, sediment load continues to increase, but concentrations progressively fall as a result of dilution, particularly where the river is joined by the large clear tributaries that flow from the Annamite Mountains in the East. By southern Lao PDR, the Mekong’s water is clear for much of the dry season, enabling light to penetrate and support a seasonal bloom of attached algae, phytoplankton and zooplankton, all important foods for river fish (Blache, 1951). Most of the Mekong’s natural particulate load is transported during the wet season, with a significant proportion depositing on floodplains and in the delta, where it is beneficial for preventing subsidence and providing organic material and nutrients.

**Figure 60:** Dams should be ‘transparent’ to suspended material

The Mekong River in flood, August 2008, transported thousands of tonnes of logs and other woody debris past Vientiane each day. Downstream, this material provides habitat structure for fish as well as substrate for algae and invertebrates, and is also an important firewood resource. Dams need to be ‘transparent’ to such material, as well as sediment.

Photo: Kent Hortle.

**Figure 61:** Matilija Reservoir in California, showing extreme sedimentation

Photo: http://www.awra.org/proceedings/Jacksonville2012/doc/ppoint/Annual2012_S1_Collins_Kent.pdf

**Figure 62:** Dams may fill completely with sediment

The San Clemente Dam on the Carmel River in California, a concrete arch dam 30 m high built in 1921, has filled with sediment. The dam is unsafe and is to be removed and the river restored with fish passage to be reinstated. However, simply removing the dam would lead to a rapid downstream flushing of several million tonnes of accumulated sediment. The dam removal project requires an expensive re-routing of the river upstream and removal or stabilisation of the accumulated sediment and other works to a total cost of US$85 million.

Photo: NOAA, http://troutunlimitedblog.com

Because a dam reduces the speed of flow of water down a river, material carried by the river in suspension or along the bed tends to be trapped in its reservoir, which reduces storage capacity and the potential to supply water and produce hydropower (Figures 61 and 2). Often a reservoir traps more sediment than predicted, because after a dam is built, population tends to increase and more land is cleared and farmed, which increases soil erosion and sediment inputs. Downstream of a dam, the reduced flow of sediment down a river can cause many physical effects such as erosion of stream banks and subsidence of floodplains, while trapping of organic particulate matter also deprives the river and its floodplains of a major food source and nutrient supply. Trapping of organic material in a reservoir also exacerbates water quality problems (turbidity and high oxygen consumption by organic material) which may limit fisheries production in the reservoir.

There are three main approaches for mitigating the problem of trapping of sediment and other particulate matter in reservoirs (Figure 63) (Kondolf *et al.*, 2014):

1) Catchment management should include measures for reducing sediment inputs to reservoirs (Figures 63, 64). As well as being beneficial for the reservoir, better farming practices can improve and stabilise farm yields, replanting of steep slopes may produce timber or other agricultural products, and controlling erosion along roads and near bridges will reduce maintenance and repair costs. Check dams may trap sediment in tributaries where it can be stabilised or more easily removed than in a large reservoir.

2) Sediment routing through a reservoir aims to transport sediment to the river downstream (Figures 63, 65, 66). In the Mekong system, the gates of many low dams are opened fully in the wet season, when high flows can transport more sediment, and this approach may be sufficient to clear sediment through a reservoir. Another approach is to install bypass tunnels to take most of the sediment that is depositing in the upstream part of the reservoir to the outflowing river. Sediment bypass tunnels are effective in slowing reservoir sedimentation, but are expensive to construct and require significant maintenance.

3) Sediment removal may be required to maintain the function of a reservoir. Sediments may be removed with dredges and barges or by conventional earthmoving equipment if the reservoir level can be drawn down. Transport and disposal can add to the cost, so sedimentation is best anticipated and averted by catchment management and sediment routing.

It should be emphasised that for the ecological functioning of a river, it is not just ‘sediment’ that needs to be passed through a reservoir, but the entire organic load from the catchment, including large woody debris which is essential in maintaining habitat structure within the downstream river channel (Figure 60).

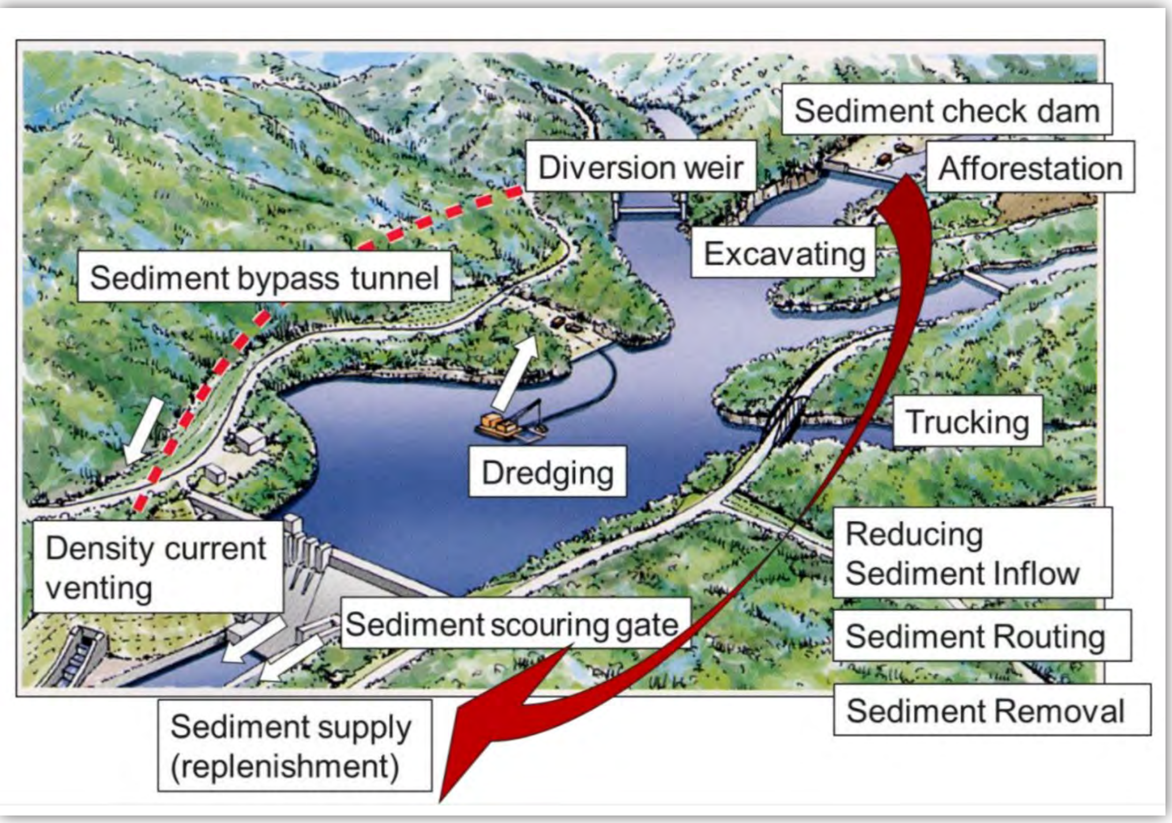


**Figure 63:** Schematic view of measures to mitigate sediment impacts in a reservoir

Illustration: Sumi (2015)

**Figure 64:** A trap reduces sediment input to Lake Mead, the reservoir of Hoover Dam, USA

Control of sediment reduces reservoir sedimentation, and also reduces turbidity, allowing light to penetrate, which increases aquatic productivity.

Photo: Kent Hortle

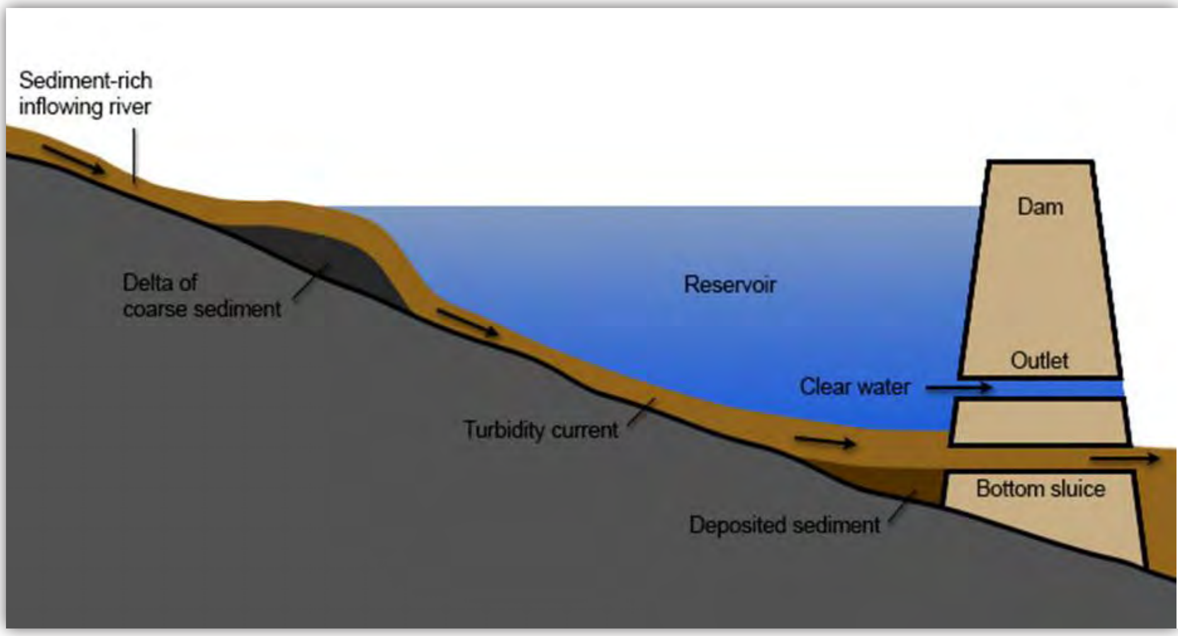


**Figure 65:** Movement of sediment within a reservoir, schematic view

Sediment is vented through a bottom sluice to reduce deposition in the reservoir.

Illustration: redrawn from De Cesare *et al.* (2011)

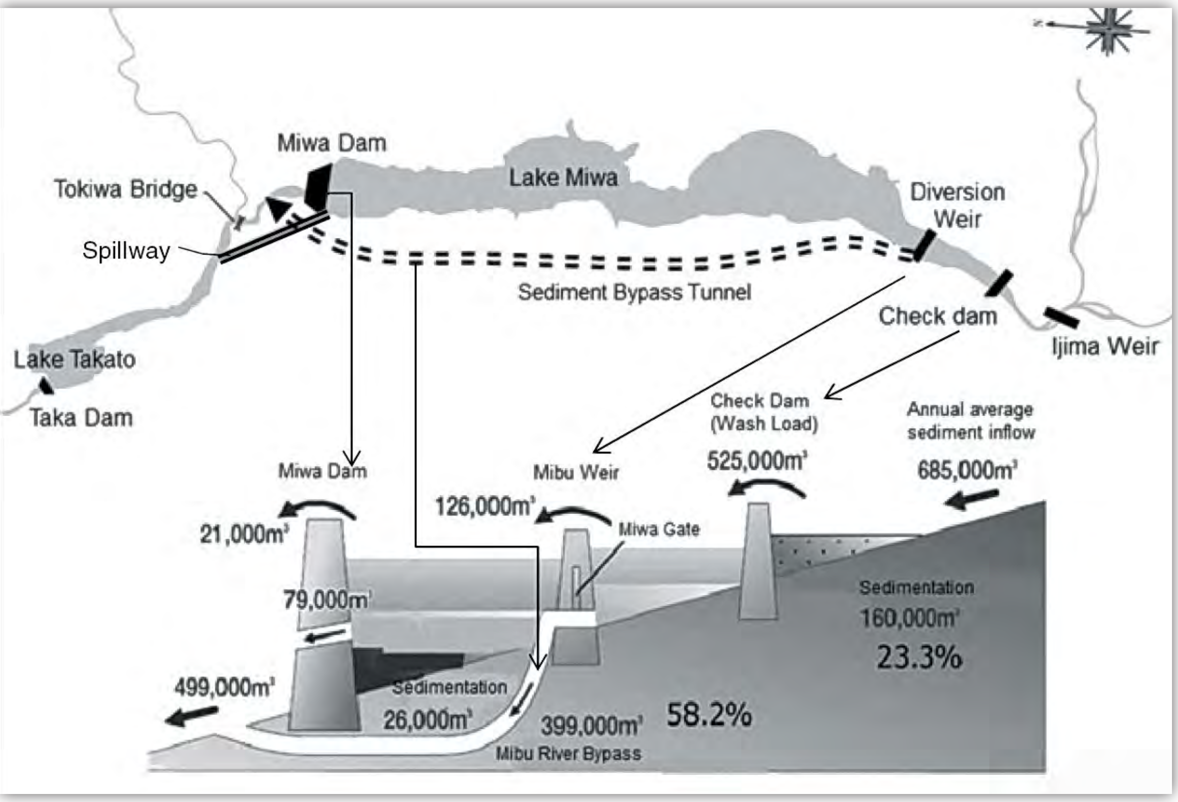


**Figure 66:** Sediment trapping and bypass system at Miwa Dam, Japan

A check dam traps coarse sediment, and a diversion weir diverts flows with high suspended sediment concentrations into a bypass tunnel.

Illustration: Kondolf *et al.* (2014)

## 2.4 Stratification and water quality issues

In the Lower Mekong Basin, water temperatures are typically 20–30°C, varying seasonally and with altitude. As shown in Figure 67, water which is warmer than 4°C is less dense than colder water so tends to 'float' on the surface of a waterbody. In rivers, water is usually well mixed, but in large deep lakes or reservoirs, surface water that is heated by sunlight may lie in a stable but well-mixed layer (epilimnion) over a colder deep layer (hypolimnion), with an intermediate zone (metalimnion) where the temperature declines rapidly with depth (Figure 68). In shallow lakes or reservoirs, wind action may be sufficient to mix the water; rivers may also mix water where they flow into a reservoir. Large Mekong Basin reservoirs such as Nam Ngum, Ubolratana and Sirindhorn are usually stratified for most of the year.

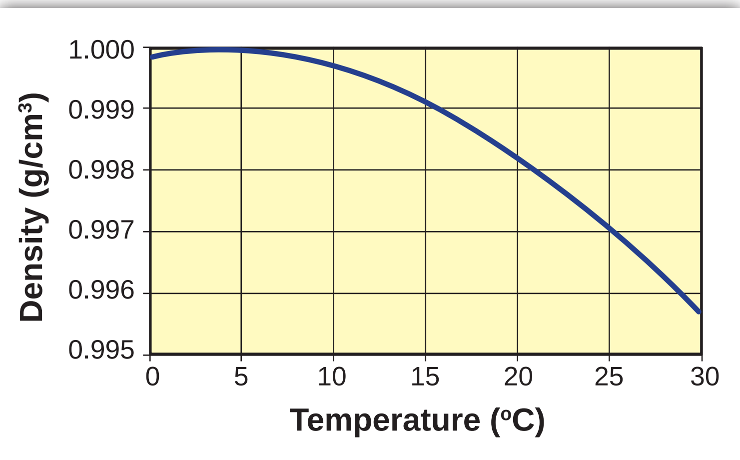


**Figure 67:** Water density versus temperature

Chart: Kent Hortle

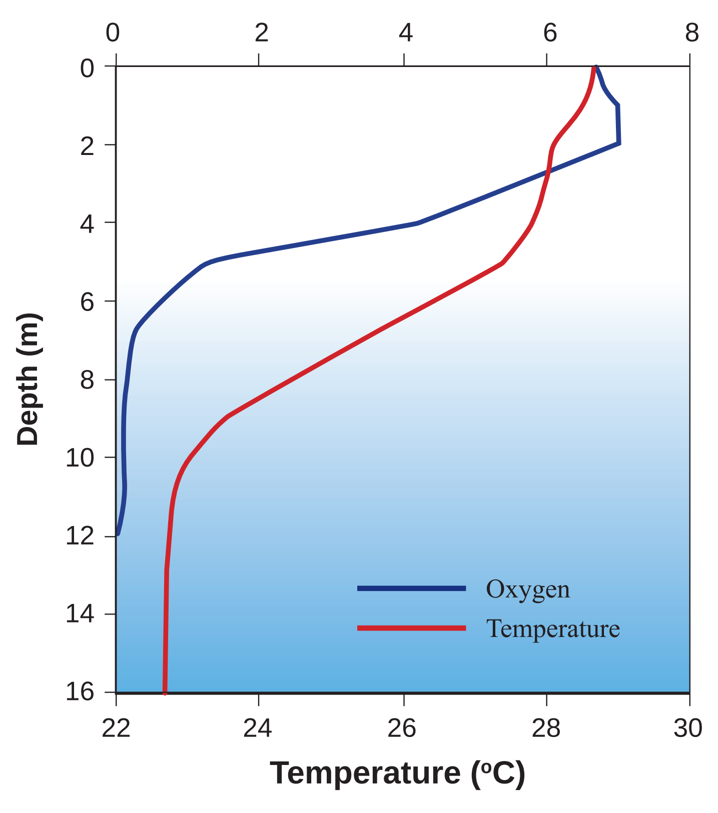


**Figure 68:** Temperature and oxygen versus depth in a stratified reservoir

Source: Nam Leuk Reservoir, Lao PDR, 2004, courtesy of RMR Consultants

Stratification may cause many negative effects in and downstream of a reservoir.

- Phytoplankton is only productive in the upper layers where light can penetrate. Phytoplankton is the basis for much of the food chain, feeding zooplankton which feed fish. Over time, the surface layer becomes depleted in nutrients which accumulate in bottom layers, so the reservoir becomes unproductive.

- Oxygen cannot penetrate to the bottom layer, which becomes anoxic, so most fish cannot live there, reducing the potential productivity of the reservoir.

- Lack of oxygen in the bottom layer creates conditions that favour generation of hydrogen sulphide, dissolved iron and manganese, which are noxious, leading to bad smell and taste in water supply or downstream. Lack of oxygen also favours methylation of mercury in sediments and ultimately its uptake and transfer to bio-accumulate in the food chain.

- Many blue-green algae (cyanobacteria) are noxious or toxic and are favoured by stratification, as they can descend to the bottom layer at night to absorb phosphorous, outcompeting other kinds of algae that are more ecologically desirable.

- Downstream of a reservoir, cold water may affect feeding, growth and reproduction of fish, and have various other effects on aquatic ecology.

Mekong Basin reservoirs often de-stratify in winter (November) as surface waters become colder and denser, sinking to the bed of the reservoir at the same time as warmer anoxic bottom water rises. This annual ‘overturn’ brings to the surface water that is oxygen depleted and contaminated by hydrogen sulphide, methane and dissolved iron. Fish kills are frequently observed at this time in large reservoirs such as Nam Ngum. A benefit of seasonal overturn is that nutrients are brought back to the surface, but a preferable situation would be to permanently de-stratify the reservoir.

Since the 1980s, hundreds of reservoirs around the world have been fitted with de-stratifying systems. Early systems used pumps to force air or oxygen to the bed of a reservoir to create an ascending plume which dragged water upwards (Figure 69) in a similar fashion to an aquarium aerator. This approach is expensive and inefficient and has been generally superseded. Most modern systems use large impellers to force surface water downwards (or upwards) through a wide tube made of thin plastic called a draft tube (Figure 70). This technology uses relatively little energy, can be solar powered, and has dramatically improved water quality and biological productivity and thereby fisheries production at many reservoirs and in rivers downstream.

The benefits of de-stratification have to be weighed against the costs, which are higher in large deep reservoirs. Where de-stratification is prohibitively expensive, downstream or offtake water quality may be improved by using an impeller to drive water down a draft tube (Figures 68, 70) or by installing multi-level offtakes (Figure 71), to direct surface water to a reservoir’s outlet.

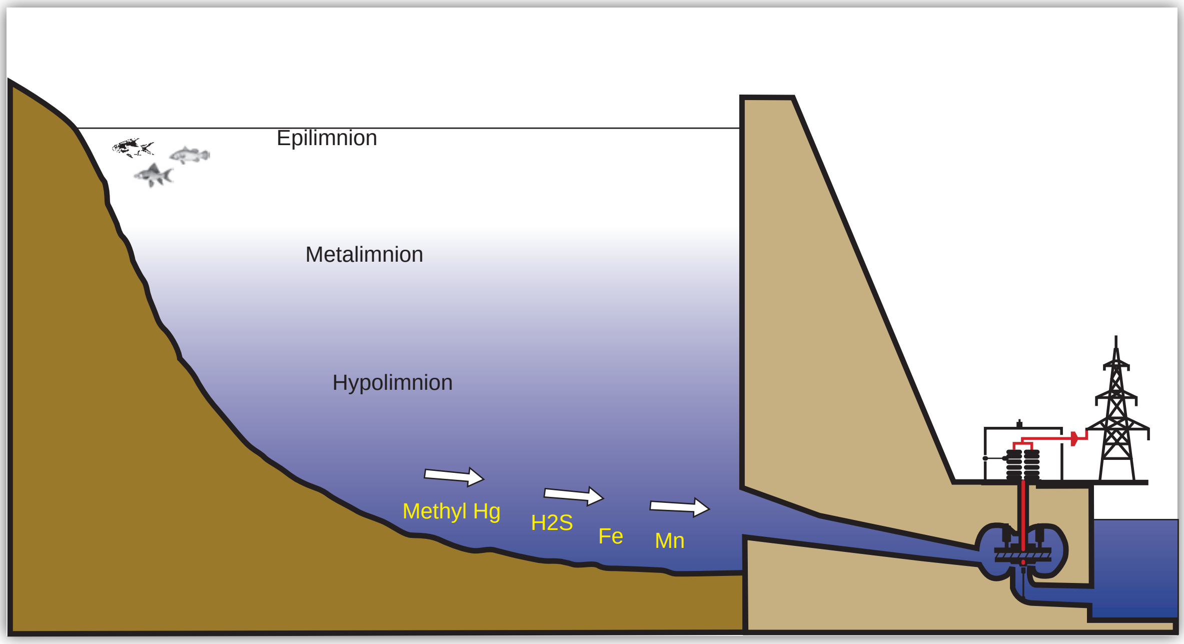


**Figure 69:** Cross-sectional view of stratification at a large hydroelectric reservoir

Illustration: Kent Hortle

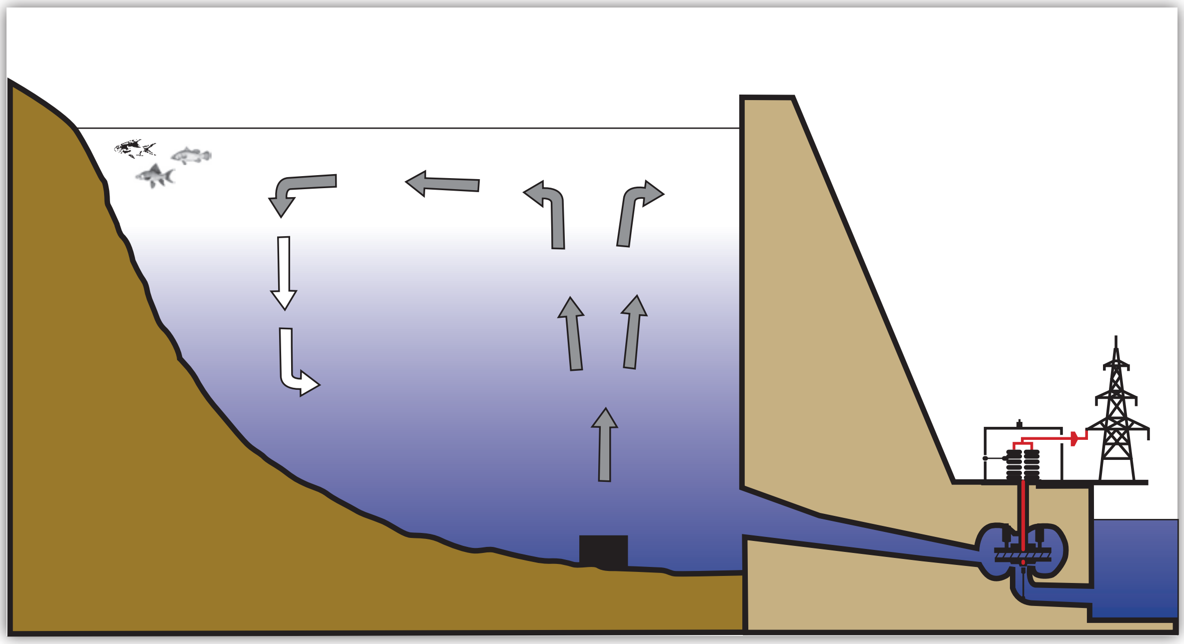


**Figure 70:** De-stratifying a reservoir by bottom-up mixing, typically by using an aerator

This technology is being superseded by systems that use impellers to force water up or down.

Illustration: Kent Hortle

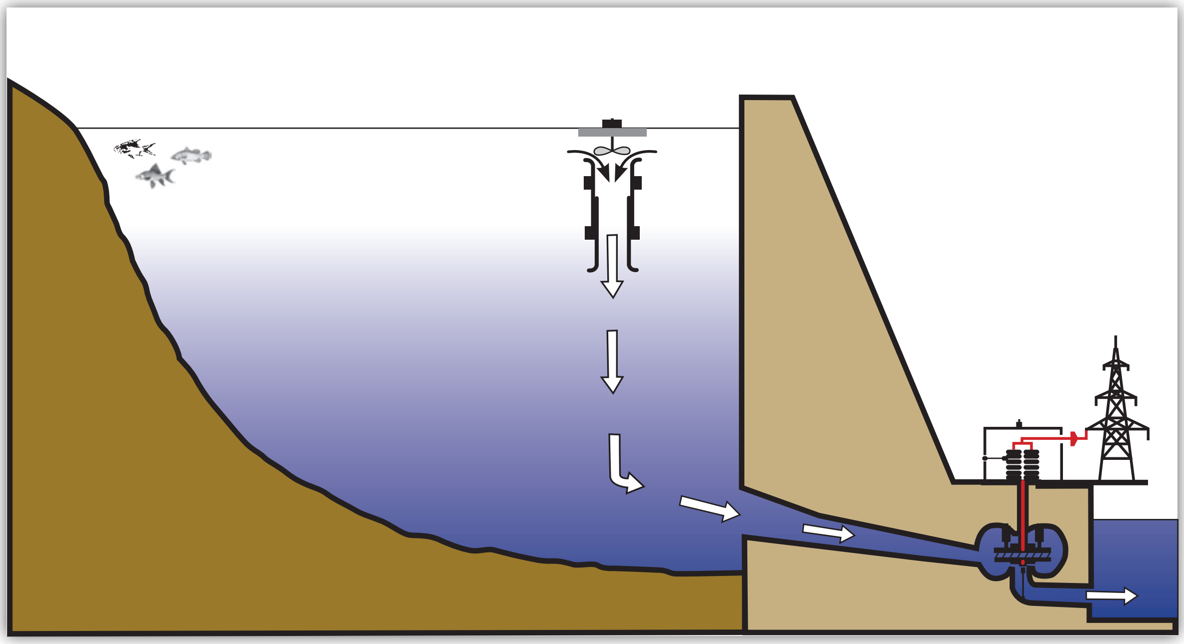


**Figure 71:** An impeller forces water down to the intake of a hydroelectric turbine

This system may also be used to de-stratify a reservoir.

Illustration: Kent Hortle

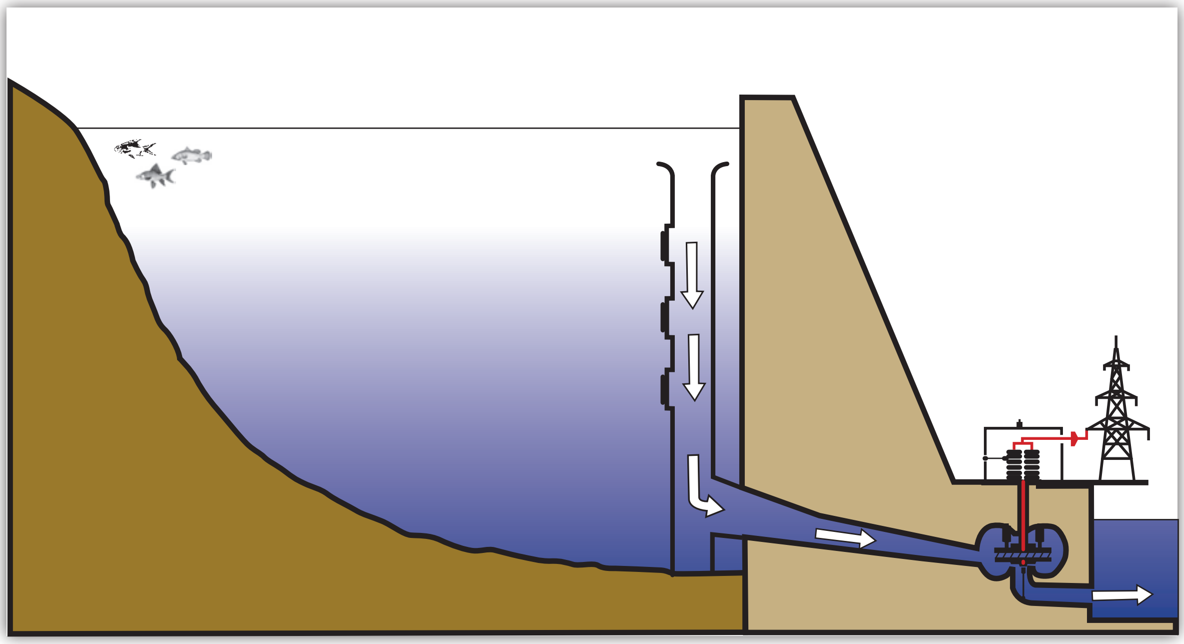


**Figure 72:** A multi-level off-take draws surface water to the intake of a hydroelectric turbine

As water levels fall, intakes are progressively opened. This approach improves water quality downstream, but does not de-stratify the reservoir.

Illustration: Kent Hortle

**Figure 73:** Surface view of a solar-powered de-stratification unit at Cotter Reservoir, Australian Capital Territory, Australia (top)

This unit has improved water quality and the suitability of the reservoir for endangered Macquarie perch *Macquaria australasica* (above). The collapsible draft tube installed at Cotter Reservoir (right). An impeller sits in a frame at the top of the tube.

Photos: WEARS Australia and Kent Hortle

Various other measures may be applied to mitigate the impact of stratification. For example, water quality may be improved by oxygenation of the discharged water, at the dam or downstream (Figure 74).

**Figure 74:** A weir oxygenates water downstream of Ubolratana Reservoir, Nam Pong River, Thailand

Photo: Kent Hortle

Many Mekong region reservoirs which supply domestic water already suffer from water quality problems, including toxic blue-green algae (e.g. Thanh *et al.*, 2010). While high nutrient levels are partially to blame, destratification is often cost effective for improving drinking water quality, with additional fisheries benefits. The potential for applying destratification and other possible approaches to mitigating the impacts of stratification should be fully appraised for new Mekong Basin reservoirs.

## 2.5 Gas bubble trauma

As well as physical damage, spillways can cause gas bubble trauma (GBT) to fish as a result of gas supersaturation downstream. GBT caused by supersaturation is also quite common downstream of waterfalls, including Phapeng Falls, the most easterly of the Khone Falls in Lao PDR (Figure 75) (Baird *et al.*, 1999).

Supersaturation occurs because the gases in air (mainly nitrogen and oxygen) can dissolve in water to a greater extent if pressure is greater. At the surface, water is under atmospheric pressure, but pressure increases by about 10 percent of surface pressure for every metre of depth, so for example at 10 m depth water is under about twice as much pressure as at it is the surface (from the mass of the water plus the atmosphere above it), so it can dissolve about twice as much gas as at the surface. Downstream of waterfalls or spillways (Figures 76), water and air are forced down towards the bed of the river, where the water absorbs more gas because of the higher pressure. Further downstream, as the river becomes shallower, pressure is reduced, so the gas diffuses back to the atmosphere, but usually more slowly than it was absorbed.

**Figure 75:** Phapeng Falls on the Mekong mainstream, southern Lao PDR, in the early wet season

Air is entrained with the water and forced down several metres, where the high pressure causes gases (mainly nitrogen and oxygen) to dissolve.

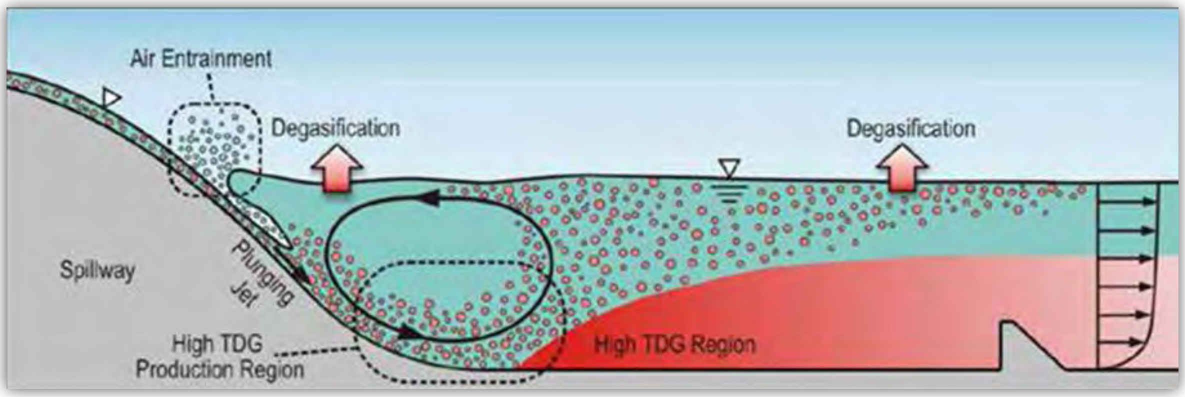
Photo: Kent Hortle

**Figure 76:** Nam Ngum Dam spilling during high flows in the 1970s, not long after filling

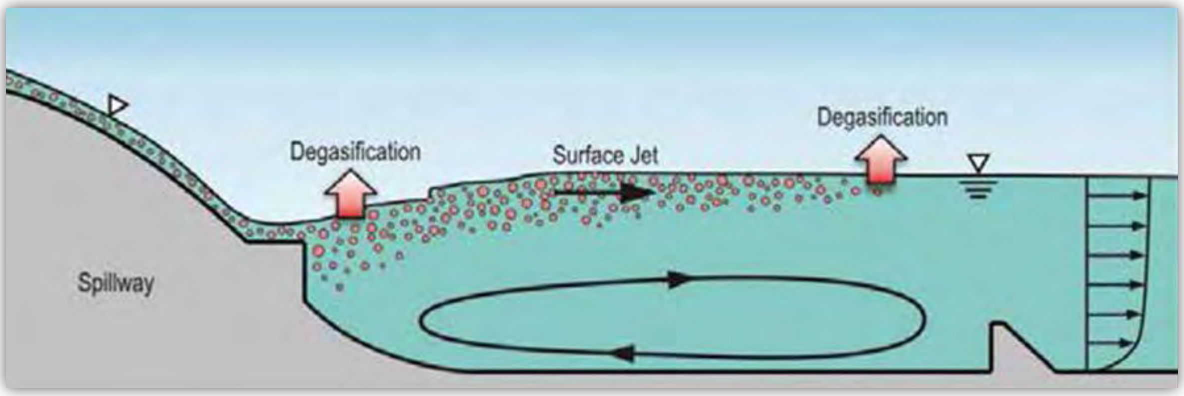
Spillway is on the left. Note also floating vegetation and woody debris, a common problem in newly filled reservoirs.

Photo: Koizumi (2006)

Fish that live in the zone of supersaturated water absorb excess gases which can then bubble out of solution in their blood. Affected fish may die if exposed to supersaturated water for extended periods, but if the fish are able to swim to deeper water they may equalise the pressure and the effects may not be permanent. In China, lethal levels of high total dissolved gas (TDG) have been reported downstream as a result of spillway releases from several high dams, including Manwan Dam on the Upper Mekong; with many more high dams under construction in China there is an urgent need to redesign spillways to mitigate this problem (Liang *et al.*, 2013). The problem of GBT has been greatly reduced downstream of some large hydropower dams in the USA by retrofitting spillways to limit gas supersaturation. Various approaches have been used (R2RC, 1997), and of these, spillway deflectors have been most successful in reducing dissolved gas concentrations (Figure 77).



Spillway downstream of a dam prior to fitting of deflectors. Spilled water plunges deeply into the stilling basin, introducing air and leading to high total dissolved gas (TDG) concentrations downstream.



Spillway after fitting of deflectors, which create a surface jet of water, preventing TDG absorption at depth.

**Figure 77:** Effects of retrofitting of deflectors on a spillway, shown here in cross section

Illustrations: Politano *et al.* (2013)

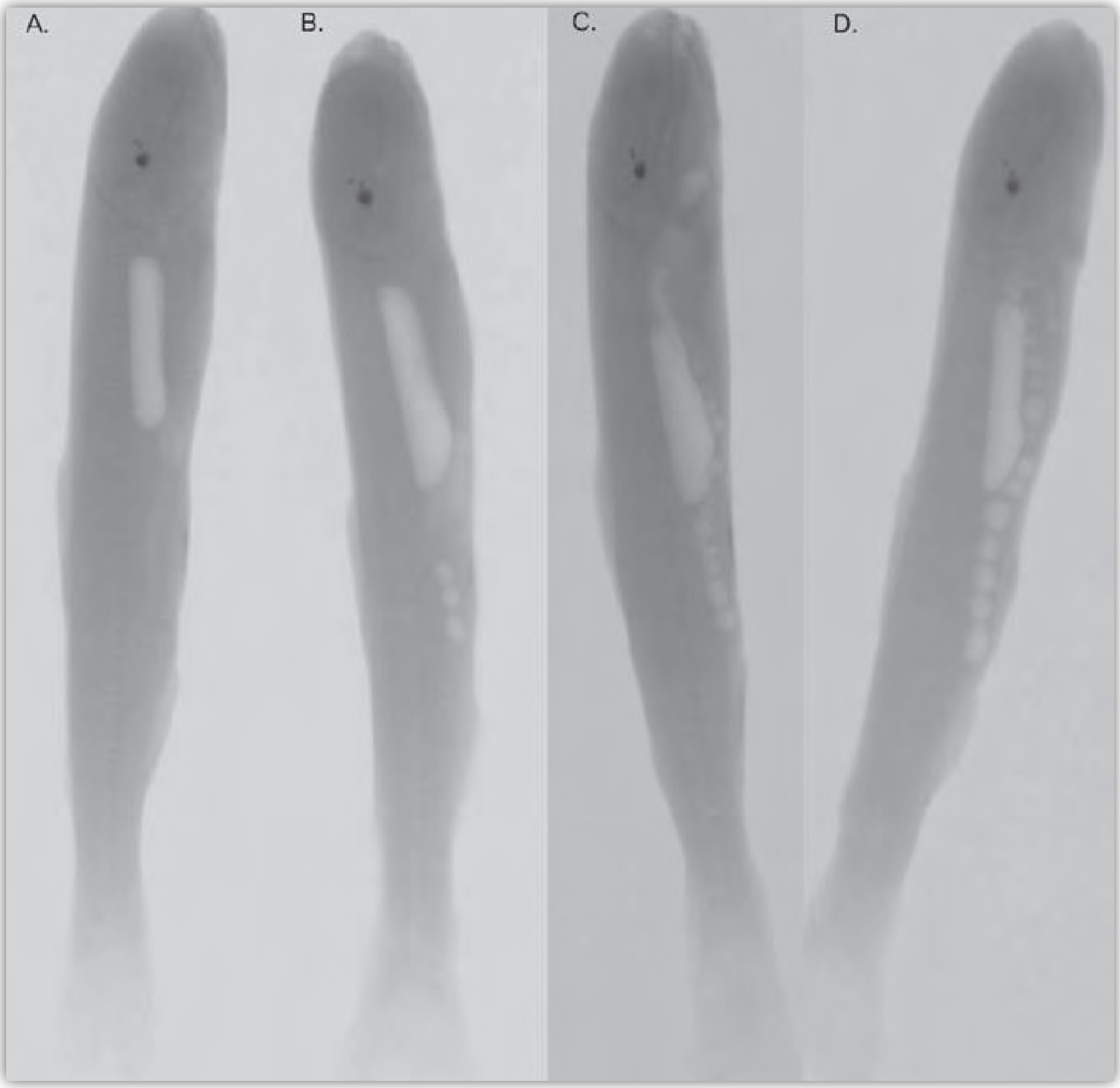


**Figure 78:** X-rays showing gas bubbles in fry of Chum salmon *Oncorhynchus keta*

The fish were exposed to increasing levels of air saturation, left to right <100%, 115% 120% and 130% saturation, the largest opaque area is the swim bladder, gas bubbles (emboli) appear in the digestive tract, gills and nasal cavity as small whitish circles.

Photo: Geist *et al.* (2013)

Spillways at new dams need careful design to prevent fish injury and gas supersaturation, and some existing dams may need retrofit to reduce the risk to fish downstream. This issue requires some attention in the LMB, where it is likely to be significant downstream of high dams with deep stilling basins below their spillways.

# 3. Reservoir fisheries and aquaculture

## 3.1 Introduction

Fisheries and aquaculture in reservoirs may mitigate the negative impacts of dams on river fisheries by replacing some proportion of lost fish production. However, compared with a river a reservoir (as a standing water body) differs in hydrology, habitat, water quality, and biological productivity. Therefore measures to maintain desirable characteristics of the original river system (for example by building fish passes) may not result in the most productive or valuable fishery in a new reservoir, particularly in very large reservoirs. In an artificial reservoir, fisheries and aquaculture enhancements are likely to be required, and the reservoir or its catchment may require environmental management to maintain a productive aquatic system.

## 3.2 Enhancement and intensification

Intensification refers collectively to various enhancements which seek to increase productivity of fisheries (Welcomme and Bartley, 1998). Fisheries of reservoirs may be enhanced by management of fish, the environment, and/or fishers.

Management of fish in LMB reservoirs usually entails stocking with desirable species, and many fish have been introduced or translocated (i.e. moved within the LMB) to reservoirs in each country. Stocking has been shown to significantly increase catches in small reservoirs (de Silva *et al*., 2006), where there may be limited natural recruitment of fish and where the stocked fish are relatively confined and can be caught. While many of the larger LMB reservoirs have also been stocked the results are more equivocal. Large LMB reservoirs may support more than 100 native fish species (Bernacsek, 1997), so there may be little additional benefit from stocking, especially as hatchery-reared fry may be eaten by native predators. Stocking also needs to be well managed to limit negative impacts on desirable species (Welcomme and Vidthayanon, 2003) and should where possible use native Mekong fishes, which are becoming more widely available from hatcheries in the region.

Environmental management may enhance reservoir productivity by providing nutrients or by adding additional habitat, especially within fish conservation zones. In the Mekong Basin there is an opportunity to adapt the widespread and traditional technology of ‘brush parks’ to be used in artificial reservoirs (Figure 84).

Controls on fishers include restricting destructive gears such as poisons, explosives and electrofishing, restricting gear types, and setting closed seasons. Fisheries legislation in LMB countries now covers such measures, but agencies generally require more support to enable them to implement legislation.

The benefits of reservoirs can also be increased through intensification of production.

Fish may be stocked and grown in reservoirs in fenced-off areas (Figure 80, foreground) or in floating cages. Reservoirs provide an assured supply of clean water, so aquaculture typically develops downstream, often in association with livestock or poultry culture.

Enhancements may be administered at the local level through co-management arrangements, which are formalised in fisheries legislation in each LMB country. Co-management has been applied at many LMB reservoirs in recent years (e.g. Niphonkit *et al.*, 2008), and should be considered as one approach in planning new dam projects. An alternative is to lease the reservoir or part of it to a private company or cooperative, which may lead to improved management where the lessee has an ongoing incentive to invest in increasing returns from the reservoir.

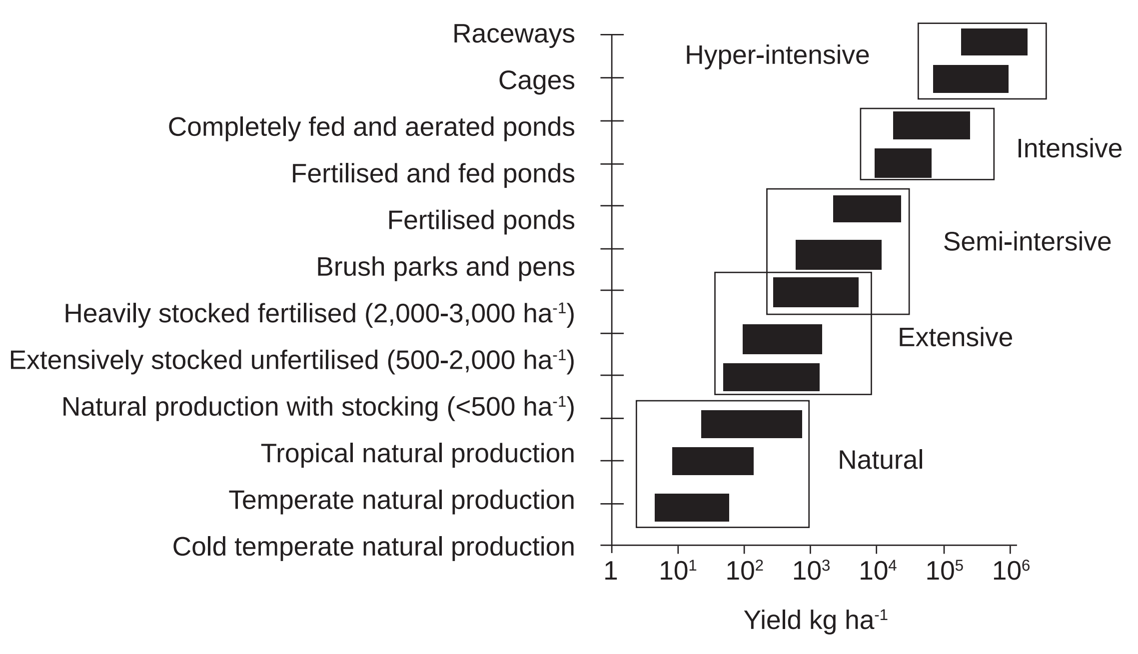


**Figure 79:** The ‘ladder of intensification’ in development of production fisheries

Increasing inputs leads to increasing outputs, here expressed as yield in kg per hectare per year.

Source: Welcomme *et al.* (2010)

**Figure 80:** Nam Houm Reservoir in Lao PDR is a productive lowland irrigation reservoir

This reservoir supports important capture fisheries, as well as cove and cage aquaculture, and provides water to aquaculture ponds downstream, which is then redirected for irrigation, maximising benefits.

Photo: Kent Hortle

**Figure 81:** Selling fish from a reservoir near Vientiane

These fish are the result of stocking and include native species (silver barb and *Pangasius* catfish) and exotics (Nile tilapia *Oreochromis niloticus*, and bighead carp *Hypophthalmichthys nobilis*). Reservoirs can provide a significant year-round supply of fish for consumers and a steady income for fishers and traders.

Photo: Kent Hortle

**Figure 82:** Stocking fish in reservoirs is popular throughout the LMB

Cambodian Prime Minister Hun Sen (left) and Deputy Prime Minister Men Sam An (right) using hand-held scoop nets to release fish into the Veal Vong Reservoir on 1 July 2009 as ministers, senior government officials and international guests look on. Stocking has been dominated by exotic fishes, but Mekong species are becoming more commonly used.

Photo: Lem Chamnap

**Figure 83:** Hatchery-bred giant freshwater prawns stocked in Pak Mun Reservoir

While the dam had many negative effects on river fisheries, stocking this high-value species (*Macrobrachium rosenbergii*) provided some benefits to local people.

Photos: Kent Hortle

**Figure 84:** Brush parks are traditional structures to attract fish and enhance fisheries production

Tonle Sap on the left and Nong Bor Ban, northeast Thailand, on the right. Brush parks increase production by providing spawning habitats, shelter and substrate for fish food organisms (Welcomme, 2002).

Photos: Kent Hortle

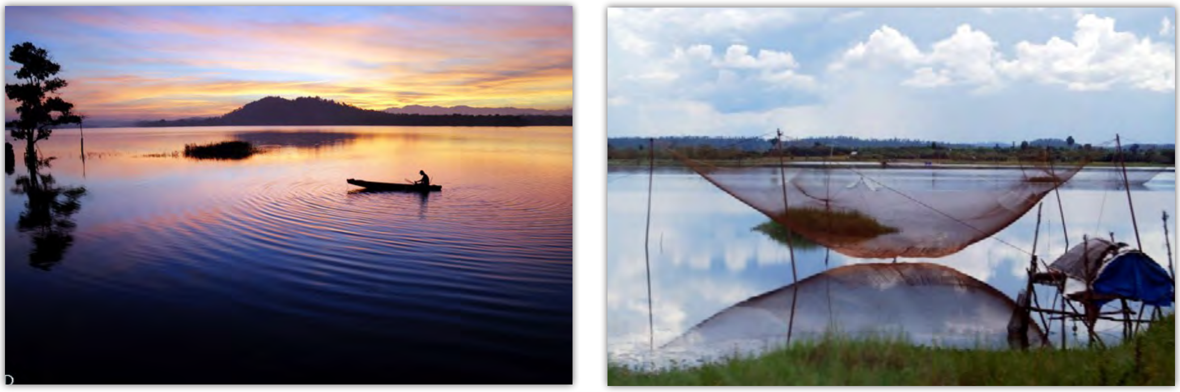


**Figure 85:** Small reservoirs in the Viet Nam highlands support productive fisheries

Left: Ea Kao Reservoir and Ea Soup Reservoir with lift net.

Photos: httptuanvuhotel.vncomponentk2item90-ho-ekao and http://www.panoramio.com/photo/25307104

Aquaculture in reservoirs or downstream is favoured by the year-round availability of water and has been developing rapidly throughout the Mekong region. The most commonly cultured species include introduced Nile tilapia (*Oreochromis niloticus*) and Indian and Chinese carps, as well as native pangasiid catfish and silver barb. In the LMB the most productive forms of aquaculture associated with dam projects are cage culture in reservoirs or in the rivers downstream, and integrated culture of fish with livestock or poultry in ponds which are constructed next to reservoirs or canals (Hortle and Khonglaliane, 2015) (Figures 86, 87).

**Figure 86:** Integrated chicken-fish farm on the downstream side of Nam Houm Dam, Lao PDR

Waste and excess food from the chickens falls into the ponds where it provides food and a rich nutrient source for algae.

Photo: Kent Hortle

**Figure 87:** Tilapia farms along the Nam Ngum River, supported by the regulated flows from Nam Ngum 1 Reservoir, Lao PDR

Tilapia farms are now the main source of fish for Vientiane.

Photos: Kent Hortle

## 3.3 Catchment management

A dam's catchment includes all the land upstream which drains towards its reservoir, via surface watercourses and underground flow. Activities in a catchment affect the supply and quality of water, so managing the catchment is necessary for a reservoir to provide a range of benefits, including fisheries, and to thereby mitigate negative impacts of a dam project. As well as environmental factors such as slope, soil type, vegetation cover and land-use, catchment management must take account of various social, economic and legal issues so should be adaptive rather than overly prescriptive. Some typical aims and approaches of catchment management are to reduce sedimentation by controlling erosion or trapping sediment, to moderate inflows by vegetating steep slopes which reduces the rate of runoff and increases infiltration of rainwater, and to improve water quality by treating sewage and other wastewaters.

In the Mekong Basin, much of the water that flows to wetlands and rivers runs through ricefields and other agricultural land, where insecticide use is increasing (Figure 88). Many insecticides are toxic to fish and also non-target invertebrates which are important in the aquatic food chain. The need for insecticide use can be reduced by integrated pest management (IPM) which should be promoted within the framework of catchment management.

**Figure 88:** Insecticides are a major threat to fisheries in the LMB

A farmer with typical backpack sprayer, and nearby a discarded insecticide packet by a dead snakehead fish in a ricefield in Cambodia. Mitigation of dam impacts alone will not protect fisheries; many other issues need to be tackled if inland fisheries are to be sustained.

Photos: Kent Hortle

## 3.4 Aquatic weed management

Many issues need to be addressed to maximise the fisheries benefits of reservoirs. A common problem in the Mekong region is excessive growth of macrophytes (large visible aquatic plants) as a result of high nutrient levels and warm tropical conditions (Figure 89). Macrophytes can benefit fisheries by providing shelter and substrate for fish to spawn and surfaces for attachment of some algae and invertebrates. But they also compete for nutrients and light with phytoplankton (microscopic organisms including algae), a more nutritious food source which supports zooplankton, an important food for fish. Macrophytes also physically occupy the waterbody, interfering with fishing activities and causing oxygen depletion at night (from respiration) and at depth (from accumulated decomposing plant material).

**Figure 89:** Aquatic plants in Boeng Kampeng, a small irrigation reservoir in Cambodia

The water here is three metres deep, but is completely choked by plants.

Photo: Kent Hortle

Excessive plant cover increases water losses through evapotranspiration compared with an open water surface, by a factor of up to three times, which can be a major problem for all water users.

Ideally, a reservoir would be managed to allow some macrophytes to grow, but also to inhibit excessive growth. A useful comparison is that in typical fish culture ponds aquatic plants may be allowed to occupy up to one quarter of a pond's surface, a desirable proportion to balance habitat benefits against nutrient losses; the target for any particular reservoir would need to be individually developed. Where control is needed, there are three broad approaches: biological, chemical and mechanical. All plants have natural enemies (especially insects and microbes) which in their native environment control their growth rate and/or recruitment. Many plants have been spread worldwide without their natural enemies, so it is not surprising that exotic weeds tend to proliferate in new reservoirs in the LMB. Biological control using insects to control major floating aquatic weeds such as water hyacinth *Eichhornia crassipes*, and salvinia *Salvinia molesta*, has been spectacularly successful in some places (Julien and Griffiths, 1998) and with no negative effects. Biological control does not generally eliminate weeds, but controls them, so that mechanical or chemical control may still need to be applied judiciously. As well as invertebrates or microbes, grass carp *Ctenopharyngodon idella* may be used to control weeds. Grass carp have a unique ability to efficiently process tough plants by finely crushing them with their distinctive comb-like pharyngeal teeth. Grass carp originate in rivers from central China to Siberia and have been widely cultured in the Mekong Basin. There have not been any major problems reported from use of this species in the Lower Mekong Basin where it is not reported to breed in the wild (Welcomme and Vidthayanon, 2003). Grass carp require long cooler rivers with fast currents for the survival of eggs and very young fish, so it is possible to limit the number of fish in a tropical water body to produce a few large and catchable fish. Grass carp are not common in the wild in the Mekong Basin; those that are caught being escapees from aquaculture. The MRC does not support introduction of exotic species to natural waters, but the fisheries agencies in each LMB country culture some grass carp for use in ponds or cages. Their use in weed-choked reservoirs should be evaluated under a risk assessment. Mechanical or chemical control of aquatic plants in reservoirs to maintain fisheries may be necessary where biological control is not effective. Boat-mounted machines are used to cut and harvest aquatic weeds (Figure 90). In Thailand, water hyacinth which would otherwise be of no value is now being processed and used to make furniture.

**Figure 90:** Weed harvesting boat

Bung Boraped, Chao Phraya River system, Thailand, in 2011.

Photo: Kent Hortle

Some aquatic plants may be directly detrimental to fish. In the LMB, the oriental lotus *Nelumbo nucifera* (Figure 91) is widely grown because its seeds and tubers are edible, the leaves are used for wrapping food and the flowers are used for religious purposes. However, some fishes cannot live around lotus plants, whose spiny stems damage their skin – this is well-known for example for the scale-less walking catfish (*Clarias* spp.), a favoured fish in standing water bodies, including small reservoirs. Lotus can be controlled by seasonal draw-down of reservoirs or with approved herbicides such as glyphosate where necessary. In July 2012 Prime Minister Hun Sen called on Cambodians to stop planting lotus in fishing areas (*Asean Affairs, July 2012*).

**Figure 91:** A lotus flower (above) and a thorny stem (right), a hazard to some fish

Photos: Kent Hortle

# 4. Offsets or compensation

## 4.1 Overview

In general, very large dams or a cascade of smaller dams on a river are likely to alter conditions to the extent that fish passes and other measures are unlikely to mitigate their impacts on the original fish fauna. Usually only a small proportion of the former populations of fish persist in heavily dammed rivers, and some species disappear completely in spite of mitigation efforts, which may include significant investments in fish passes and hatcheries (Williams, 2008; Brown *et al.*, 2013b). The often poor returns from investment in direct mitigation suggest that it is worth considering other approaches. Reservoir fisheries and aquaculture may mitigate the effects of a dam on production to a varying extent, but the beneficiaries are often newcomers, with fishers downstream from a dam site not able to benefit from new industries. In addition to fish production, the rich biodiversity of the Mekong River system will not be maintained without some concerted effort to conserve the natural environment of rivers and associated wetlands.

One way to improve environmental outcomes is to compensate for a dam's negative effects by spending available funds at other locations where there is likely to be a greater environmental benefit. Such environmental offsets or compensation have been widely applied in some jurisdictions, often as a result of EIA processes, but not yet in the LMB. Environmental offsets could also be incorporated within integrated water resources management and benefit-sharing approaches, which are being developed in the Mekong region in an effort to manage development impacts.

In the Mekong Basin generally, there are many ways that environmental offsets could be used to improve fisheries: improved policing to prevent overfishing, stocking of some species that are in decline, treatment of polluted wastewaters, and various measures for rehabilitation of rivers (see below). Such offsets could be funded as part of the cost of development of a dam, or by using revenue from hydropower, and could help to compensate for impacts of a dam.

Large dams are likely to unavoidably affect fish passage, even with major investments at the dam site. Investing money at low barriers such as irrigation weirs (e.g. Figure 92) is more likely to provide both efficient and effective fish passage at those sites (Baumgartner *et al.*, 2012). In the Mekong Basin there are thousands of low barriers already impeding fish passage along rivers and between rivers and floodplains (Figure 2 and Box 2). Many smaller fish passes could be built at low barriers for the cost of a single fish pass at a large dam, with the possibility of a greater overall improvement in conditions for fish passage. Prioritisation of sites for fish passage improvement should follow a systematic procedure as outlined for example by Nunn and Cowx (2012).

**Figure 92:** A prime site for improving fish passage – a regulator on a small tributary

The photo is taken from the Mekong side, with the dammed tributary near Vientiane behind the regulator. Fish from the Mekong – about 100 m downstream - cannot access the tributary or floodplain. Villagers catch the few migrating fish that pass downstream under the gates. Fish passage is relatively easy to reinstate at such sites compared with large dams.

Photo: Kent Hortle

## 4.2 Rehabilitation of rivers for fish

Rehabilitating rivers for fisheries is one option for using offsets to mitigate the impact of a large dam. Part of the capital cost of a project, and/or a percentage of operating income could be spent at other locations where there is likely to be a better return on the investment, evident as improved fisheries production or maintenance of biodiversity.

Rehabilitation of rivers should be based on ecological concepts and should aim to restore the river continuum – the natural flow of water with dissolved and suspended materials, as well as the annual flood pulse, to reinstate natural channels and wetlands and their connections, and to protect and revegetate the riverine corridor. Other anthropogenic impacts such as storm water runoff and point-source pollution should also be addressed, and various measures may be required to manage fish, including control of nuisance species and reintroduction of desirable fishes. Useful introductions to concepts and approaches are provided by Cowx and Welcomme (1998), Dudgeon (2005), and Nunn and Cowx (2012).

It should be noted that in the Mekong Basin, quite apart from the impacts of dams, many rivers and streams require rehabilitation, for example to stabilise their banks, to provide riparian vegetation, and to reconnect them with their floodplains (Figures 93, 94).


**Figure 93:** Riverbanks along the Mekong and its tributaries are eroding in many places

Tree clearing and cattle grazing lead to lateral bank erosion. Farmers lose their land, and fisheries habitats and aquatic food sources are degraded. Replanting and protecting riparian trees creates a win-win situation for farmers and fishers.

Photos: Kent Hortle

**Figure 94:** Flooded riparian forest along the Stung Sen River in Cambodia in 2002

Riparian and flooded forest provides food and shelter for many species of fish. This image shows one example of diverse and productive aquatic habitats along a river which can provide food and shelter for fish. Such habitats can be rapidly destroyed, but take many decades to be rehabilitated.

Photo: Niek van Zalinge

Another way to offset the impacts of new dams may be to remove old dams which are no longer functional or are unsafe, which can restore riverine habitats and fish passage and lead to recovery of fish populations (Burroughs *et al.*, 2010; Kanehl *et al.*, 1997). Increasing appreciation of the value of aquatic biodiversity and the various uses of rivers, including fisheries has led to a recent increase in dam removal in many countries. For example, about 1,200 dams have been removed in the USA since 1912, of which about 900 were removed in the last 20 years, with 51 removed in 2013 alone (Kober, 2013). In the Mekong Basin there are many small non-functional dams which could be removed to improve ecological conditions within streams and rivers.

Removal of small dams may be straightforward, but removing large dams can be expensive and hazardous, as well as affecting other uses that have developed around a reservoir, so needs careful appraisal and planning.

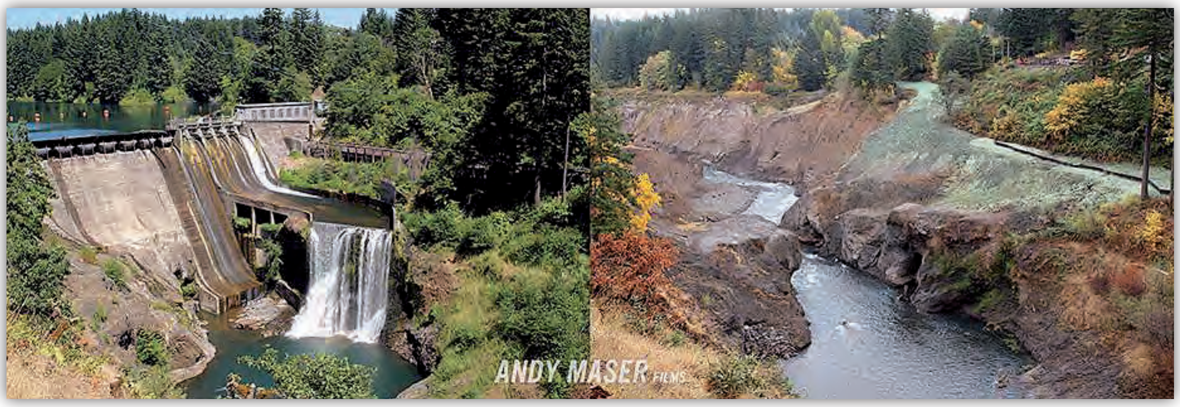


**Figure 95:** Condit Dam, shown here before and one year after demolition (2011 to 2012)

This is the largest dam removed to date in the USA. Salmon returned within one year, but vegetation will take decades to regrow along the exposed banks.

Photos: http://whitesalmontimelapse.wordpress.com/2012/12/03/condit-dam-removal-complete/

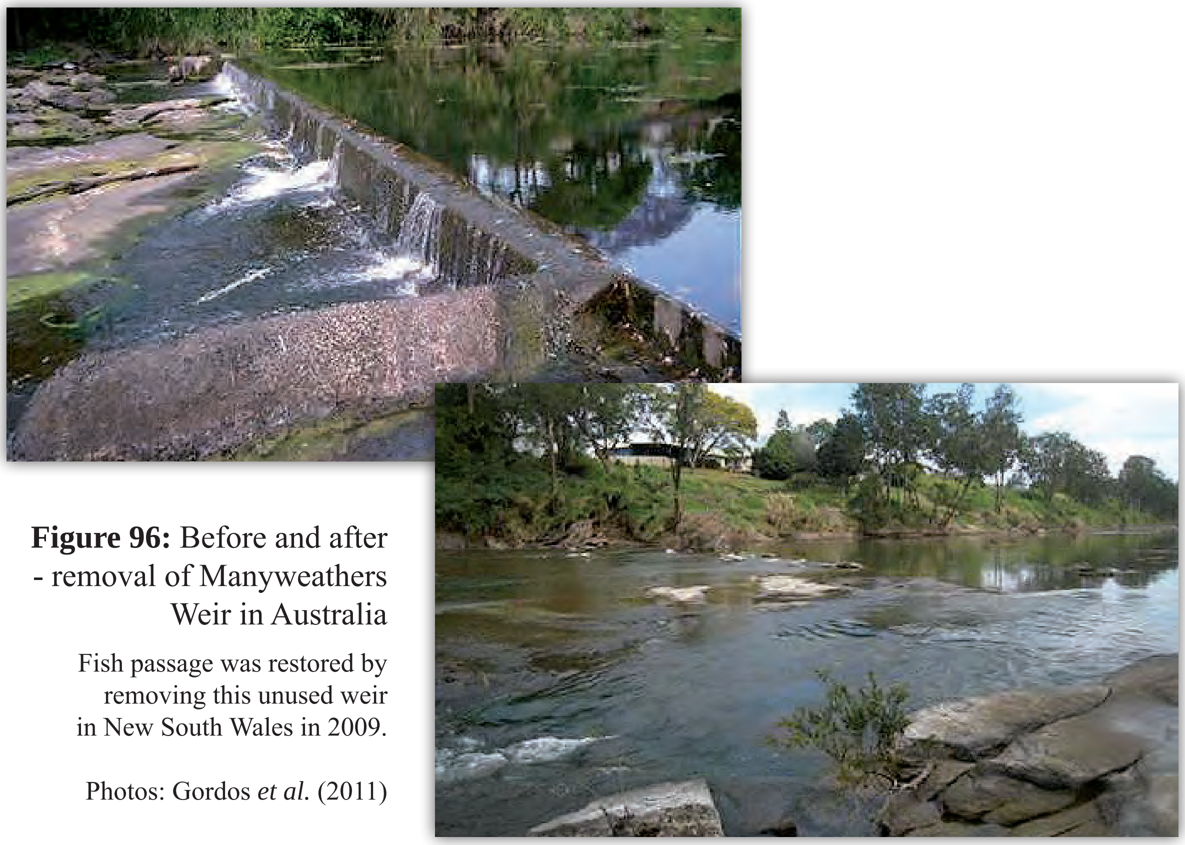


**Figure 96:** Before and after - removal of Manyweathers Weir in Australia

Fish passage was restored by removing this unused weir in New South Wales in 2009.

Photos: Gordos *et al.* (2011)

# 5. Conclusions

In the LMB dams are needed to support irrigation, hydropower, water supply and other needs of growing populations. At the same time, fisheries are very important, providing nutrition and livelihoods for millions of people, so there is a clear need to mitigate any negative impacts of dams on fisheries. This report provides a brief introduction and overview of some of the main impacts of dams on fisheries and discusses some mitigation measures.

In the LMB the most common approaches to mitigate dam impacts have been stocking of fish in reservoirs and development of aquaculture, with both measures widely promoted in each of the Lower Mekong countries and administered by fisheries agencies, which have also promoted fisheries management in some reservoirs.

As described briefly in this report, the various other impacts of dams on fisheries are well understood and include obstruction of fish passage upstream and downstream, seasonal and daily flow changes, trapping of sediment and other material in reservoirs, and stratification and water quality impacts. Technical approaches to mitigate these impacts are available but have been used at very few dams in the Mekong Basin. Fish passes, a relatively popular element of mitigation efforts, have only been constructed at a handful of dams and it is only recently that trials with Mekong species have set parameters for fish pass design based on systematic field experiments on Mekong fish. There is a long-standing opportunity to greatly improve the benefits of existing and new dams for a range of users by applying known mitigation measures.

For fisheries at existing and planned dam projects, practical solutions need to be developed from general concepts or examples from elsewhere. Technical approaches need to be tested and refined at new dams and in pilot studies in the Mekong Basin, so their costs, effectiveness, sustainability and socioeconomic effects can be documented. The results can then guide design of mitigation in new projects and can be applied to remedy problems at existing dams. Given limited regional experience with mitigation of dam impacts, capacity building should be supported across a range of disciplines, including fisheries ecology, engineering and socio-economics.

As well as developing practical technical solutions, there is a requirement for institutional frameworks which will support mitigation. For large dams in the LMB, environmental agencies implement EIA procedures, which should include appraisal of the full costs and benefits of all possible dam options, including the ‘no dam’ option prior to the decision to proceed. Early planning during feasibility studies and EIA processes can screen out projects with unacceptable negative impacts and reduce the need for later mitigation. Impacts and proposed mitigation measures should be prescribed within EIAs as required under legislation. Because environmental legislation is relatively new in the LMB countries, ongoing support for implementation is needed to improve outcomes in new dam projects. Additional provisions could be developed to support environmental flow rules and environmental offsets based on lessons learned elsewhere.

While an EIA can be a useful process, the vast majority of Mekong Basin dams are not subject to EIAs and are developed to specifically support irrigation and/or hydropower, so other approaches are needed if mitigation for fisheries is to be improved. Problems at existing dams also need to be addressed. While some measures such as fish passes may fall clearly within the mandate of a fisheries agency, for others new statutes are required. For example, de-stratification of a small reservoir may provide multiple benefits to various users, but responsibility for designing and implementing such a system needs to be clarified and institutionalised. Incentives need to be provided for the capital and operational expenditure required by developers and the institutions responsible for water resource management for mitigation to be applied and sustained. These institutional issues are outside the scope of this report, but need to be addressed in parallel with improvements in capacity and in the technical performance of mitigation as mentioned above.

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