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Mekong River Commission

Review of Existing Research on Fish Passage through Large Dams and its Applicability to Mekong Mainstream Dams

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Cambodia · Lao PDR · Thailand · Viet Nam

For sustainable development

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Abbreviations and acronyms

Δh	Height difference
BDP	Basin Development Plan
BL	Total body length
BL/s	Body length per second (fish swimming speed)
DFP(s)	Downstream fish pass(es)
D_{min}	Min. hydraulic depth
d_{min}	Min. hydraulic depth in bottlenecks and sluices
FP(s)	Fish pass(es)
g	Force of gravity (9.81 m/s^2)
GIZ	Deutsche Gesellschaft für Internationale Zusammenarbeit
h	Height
H_{fish}	Maximum fish height of size-decisive species
HP	Hydropower
HPP	Hydropower plant
HQ_x	X-years flood
h_{tot}	Total water level difference
ISH	Initiative on Sustainable Hydropower
IWRM	Integrated Water Resource Management
kg	Kilogram
L_{fish}	Length of size-decisive species
LMB	Lower Mekong Basin
L_p	Minimum length of the pool
l	Litre
l/s	Litres per second
l_{tot}	Total length of fish pass
MALF	Mean annual low flow
MF	Mean flow
MFD	Mekong Fish Database
MRC	Mekong River Commission
n	Number of pools/basins
P_D	Power density
PNPCA	Procedures for Notification, Prior Consultation and Agreement

pw	Water density (1,000 kg/m³)
Q	Discharge
Q_a	Discharge of attraction flow
Q_O	Operational discharge of the fish pass
Q_{tot}	Total discharge ($Q_O + Q_a$)
Q_x	Discharge exceeded x days per year
rpm	Rotations per minute
v	Flow velocity
V	Volume of the pool
v_m	Mean flow velocity
v_{max}	Maximum velocity
W	Watt
wb	Width of the borders between the pools
W_{fish}	Maximum width of size-decisive species
w_p	Minimum width of the pool
w_s	Slot width
WFD	Water Framework Directive

Glossary

1+ fish	Fish with an age of one year or older
Attraction flow	Flow which is required to guide fish towards the entry of a fish pass
Attraction flow discharge	Required discharge to provide sufficient attraction flow
Autochthonous fish species	All indigenous fish species that would occur under natural (anthropogenically undisturbed) conditions. With regard to the WFD, not only species composition but also species abundance and age-structure of populations are considered.
Bottom roughness	Roughness of the riverbed
Cavitation	Formation and implosion of low-pressure cavities in turbined water, possibly causing damage to the turbine and fish
Competitive current/flow	Flows that compete with the attraction flow of a fish pass (e.g. flow coming from the turbines)
Continuity interruption	(see Migration barrier)
Critical velocity	Velocity at which fish start to drift downstream after 20 s
Facultative migrations	Migration in response to altered environmental conditions
Fish coenosis	Typical fish community of a river section
Homing effect	Fish returning to their birthplace for spawning
Ichthyoplankton	Eggs and larvae of fish which are suspended in the water column
Impulse	Product of discharge and flow velocity
Key species	Typical species of a fish region
Migration barrier	Barrier/weir which is not passable for fish and interrupts continuity
Obligatory migrations	Migrations that are required to fulfil life cycles and coincide with a series of physiological modifications
Operational discharge	Required discharge in a fish pass to ensure the required morphometric thresholds
Passability	Possible and safe passage of fish with regard to morphometric and hydraulic conditions in a fish pass
Perceptibility	Conditions of the attraction flow and at the entry of a fish pass which ensure that fish find the fish pass
Potamal	Lowland rivers characterised by large dimensions and low slopes, finer substrates, warmer water and lower oxygen content than upland rivers (see Rhithral rivers)
Residual current/flow	Flow, which is present in the main channel after water abstraction (e.g. at a diversion hydropower plant)
Rheoactive velocity	Required minimum flow velocity of fish for orientation in a river (species- and age-specific)
Rheophilic species	Species preferring higher flow velocities

Rhithral rivers	Rhithral rivers are highland rivers characterised by smaller dimensions, steeper slopes, cooler water and higher oxygen content than lowland rivers (see Potamal rivers)
Screen/rake	A combination of several bars to prevent floating debris (or fish) from entering turbine intakes or other structures
Size-decisive species	The largest species or species with the highest spatial demands in a river stretch
Support corset	Support corsets are used to ensure substrate stability in a fish pass. Larger boulders are placed above a layer of smaller gravel to avoid erosion.

Executive Summary

The Mekong River is the world's tenth-longest river (4,909 km) and flows through six countries in East Asia. The Mekong is an ecologically unique river with more than 800 fish species, which provide food and socio-economic opportunities for several million people. The Mekong supports the highest fish productivity compared to other inland fishery regions in the world with an estimated harvest of between 755,000 t/year and 2.5 million t/year. The Lower Mekong Basin (LMB) does not currently have a hydropower plant on the mainstream. However, twelve hydropower plants are planned for the mainstream of the LMB and the first, the Xayaburi Hydropower Project, is already under construction.

Hydropower plants lead to alteration of the aquatic ecosystem. The disruption of river continuity is considered the main cause of impact to aquatic organisms, especially migratory fish. The impact will most likely increase with ongoing hydropower exploitation. In order to mitigate the effect of hydropower plants on aquatic organisms, fish passes should be considered for all existing and planned hydropower plants as referenced in the Mekong River Commissions's Preliminary Design Guidance for proposed mainstream dams in the LMB (MRC, 2009). This does, however, require a sound understanding of the fish-passage types available as well as their efficiency and effectiveness under certain aquatic, ecological and biological conditions.

The **aim of this report** is therefore to:

- summarise current knowledge and research on fish-pass solutions for both upstream and downstream migration, with a particular interest in lessons learned from around the world and their applicability to the Mekong River;
- provide guidance to consultants and practitioners in the Mekong River Basin (as well as other rivers facing similar challenges) on the current state of research concerning fish passage through large dams;
- highlight knowledge gaps in design and operation of fish passes and propose research required to fill these gaps; and
- contribute to the ultimate aim of developing effective mitigation measures for large dams in the Mekong River.

Fish migration in the Mekong

Fish migration in the LMB is currently undertstood to involve shifts between marine and freshwater habitats, between upstream and downstream areas within the Mekong River, between the Mekong River and its tributaries, and between rivers and floodplains. There are distinct migrations between and within the three sub-units of the river – the upper, the middle and the lower part of the LMB. The so-called "white fishes" migrate within the mainstream and into the floodplains during the wet season whereas "black fishes" and "grey fishes" demonstrate restricted migratory behaviour.

Mekong fish species migrate for several purposes, including spawning, feeding, and refuge (deep pools), in both directions – upstream and downstream. Migration takes place throughout the year and throughout the life cycle of fish (i.e. as larvae, juveniles, sub-adults and adults). Migration peaks occur at the onset and during the wet season.

Knowledge concerning the effective design of fish passes for large tropical rivers remains limited. Data and information is available largely on South American rivers (which are of particular interest for this study due to their diverse fish fauna and high productivity – similar to the Mekong River), North America and Europe. For the Mekong River Basin, only few case studies on fish passes exist.

At the same time, multiple challenges to effective fish passes exist, especially with regard to the large scale of required fish passes, the migration of large species, migration peaks with high biomass, and the high diversity of species – all constituting different requirements for fish passes.

Upstream fish passage options

Different **types of upstream fish passes** have been developed in recent decades. Technologies vary in terms of:

- Conceptual design (e.g. continuous vs. discontinuous operation);
- Spatial demands (e.g. channel-type fish passes vs. fish lifts); and
- Applicability for single or multiple species (e.g. eel ladders vs. nature-like fish passes).

So far, however, most existing fish passes have been built for small or medium-sized dams (up to 15 metres high). For large dams, many challenges remain, including for those constructed in multi-species tropical rivers.

Upstream fish pass efficiency depends on fish finding the entrance to the passage (perceptibility) and the passability of the fish pass.

- **Perceptibility** is required to ensure the migrating fish can find the entrance to the fish passage and includes questions relating to the design of the entrance of the fish pass and the attraction flow.
- **Passability** is important to ensure the capacity of the fish pass is sufficient to accommodate large fish species and large amounts of biomass. In addition, small fish with low swimming abilities must be accomodated.

For large multi-species rivers, vertical-slot fish passse and nature-like bypass channels can therefore be considered as state-of-the-art solutions. Other fish pass types may favour species with high swimming abilities only. Likewise, trap-and-truck solutions, fish lifts and fish locks might be suitable for specific species only.

The dimension of a fish pass depends on the largest species as well as the biomass that it is required to pass. For the Mekong River, the required fish pass dimensions are yet to be established.

Several fish passes with complementary features would generally be required for the Mekong in order to accommodate the different migration corridors and different species. Bypass systems, consisting of near-natural channels that circumvent the entire reservoir, are a valuable alternative to re-establish the migratory route for fish.

All fish pass solutions in the Mekong River must deal with the seasonal variations in the discharge and water level. Seasonal variations of tailwater levels may exceed 10 m in the Mekong River and fish passes have to accommodate these variations by providing different entrances at different water levels.

Downstream fish passage options

Solutions for downstream migration are largely lacking for large, multi-species rivers. Potential downstream pathways are through turbines, spillway flows or fish passes designed for downstream migration. The protection of fish is the critical consideration in the design of downstream migration pathways – especially with regard to preventing turbine injuries, but also taking into consideration the drift of larval fish. The challenge is to avoid fish mortality through turbines and spillway gates and to guide fish efficiently to downstream bypass systems.

Research requirements

In spite of the substantial global knowledge on fish passes outlined in this report, a number of challenges and open research questions remain to be answered in order to develop effective mitigation options for fish passage through dams on the Mekong mainstream.

- Baseline information is required in many areas relevant for sustainable hydropower in large tropical rivers. This requirement is particularly around the ecology of key fish species and commercial species.
- Better understanding of the specific nature of **potential impacts** of hydropower on the Mekong species and fish production.
- Improved understanding of **migratory behaviour** is required to adapt existing fish pass technologies to the requirements of large tropical rivers - preferably before project implementation. This includes key species and their migration distances, their swimming behaviour, their migratory routes, the locations of their spawning habitats, their migration periods, the environmental conditions triggering their migration as well as the role of flood plain migrations, sub-adult migration and larval drift.

- For specific projects, the design of the fish pass requires a detailed understanding of the hydromorphological and hydraulic conditions at the dam.
- Improved knowledge of efficiency of fish passes at the river-system and fish-population level including situations with multiple dams is needed.
- Regarding the **design of fish passage**, research questions include:
    - Assessment of fish pass effectiveness for multiple species at existing facilities including small and large species and the high number of migratory fish in large tropical rivers.
    - The potential locations for fish pass entrances and solutions to efficiently guide fish into the entrance. This is particularly challenging given the high variability of discharge and water level in tropical rivers.
    - Hydraulic characteristics of the fish passage element with respect to the swimming capability of different species and their size.
    - Improved and new designs for downstream migration.

Follow-up actions

The Initiative on Sustainable Hydropower of the Mekong River Commission (MRC/ISH) and the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ commissioned this report to ensure a sound knowledge base on global experience exists to underpin the further work being done in the MRC on sustainable hydropower development and specifically on risk mitigation options for large hydropower projects.

Further MRC studies by ISH and the Fisheries Programme will initiate work on certain research topics described above and pursue in more depth the design options for specific river reaches. Mainstream hydropower dam developers are also currently undertaking research and design for fish passage for those projects. Ideally the knowledge gathered on those projects should be combined in collaborative forums towards an improved design and operations approach for fish passage and impact mitigation in the Mekong.

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1. Introduction

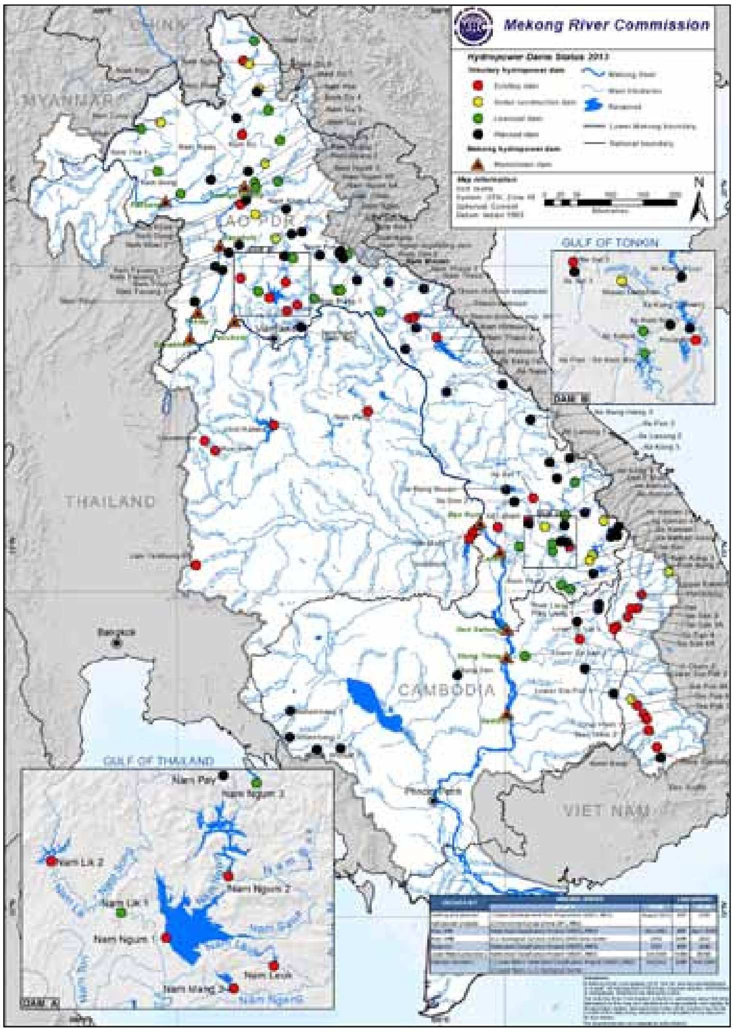

Figure 1: Location of existing and proposed hydropower schemes in the Mekong River Basin

Hydropower is recognised as an important development opportunity for the Lower Mekong Basin (LMB). All countries of the LMB (Cambodia, Lao PDR, Thailand and Viet Nam), are experiencing rapid economic development accompanied by an increase in electricity demand. As a response, Mekong countries have embarked on the development of hydropower. According to the MRC's Strategic Plan (2011 - 2015) and the MRC Basin Development Plan (BDP, approved in January 2011), basin development is to follow Integrated Water Resource Management (IWRM) principles. The need to improve the sustainability of the basin's hydropower developments is a key Strategic Priority in the Mekong Basin Development Strategy. With significant increase in scale and prevalence of hydropower, all MRC Member Countries are taking steps to understand and employ sustainable hydropower principles. At the same time, hydropower development can pose several challenges to the environmental and social sustainability of the basin.

The MRC established the Initiative on Sustainable Hydropower (ISH) in order to embed sustainable hydropower considerations into the regulatory frameworks and planning systems of Member Countries and into project-level design, implementation, and operational activities. The ISH 2011-2015 Strategy emphasises this requirement as well as the need to consider the wider implications, including the development of environmental and socio-economic baseline information. The Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) supports these efforts through its MRC-GIZ Cooperation Programme. The programme aims to improve the application of and the compliance with sustainability principles in the development of the basin's hydropower potential. This includes, the sharing of knowledge on current issues of sustainable hydropower as well as the development and promotion of guidelines for sustainable hydropower.

To date, 12 hydropower projects have been proposed for the Mekong mainstream in the LMB. In addition, the LMB tributaries also support many existing dams with others planned. The development of hydropower schemes on the Mekong mainstream and its tributaries plays an important role in contributing to economic growth and welfare in the LMB. However, these schemes may also jeopardise the existing fishery that substantially contributes to food supply in the LMB.

Based on limited knowledge available in 2008, members of the MRC Secretariat's Expert Group on Fisheries, which was established for the Procedures for Notification, Prior Consultation and Agreement (PNPCA) for the Xayaburi Hydropower Project, concluded that "there is currently no evidence that fish-passage facilities used in large tropical rivers in Latin America, Africa and Asia can cope with the massive fish migrations and high species biodiversity in the Mekong" (Dugan, 2008). To address the dearth in evidence, this report assesses existing literature, research, and practical experiences on fish passage solutions for hydropower dams to present its relevance for and applicability to the Mekong River. It also provides a summary of evidence and a bibliography to inform research, planning, and implementation processes among stakeholders in the basin with a focus on the requirements of Mekong fish species.

The report investigates both upstream and downstream fish migration facilities. Since upstream and downstream migrations require different approaches that cannot be combined easily into one facility, two separate fish passes are required. Facilities for upstream and downstream migration are therefore discussed in separate sections (Chapters 3 and 4). The report analyses these different facilities with regard to their functionality, perceptibility and passability. It aims to provide a comprehensive overview of the current state of research as well as remaining knowledge gaps and required research (Chapter 5) – especially with respect to the Mekong River and the impact large dams might have on its fish and, consequently, the Mekong River Basin's population and economies. This analysis is based on both general theoretical considerations as well as lessons learned from large (tropical) rivers, including the Mekong.

1.1 General overview of the Mekong River

The Mekong River is the world's tenth longest river. It has its source in the Tibetan Plateau (Tanggula Mountain) in China at around 5,000 m elevation and extends 4,909 km to its mouth in southern Viet Nam (Liu *et al.,* 2009; MRC, 2005; Kang *et al.,* 2009). It runs through six countries in East Asia (Kang *et al.,* 2009). The Upper Mekong Basin (Lancang River) extends over 1,129 km in China (He & Tang, 2000) and flows through a narrow valley bordered by mountains. The LMB starts at the border of China where the Mekong River drops to ~350 m in elevation in northern Lao PDR. The LMB is characterised by extensive floodplains and wetlands. Although the Mekong approaches sea level in northern Cambodia, the river still flows approximately 500 km until it drains into the South China Sea (MRC, 2005).

The Mekong has a catchment of 795,000 km^2 and is the biggest river in Southeast Asia. Major tributaries include Nam On, Nam Ngum, Nam Cading, Chi-Mun, Se Kong, Se San and the Tonle Sap. The mean annual flow is 470 km^3 in total with a mean annual discharge of 15,000 m^3/s. Due to the Southwest Monsoon, the flow is highly variable with a maximum of 45,000 m^3/s in September or October and a minimum of 1,500 m^3/s in March or April (gauging station Kratie, Lu & Siew, 2005; MRC, 2005). During the wet season, high flows inundate large wetlands and floodplains in the LMB. As a result, the Tonle Sap, a large tributary of the Mekong, flows upstream during the seasonal floods (Campbell, 2009).

1.2 Hydropower exploitation on the Mekong River

The first mainstream dam in China was completed in 1995 (Li & He, 2008). Today, there are seven commissioned dams (i.e. Jinhe, Gongguoquiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu and Jinghong), six under construction (i.e. Kagong, Gushui, Wunonglong, Lidi, Huangdeng and Miaowei) and another planned (i.e. Tuoba). Two dams, which were planned earlier (i.e. Mengsong and Guonian) have been cancelled. The completion of the dams in China is expected to have a large impact on the hydrology and aquatic ecology of the downstream reaches (Kang *et al.,* 2009). Furthermore, these dams are expected to have significant influence on the sediment balance of the Mekong River (Fu *et al.,* 2008, see Chapter 6.3).

Currently, approximately 200 larger dams are in operation, under construction or planned in the Mekong Basin (Baran *et al.,* 2009; MRC, 2010). In total, 12 hydropower projects are planned for the LMB mainstream (i.e. Pakbeng, Luang Prabang, Xayaburi, Paklay, Sanakham, Pakchom, Ban Kum, Latsu, Don Sahong, Thakho, Stung Treng and Sambor). One (Thakho) is designed as a diversion HPP without a dam while eleven are mainstream dams with 10 across the entire river and one across a mainstream branch. The proposed projects are planned in Lao (7 dams), Lao-Thai (2 dams) and Cambodian reaches (2 dams) of the Mekong River (MRC, 2008). These dams will divide the Mekong into several huge reservoirs, interrupt connectivity and lead to fish habitat fragmentation (Kang *et al.,* 2009).

To date, the LMB tributaries are already exploited by many hydropower plants. According to MRC (2011a), 70 additional hydropower dams will be constructed in the tributaries of the LMB by 2030 (MRC, 2011a).

Currently, the LMB does not have a completed mainstream dam. However, some details are available regarding the first dam that will be constructed, under the Xayaburi Hydropower Project. Although the planned project is not considered itself in this report, the river characteristics at Xayaburi are used as a case study to exemplify environmental conditions for fish passes in the LMB.

At Xayaburi, the Mekong River has a mean annual flow of 3,971 m^3/s. The highest flow (probable maximum flood) is estimated at 47,500 m^3/s and the minimum flow is 650 – 1,000 m^3/s (MRC, 2011b). The planned dam is 830 m wide and 49 m high, creating a reservoir of 60 – 90 km length, 34 m maximum depth, an area of 49 km^2 and a water level variation of up to 5 m (between 270 and 275 m above sea level).

2 Fish fauna of the Mekong River

While the physical diversity and high productivity of the Mekong has favoured the development of numerous fish species (Valbo-Jorgensen *et al*., 2009), the exact number of fish species is unknown. In the 1970s, it was assumed that there were 300 species in the Mekong River (Taki, 1978). Welcomme (1985) cited 600 species in the 1980s and recent estimates account for up to 1,200 (Hortle, 2009a; Rainboth, 1996) or 2,000 species (Van Zalinge *et al.*, 2004). Kottelat (2001), however, stated that there are only records of approximately 700 species. Since data supporting higher numbers are not available, Kottelat suggests to use 700 species as a reference. Based on the Mekong Fish Database (MFD, MRC, 2003) there are 898 indigenous fish species as well as 24 introduced species which can be grouped as follows (Hortle, 2009b):

- Freshwater only: 539
- Freshwater-brackish: 79
- Fresh-brackish marine: 113
- Brackish only: 4
- Brackish and marine: 115
- Marine: 48

According to the MFD, there are approximately 750 species in the Mekong using freshwater to some extent (Hortle, 2009a). Therefore, the Mekong has the second highest richness of species in the world after the Amazon River that contains 1,212 species (FishBase, Froese & Pauly, 2010; Baran & Myschowoda, 2009), and fish species diversity increases from headwaters to the lower sections, as is usual in rivers.

According to Valbo-Jorgensen *et al.* (2009), the Mekong fish fauna comprises 87 families, whereby cyprinids are dominant, followed by catfishes of the families Bagridae, Siluridae, Pangasiidae, Sisoridae and Clariidae.

In particular, the Mekong provides habitats for at least seven species of giant fish, and therefore has the highest number of giant freshwater fish in the world (Stone, 2007). This includes the critically endangered Mekong giant catfish (*Pangasianodon gigas*), giant pangasius (*Pangasius sanitwongsei*) and giant barb (*Catlocarpio siamensis*) as well as the endangered seven-striped barb (*Probarbus jullieni*) (Hortle, 2009b; Hogan *et al.*, 2004; Baird, 2006).

Detailed information on the Mekong fishery is limited. Besides catch data from the *Dai* Fishery Monitoring Programme on the Tonle Sap River, the Lee Trap Fishery Monitoring Programme at Khone Falls and fish larvae monitoring, it primarily relies on indirect data from interviews with

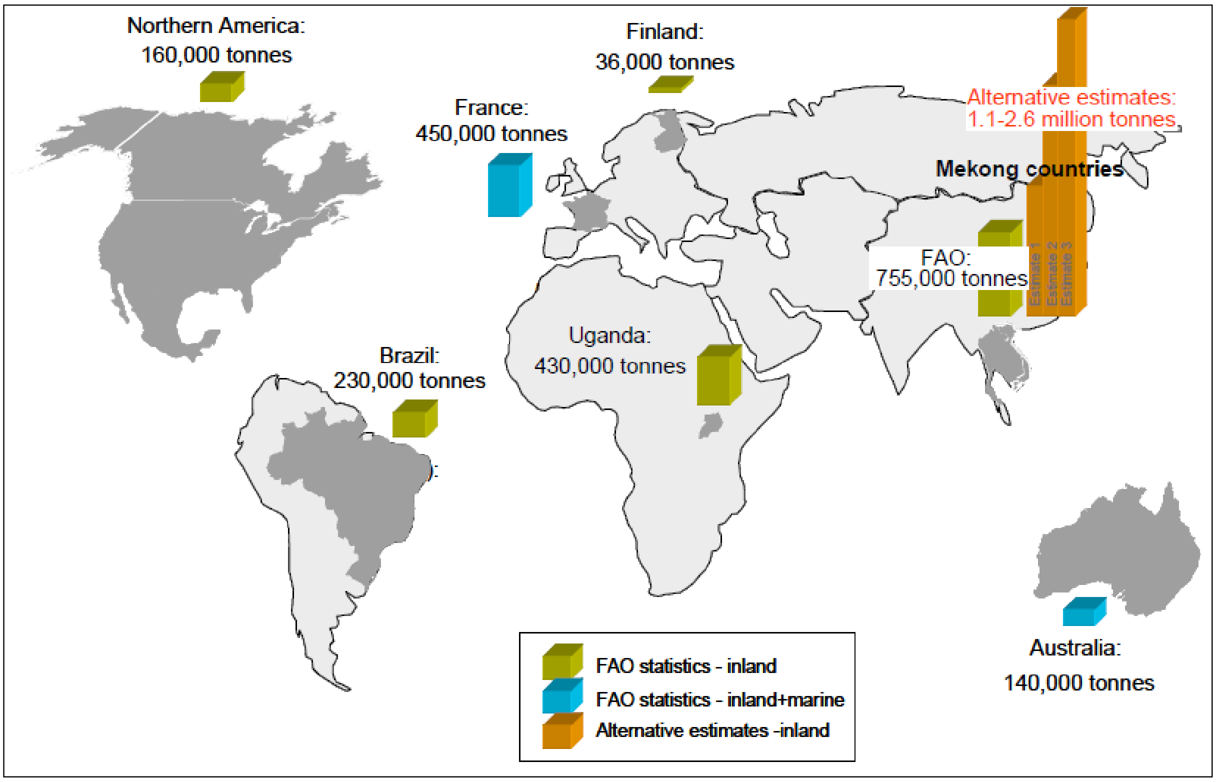

Figure 2: Comparison of fish productivity estimates (MRC 2010, based on FAO statistics 2005-2007)

fishers, fish market analyses, and expert judgement (Halls *et al.*, 2013). Compared to other inland fishery regions in the world, the Mekong supports the highest fish productivity with an estimated harvest of between 755,000 t/year (FAO, 2005-2007) and 2.5 million t/year with a value of up to US$6.5 billion/year (Hogan 2011; see Figure 2).

The Mekong fishery contributes greatly to the socio-economic development of the Mekong countries. Furthermore, the fishery provides the main income for many riparian people and increases their food security and socio-economic development. According to Dugan (2008), there are areas, as in southern Lao PDR, that have a high dependence on the sector where up to 80% of the population is involved in fishing.

2.1 Biology of fish migration

Northcote (1984) defines migration as “movements that result in an alternation between two or more separate habitats, occur with a regular periodicity, and involve a large proportion of the population”.

All species perform targeted “habitat shifts” at least during certain life stages (e.g. larvae or juveniles). As a consequence of changing habitat requirements (Schmutz *et al.*, 1997; Jungwirth, 1998 & Northcote, 1998), fish migrate to different habitats to optimise use of resources and productivity (e.g. distribution, growth, reproduction, shelter, protection from predators) (Northcote, 1978 &

Larinier, 2000). Reproductive migrations mostly occur in an upstream direction followed by post-spawning downstream migrations if reproducing several times. Some species perform spawning migrations at low flows, whereas other species reproduce at higher discharges (Zitek *et al*., 2007). Downstream migrations of juveniles occur for the purpose of dispersal by active movement or passive drift back to their main habitats (Seifert, 2012; BMLFUW, 2012).

2.1.1 Migration triggers

Fish migrations are usually triggered by several complex interacting factors, which can be grouped into internal and external factors (Pavlov, 1989; Colgan, 1993; Lucas & Baras, 2001):

- External factors are abiotic conditions such as water temperature, season, moon phase, light, discharge, water quality, and oxygen saturation.
- Internal factors are hormonal readiness for reproduction, nutrition requirements, stress or other endogenic (genetic or ontogenetic) determinants such as imprinting and homing to a birth place (i.e. “homing effect”) (Lucas & Baras, 2001).

In general, internal factors are highly influenced by external factors (Pavlov 1989; Albanese *et al.*, 2004). Migrations may occur at seasonal, monthly or daily intervals (Northcote, 1984; Jonsson, 1991; Hvidsten *et al*., 1995; Lucas & Baras, 2001).

The most important triggers under discussion in tropical freshwater fish are water level, current, discharge, precipitation, lunar cycle, water colour, turbidity and the appearance of insects. For approximately 30 species in the Mekong, it is assumed that certain thresholds or changes in water level, discharge or current act as a trigger. Based on fisher experience, approximately 11 species are supposed to use the first rainfalls of the wet season (sometimes in combination with the lunar cycle) to start their migrations. Furthermore, nine species react to turbidity or water colour and five species use the appearance of insects as a trigger (Baran, 2006). It has to be considered that spawning and migration triggers can act independently. Spawning triggers also act on species which do not migrate, and migrations can occur for purposes not related to reproduction (Baran, 2006). Similar triggers are also reported for temperate freshwater fish species (Lucas & Baras, 2001).

Furthermore, obligatory migration, which coincides with a series of physiological modifications in fishes, have to be separated from facultative migration, defined as a response to altered environmental conditions (e.g. reduced oxygen, food scarcity, predation pressure) (Baran, 2006).

Fish species are classified according to migrations between and within freshwater and marine environments and grouped into the following migration guilds (Jungwirth *et al.*, 2003):

Diadromous species inhabit both the sea and freshwaters and can be further divided into anadromous, catadromous and amphydromous species. While anadromous species live in the sea and migrate to freshwater habitats for spawning, catadromous species live in freshwater and reproduce in the sea. Amphidromous species frequently switch between the sea and freshwater but also for other purposes than reproduction.

Potamodromous species migrate only within freshwater and can be further divided into long-, medium- and short-distance migratory species (i.e. > 300 km, 30 – 300 km or < 30 km in one direction per year; Waidbacher & Haidvogi, 1998).

Details of the migration behaviour are only known for about 189 species of the Mekong River, of which 165 are considered to be explicitly migratory. Around 135 fish species in the Mekong River are potamodromous (Baran, 2006). One of the most famous migratory species is the Mekong giant catfish (*Pangasianodon gigas*). Species migrating long distances along the Mekong mainstream and tributaries make up 40 – 70% of the fish catch along the mainstream Mekong River (Barlow *et al.*, 2008; Baran & Myschowoda, 2008). Detailed information on migration pathways, the role of tributaries for reproduction, migration into floodplains, timing of migration and contribution to fish catches is missing for most migratory species.

While existing evidence suggested that reproduction cycles were related to rising water levels at the beginning of the rainy season in May to July, the latest research shows that reproduction may also take place during the dry season of February to May (Cowx *et al.,* 2015).

Fish inhabiting the Mekong floodplain are usually highly adapted to their short lifespan and early sexual maturation (Lowe-McConnell, 1987). The short reproductive cycle leads to high resilience if suitable conditions for reproduction are available (e.g. floods with suitable duration, magnitude, frequency and timing) (Bayley, 1995).

While adults migrate actively up- and downstream, ichthyoplankton develops while drifting passively downstream (Agostinho & Gomes, 1997a; Nakatani *et al.*, 1997; Agostinho et *al.*, 2000). Since reproduction often coincides with floods, the rising flows carry the eggs and larvae to downstream river sections and/or lateral floodplains which are important nursery habitats. As juveniles, the fish migrate further downstream to occupy suitable habitats (Agostinho *et al.*, 2000). Cowx *et al*. (2015) investigated the larval and juvenile fish community of the LMB and found that in general the greatest abundance and diversity of species occurs during the flood in May to September.

The most important discharge for fisheries in the Mekong River at the Khone Falls is between 2,000 and 3,000 m^3/s, flows that occur after the flood season. At these discharges fish are more crowded and therefore the most diverse catches are obtained (Baran, 2006). The migratory biomass of the Mekong River is one of the largest of any river in the world.

Fish of the Mekong are usually grouped according to their migration patterns and ecological requirements into black, white and grey species:

- Black fishes spend most time in lakes, swamps and floodplains. They inhabit swamps/lakes in the wet season and migrate laterally to tributaries in the dry season. Examples are some catfishes of the family Bagridae (Baran, 2010). They are physiologically adapted to low oxygen levels, and can therefore inhabit swamps and small floodplain lakes during the dry season. During the wet season, they inhabit flooded areas. They are usually classified as non-migratory though they perform restricted seasonal movements between permanent and seasonal water bodies. Other examples of black fishes are species from the families Anabantidae, such as the climbing perch

(*Anabas testudineus*), Clariidae (e.g. *Clarias batrachus*) and Channidae such as the striped snakehead (*Channa striata*) (Mattson *et al.*, 2002; Poulsen *et al.*, 2002).

- White fishes spend most of their time in the mainstream of the river. They only migrate towards the floodplain during the wet season and return to the river habitats at the end of the wet season. Representatives are cyprinids (e.g. *Cyclocheilichthys enoplos*, *Cirrhinus microlepis*) and pangasiid catfishes (Mattson *et al*., 2002). Migrations of white fishes are grouped into three distinct but interconnected migration systems (see next page Figure 3; Ferguson *et al.*, 2011; Baran, 2006).

- Grey fishes, as an intermediate group, perform short migrations between floodplains and adjacent rivers (Chanh *et al.*, 2001; Welcomme, 2001).

Barlow *et al.* (2008) used three methods to estimate the Mekong fish catch under risk from mainstream dam development: an expert panel approach, a guild-catch survey and a literature review. Experts assume that migratory species comprise more than 70% of the fisheries yield in the floodplain-river system of the LMB. The guild-catch survey of the MRC (November 2003 - December 2004) showed approximately 150 highly migratory species, whereby 58 species (i.e. 744,000 tonnes) were assigned to highly vulnerable guilds (Halls & Kshatriya, 2009; Barlow *et al.*, 2008). Furthermore, the literature review yielded the following estimates for the three LMB sections (Barlow *et al.*, 2008):

- The lower LMB expands from the Vietnamese coast up to the Khone Falls in southern Lao PDR (0 to ~150 m above sea level). During the dry period, migrations occur out of the floodplains and tributaries (including the Tonle Sap) towards and upstream of the mainstream of the Mekong River. Several species spawn with the onset of the wet season (Baran, 2006). The lower LMB includes the whole Cambodian and Vietnamese Mekong. According to Van Zalinge *et al*., (2004), the total yield of Cambodia and Viet Nam is 1.53 million tonnes with 682,000 tonnes in Cambodia and 845,000 tonnes in Viet Nam. Hortle (2007) estimated the household consumption of Cambodia and Viet Nam at 1.17 million tonnes for the lower LMB with 481,000 tonnes and 692,000 tonnes for each country respectively. Thus, a range of 1.2 to 1.5 million tonnes of fish is produced annually. Considering only white fish which account for 63% of all fish (Van Zalinge *et al.*, 2000), 750,000 tonnes would be at risk if mainstream dams are constructed.

- The middle LMB covers the area between the Khone Falls and Vientiane (Lao PDR) (~150 - 300 above sea level) (Poulsen *et al*., 2002). Upstream migrations often coincide with the wet season and rising water levels when species enter the tributaries and floodplains for feeding and reproduction. During lower water levels, refuges downstream in the Mekong are inhabited (Poulsen, 2003). The middle LMB includes the entire Thai Mekong and around 80% of the Lao Mekong. Production is estimated at between 720,000 tonnes and 932,000 tonnes in Thailand and between 168,000 tonnes and 183,000 tonnes in Lao PDR (Van Zalinge *et al*., 2004, Hortle, 2007). The total production of the middle LMB is estimated at between 850,000 t and 1 million tonnes annually. Therefore, assuming a proportion of 60% white fish, 0.5 – 0.6 million tonnes would be at risk in the development of mainstream dams.

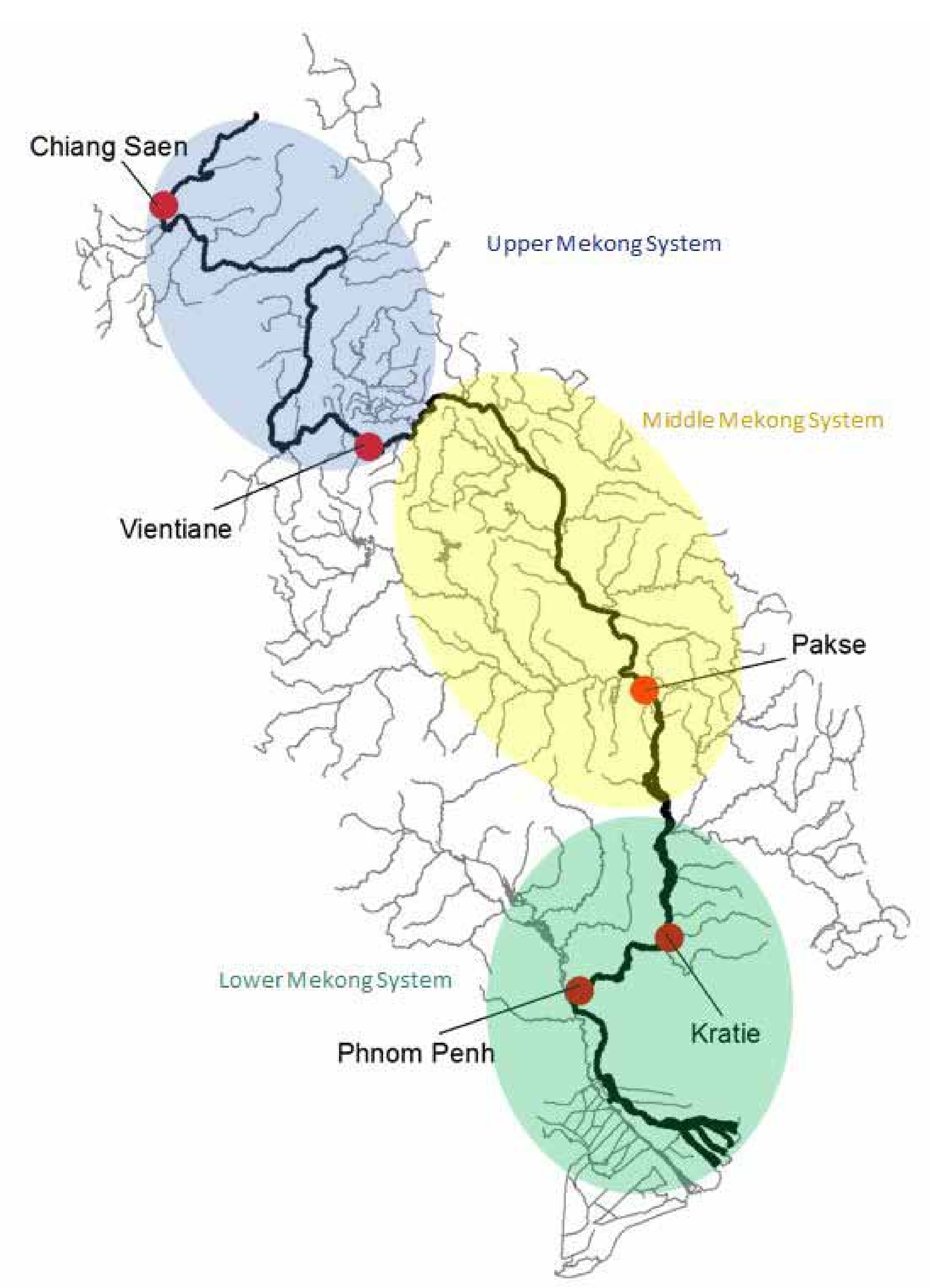

Figure 3: Migration systems of the Lower Mekong Basin (based on Baran (2006), after Poulsen *et al.* (2002))

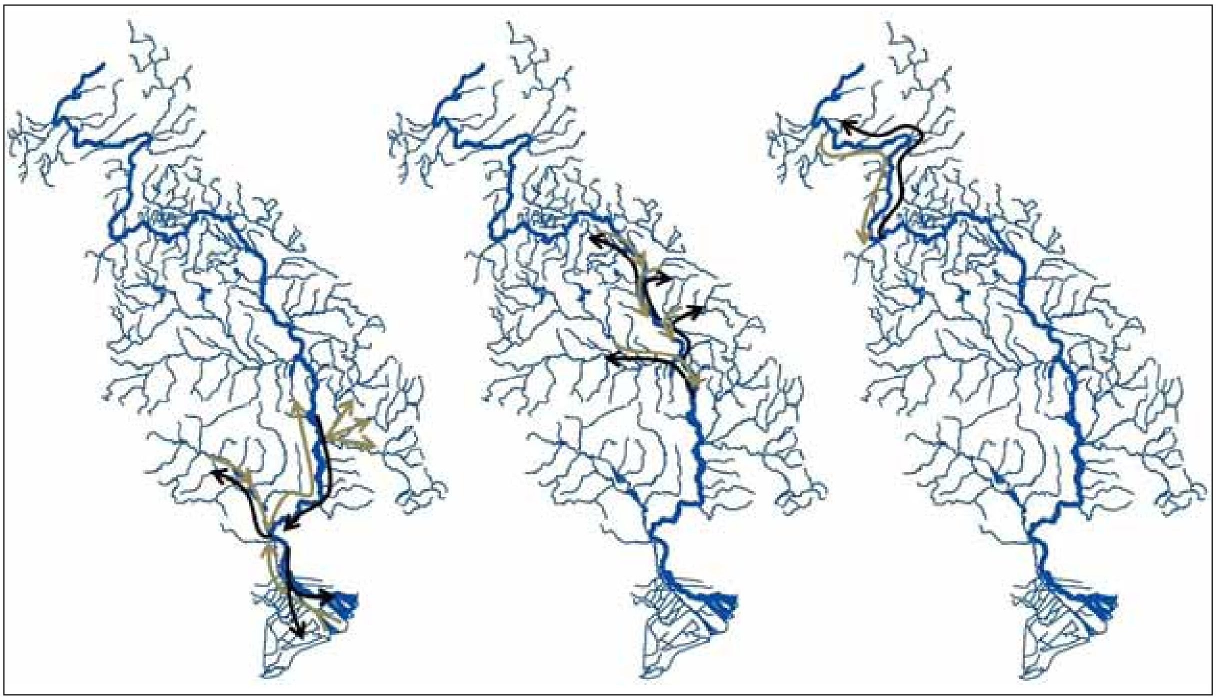

Figure 4: Lower, middle and upper migration systems with major migration routes in which black arrows indicate migrations at the beginning of the wet season and brown arrows indicate migrations at the beginning of the dry season (based on Poulsen *et al*., 2002)

- The upper LMB is located in Lao PDR upstream from Vientiane (Poulsen *et al.*, 2002), ranging from ca. 300 – 500 m above sea level. While the wet season triggers upstream migrations for spawning, dry season habitats can be found within the mainstream of the Mekong (Van Zalinge *et al.*, 2004). The upper LMB includes the remaining 20% of the Lao Mekong (168,000 – 183,000 tonnes) and yields around 25,000 tonnes per year, with 20,000 tonnes at risk if mainstream dams are constructed. Furthermore, the catch of the Chinese part of the Mekong River (Lancang) is about 25,000 tonnes (Xie & Li, 2003) but is not considered in this report.

The three methods applied by Barlow *et al.* (2008) show that mainstream dam development in the LMB potentially threatens 0.7 – 1.6 million tonnes of fish per year, whereby a higher impact is expected from dams built in the lower basin than dams in the upper basin. Furthermore, considerations should be made that the three systems cannot be investigated independently because migrations are not limited to their borders but can expand to the entire LMB (Barlow *et al.*, 2008).

2.1.2 Ecological characterisation of commercially important fish species

The LMB supports several species with high importance for Mekong fisheries. Although the main characteristics of important species are known, species widely distributed in the LMB might show varying migration patterns (e.g. temporal) in different regions of the LMB. Using existing literature, this chapter presents characteristics of important species for fisheries.

Poulsen *et al.* (2004) discussed relevant ecological characteristics, including distribution, feeding, size, population structure, critical habitats and life cycle, of 40 species important for the LMB fisheries. Furthermore, Baran *et al.* (2005) analysed species relevant for the Khone Fall fisheries. A report including an integrated analysis of four MRC fisheries monitoring programmes in the LMB was published by Halls *et al.* (2013). The report includes data from the *Dai* Fishery Monitoring Programme (DFMP) on the Tonle Sap (1994 – 2010), the Lee Trap Monitoring Programme (LTMP) at Khone Falls (1994 – 2010), the Fish Abundance and Diversity Monitoring Programme (FADMP) at 40 sites in the LMB (2003 – 2010) and the Fish Larvae Density Monitoring Programme (FLDMP) in Cambodia and Viet Nam (1999 – 2010). The report highlights species that are considered valuable for fisheries as evidenced in the literature with the exception of the FLDMP as the programme was not designed only for species targeted by fisheries. Furthermore, the importance of the species was updated based on information from the online database "FishBase" (www.fishbase.org).

In Figure 5, commercially important species are grouped with regard to their maximum length. There are 10 species with a maximum length < 25 cm, 12 species with a maximum length of 25 – < 50 cm, 13 species with a maximum length of 50 – < 100 cm and 17 species with a maximum length of more than 100 cm. Some of the large species were previously important for the Mekong fishery but have lost their importance due to reduced stocks. A detailed table is provided in the Annex.

Halls *et al.* (2013) summarises the available monitoring data and shows that the 16 most important species represent 50 % of the total catch. Considering only these species and classifying these spcies according to their length (Figure 5) reveals that about 25% of the commercially important species (i.e. 4 species) can be considered as large species with a maximum body length ≥ 100 cm. The share of smaller fish amouts to 9% (50 – 100 cm), 7% (25 – 50 cm) and 12% (< 25 cm) respectively. The remaining species are not classified due to missing length data (Figure 5). However, small fish species (< 20 cm) are also very important for fisheries and can make up more than 50% of the total catch in local fishery (e.g. in the context of *Dai* fisheries on the Tonle Sap; Poulsen *et al*., 2004).

The following chapters provide key information on important fish species for the LMB fisheries based on Poulsen *et al.* (2004) (see next page Figure 5). Furthermore, Figure 6 summarises the most important migration patterns of these species.

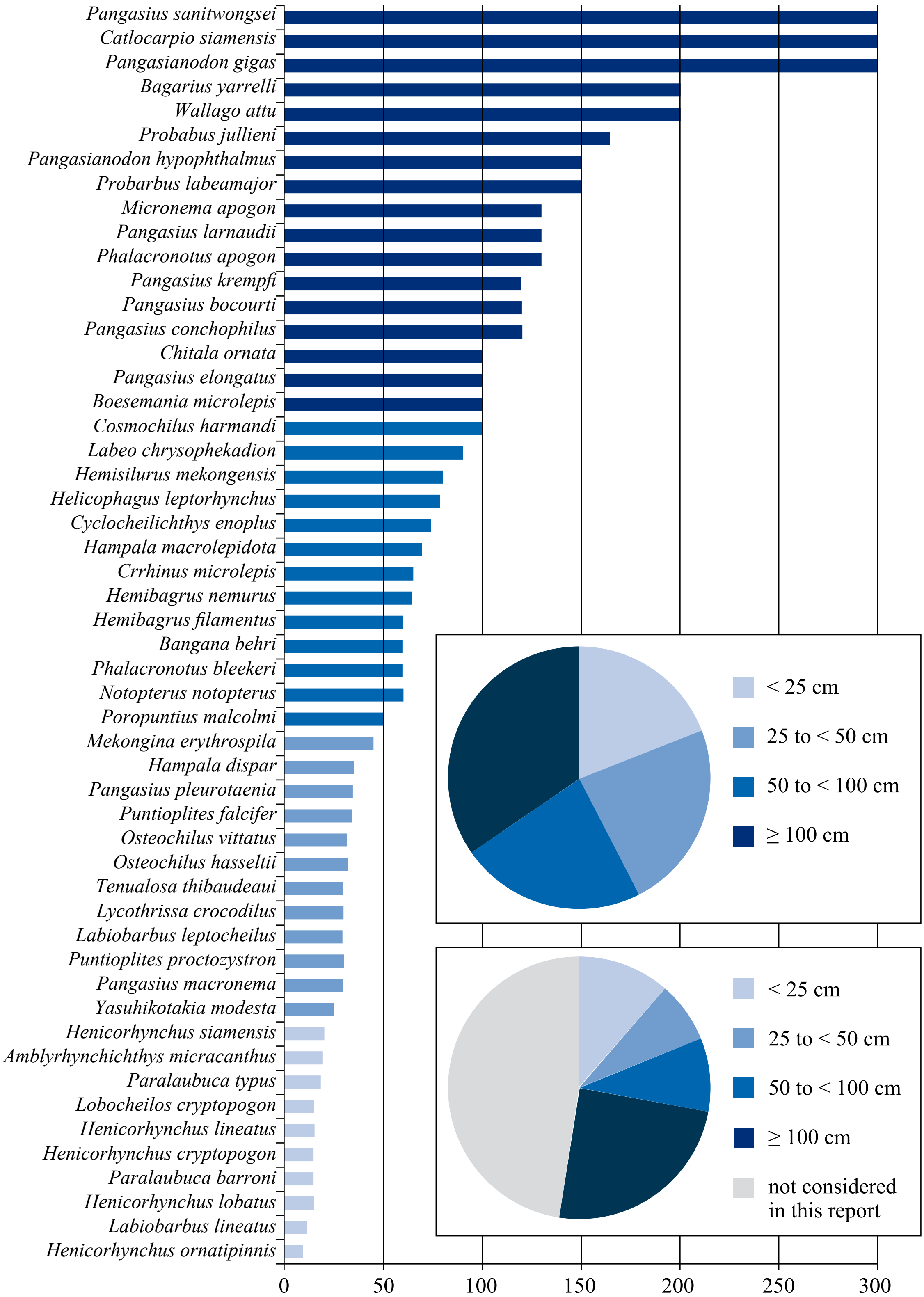

Figure 5: Length (cm) of selected important fish species for the LMB fishery (data retrieved from Poulsen *et al.* (2004), Baran *et al.* (2005), Halls *et al.* (2013) and fishbase.org). The pie diagrams show (a) the percentage of species per length class and (b) the average contribution of length classes to the total catch (biomass) based on Halls *et al.* (2013)

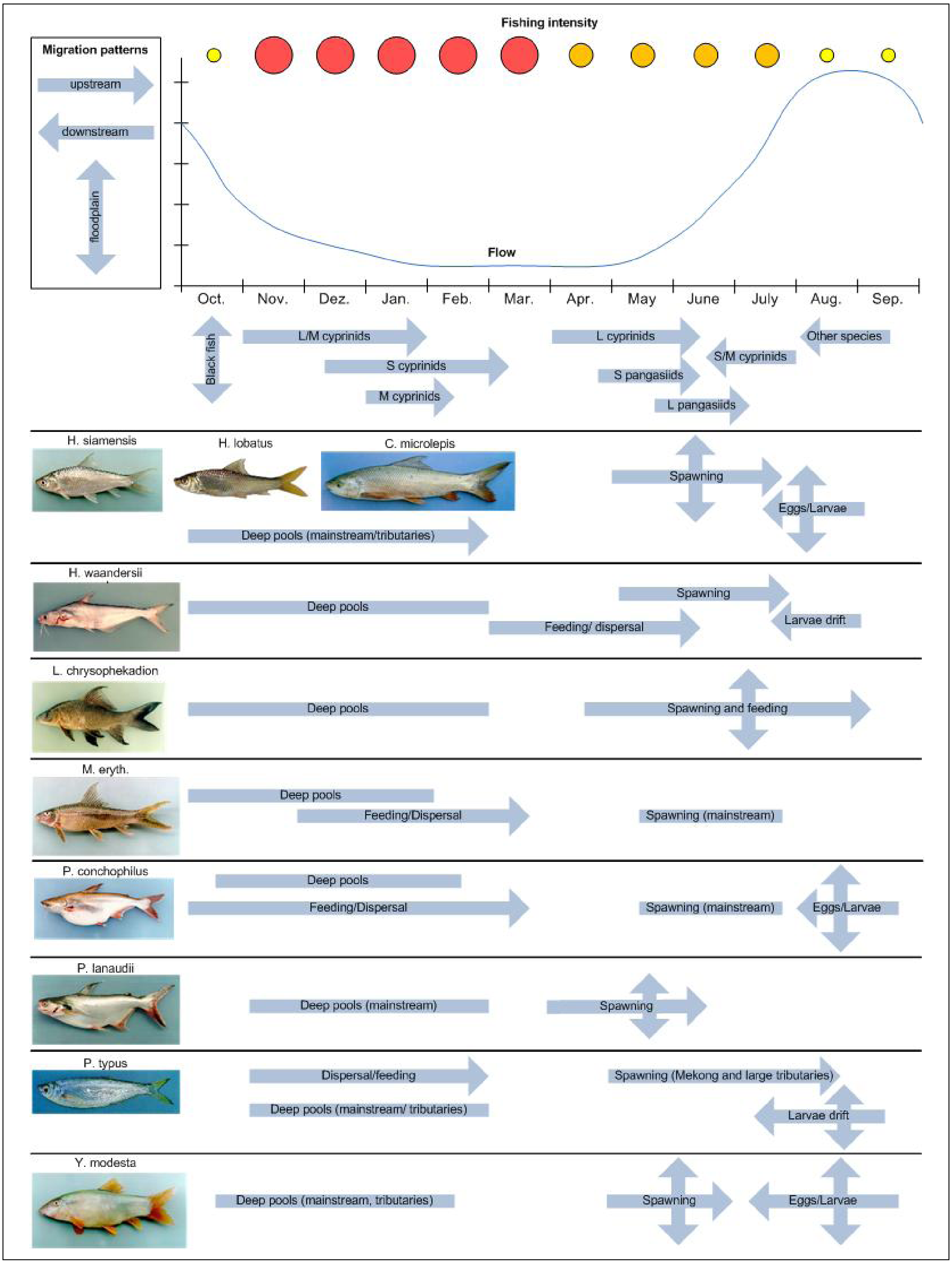

Figure 6: Major migration patterns below Khone Falls (based on Baran, 2006 and Baird, 2001) and main migrations of selected species (based on Poulsen *et al*., 2004 and fishbase.org) (The circles indicate the fishing intensity: red = high, orange = medium and yellow = low; the arrows indicate the main migration patterns (→ upstream,← downstream, ↕ floodplain; L = large, M = medium, S = small fish); pictures by T. Warren, C. Vidthayanon and T.R. Roberts).

2.1.2.1 Henicorhynchus siamensis (Siamese mud carp) and Henicorhynchus lobatus

H. siamensis and *H. lobatus* may be the most common species in the middle and lower Mekong (Roberts, 1997) and are also considered keystone species (Roberts & Baird, 1995, Roberts, 1997). While *H. lobatus* (≤ 15 cm length) is endemic to the Mekong, *H. siamensis* (≤ 20 cm length) can also be found in the Chao Phraya system. They inhabit the mainstream and tributaries between the Mekong Delta and the border between Lao PDR, Thailand and Myanmar. Given their similarities, these species are usually not separated in catch data. Other species from the family Cyprinidae, such as *Cirrhinus* spp. (e.g. *Cirrhinus jullieni*) and similar small cyprinids, are often combined in fisheries reports. Therefore, detailed knowledge exclusive to each species is still sparse.

It is assumed that there are many overlapping populations, including both long-distance and short-distance migratory fish. Data indicate that some of the most important migratory populations cover large areas of the Lower LMB (from Pakse to the Mekong Delta, including the Tonle Sap System). The population structure is assumed to be very complex and requires further investigation.

While some populations are reported to spawn in floodplains, others might spawn in river channels during mean flow (e.g. reported for *H. siamensis* in the Mekong and some large tributaries). Spawning occurs at the beginning of the flood season. Larvae and eggs are transported to nursery habitats on floodplains by flow. At the beginning of the dry season, the small cyprinids migrate to deep pools of the mainstream and large tributaries (e.g. Se San/Sre Pok/Se Kong). Maturity is gained in the first year. Due to the short life cycle, they are well adapted to environmental variability.

These small cyprinids are very important for dry-season migrations in the lower LMB when they migrate from the floodplain (Tonle Sap, Great Lake system) to the Mekong and beyond the Khone Falls, whereby large numbers also enter the Sesan/Sekong/Srepok system. Since these migrations are highly influenced by the lunar cycle, they occur in a short period (~5 days) around the full moon.

Figure 7: *H. siamensis* (picture by T. Warren)

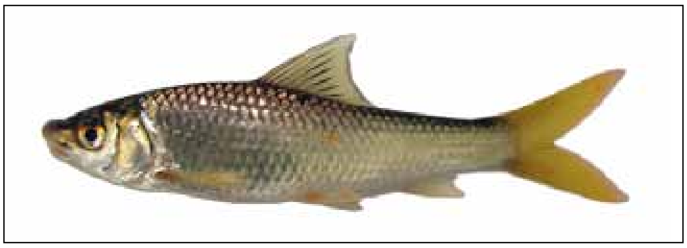

Figure 8: *H. lobatus* (picture by C. Vidthayanon)

These small cyprinids are one the most important group of species in many fisheries, as demonstrated by Poulsen *et al.* (2004), Baran *et al.* (2004) and in three data sets (DFMP, LTMP and FADMP) of Halls *et al.* (2013). They are especially important for the *Dai* fishery of the Tonle Sap River, where they represents approximately 50% of the total catch and are often caught in high numbers during their migration from November to February.

2.1.2.2 Cirrhinus microlepis (small-scale river carp)

Figure 9: *C. microlepis* (picture by T.R. Roberts)

Existing data suggest that two populations of *C. microlepis* are found in the entire LMB. The first population can be found between Loei and Chiang Saen and migrates upstream between May and August to spawn in the main river channel from June to July. The second population inhabits the stretch between Boulikhamxay in the north and the Mekong Delta. During the flood season, juveniles migrate to the floodplains (e.g. in southern Cambodia and Viet Nam, up through the Tonle Sap River) and adults move towards the spawning areas (e.g. at Patomphone village, 50 km downstream from Pakse in Lao PDR). Spawning is assumed to occur between June and July followed by a downstream drift of eggs and larvae towards the floodplains. When the water recedes, the fish return to the rivers and undertake large-scale upstream migrations to disperse and inhabit refuges in deep pools along the Mekong mainstream.

Above the Khone Falls, migration patterns are less clear. At Klong Kaem district, C. *microlepis* migrate upstream in February. In contrast, migration in further upstream areas takes place between March and April in Ubon Ratchatani at Khemmaratch and during May in Mukdahan. From Xayaburi to Chiang Saen, upstream migrations are documented from March to August, with a first peak of sub-adults between March and April and a second peak of adult migration towards spawning sites between June and July.

C. microlepis was documented in Poulsen *et al.* (2004), Baran *et al*. (2005) and the DFMP of Halls *et al.* (2013). *C. microlepis* is significant for fisheries during the dry season from January to March when it migrates upstream (Warren *et al.,* 1998 & Baird, 1998). During its downstream migrations (December - February), the species is valuable for the *Dai* fisheries in the Tonle Sap River (Lieng *et al.*, 1995). Furthermore, large adults are sporadically caught in the middle Mekong by gillnets (Poulsen *et al.*, 2004). According to the IUCN red list, the species is considered vulnerable.

2.1.2.3 Helicophagus leptorhynchus

Figure 10: *H. leptorhynchus* (picture by T. Warren)

H. leptorhynchus (≤ 79 cm length) occurs throughout the LMB with higher frequencies in the middle LMB (from Khone Falls up to the Loei River). Its habitat is found in the mainstream Mekong and its large tributaries (e.g. Se San/Sre Pok/Se Kong) (Rainboth, 1996). There may be several distinct populations associated with a particular tributary which use the Mekong mainstream as a habitat during the dry season (Poulsen *et al.*, 2004).

H. leptorhynchus is the first pangasiid species starting its upstream migration between March and May (peak of dry season) from the Khone Falls to northern Lao PDR and Thailand (1st peak). Most species performing this migration are still immature and migrate for feeding or dispersal. However the maturation age is still unknown. Spawning migrations occur in a second migration peak at the start of the wet season (May - June) in the Mekong mainstream and large tributaries (Poulsen *et al.,* 2004). Ovaries of female fish develop in the dry season until they are fully developed for the crucial months of spawning during the rainy season (May - July) (Jutagate *et al.,* 2007). After spawning, adults and larvae migrate to their feeding habitats. While adults feed on molluscs in the mainstream and large tributaries, larvae drift downstream to their nursery habitats, which are likely to be in the main river and not in the floodplains. During the dry season, both adults and juveniles inhabit deep pools in the Mekong (Poulsen *et al.,* 2004).

H. leptorhynchus was documented only in Poulsen *et al.* (2004). Nevertheless, it was selected because it is one of few fishes available during the late dry season (March – May) in the middle LMB.

2.1.2.4 Labeo chrysophekadion (black sharkminnow)

Figure 11: *L. chrysophekadion* (picture by T. Warren)

L. chrysophekadion is widespread in the entire Mekong Basin with possibly multiple populations associated with tributaries. At the beginning of the monsoon season (May - June), adult fish migrate towards the floodplains for spawning and feeding. When the water recedes, both adults and juveniles migrate back to refuge habitats in deep pools of the main river. While fish in the lower Mekong access the floodplains directly from the Mekong mainstream, fish in the middle Mekong migrate upstream in the Mekong to enter smaller tributaries and flooded areas.

L. chrysophekadion is considered an important species in the entire LMB and can also be caught in reservoirs as noted by various reports (Poulsen *et al.,* 2004; Baran *et al.,* 2005, three programmes included in Halls *et al.,* 2013).

2.1.2.5 Mekongina erythrospila (striped river barb)

Figure 12: *M. erythrophila* (picture by T. Warren)

M. erythrospila (≤ 45 cm length) is endemic to the Mekong Basin and inhabits the Mekong mainstream from Kratie up to the border between Lao PDR, Thailand and Myanmar. It can also be found in the Se San catchment. There are likely two populations in the Mekong mainstream: the northern population upstream from Xayaburi and the southern populations between Sambor and Makudahan, including the Se San/Sre Pok/Se Kong system.

Although knowledge is limited for this species, its habitat requirements are considered migratory as the species perform migrations around the Khone Falls up to Pakse from December to March (Warren *et al.*, 1998). Spawning most likely occurs in the Mekong mainstream at the beginning of the rainy season. Furthermore, feeding and dispersal migrations occur in big schools that include hundreds of fish, mostly together with other cyprinids and loaches (*Hypsibarbus* spp., *Scaphognathops* spp., *Cirrhinchus siamensis* and *Yasuhikotakia modesta*; Warren *et al.*, 1998).

With regard to fisheries, *M. erythrospila* was mentioned in Poulsen *et al.* (2004) and Baran *et al.* (2005) as an important species during dry season migrations (December – March) around the Khone Falls, the border between Lao PDR and Cambodia, and particularly the Se San/Sre Pok/Se Kong catchments. According to the IUCN, it is listed as near threatened.

2.1.2.6 Pangasius conchophilus (sharp-nosed catfish)

Figure 13: *P. conchiphilus* (picture by T. Warren)

P. conchophilus inhabits the LMB with one population assumed to be below the Khone Falls and one (or more) above the Khone Falls.

Spawning occurs at the beginning of the flood season in the Mekong mainstream from Kratie to the Khone Falls and further upstream. Larvae feed and grow in the floodplain habitats of southern Cambodia (also Tonle Sap) and the Mekong Delta. When the water recedes, juveniles migrate back to the Mekong further upstream beyond the Khone Falls to disperse. In the middle Mekong, juveniles migrate from the floodplain towards the Mekong mainstream or large tributaries. During the dry season, they inhabit deep pools in the main river.

P. conchophilus was mentioned in Poulsen *et al.* (2004), Baran *et al.* (2005) and all three programmes of Halls *et al.* (2013). It is considered important for fisheries around the Khone Falls, especially during the early flood season from May to July and also in the Middle Mekong for gillnet fisheries (Baird, 1998).

2.1.2.7 *Pangasius larnaudii* (black-spotted catfish, spot pangasius)

P. larnaudii (≤150 cm length) occurs basin-wide in large rivers and floodplains. The species is migratory and constitutes one single population in the lower LMB (Pakse to Mekong Delta, including Tonle Sap). Data are not available about the upstream population structure (Poulsen *et al.*, 2004).

Different opinions exist regarding their spawning habitat. According to Rainboth (1996), they spawn at the beginning of the rainy season in floodplains. Furthermore, Bardach (1959) suggests that their spawning habitats are in the Mekong River near Stung Treng whereby larvae reach the Bassac River (southern Cambodia) within 6 – 8 days. *P. larnaudii* was observed to migrate over the Khone Falls in spawning conditions leading to speculation of spawning grounds above the Khone Falls. Young fish feed in floodplain habitats during the rainy season. During the dry season, they inhabit deep pools in the Mekong mainstream (Kratie-Stung Treng reaches).

Figure 14: *P. larnaudii* (picture by T. Warren)

P. larnaudii is an easy target for fisheries because it can be seen near the water surface. It is included in Poulsen *et al.* (2004), Baran *et al.* (2005) and two programmes (DFMP, LTMP) of Halls *et al.* (2013). Together with *P. conchophilus,* it is most important in the wet season fishery (May – June) when fish migrate through Hoo Som Yai (channel at the Khone Falls; Singanouvong *et al.,* 1996), most likely for reproduction. The species is in third place after *P. conchophilus* and *P. krempfi* in the tone- and lee-trap fisheries at Ban Hang Khone (Khone Falls; Baird, 1998) but is also considered important throughout its remaining range of appearance (particularly in Cambodia).

2.1.2.8 Paralaubuca typus (pelagic river carp)

P. typus (≤ 18 cm length) occurs throughout the LMB and possibly in China. While there is one single population in the lower LMB (Khone Falls to Mekong Delta) which possibly migrates to several spawning sites, it is assumed that the middle LMB constitutes several populations associated with major tributaries. Furthermore, there seems to be a distinct population in the upper LMB (upstream from Loei River) (Poulsen *et al.,* 2004).

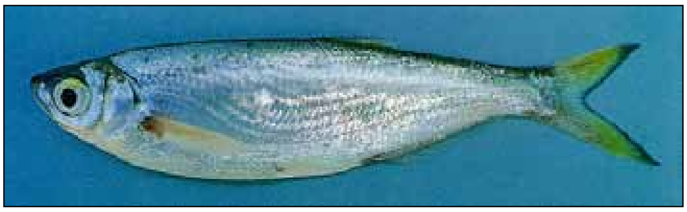

Figure 15: *P. typus* (picture by T.R. Roberts)

Spawning occurs at the beginning of the flood season (May – July) in the pelagic zone of the Mekong and large tributaries. Larvae and eggs are then transported to nursery habitats in floodplains (e.g. Tonle Sap system) and the Mekong Delta. The adults spend the wet season in the floodplain. At the beginning of the dry season, the adults return to the mainstream Mekong and larger tributaries (e.g. Tonle Sap River) where they inhabit deep pools. Starting from the Great Lake/Tonle Sap River system to the Mekong and upstream from the Khone Falls, dispersal migrations occur from November to February together with other small fishes.

P. typus was mentioned by Poulsen *et al.* (2004) and Baran *et al.* (2005). Considered an important species for fisheries, it is part of the specialised tone trap fishery at Ban Hang Khone in the Khone Falls area in southern Lao PDR (January – March; Baird, 1998) that focuses mainly on small migratory cyprinids. Furthermore, it is relevant for the *Dai* fisheries of the Tonle Sap (Lieng *et al.,* 1995).

2.1.2.9 *Yasuhikotakia modesta (redtail botia)*

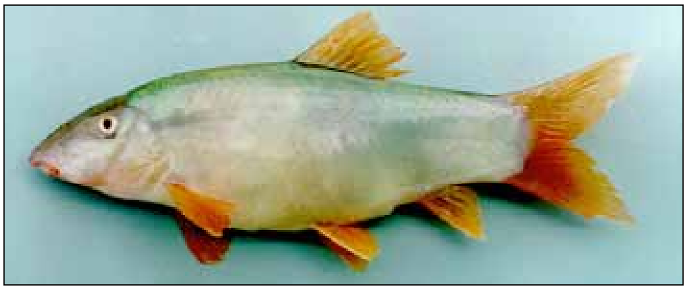

Figure 16: *Y. modesta* (picture by T. Warren)

This species occurs basin-wide from the Mekong Delta to the border between Lao PDR, Thailand and Myanmar. It inhabits most rivers in the Mekong Basin with possibly several populations associated with different tributary systems. It is also found in reservoirs (Poulsen *et al.*, 2004).

During the dry season, *Y. modesta* inhabits deep pools in the Mekong mainstream and lower reaches of large tributaries. Spawning takes place in May and June with possible spawning habitats in upper reaches of tributaries or floodplains. At the beginning of the dry season, they return to the main river.

Y. modesta was mentioned in all three reports (Poulsen *et al.*, 2004; Baran *et al.,* 2005; Halls *et al.* 2013). From January to March, *Y. modesta* is one of the most important species for the tone trap fisheries at Ba Hang Khone (Baird, 1998).

2.1.3 Migratory behaviour, orientation and swimming capabilities

An important factor in the planning of fish passes is the swimming capability of fish species (Williams *et al.*, 2012). The swimming speed is not consistent but rather depends on influencing factors such as body shape, size, muscular system, oxygen saturation, water temperature and behaviour (Wardle, 1975; Beamish, 1978; Jens *et al.*, 1997; Videler & Wardle, 1991; Videler, 1993; Hammer 1995). Furthermore, the swimming speed of a fish in relation to its environment also depends on flow velocity (DWA, 2010). The swimming abilities can limit the use of habitats or fish passes (Sambilay, 1990; Bandyopadhyay *et al.*, 1997; Gerstner, 1999). The swimming speed is expressed in body length per second (BL/s) (DVWK, 1996; Jens *et al.*, 1997; ATV-DVWK, 2004) and can be categorised into four groups depending on its duration (Beamish, 1978):

- Sustained swimming speed is used for normal locomotion and can be sustained for a long time (> 200 min) without fatigue of the muscles. This speed is approximately 2 BL/s (DWA, 2005) and is usually used for migration.

- Prolonged swimming speed can only be sustained for shorter periods (20 sec to 200 min) and leads to fatigue of the muscles.

- Burst swimming speed can be sustained by the use of anaerobic metabolism of the muscles for very short periods (< 20 sec) and has to be followed by a relaxation phase.
    - According to Clough & Turnpenny (2001), the critical burst swimming speed is the speed at which a drift occurs after 20 seconds. New approaches note that this speed is used for ecohydraulic planning (Clough *et al.*, 2001; Clough & Turnpenny, 2001; Turnpenny et *al.*, 2001; Clough *et al.*, 2004; Watkins, 2007). SWIMIT 3.3 (Jacobsaquatic, 2006) is a special software used to calculate swimming capability of fish species, fish size and water temperature. Approximations for salmonids are 10 BL/s and for cyprinids 4 – 5 BL/s (e.g. roach with 15 – 30 cm or bream with 20 – 50 cm BL, Jens *et al.*, 1997).
- Maximal burst swimming speed is the theoretically maximal achievable speed of a certain fish. Maximum burst swimming speeds are 2 – 3 m/s for brown trout or 0.7 – 1.5 m/s for cyprinids (Jens, 1982; Jens *et al.*, 1997). This speed can be relevant for the possibility of bottlenecks in a fish pass.

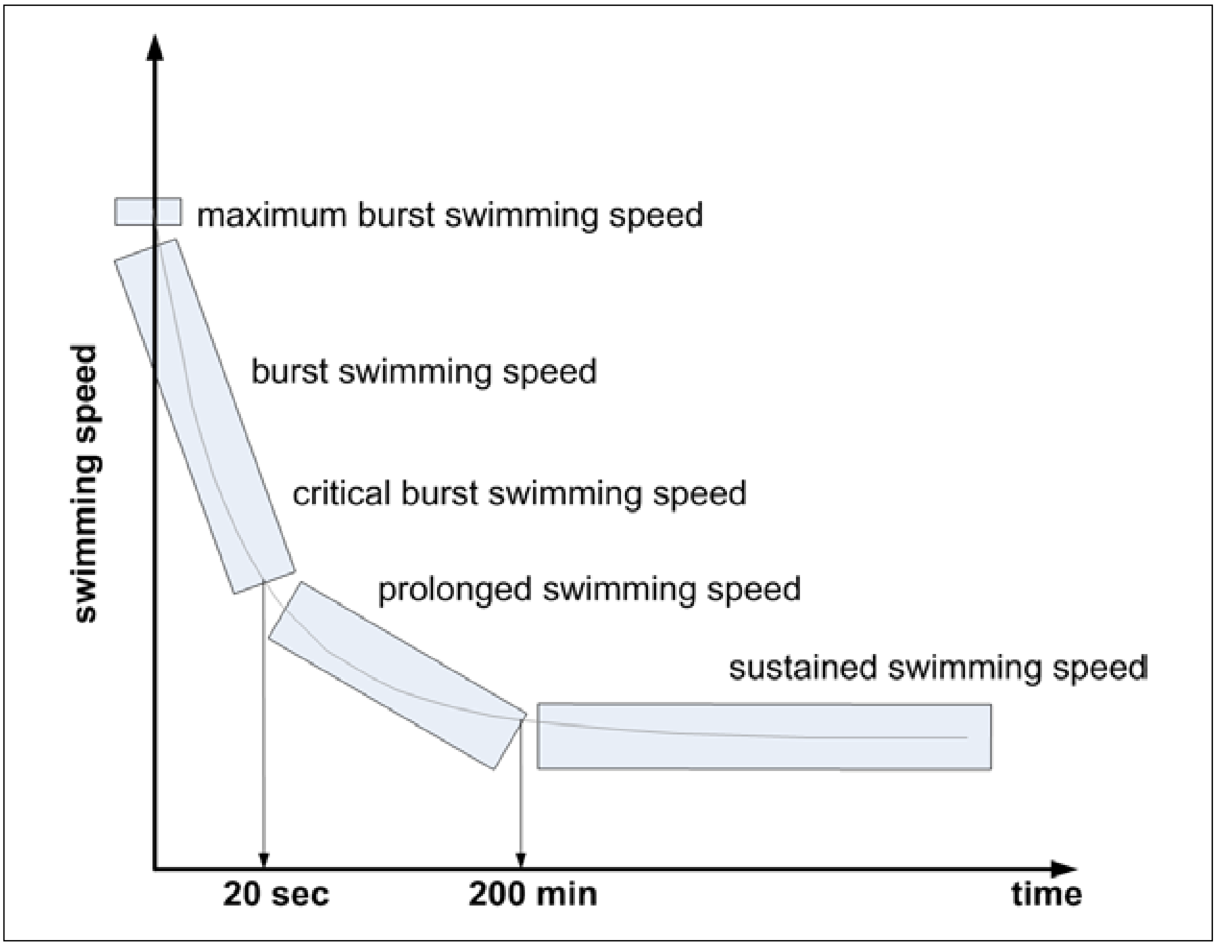

Figure 17: Relation between swimming speed and its duration (adapted from BMLFUW, 2012, based on Pavlov, 1989 and Clough & Turnpenny, 2001)

The (critical) burst swimming speed of the "weakest swimmer" within the river-specific fish fauna should be used to define the thresholds of flow velocities within the migration corridor of a fish pass. The "weakest" are usually juveniles and small fish species (BMLFUW, 2012).

Effective fish passes in large dams in the Mekong require consideration of diverse species with different sizes and swimming capabilities. Consequently, fish pass facilities would need to accommodate small-sized species, those with weak swimming capabilities, and large fish. Among Mekong species, the swimming capabilities of "weak" species and age classes can be estimated based on experience from temperate rivers. Nevertheless, specific data on the swimming capabilities of fish in tropical rivers are required.

Fish use all their senses for orientation. For orientation in the immediate environment and the alignment of the swimming direction (e.g. upstream), the optical and tactile senses as well as the lateral line organ are highly important. The relevance of hearing is currently inconclusive. However, flow conditions and underwater structures are known to show typical acoustic signatures, which also might act as orientation guides. The terrestrial magnetic field guides diadromous fish species in the sea (e.g. Atlantic salmon (Rommel & McCleave, 1973, Varanelli & McCleave, 1974) and European eel (Tesch & Lelek, 1974, Tesch *et al.*, 1992). The sense of temperature and smell are relevant in identifying specific rivers and may also serve as triggers for migration (Hasler & Scholz, 1983).

The perception of flow, orientation and swimming behaviour of fish can be summarised as follows: all fish are able to detect flow, use it for orientation and swim towards it (positive rheotaxis) (Lucas & Baras, 2001). If the flow velocity is below a species- and age-specific threshold (i.e. between 0.15 and 0.30 m/s; see also Table 13 in Annex), fish lose their positive rheoactive orientation (DWA, 2010). Therefore, the flow velocity in the migration corridor should be larger than the rheoactive velocity.

In general, fish migrate upstream in or parallel to the main current as long as their swimming capabilities allow it. They primarily use the flow that acts directly on their body for orientation while laterally-occurring weaker flows remain unnoticed. If flow paths with different velocities intersect, fish mostly choose the current with the highest velocity for orientation. If fish cannot find an appropriate way upstream, they start a lateral search for opportunities. However, the search radius is reduced to the border zones of the main current (Seifert, 2012). These factors should be considered in designing the dimensions of the attraction flow and the location of fish pass entrances (see Chapter 3.1.2). Furthermore, highly turbulent flow conditions, reverse flows or still waters (e.g. in a reservoir) can disturb or interrupt the upstream orientation of fish (Pavlov *et al.,* 2000). Tropical rivers are characterised by a large variation of flow. Thus, in large dams in tropical rivers, turbulent flows may occur across vast areas below turbines and spillways and lead to impairment of orientation among fish (see also Chapter 6).

In addition to these important factors for orientation, the selected migration corridor depends on species-specific preferences, morphology and structural characteristics of the river. Fish show different behaviour during upstream migration and can be classified based on their preferred migration corridor as (1) mid channel, (2) shore line, (3) close to the bottom or (4) mid-water or surface orientated. For bottom-dwelling species, vertical drops of only several centimetres can represent migration barriers

(Utzinger *et al.,* 1998). While only a few species such as salmon are able to overcome barriers by leaping, other species that overcome barriers by swimming require a water column with sufficient depth. In diverse fish communities such as in the Mekong, all aforementioned types of fish migration are represented. Therefore, fish pass solutions should provide multiple migration corridors along the riverbed, in mid-channel sections, along the shore line, within the mid-water column and at the surface.

In large dams, the areas where fishes are attracted by high-flow velocities (below turbines and spillway), the entrances of fish passes must be relatively close. Such design prevents fish from spending much time and energy searching for the entrances (see also Chapter 3.1.2.4).

3 Upstream migration

3.1 Current state of knowledge

Fish passes are structures supporting fish and other aquatic organisms to overcome an artificial barrier (Jungwirth & Pelikan, 1989). Fish passes have been built for more than 100 years. The first installations focused on commercially important fish species such as salmon. In recent decades, migration has been recognised as important for most riverine fish species (Lucas & Baras, 2001). Therefore, fish passes should be designed for all fish species that depend on migration to fulfill their life cycle (Jungwirth *et al*., 1998). In this context, knowledge of fish's response to certain conditions and factors that attract and repel them is critical for a successful fish pass design (Williams *et al.,* 2012).

Accordingly, research has increasingly focused on such fish passes and, in particular, their functionality, perceptibility and passability (Cooke & Hinch, 2013). This report draws on existing research on upstream fish passes, literature in the USA, albeit largely focusing on salmon, as well as Austrian and German guidelines (e.g. BMLFUW, 2012; Seifert, 2012; DWA, 2010, draft), being more multi species-oriented and therefore providing helpful information for the Mekong River. In addition, case studies from South American rivers with diverse fish fauna and high productivity can provide important insights for the Mekong and the role of fish passes as mitigation measures for large dams (Agostinho *et al.,* 2007d, 2011, 2012; Makrakis *et al.,* 2007a, 2007b, 2011; Pompeu *et al.,* 2006, 2007 and 2011).

In spite of this growing academic and technical interest in fish passes over recent decades and the development of new technologies such as fish lifts, fish-friendly turbines or natural fish passes with promising technical innovations, most fish passes are still built for small or medium-sized dams (<15 m height). Large dams, on the other hand, remain a challenge – in temperate but especially in tropical rivers. Knowledge of fish pass solutions for large tropical rivers such as the Mekong River remains limited. Overall, information and experiences from fish passes in the Mekong are extremely limited, with only very few case studies existing for Thai tributaries to the Mekong (Mun-Chin and Nam Kan) and Stung Chinit, a tributary of the Tonle Sap in Cambodia (e.g. Roberts 2001, Baran et *al.,* 2007, Amornsakchai *et al.,* 2000).

Based on the available research, the following twelve principles for effective fish passes can be identified (Baumann & Stevanella, 2012), especially for rivers where ecological knowledge is limited and examples of functional fish passes are not available yet:

1. Increase/investigate knowledge on fish (e.g. requirements, behaviour and life cycle);

2. Get to know the project (technical, economic, financial aspects);

3. Investigate the applicability of existing standards;

4. Adapt existing fish pass designs (if knowledge of fish species is missing, design ranges derived from other projects can serve as the basis);

5. Allow for the possibility of adjustments in the overall design;

6. Allow for a continuous monitoring of fish;

7. Allow for the possibility of trapping and analysing fish;

8. Identify unanswered questions and define research needs;

9. Address concerns related to fisheries management;

10. Participate in technical cooperation and communication;

11. Consider opportunities and possible threats; and

12. Apply an adaptive approach to project management.

Likewise, Mallen-Cooper (1999) suggested the following steps for assessing the efficiency of fish passes (and the potential need for adaptation) for non-salmonids:

1. Identification of migratory fish species;

2. Testing of fish species in experimental fish passes (different settings such as slope, flow velocity, turbulence);

3. Design and construction of fish passes based on test results; and

4. Assessment of fish passes.

These lessons learned from other basins do, however, require adaptation to the Mekong. Since fish pass solutions implemented in other regions have not always been successful, Thorncraft *et al.* (2005) recommended the development of specific fish pass solutions for the Mekong, starting with design criteria for small barriers (including field experiments) and the adaptation of knowledge gained to large dams.

The following sections focus on three key criteria for effective upstream fish passes – (1) fish pass functionality, (2) fish pass perceptibility and (3) fish pass passability.

3.1.1 Functionality of fish passes for upstream migration

Efficiency examines overall passage efficiency of individuals or species at fish passes, i.e. proportion of individuals successfully passing a fish pass or number of species within a community observed passing a fish pass (Castro-Santos *et al.,* 2009; Roscoe & Hinch, 2010). In contrast to "efficiency", the qualitative assessment of the ability of a fishway to pass target species has been called effectiveness (Larinier, 2000). Odeh (1999) proposed three sequential components of assessing the functionality of a fish pass relevant to both up- and downstream migrations: attraction, passage itself and post-passage effects.

A fish pass should be functional all year round to meet the migratory requirements of seasonal spawning runs and to enable habitat shifts in other periods (BMLFUW, 2012). Research on temperate rivers shows that there are periods during which fish migration is less important or extreme hydrological conditions (high flows, low flows) might occur that prevent the operation of a fish pass. This necessarily reduces the functionality of a fish pass. It is, however, suggested that fish passes should operate at least 300 days per year (between Q_{30} and Q_{330}[1]; BMLFUW, 2012; DWA, 2010). Given the different conditions in tropical rivers, adaptation might be necessary.

In any case, however, fish passes should be functional as many days as possible, especially when reproduction migration occurs. For the Mekong, for example, the functionality of fish passes in rivers with Jullien's barb (*Probarbus jullieni*) should be guaranteed in low-flow situations because these species migrate to spawn during the dry season. On the other hand, for species migrating during the wet season (majority of migrating species), functionality has to be guaranteed for higher flows.

Moreover, even in periods when the fish pass itself is not fully functional due to extreme hydrological conditions, sufficient flow should be provided to ensure the survival of the fish in the fish pass (BMLFUW, 2012).

In addition to time-related functionality, fish passes should support the majority of fish in their migration, enabling all types of species, life stages and fish sizes to pass the barrier.

The size of a fish pass will depend on the size of a fish species. The largest species of the species with the highest space demand thereby function as size-decisive species, determining the size of the fish pass. This in turn depends on the regional fish fauna (see Chapter 4.1.3).

3.1.2 Perceptibility of fish passes for upstream migration

Perceptibility of fish passes refers to fish finding the entrance of a fish pass. This is a key challenge for the effectiveness of a fish pass because unfavourably located fish pass entrances can make a fish pass inefficient or cause time delays in migration because fish need more time to find their way upstream (Agostinho *et al.,* 2002). This is particularly problematic when several consecutive barriers with unsuitable perceptibility intensify the time lag. As a consequence, fish may not reach the reproduction habitat in time which can cause reproduction losses or even extinction of the species (DWA, 2010).

This section therefore studies the perceptibility of fish passes in more detail by looking at the key elements of perceptible fish passes, most notably the position of a fish pass and its entry, the operational discharge of a fish pass, the influence of different water levels at the a fish pass entry,

[1] Flow exceeded at 30/330 days a year

different fish passes and entry types as well as the specific case of large nature-like fish passes and bypass systems. While general lessons learned can be drawn from international experience, detailed documentation of a specific project (including knowledge on the flow regime, hydraulic conditions at the barrier/hydropower plant, competitive flows and the requirements of the local fish community) is necessary to understand the functionality of a fish pass in detail and ensure its overall effectiveness.

3.1.2.1 Position of a fish pass and its entry

Francis (1870) emphasised that even the best designed fish passes are not functional if fish cannot find the entrance in time. Fish pass entrances should have characteristics that attract fish to enter (Denil, 1909; McLeod & Nemenyi, 1941) or at least do not repel them (Williams *et al.*, 2012). The conditions should mirror a continuation of the preferred migratory pathway. Upstream migrating fish prefer areas with high-velocity gradients because they are present on the edges of the main water body (shoreline or river bottom). Downstream migrants, however, seem to avoid these areas and prefer to migrate in the area with the highest flow volume and velocity (Williams *et al.,* 2012).

In large rivers with a width greater than 100 m, at least two fish passes on either side of the dam should be built to ensure the perceptibility for all fish species (Larinier *et al.,* 2002). Some fish migrate along banks or are forced to migrate toward the banks (e.g. by strong turbulent currents induced by the hydropower operation), thus requiring an entrance in these areas. Furthermore, several entrances can be included in one fish pass to provide favoured conditions for different species.

At least two upstream fish passes (one at either side) should be constructed for mainstream dams on the Mekong that would commonly be several hundred metres wide. However, additional fish passes (e.g. fish lifts/locks in the middle of the river) should be considered to increase the overall efficiency of fish passage.

Regarding the most suitable position of a fish pass, the purpose of the barrier should be taken into account. The following situations should be considered (DWA, 2010; Seifert, 2012):

- Barriers without water use: competitive currents are absent in this situation. Controllable weirs can be used to attract the fish to one river side. In general, a fish pass should be situated close to the shoreline and the main current (i.e. undercut bank). This type of barrier might not be present in the Mekong because dams for flood control do not allow the release of extensive amounts of water without loss of their general purpose.

- At diagonal barriers, a fish pass should be situated on the river side with the pointed angle where fish usually gather (see Figure 18 and Figure 22a).

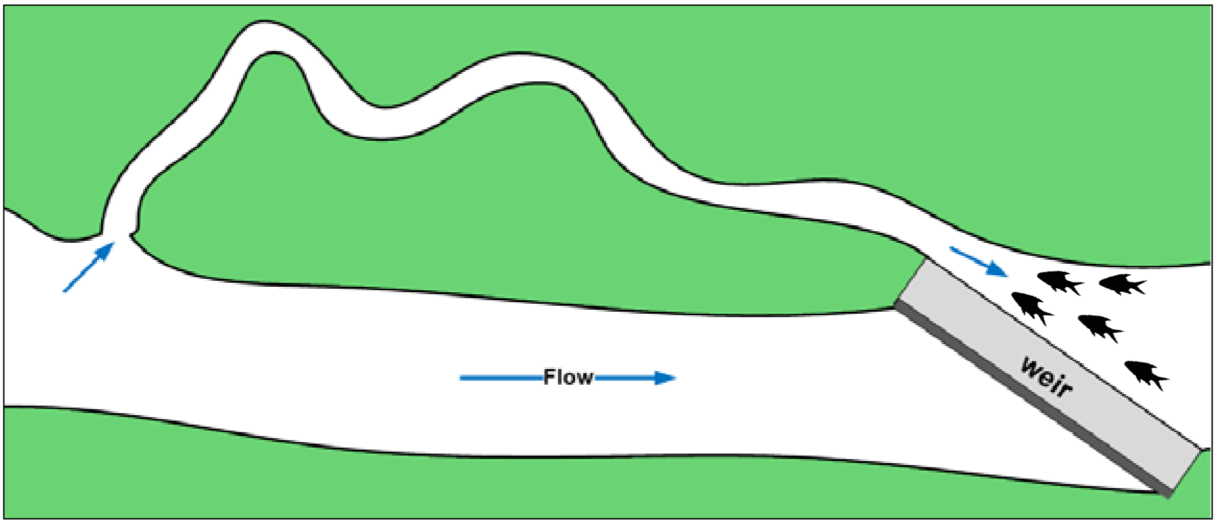

Figure 18: Upstream fish pass entry in the pointed angle of an oblique weir (adapted from Dumont *et al.,* 2005)

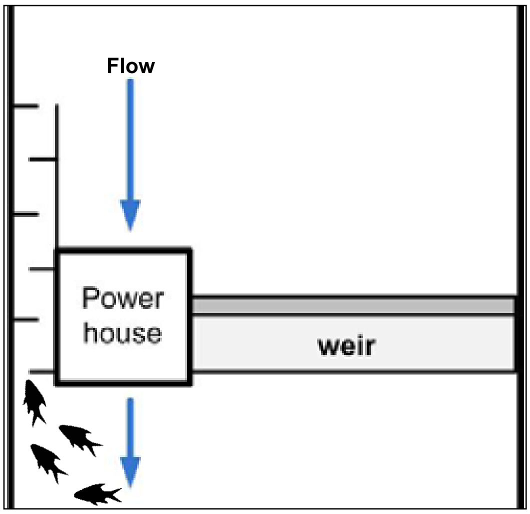

Figure 19: Location of upstream fish pass close to a power house (based on DWA, 2010)

- Barriers with hydropower plant: in most cases, the main current of the hydropower plant leads fish towards the power house (i.e. turbines). Therefore, a fish pass should be located close to the power house and the shoreline (see Figure 19). This might be the case for fish passes on tributaries of the Mekong. For the Mekong itself, at least two fish passes (as mentioned above) should be included.

- Barriers with water diversion represent a special challenge because fish usually follow the main current that leads them into the tailrace channel. The main channel often contains residual flow that provides only limited attraction flow in comparison to the water coming from the hydropower plant. Since most fish will follow the tailrace channel, fish passes located in the main channel (at the diversion weir) might have reduced functionality. The flow velocity in the main channel during low flows might not provide the required rheoactive velocity or sufficient depth for fish to migrate upstream. To address this issue, two fish passes could be constructed with one at the diversion weir and one at the power house. It is unlikely that diversion type dams are planned for the Mekong River.

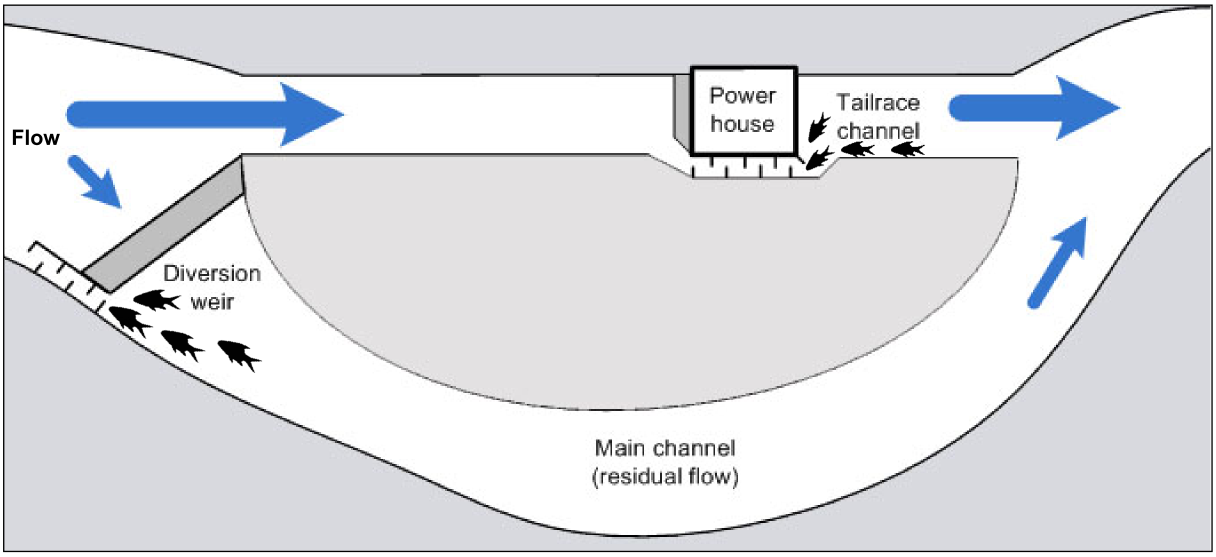

Figure 20: Location of upstream fish pass for diversion hydropower plants (based on DWA, 2010)

- For large weirs, the construction of two fish passes may be required (see Figure 21). This is the case for mainstream Mekong dams. For large tributaries of the Mekong, at least two fish passes may be required to “pick up” all fish searching for a possibility to migrate upstream.

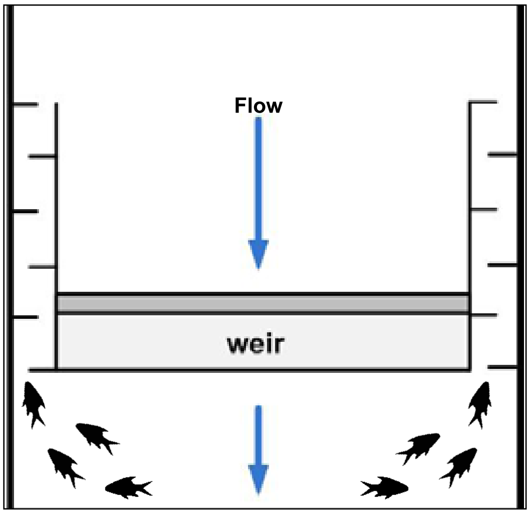

Figure 21: Location of upstream fish pass if both sides are equal or for large weirs (adapted from DWA, 2010)

As noted above, the entry of a fish pass should be easily and quickly recognised by upstream migrating fish. In addition, the eco-hydraulic conditions (e.g. attraction flow, competitive currents) should be planned in a way that fish are guided into the fish pass and not to a dead-end towards the barrier.

There is at least one optimal position of the entry which lies in the interface between the downstream limits of the barrier (or the turbulent zone) and the longitudinal migration corridor (Dumont *et al.,* 2005). Directly at the fish pass entry, the attraction flow should be as parallel as possible (<30°) to the main current (DWA, 2010).

The location of the entry is discussed by several authors and guidelines (e.g. BMLFUW, 2012; DVWK, 1996; Adam & Schwevers, 2001; Gebler, 2009; Dumont *et al.,* 2005 and Larinier *et al.,* 2002). The approximate location can be determined by the following parameters:

a) Within or in close proximity to the migration corridor;

b) Close to the barrier but downstream from the area with high turbulence (below white water zone);

c) Close to the shoreline;

d) On the side of the main current (outer bank);

e) On the side where the hydropower plant is located;

f) On the side of the turbine outlet close to the end of the suction hose and parallel or in pointed angle (<30°) to the current coming from the head race;

g) Regarding bottom-dwelling fish, a continuous connection to the river bottom is very important (bottom ramp with slope <1:2) (see Chapter 3.1.3.3); and

h) For diagonal weirs, the pointed angle of the weir (upstream view) might be more suitable (see Figure 22, left diagram– correct, middle and right diagram – incorrect.

i) For centred turbine outlets or if the optimal location is not clearly visible, it might be necessary to include two entries (one at the side and one in the middle) (Larinier *et al.,* 2002). Several entries are also suitable to cover the requirements of species with different migratory demands.

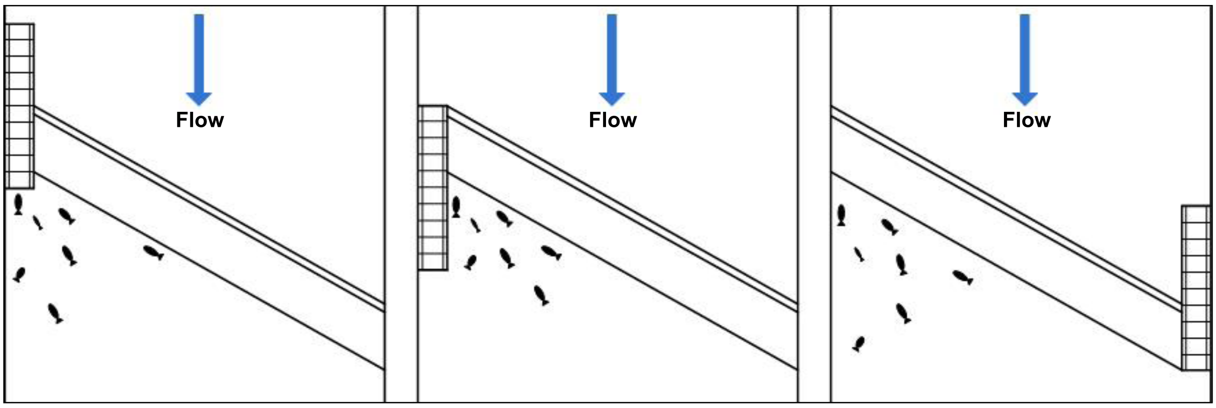

Figure 22: Schematic plans illustrating the installation of an upstream fish pass at an oblique weir (adapted from Larinier, 2002a).

Although these recommendations provide general guidelines on how to define the optimal location of fish passes, all flow and hydraulic conditions at the location should be considered. This assessment can inform the optimal solution related to the biological requirements for fish. During high flows, the main flow should be released in the middle of the dam because fish may prefer migrating outside of the area with high-flow velocity and turbulence. In contrast, during low flows, the main flow should be released close to a fish pass to guide the fish towards the fish pass entry (DWA, 2010).

Defining the appropriate location for a fish pass in large rivers such as the Mekong is a challenge because the optimal positions are limited to particular locations. The number and area of optimal locations do not increase with the river width. As such, the potential for creating deadends where fish are trapped increases with the dimension of the river.

3.1.2.2 Operational discharge and attraction flow

The perceptibility of a fish pass is crucial for its success. The adequate discharge for a fish pass is a result of the criteria defined in the previous chapters. The overall discharge (Q_{tot}) is the sum of the required operational discharge (Q_O) and additional discharge for attraction flow (Q_a). While Q_a depends on many factors that are not possible to capture entirely in a formula, Q_O can be calculated hydraulically with regard to the morphometric thresholds of the fish pass and the slope (see Chapter 3.1.3; Seifert, 2012).

If (Q_O) is not sufficient to attract fish, attraction flow is used to increase the perceptibility of the entry. The attraction flow connects the downstream river section with a fish pass. Since especially rheophilic fish species follow the main current, the attraction flow should be connected to the main current of the river (Zitek *et al.,* 2008). However, juveniles, stagnophilic and indifferent species may prefer a different position of the entry because they usually migrate in areas with lower flow velocity or closer to the shoreline (Ecker, 2000; Zitek *et al.,* 2008). For large rivers with several species that have varying swimming capabilities, several entries or collection galleries might be required (Larinier *et al.,* 2002, Dumont *et al.,* 2005).

The functionality of the attraction flow is related to the flow velocity, flow volume and the position of the entry. The amount of attraction flow is usually kept to a minimum, since more water volume requires a larger fish pass leading to higher costs and more water for the fish pass leads to a reduced water supply for energy production.

The attraction flow coming from a fish pass has to be actively recognised and tracked by fish, which is the case if its velocity is high enough or comparable to the competing current in the vicinity of the entrance. The flow velocity of the attraction flow should be between the rheoactive velocity and the critical velocity (see Chapter 2.1), i.e. 0.7 – 0.8 times the critical velocity (Pavlov, 1989; BMLFUW, 2012). According to Pavlov (1989), flow velocities between 0.7 – 1.0 m/s are suitable for most potamal species. BAFU (2012) recommends velocities at the entrance of 0.8 – 1.5 m/s. Salmonids and anadromous species prefer higher flow velocities of 2.0 – 2.4 m/s (Larinier, 2002a). An attraction flow of 1.0 m/s might still attract species with high swimming performance without excluding weaker fish (DWA, 2010). To ensure suitable conditions for all species, two entries with different flow velocities might be advantageous for the functionality of fish passes in particular situations (DWA, 2010).

The attraction should be able to compete with the flow coming from the power house or the spillways. Since these flows vary over time, the attraction flow can be adapted to the actual conditions to keep the losses of hydropower production at a minimum. Sufficient attraction flow is critical in times of high migration. As upstream migrations often coincide with high water levels, the conflict with hydropower production can be minimised.

Guidelines for functional attraction flow are given in DWA (2010) and Seifert (2012) as follows:

- Low turbulence (consideration of turbulence caused by the turbines).

- No interruption of the current towards the entry of a fish pass to provide a "connected" migration corridor.

- Higher velocity than the competing current but without exceeding the maximum swimming capabilities of critical species.

- A low angle between the migration corridor and the competitive main current (<30°). At higher angles, the attraction flow might be dissolved by the turbulence of the main current. Examples of fish passes with unacceptably large angles between the entry/attraction flow and the main current are the Canal da Piracema (60° angle) or the Porto Primavera Dam (45° angle), which are both located on the Paraná River (South America) (Makrakis *et al.,* 2007a; 2007b, see Chapter 3.2.3.1).

- High impulse of the flow (as product of volume and flow velocity, based on Larinier, 2002a). While the flow velocity is restricted to the swimming capabilities of fish with low performance, the water volume can be increased to optimise the attraction flow in comparison to the competitive flow (DWA, 2010).

An attraction flow of approximately 1 – 5% of the competing flow might be sufficient if the fish pass and its entrance are in an optimal position (Larinier, 2002b; Bell, 1980; Larinier *et al.,* 2002; Dumont *et al.,* 2005; Larinier, 2008). However, depending on the local conditions, recommendations for attraction flow may account for 5 – 10% of the total discharge (Williams *et al.,* 2011). Increased attraction flows might be required if the fish pass is not ideally located (Calles & Greenberg, 2005; Larinier, 2002a).

As an example, additional attraction flow is usually required only for rivers with a MF > 25 – 50 m³/s. For large rivers like the Mekong, where 1% of the MF would result in a very high flow, individual considerations are recommended (BMLFUW, 2012).

For the Xayaburi case study, 1 – 10% of the low, mean and high flow would result in the following values:

Table 1: Estimated attraction flow required for sample case study

Xayaburi	River flow	1% of flow	5% of flow	10% of flow
Dry season	2,000 m³/s	20 m³/s	100 m³/s	200 m³/s
Mean flow	3,971 m³/s	40 m³/s	198 m³/s	397 m³/s
Wet season	10,000 m³/s	100 m³/s	500 m³/s	1,000 m³/s

Since the operational discharge of a fish pass serves mainly the passability of the fish pass, it might not be sufficient to act as attraction flow. If this is the case, additional flow can be introduced into the lowest pool of the fish pass to enhance the attraction flow. However, the introduced water should be stilled (sufficient energy dissipation) before released into the fish pass. Furthermore, the water has to be adequately degassed (Larinier, 2002a) and measures should be taken to prevent fish from migrating into the inlet of the attraction flow (DWA, 2010; Seifert, 2012).

There are two possibilities to increase the attraction flow at large rivers:

1. Installation of a small hydropower plant to increase attraction flow, which also produces additional energy (see example of the fish pass in Iffezheim on the Rhine River, Chapter 3.2.6.2).

2. Installation of special pumps that use water coming directly from the forebay together with water from the tailrace to reinforce the attraction flow (see Figure 23). Such an attraction flow pump was developed and patented by the University of Kassel (Germany, Hassinger s.a.).

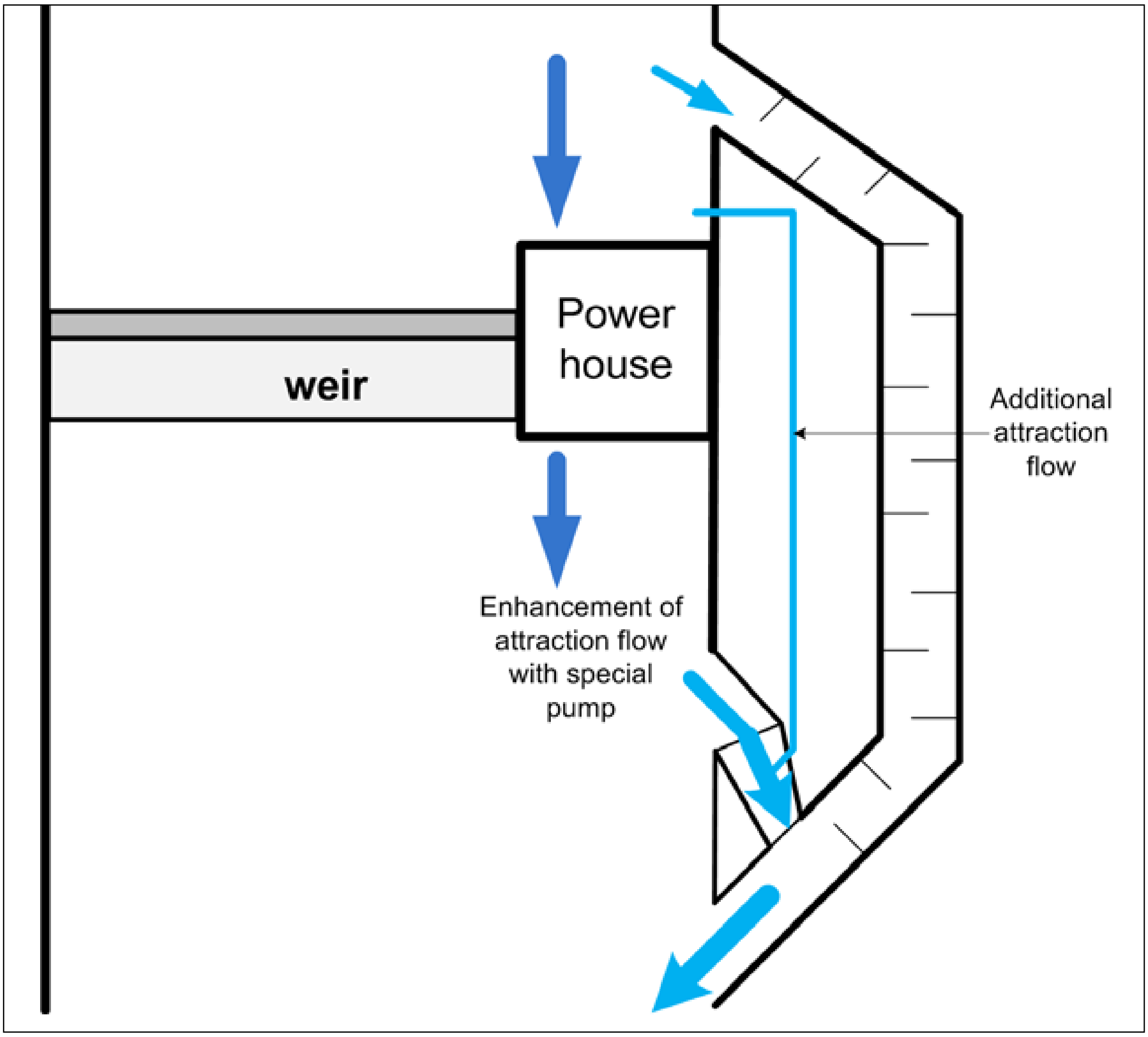

Figure 23: Schematic sketch of attraction flow pump (adapted from Hassinger 2008)

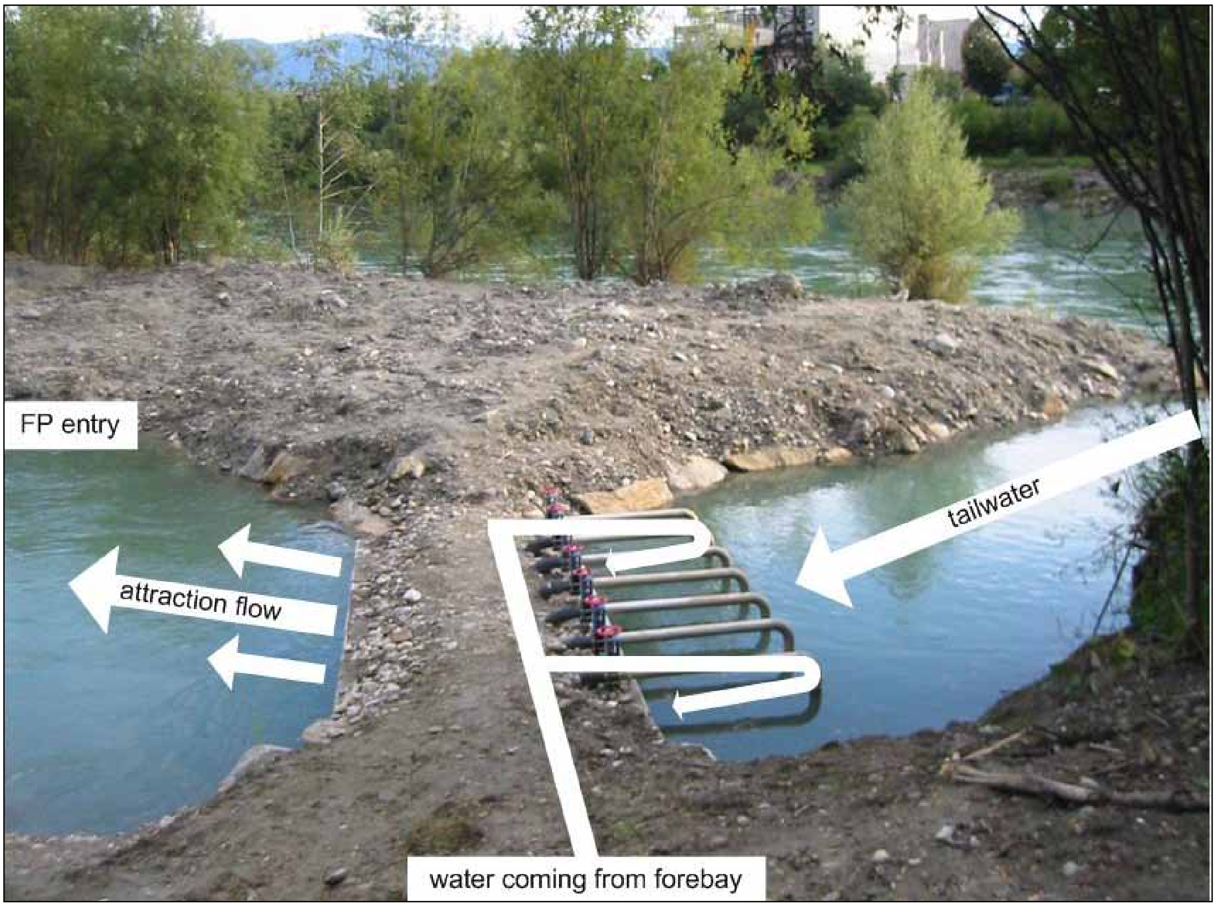

Figure 24: Attraction flow pump in operation (Universität Kassel s.a.)

The pump is based on the Venturi principle. It utilises a small, but energy-rich flow from the forebay to set a larger flow into motion. The water coming from the forebay is accelerated due to the level difference, exits at several jets and takes additional water from the tailwater. This design, including an increase in width, leads to a reduction of velocity. The pump is designed to prevent fish entry. Only 25% (for low head dams) to 10% (head > 8 m) of the difference between the operational discharge and the required attraction flow are needed from the forebay water (jet) while a large proportion enters from the tailrace (Hassinger, 2008, 2011).

Such an attraction flow pump was installed on the River Drau in Villach (Austria) and showed promising results. In the River Drau, the attraction flow should account for approximately 1,600 l/s but the operational discharge requires only 325 l/s (difference = 1,275 l/s). The attraction flow pump could process around 116 l/s (~9 %) thereby enhancing the movement of around 1,160 l/s from the tailrace. In total, the operational discharge, the discharge from the pump and the discharge from the tailrace would account for the required 1,600 l/s. As a consequence, the flow for energy production is only reduced by ~441 l/s instead of 1,600 l/s. As losses are kept to a minimum, attraction flow is enhanced. The system has not been tested yet for large rivers (Hassinger, 2008, 2011). However, it is likely that this principle also applies for large rivers such as the Mekong though additional tests are needed.

3.1.2.3 Perceptibility of fish pass entry at different water levels

Proper positioning of a fish pass entry under changing water levels requires expert knowledge and experience. An increase of the tailwater level can cause an inundation of lower pools of a fish pass. This can lead to the loss of the attraction flow at this location while the actual entry at the end of the fish pass becomes untraceable for fish. Unfortunately, there is no overall solution for this problem. Therefore, fish passes should be designed to at least function during the main migration periods and the respective flows (see Chapter 3.1.1). However, for all flows and water levels between Q_{30} and Q_{300}, requirements related to maximum flow velocities, attraction flow and minimum depth should be addressed during the planning of a fish pass (DWA, 2010). Thus, technical solutions to optimise the perceptibility for a certain range of variation are required (DWA, 2010; Seifert, 2012):

1. Fish passes with adaptable discharge (over the entire fish pass or by means of an additional attraction flow at the lower part): adjustable sluices or additional water intakes are only possible for rectangular pools with sufficient high walls. Furthermore, the walls of the most downstream pool (entry) have to be higher than the highest water level.

2. Fish passes with several entries: various entries for different levels are included. The entries are locked or opened on demand by regulatory devices (i.e. high controlling effort).

Such solutions require detailed hydraulic calculations covering the entire range of possible flow conditions. A negative example is the fish pass at the Lajeado Dam on Tocantins River, where the sills of the first pools impede migration into the fish pass during low flows (Agostinho *et al.,* 2007d).

3.1.2.4 Several fish passes/entries

The construction of several entries and/or fish passes is recommended for rivers such as the Mekong that contain a high diversity of fish species, sizes and swimming capabilities as well as a high biomass of fish. Strong swimmers usually require higher attraction flows and can be attracted to fish passes with higher slopes (Pon *et al.,* 2009). In contrast, weaker species can pass through a fish pass with more moderate conditions (Stuart *et al.*, 2008a, 2008b). Furthermore, several entries can be provided for one fish pass which collects species from different migration corridors (e.g. close to the shoreline, middle of the river, bottom, surface) and with different requirements for attraction flow.

Several entries are also recommended for some fish pass types and highly variable water levels, whereby usually only one entrance is opened (see Chapter 3.1.2.3).

Given that proposed dams in the Mekong River are very wide, it is necessary to provide several fish passes to facilitate the passage of as many species as possible at any given location (Baumgartner *et al.,* 2012).

3.1.2.5 Large nature-like fish pass or bypass system

A large nature-like fish pass or bypass-system acting like a tributary enables fish passage under varying flow conditions. This solution requires a lot of space, flow and appropriate topography. A large nature-like fish pass was recommended by fish experts as one of the solutions for the Xayaburi Hydropower Project.

3.1.3 Passability

A fish pass is only functional if it represents a suitable migration corridor for all relevant species and age classes. This is the case if:

- the hydraulic conditions allow the weakest species and age classes to pass;
- the fish pass has a continuous minimum flow velocity of 0.2 – 0.3 m/s (rheoactive limit velocity, see Chapter 2.1); and
- the spatial dimensions and geometry (depth, width, length) allow large adult fish to pass the fish pass.

Fish should be studied in field experiments within their natural environment where they are motivated to perform their natural migrations (Williams *et al.,* 2012; Baumgartner *et al.,* 2012).

The morphometric thresholds for maximum height differences, flow velocities, turbulences or water depths should be selected with regard to the respective river section and its fish community (length, width and height of key species).

3.1.3.1 Morphometric thresholds for dimensioning a fish pass

Morphometric thresholds and reference values are based on the body measurements of the fish with the highest spatial demands of the respective river section (i.e. size-determining fish species). Prerequisite for successful passage is a sufficient hydraulic water depth (D_{min}, measured from the stone pits to the water surface), pool width (W_p) and pool length (L_p) for size-decisive fish to pass contact-free. In addition, the dimensions of bottlenecks and slots (i.e. ds_{min} as the minimum depth and ws_{min} as the min width of slots and bottlenecks) should be considered. Suggested thresholds for these parameters are provided in the Annex (Table 14).

The morphometric thresholds should also consider the migration of fish shoals. Given that the Mekong has a high fish biomass and density, a fish pass has to be large enough to provide passage for all migrating fish, especially during migration periods. Based on this consideration of size-decisive fish species, the dimensions might be larger to meet their migratory requirements.

A minimum depth of 1.7 m should be provided for larger rivers (AG-FAH, 2011). The aforementioned parameters should be defined with regard to the size-decisive fish species. Wels catfish (*Silurus glanis*), native to Europe and Asia, has a length of 160 cm, a height of 35 cm and a width of 22 cm (DWA, 2010). If the values were extrapolated (without consideration of different growth in length, width and height), Wels catfish of 200 and 300 cm in length would have heights of 41/66 cm and widths of 28/44 cm, respectively. If these values are transposed to the Mekong giant catfish (*Pangasianodon gigas*) the morphometric values shown in Table 2 would be required. It is known that the Mekong giant catfish can reach a length of 300 cm and has an average length of 250 cm, although a large proportion of migrating individuals might be smaller. The morphometric values below were calculated for 200 – 300 cm long fish.

Table 2: Estimated morphometric values of a fish pass designed for Mekong giant catfish

Parameter	Formula	Thresholds for Mekong giant catfish	
		L = 300 H = 66 W = 41 cm	**L = 200 H = 44 W = 28 cm**
min. hydr. depth (D_{min})	2.5 • H_{fish}	165 cm	110 cm
min. pool length (L_p)	3 • L_{fish} 1) 2)	900 cm	600 cm
min. pool width (W_p)	2• L_{fish} (50 – 67% of L_p)	600 cm (450 – 600 cm)	400 cm (300 – 400 cm)
min. hydr. depth of slots d_s)	General: 2 • H_{fish}	132 cm	88 cm
	Nature-like: 2.5 • H_{fish}	165 cm	110 cm
min. width of slots (w_s)	General: 3 • W_{fish}	123 cm	84 cm
	Nature-like: 1.25 to 1.5 • (3 • W_{fish})	154 – 185 cm	105 – 126 cm

The values in Table 2 represent a rough estimation. For the definition of the required morphometric values, information on the distribution of (large) fish species and their body sizes is required. However, the values in Table 2 are similar to the values used for the vertical-slot fish pass at Geesthacht (see Chapter 3.2.6.4) designed for Atlantic sturgeons (*Acipenser oxyrinchus*) with a length of 300 cm. The Geesthacht Fish Pass has pools with a length of 900 cm, a minimum depth of 175 cm and a slot width of 120 cm. Only the width of the Geesthacht Fish Pass is with 16 m much larger than the above stated value. However, the Geesthacht Fish Pass includes two slots for each pool, which might explain the high width.

3.1.3.2 Hydraulic thresholds

Both biologists and engineers are required to determine hydraulic conditions suitable for fish to pass and translate these conditions into successful design criteria for fish passes (Williams *et al.,* 2012).

The hydraulic thresholds should be selected with regard to the natural river type (DWA, 2010) and the local fish community (BMLFUW, 2012) to reflect the swimming capabilities of the fish assemblage. In general, the flow velocity, energy dissipation (in W/m³) and the roughness decrease in downstream direction along the natural river course.

The maximum flow velocity (v_{max} in m/s) in the area of bottlenecks, slots or spillways depends on the height difference (Δh in m) and can be calculated as

$$v_{max}=\sqrt{2g\Delta h}$$

where (g) represents the force of gravity which is 9.81 m/s².

The velocity calculated occurs close to the surface where the water jet submerges in the water of the lower pool (Gebler, 2009; Larinier, 2006). The velocity decreases towards the bottom where weaker fish are able to pass.

The application of the equation for height differences of 20, 15, 13, 10 and 5 cm results in maximum flow velocities of 2.0, 1.7, 1.6, 1, 4 and 1.0 m/s, respectively. Therefore, the maximum flow velocities can be used to define the maximum height differences in a fish pass. As discussed in Chapter 2.1.3, the critical burst swimming speed of cyprinids is around 4 – 5 BL/s. DWA (2010, draft) specifies thresholds for the maximum velocity in potamal rivers at 0.8 – 1.8 m/s. In the Mekong River, small migratory fish of 15 – 30 cm length would be able to negotiate flow velocities of 0.8 – 1.8 m/s over short distances and, thus, set the limit for the height differences between the pools. The flow velocities within the pools should be less than 0.8 m/s.

For fish passes imitating natural rivers with continuous reduction of the fall height (i.e. without consecutive pools), the maximum flow velocity is related to the slope (I):

$$v_{max} \approx \sqrt{I}$$

The maximum flow velocity also depends on the total length of a fish pass. To reduce the exhaustion of fish, long fish passes should have a lower flow velocity than short fish passes. Furthermore, the introduction of resting pools is desirable. However, the characteristics of such resting pools (e.g. low-flow velocity and turbulence) favour the deposition and accumulation of fine sediments and might impair the functionality of a fish pass (DWA, 2010).

For temperate fish species, maximum flow velocities for potamal rivers are set at 0.8 – 1.4 m/s (Seifert *et al.,* 2012; BMLFUW, 2013). Several authors suggest maximum flow velocities of 1 m/s for potamal rivers (Jungwirth & Pelikan, 1989; Gebler, 1991; Steiner, 1992; Dumont *et al.,* 2005). Laboratory tests showed that the critical burst swimming speed for small and juvenile fish is approximately 0.35 – 0.6 m/s (Jens *et al.,* 1997). These moderate velocities can be ensured close to the bottom or in peripheral areas by means of roughness (BMLFUW, 2012). Although theoretically derived values provide a suitable indication, Turnpenny *et al.* (1998) recommend applying lower velocities for the construction of fish passes to avoid migratory bottlenecks. Therefore, the above stated values represent only rules-of-thumb and should be considered an upper limit (Seifert, 2012). More detailed information can be found in Clough *et al.* (2001), Clough & Turnpenny (2001), Turnpenny *et al.* (2001), Clough *et al.* (2004) and Watkins (2007).

Regarding the LMB, long fish passes might be the solution as the LMB requires fish passes to cover heights up to 30 m. For slopes of 0.5 – 1 % and a height difference of 30 m, 3,000 – 6,000 m long fish passes are required. However, this estimate does not account for other relevant factors such as flow velocity, turbulence or the fish pass type.

In addition, **minimum flow velocities** should be ensured to allow a rheotactic orientation of the fish because stagnant areas could become barriers for fish such as the rheophilic species (see Chapter 2.1.3).

As discussed in Chapter 3.1.2.2, the attraction flow should represent approximately 70 – 80% of the maximum burst swimming speed. For a 20 cm long cyprinid with a maximum burst swimming speed of 0.8 – 1.0 m/s, this would result in a suitable attraction flow of 0.56 – 0.8 m/s.

Since larger species might require higher flow velocities for attraction, several entries that meet the requirements of different species may be needed.

For a 20 cm long cyprinid with a burst swimming speed of 1 m/s, the height difference between two pools should not exceed 5.09 cm.

Turbulence reduces the swimming capabilities of fish (Pavlov *et al.*, 2008) and causes exhaustion or even injuries such as scale losses (Degel, 2006). Therefore, while turbulent flow might repel fish, flows with a component of predictability may attract them (Liao, 2007 in Williams *et al.,* 2012).

Turbulence is measured in W/m^3 and describes the reduction of introduced power with regard to the pool volume (i.e. energy dissipation) (DVWK, 1996). It changes in relation to the water level (head- and tailwater). The specific power density for pool-like fish passes (P_D in W/m^3) is calculated as

$$P_D = pw \cdot g \cdot Q \cdot \frac{\Delta h}{V}$$

where (pw) represents the water density (1,000 kg/m³), (Q) is the discharge (in m³/s), (Δh) the fall height between two pools and (V) the volume of the pool (= length • width • mean depth).

The specific power density for bypass channels is calculated as:

$$P_D = pw \cdot g \cdot v_m \cdot I$$

where (v_m) is the mean flow velocity and (I) is the slope (DWA, 2010).

Maximum thresholds are set to 300 W/m³ (Larinier, 2007) and 200 W/m³ (Dumont *et al.*, 2005) in rhithral rivers, 80 W/m³ in the bream region (Dumont *et al.,* 2005) or even 55 W/m³ for smaller species or age classes with low swimming capabilities (Larinier, 2007). The evidence of compliance with these thresholds should be provided for extreme situations where the total energy dissipation can be ensured (DWA, 2010).

According to Larinier (1998), species of lowland rivers, such as pike-perch (*Sander luciopeca*) and Northern pike (*Esox lucius*), avoid power densities above 100 W/m³.

To counteract the fatigue of the fish, several options are available. It is suggested to include a resting pool (< 50 W/m³, BAFU, 2012) every 2 (BAFU, 2012) to 3 m (Seifert, 2012) of height difference or to reduce the height differences between the single pools. Another option is to increase the fish pass length in upstream direction.

BMLFUW (2012) suggest a maximum height difference between two pools of 8 – 10 cm and a maximum specific power density of 80 – 100 W/m³ for potamal rivers. These values consider a nonexhaustive and safe passage for small and juvenile fish. These values can serve as a rough orientation for fish passes in the Mekong.

3.1.3.3 Continuous rough substrate, connection to head- and tailrace water

The bottom of a fish pass should consist of coarse substrate with a thickness of at least 0.2 m, thereby reducing the flow velocity towards the bottom (Gebler, 1991). Since bottom substrate with high diameter can increase turbulence and therefore worsen conditions for weaker fish, Adam *et al.* (2009) suggest the construction of a “support corset.” The “support corset” involves larger stones (35 – 45 cm and 4 – 5 stones/m²) surrounded by a mixture of rubble stones (5 – 15 cm) and gravel (8 – 32 mm) so that the larger stones still project at least 0.1 m. The substrate of the fish pass should be continuously connected to the natural river, which can be ensured by a ramp with a maximum slope of 1:2 (DWA, 2010). These considerations can ensure the upstream migration of other aquatic organisms. A negative example is the entrance of the fish pass at Ourinhos Dam (Salto Grande, Paranapanema River, Brazil) which is positioned in a way that fish may not reach the entrance if they migrate near the bottom (Arcifa & Esguícero, 2012).

Figure 25: Example for coarse substrate in a fish pass (picture of vertical slot at hydropower plant Rottau River, Möll, Austria, picture by Friedrich T.)

3.1.3.4 Light conditions

Although it is assumed that fish do not migrate through longer canalised river sections, it is known that fish migrate occasionally through darkened constructions such as pipes (Ökoplan, 2002). Nevertheless, if possible, a fish pass should provide natural light conditions without abrupt changes in light (DWA, 2010).

3.1.3.5 Exit in the forebay

The exit should have sufficient distance from the turbine inlets (Jäger, 2002) whereby 5 m seems appropriate for a turbine inflow velocity of 0.5 m/s. For higher velocities, a minimum distance of 10 m should be guaranteed (DWA, 2010). In large rivers, distances of 100 m and more might be required. The selected distance should consider the flow velocity and ensure that fish leaving the fish pass are not involuntarily displaced downstream towards the barrier. For example, the exit at Canal da Piracema (Paraná River) has a distance of ~6.6 km east of the spillway and 4.8 km from the nearest turbine (Makrakis *et al.,* 2007a). The water entering a fish pass should have a higher flow velocity than the flow passing the fish pass (DWA, 2010).

If the water level in the upstream area (forebay) is constant, the inflow construction is usually not problematic. For varying levels, the top pool may be used to adjust to different headwater levels while the second pool can be used for fine-tuning the flow (Jäger *et al.,* 2010). In general, a discharge control should be possible for the inflow. For level fluctuations of 0.5 – 1.0 m, a vertical-intake slot can be adequate. If the level differences are higher (e.g. 5 m level difference), several inflows with closure possibility should be included (DWA, 2010).

The inflow should be constructed to allow the introduction of monitoring equipment (e.g. fish traps or counting basins, see Chapter 5). Furthermore, the entrance should be protected from driftwood jams by means of submerged baffles of floating beams. Performance checks and maintenance work should be planned on a regular basis (DWA, 2010; Seifert, 2012; BMLFUW, 2012).

3.1.4 Evaluation of site conditions and selection of fish pass type

If the migration corridors and specific requirements of the key species are identified, it is possible to plan the hydraulic and spatial conditions so that the entrance is perceivable and the fish pass is passable.

Significant details should be investigated to serve as a basis for the design and planning of a fish pass, including: (1) the local conditions as the barrier itself, (2) its environment (possible building areas or constraints), (3) the total height difference between entry and outlet, (4) water-level variations over time, and (5) basic data of the fish fauna and the migration corridors.

Hydrological data are necessary to define the operating time of a fish pass (usually Q_{30} - Q_{300}), the corresponding water levels up- and downstream and their natural or artificial variation. The total water level difference (h_{tot}) and the maximum height differences (in- and outflow) between the pools

(Δh, defined by the key species) allow the definition of the total number of pools to overcome the total height difference:

$$n = \frac{h_{tot}}{\Delta h} - 1$$

The total fish pass length (l_{tot}) is defined by the number of pools (n), their required length (L_p) with regard to the size-decisive fish species and the width of the borders between the pools (w_b):

$$l_{tot} = n\ (L_p + w_b)$$

The hydraulic, hydrological, morphological (river bed formation) and ecological investigations should be integrated into an eco-hydraulic overall assessment to define the migration corridors and the most suitable location for a fish pass entrance.

The selection of the most suitable fish pass requires advanced technical and ecological knowledge and is based on the following main criteria:

(a) Type of barrier (is it still in operation, is it used for hydropower production?);

(b) Slope and availability of space:

- For big height differences and less space, technical solutions (vertical slot, rough channel ramp) are more suitable;
- For small height differences and sufficient space, nature-like types (pool pass, nature-like bypass channel) are usually preferred; and
- For big height differences and sufficient space, nature-like and technical types or their combination are possible.

3.2 Facilities for upstream migration

Fish passes may provide passage for a high abundance and biomass of fish within a short time span (Kowarsky & Ross, 1981; Schwalme & Mackay, 1985; Mallen-Cooper, 1996; Stuart & Mallen-Cooper, 1999; Schmetterling *et al.,* 2002; King & Torre, 2007; Stuart *et al.,* 2008a, 2008b; Roscoe & Hinch, 2010). However, according to many authors (Dugan *et al.,* 2010; Dugan, 2008; Baran *et al.,* 2001; Halls & Kshatriya, 2009) existing fish passes may not be able to cope with the high requirements of a Mekong mainstream dam due to species variety, high number of fish and biomass.

Substantial research on several types of fish passes has been performed and is currently underway to define design criteria for functional fish passes (e.g. Bell, 1990; Clay, 1995; FAO and DVWK, 2002; Katopodis, 2005; Larinier *et al.,* 2002; Orsborn, 1987). However, poor performance is often attributed to violations of principal design criteria or their application to different areas (species) without appropriate adaptations (Agostinho *et al.,* 2007a; Armonsakchai *et al.*, 2000; Godinho *et al.,* 1991; Godinho & Kynard, 2009; Larinier, 2002b; Makrakis *et al.,* 2007a; Roberts, 2001).

In consideration of different strategies of species in tropical rivers, different fish pass design criteria might be required for mainstream, tributary and floodplain migrations (Baumgartner *et al.,* 2012).

Measures to restore the continuum are commonly classified into the following groups:

- Removal of the barrier.
- Nature-like bypass channels or nature-like pool-type fish passes are nature-like constructed fish passes circumventing the barrier on short distance (pool-type fish pass) or spacious (bypass channel).
- Technical fish passes with mainly geometrical channel form constructed mainly with artificial or processed material (concrete, wood or plastics) that guide the fish through the barrier (e.g. pool-pass, vertical-slot pass).
- Special constructions (e.g. fish locks, fish elevators).

In the following chapters, the various fish pass types will be explained in detail. The applicability and suitability for the Mekong River is assessed by comparing experiences from the literature. Open research questions and design criteria are also discussed.

3.2.1 Removal of existing or waiver of planned dams

The removal or partial removal of the barrier is a sustainable solution and should be discussed first. Many existing barriers no longer fulfil their purpose as they have lost their functionality. Although this opportunity should be considered, this report does not cover this solution. Of note, the consequences of a removal should be thoroughly investigated to avoid damage to other facilities such as flood protection measures (DWA, 2010).

Furthermore, the waiver of certain dams should be considered in relation to the detrimental effects of planned hydropower developments. This solution may be favourable until suitable mitigation measures are developed and successfully tested (e.g. continuity restoration, other impacts caused by dams).

3.2.2 Adapted hydropower operation

Hydropower plants may be adapted to operate during selected periods when fish migration is negligible or shut down (with all gates opened) during periods of high migration.

Heublein *et al.* (2009) investigated the migration of green sturgeons (*Acipenser medirostris*) in the Sacramento River (2004 - 2006) by monitoring their movements. The Red Bluff Diversion Dam is a seasonal irrigation dam without a fish pass and with flow-control gates that are selectively closed from 15 May to 14 September. Sturgeons enter San Francisco Bay in March/April and migrate further upstream in the Sacramento River where they spawn in May/June. While specimens that already start their migrations in March are able to pass the dam, later specimens (April/May) are not able to pass the barrier and are therefore excluded from reproduction. A delay of the closure could allow the ascent of most specimens (Heublein *et al.,* 2009).

Although a poorly designed and implemented fish pass is present at Pak Mun Dam (Mun River) in northeast Thailand, it does not support ascent of all species (especially large-sized Pangasiidae and Sisoridae). As a result, the sluice gates are opened for four months during the rainy season (May - August) every year. During this period, hydropower production is not possible due to reversed flow from the Mekong up the Mun River. Analyses showed that the opened sluice gates are advantageous because fish can access feeding and nursery grounds in upstream areas (Jutagate *et al.,* 2007).

3.2.3 Nature-like bypass channels

Nature-like bypass channels became popular in the 1980s in central Europe (Jungwirth *et al.,* 1998) and are now built worldwide (Gough *et al.,* 2012). They mimic a natural river and circumvent the barriers using the space along the banks of the river. In addition to restoring the continuity, this type creates a free-flowing section that includes suitable habitats for reproduction and juveniles. Thus, nature-like bypass channels partially substitute lost fluvial habitat in case of chains of impoundments. A disadvantage is the large spatial requirement. In particular, difficulties arise in the design of an optimal entry under restricted spatial conditions (BMLFUW, 2012).

Figure 26: Nature-like fish pass at Kemmelbach Hydropower Plant on the River Ybbs in Austria (© Mielach)

It is essential to consider the natural river characteristics related to the slope, geometry, morphology, structures, substrate and materials. In all cases, heterogenic depths with pool-riffle sequences should be ensured.

The slope values are selected for the type of river whereby in Austria slopes of 0.3% are recommended for large rivers (BMLWUF, 2012).

The hydro-morphological conditions, including cross section, discharge, slope, fall height, and flow velocity, should match the ecological requirements of fish. Partly dynamic discharges ensure some kind of dynamic channel development while the substrates should be suitable for reproduction in at least some areas.

Suggestions for constructions in lowland rivers (based on Seifert, 2012) are:

- Mean flow velocity in mid-channel sections ~ 0.5 – 1 m/s.
- Maximum flow velocity at chutes 1 – 1.2 m/s.
- Asymmetric cross section to favour a deeper channel.
- Pool-riffle sequences to reflect natural flow conditions.
- Maximum fall height between pools of 0.10 – 0.15 m. The water depth at chutes should be high enough for all fish to pass.
- Substrate layer should be at least 0.2 m high; the gravel size selected should be suitable for reproduction and should consider hydraulic conditions.
- Regular "flushing" and gravel introductions are required to maintain suitable conditions for reproduction (e.g. to avoid clogging).

3.2.3.1 Canal da Piracema, Paraná River

The Canal da Piracema is a fish pass system that connects the Itaipú Reservoir with the Paraná River. The Itaipú Reservoir inundated a natural barrier (Sete Quedas Falls) which prohibited upstream migration of fish before the dam was constructed (Bonetto, 1986). The construction of a fish pass was therefore highly controversial because it would provide a connection between two distinct ichthyological assemblages (Makrakis *et al.,* 2007a). Nevertheless, the objective of the fish pass was to provide suitable spawning and nursery habitats (in tributaries and floodplains upstream) for long-distant migratory species (Agostinho *et al.,* 1993; Gomes & Agostinho, 1997).

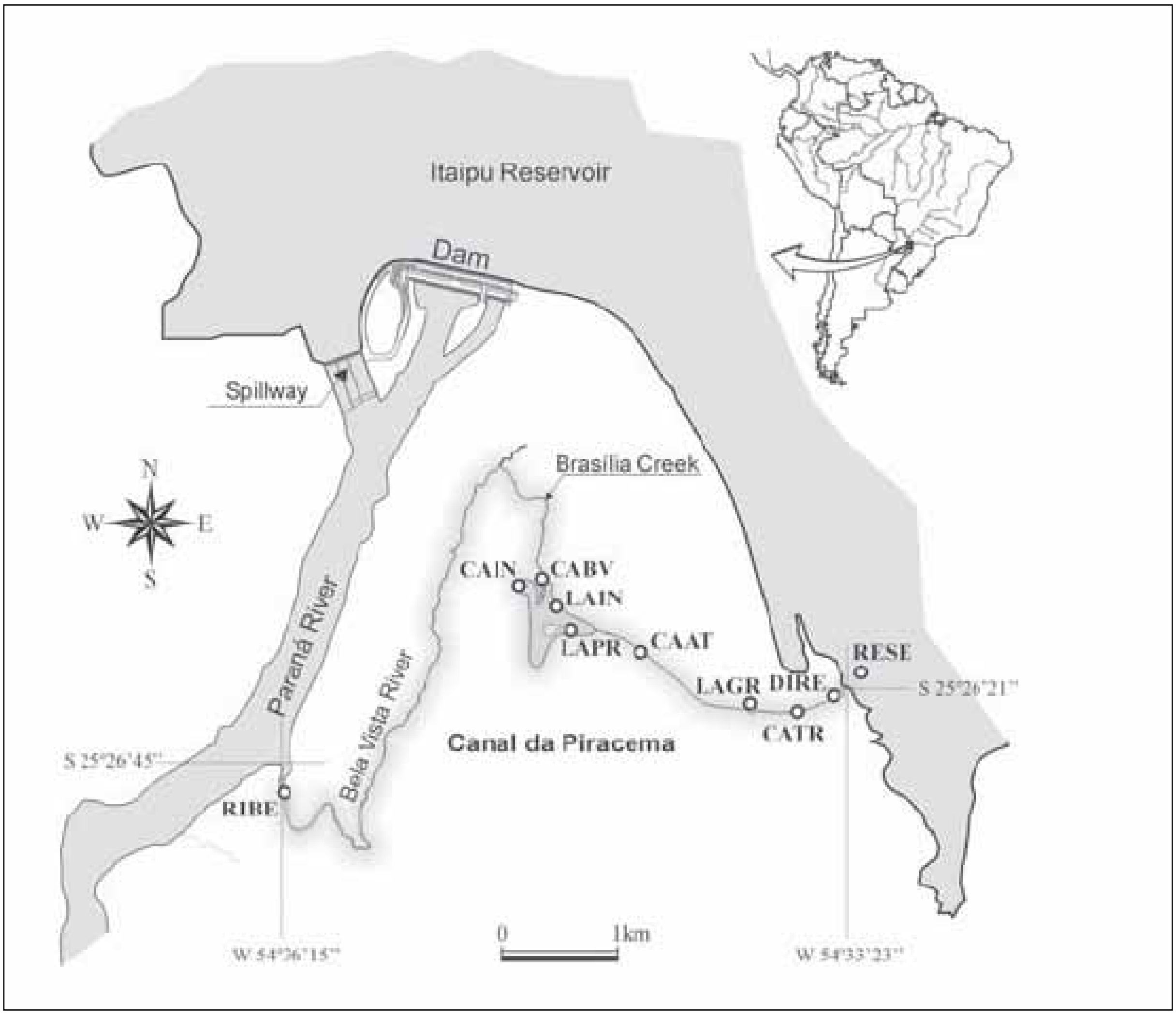

Figure 27: Canal da Piracema at Paraná River located on the border between Brazil and Paraguay (Makrakis *et al.,* 2007a)

The Canal da Piracema is the longest fish pass in the world (Makrakis *et al.,* 2007a) and consists of five different fish pass segments with intermittent resting pools. The entire system includes 6.7 km of a natural river channel (Bela Vista Riverbed) and several fish passes and resting ponds covering 120 m height difference in total. The channel has a mean discharge of 12 m^3/s and is 10 km long in total (Makrakis *et al.,* 2007a, 2011). The exit (upstream) is located on the left bank at about 6.6 km east of the spillway and 4.8 km from the closest turbine. The entrance is located 2.5 km below the dam. At this location, the Paraná River has a width of approximately 720 m, a mean discharge of 10,000 m^3/s and a mean flow velocity of 2.0 m/s at the surface (Makrakis *et al.,* 2007a, 2011). The first fish pass segment is nature-like and has a length of 6.8 km. The fish pass has a mean width of 4 – 6 m, a depth between 0.5 and 2 m, a mean slope of 4% and a mean discharge of 1.44 m^3/s. The fish pass enters the Paraná River in a 60° angle, which might cause efficiency losses of the attraction flow. Table 3 provides the key characteristics of the fish pass.

Table 3: Key characteristics of the Canal da Piracema (Makrakis *et al.,* 2007a, 2011; Júnior *et al.,* 2012)

	FP segments	Length [m]	Width [m]	Depth [m]	Mean slope [%]	Additional information
1	RIBE: Rio Bela Vista (along Bela Vista River and Brasilia Creek)	6,800	4 – 6	0.5 – 2	4%	Nature-like, enters Paraná in 60° angle
2	Riacho Brasília: Brasilia Creek	800 – 850	5	0.5 – 1	4	Shallowest and most turbulent
	CABV: Canal de deságue no rio Bela Vista (Bela Vista River mouth drainage canal)	150 – 200	5		5 – 6, 25	Head difference 12.5 m, rectangular cross section, 5 m wide, 2.5 m high, alternating concrete deflectors every 4 m with 1 m slot
L	LAIN: Lago Inferior (Lower Lake, fish resting pool)			4		1.2 ha
3	CAIN: Canal de Iniciação (Fish Ladder)	521			1.5	As CABV
L	LAPR: Lago Principal (Principal Lake, fish resting pool)			5		14 ha
4	CAAT: Canal de Alimentação em Aterro (Fish Ladder)	1,600	Max. 12		3.1 (2.1, 0.8)	Trapezoidal cross section, max width of 12 m, bank slope 2:3
L	LAGR: Lago Grevilhas (Grevilhas Lake, fish resting pool)			3		0.5 ha
5	CATR: Canal de Alimentação em Trincheiras (Fish Ladder)	2,400	8 (at bottom)		5 (0.7, 5)	Trapezoidal cross section (2:3 slope), riprap at bottom, concrete deflectors 0.6 m high, 1 m alternating openings
I	DIRE: Dique de Regulagem (Water Intake)			3.3		0.4 ha, 3 floodgates (2 m in height) to keep level 0.45 m below reservoir and velocity below 3 m/s

Makrakis *et al.* (2007a) investigated the Canal da Piracema from April 2004 to May 2005 and caught a total of 21,987 individuals of 116 species. The predominant orders were Characiformes with 57 species (30 Characidae species and 14 Anostomidae species) and Siluriformes with 30 species. Furthermore, 17 long-distant migrating species were caught. However, they contributed only 5.5% to the total catch. Species successfully ascending the fish pass (i.e. *Leporinus elongates, L. obtusidens, Prochilodus lineatus* and *Salminus brasiliensis*) are all considered to have advanced swimming capabilities. However, since the highest number of species was found in the first segment, many species may not have been able to reach the upper parts of the fish pass. This is most likely due to the hydrodynamic characteristics (i.e. velocity, turbulence, etc.) of the first two sections (RIBE, CABV) (Makrakis *et al.,* 2007a).

Another investigation of Makrakis *et al.* (2011) was performed from October 2004 to March 2005 (migration period) with a focus on migratory species. A total of 636 individuals of 17 migratory species (out of 19 species downstream from the dam) were detected in the fish pass. However, only

0.5% of fish entering the fish pass managed a successful ascent. During evaluations, only 449 fish of 17 species were caught in the first segment, while the next segment included only 11 species. The ascent efficiency between the first two segments is should be only 30%. Table 4 shows the distribution of fish and species in the segments and a derived probability of ascent.

Table 4: Ascent of migratory fish at Canal da Piracema (based on Makrakis *et al.,* 2011)

Sampling segment	Number of migratory fish	Number of migratory species	Ascension Probability [%]
1	449	17	100.00
2	22	11	29.40
3	145	10	25.90
4	17	5	3.10
5	3	2	0.05

The results showed that the maximum velocity is highly related with the ascent probability. The strong reduction of fish along the fish pass indicates a high selectivity of the fish pass. Segments 1 – 3 showed the highest values of mean flow velocity (1.4 – 1.7 m/s) and maximum flow velocity (1.8 – 3.2 m/s) with the highest values in segment 1.

In particular, Júnior *et al.* (2012) focused on the investigation of the CABV as a possible migration barrier in the fish pass. They tagged 219 individuals of two migratory species (181 *P. lineatus* with a length of 39.5 – 70 cm and 38 *L. elongatus* with a length of 40.5 – 64.5 cm) and released them up- and downstream from the CABV. In total, 83 specimens successfully ascended the entire fish pass (21 released downstream and 62 released upstream from CABV). Overall, 18% of downstream released fish and 60.8% of upstream released fish ascended successfully in which *P. lineatus* showed higher percentages (19.8 – 62.2%) compared to *L. elongatus* (11.5 – 50.0%). These findings confirm the high selectivity of the CABV.

3.2.3.2 Freudenau Fish Pass, Danube River

The Freudenau Hydropower Plant is located on the Danube River southeast of Vienna (river km 1921.05). The HPP includes six Kaplan turbines with a total discharge capacity of 3,000 m³/s located on the right site of the dam. The fish pass is located on the left bank beside the spill gates. It overcomes a height difference of 8.7 m and consists of a 1,000 m long nature-like bypass channel and a 420 m long pool-pass at the upper end. The entry is located 500 m downstream from the dam, forming a delta with two permanent channels (L = 200 m, W = 6 m each). A third channel is covered only by water for discharges above mean flow and provides additional attraction flow (Eberstaller & Pinka, 2001).

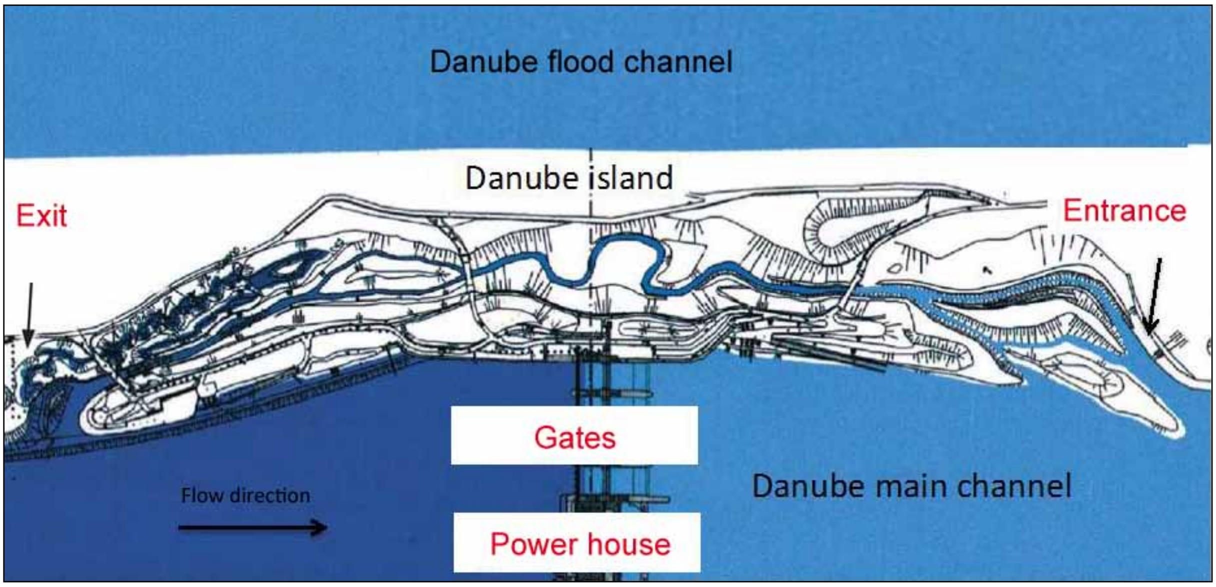

Figure 28: Freudenau Fish Pass on the Danube River (adapted from Verbund Austria AG)

The first section of the bypass has a slope of 10 %, a maximum depth of 1.3 m and a width of 8 – 15 m, including gravel bars. The subsequent section has a slope of 3 %, a length of 140 m, and a width of 4 – 8 m. The second section is divided into two channels flowing around a 25 m wide island. The remaining section has a slope of 3 %, a maximum depth of 1 m, a length of 170 m, and a width of 10 m. This section is connected to the pool pass, which covers the remaining height difference of 2 m. It has a length of 420 m and includes 19 pools with lengths between 20 – 40 m and widths of 3 – 16 m. The mean height difference between two pools is 11 cm. The pools are up to 1.5 m deep and have flow velocities < 1 m/s. The end of the pool pass (exit upstream) includes an inlet to control the inflow which is up to 900 l/s. Furthermore, the bypass section is additionally charged with water from the Danube. As a result, the entire discharge is approximately 1,500 l/s during winter, 1,800 l/s during spring and up to 3,600 l/s when the discharge of the Danube is above mean flow (about 2,000 m^3/s). Further fish pass discharge increases are provided during higher flows of the Danube (> 3,000 m^3/s). When the upstream water level decreases (e.g. during floods), an emergency pump ensures discharge of the fish pass. In such cases (~17 days per year), the fish pass is not passable (Eberstaller & Pinka, 2001).

Investigations (1999 - 2000) showed that 19,801 fish from 38 species used the fish pass. The passability is proven for most species and age classes (also juveniles). However, a slight selectivity towards stagnophilic species was observed. Rheophilic species are obviously attracted by the turbines located on the right side and, therefore, underrepresented in the catches of the fish pass.

The use of the fish pass for downstream migration is negligible (Eberstaller & Pinka, 2001). It is assumed that most downstream migrations occur via the turbines and opened gates during floods. As these are very large Kaplan turbines (slow rotation with 65.2 rpm, capacity 600 m^3/s, diameter 7.5 m) with a low fall height, higher survival rates are assumed (Larinier, 1998; Hadderingh & Bakker, 1998). Furthermore, discharges above turbine capacity are released via gates thereby providing migration possibilities during high flows.

3.2.3.3 Marchfeldkanal Fish Pass, Danube River

Another example of a nature-like fish pass is on the Marchfeld Channel in Austria. The investigated system is a man-made irrigation channel which corresponds to a side channel of the Danube. The upstream section (19 km) is a newly-created river bed entering in the lower section (27 km) which in turn is a natural river bed re-entering the Danube further downstream (Schmutz *et al.,* 1998). The channel has a width of 10 – 20 m and a maximum depth of 0.7 – 1.8 m. The Marchfeld Channel resembles a lowland river with a low gradient (0.022%), warm water temperatures during the summer and a mean flow velocity of 0.3 – 0.9 m/s. The discharge in the channel depends on the discharge in the Danube and ranges from 2 – 10 m^3/s. Furthermore, the channel includes three weirs (for discharge and level regulation) equipped with nature-like bypass channels (Mader *et al.,* 1998; Schmutz *et al.,* 1998). The lowermost fish pass is located at a weir with a height of 2 m, a length of 400 m and an average slope of 0.5%. The fish pass consists of 13 nature-like pools (length 6 – 58 m) divided by flumes (1 m bottom width). The lowermost pool was divided into three pools because the upstream flume with a head > 70 cm was too high. The colonisation of the channel occurred by downstream drift of juveniles and species entering the channel via the Danube tributary (Russbach) by migrating 37 km upstream. A total of 47 species inhabited the channel three years after the flooding (Schmutz *et al.,* 1994; Schmutz *et al.,* 1995). The fish pass passed 40 species and more than 20,000 fish per year including fish with low swimming capabilities. However, a negative selectivity for large-sized pike-perch fish (*Sander lucioperca*) was also shown (Schmutz *et al.,* 1998; Mader *et al.,* 1998).

Figure 29: Nature-like fish pass at Marchfeldkanal, side channel of the Danube River, Austria

3.2.3.4 Melk Fish Pass, Danube River

The Melk Hydropower Plant is a run-of-the-river HPP located upstream from Vienna and has a 22.5 km long impoundment. At Melk, the Danube has a mean flow of 1,850 m³/s.

Figure 30: Melk Fish Pass on the Danube River (© Verbund Austria AG)

The fish pass is 1,040 m long, has a mean width of 12 m and processes a height difference of 11.8 m. The fish pass is designed as a natural bypass from the entrance to the exit. However, the last section of the fish pass also includes a vertical-slot section with 10 pools (L = 4 m, W = 4 m, slot width 0.6 mm, head 13 cm) and a movable inlet. This vertical slot ensures the passability of the fish pass if the upstream water level is lowered. An emergency pump ensures flow in the fish pass if the upstream water level decreases below the inlet of the fish pass (Frangez *et al.,* 2009).

The operational discharge of the HPP is 2,700 m³/s. Up to this discharge, the fish pass has a flow of 1.4 – 1.5 m³/s. If the discharge in the Danube is greater than the operational discharge (≤ 3,500 m³/s), the flow in the fish pass increases up to 3.2 m³/s. For flows > 3,500 m³/s, the discharge in the fish pass decreases again due to lower water levels upstream. The discharge in the fish pass also varies with the season. During the summer, the discharge is approximately 1.4 – 1.5 m³/s while the discharge reduces to 1.0 m³/s during the winter months (Frangez *et al.,* 2009).

The functionality of the fish pass was assessed using the Austrian assessment method (Woschitz *et al.,* 2003). Fish ecological monitoring proved passage of 42 species (35 in fish traps).

With regard to the species community of 40 documented species in the Danube, the fish pass can be rated as highly qualitatively functional. Furthermore, juveniles of several species were able to pass and species representing all ecological guilds were documented in the fish pass. Electro-fishing in 2007 showed that there are 2,550 individuals/100 m in the fish pass. In general, the high number of fish entering the fish pass serves as evidence for perceptibility. However, the quantitative functionality cannot be assessed due to the low fish stock and small number of migrating species in the Danube. Nevertheless, suitability for rheophilic spawners was rated as being only moderate. Similar to the situation of the Freudenau HPP, one potential reason is that the turbines are located on the right side and the fish pass on the left side which is located on an island between the main channel and an oxbow (Frangez *et al.,* 2009).

3.2.4 Nature-like or technical pool and weir fish pass

This type can be constructed either nature-like using boulders or in a technical way with concrete pools and weirs.

A nature-like pool pass consists of several drop structures with pools in between, leading to a pool-riffle sequence in longitudinal direction. The drops have to be designed in an asymmetric way. The openings should have a rectangular or trapezoidal shape (reaching down to the bottom). The openings/slots between consecutive drops should alternate to ensure a pendulous flow. Asymmetric cross sections with the highest depth below the outlets are suggested. The geometric dimensions can be derived from the thresholds for technical solutions. However, adaptations are necessary: length and width should have an increase of 25 – 50% and the depth should have an increase of 20 – 30% in comparison to vertical-slot passes (Seifert, 2012). Sometimes the weirs are also equipped with orifices to enable passage of benthic fish.

Typical dimensions of this fish pass type are pools with lengths of 3 – 4 m, widths of 2.5 – 3.0 m, depths of 1.5 m and openings with a width of 0.6 – 1.0 m and a length of 1.0 – 2.0 m (Katopodis & Williams, 2012). Furthermore, the slope ranges from 5 – 12.5% (Berg, 1973). Pool and weir fish pass have a long tradition and were already constructed in large rivers such as the Columbia River (USA) and the Paraná River (South America).

3.2.4.1 Porto Primavera Dam, Paraná River

An example of the weir and orifice fish pass is located at the Porto Primavera Dam. The fish pass is 520 m long and consists of 50 concrete weirs forming pools of 5 m wide, 2 m tall and 9 m long. Each weir includes 6 orifices (3 upper and 3 lower orifices). Furthermore, moving metal plates allow the closure of the orifices to change the flow in the fish pass. Evaluations recorded 37 species passing the fish pass, 17 species ascending, 18 species descending and 12 species moving in both directions). Out of nine migratory species, seven were found in the fish pass (3 ascending, 4 ascending and descending) (Makrakis *et al.,* 2007b). However, Makrakis *et al.* (2007b) report that the fish pass favours fish with high swimming capabilities.

3.2.4.2 Itaipú Reservoir, Paraná River

A pool and weir fish pass were built at the Itaipú Reservoir (Paraná River) for a height difference of 27 m. The fish pass has step-pools with a dimension of 1.8 x 1.4 x 1.0 m. Furthermore, surface (0.3 x 0.4 m) and bottom orifices (0.3 x 0.6 m) in alternating positions are included. The discharge is approximately 340 l/s. Investigations (1994 - 1997) showed that the fish pass, especially the orifices, is size-selective. In this case, more than half of the potentially occurring species (i.e. 65 species downstream from the dam) did not use the fish pass and typical large long-distant migrants such as *Pseudoplatystoma corruscans* and *Rhaphiodon vulpinus* were absent (Fernandez *et al.,* 2004). It is evident that the dimension of the fish pass is too small for such a large river.

3.2.5 Bypass systems

A bypass system is a system of near-natural channels that circumvent the entire impoundment or reservoir. It represents a substitute for lost fluvial habitat of the mainstream river. This solution is particularly suitable when several barriers cause a chain of impoundments and flowing sections are heavily reduced. The bypass system may range from the tailrace of the dam up to the head of the impoundment. In case of a chain of impoundments, several bypass systems can be connected. The bypass system should mimic the conditions in the main river at a smaller scale. Rheophilic species might spawn in the bypass system and use this habitat throughout the year. During migration, fish can use these bypass systems to circumvent the entire chain of dams without the need of searching for entries at several individual fish passes.

3.2.5.1 Bypass system, Danube River

A bypass system is currently constructed on the Danube (Mühlbauer & Zauner, 2010, unpublished report). The aim of the project is the restoration of typical flowing river habitats and re-establishment of connectivity. Due to the high functionality with regard to passability and habitat suitability, a high cost-benefit ratio is expected. The planned bypass system has a length of 15 km and an area of ~30 ha. The discharge ranges from 2.5 to 20 m^3/s according to the discharge of the Danube (Figure 31).

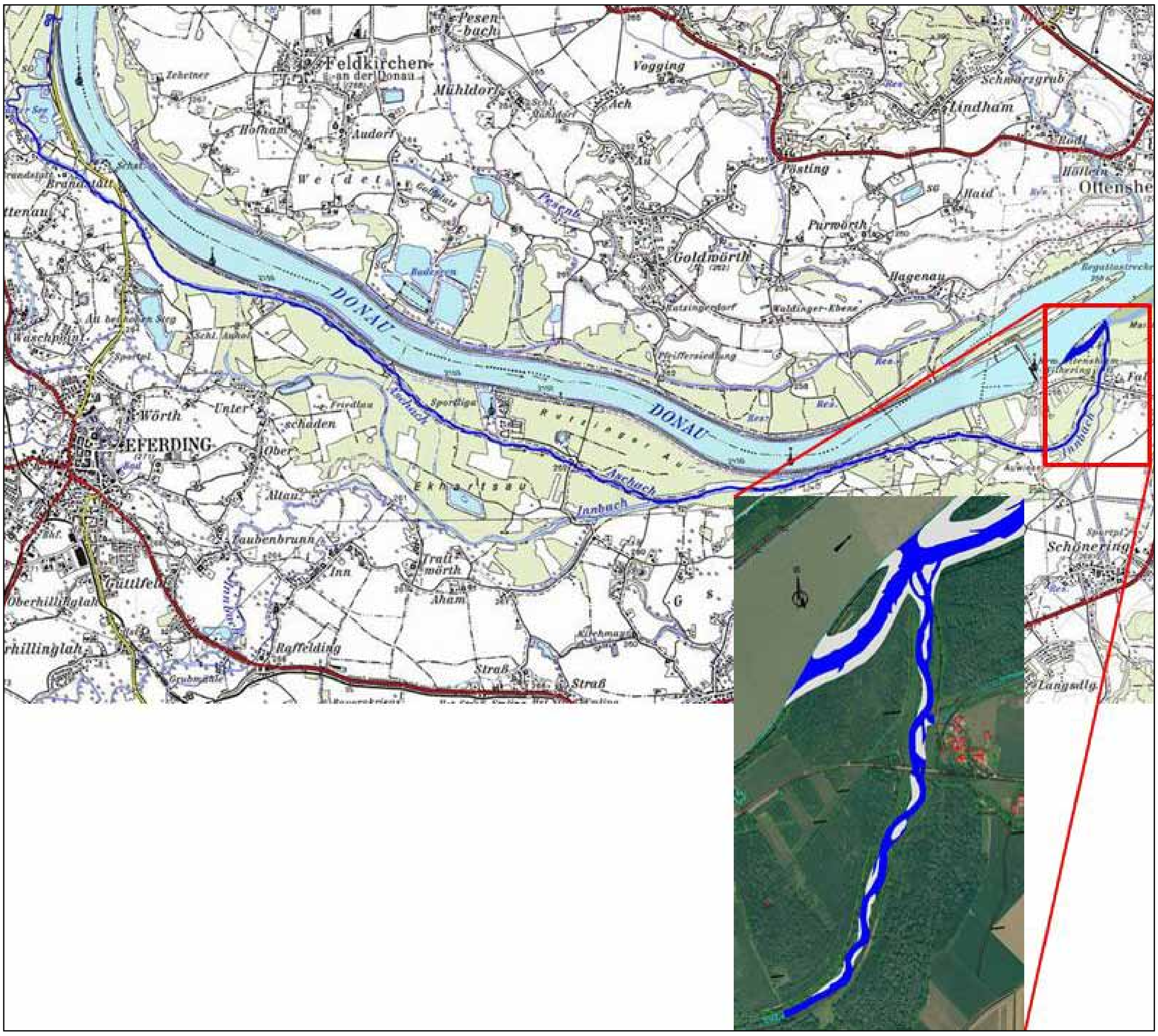

Figure 31: Planned bypass system for the Danube River. The figure shows the integration of the bypass system into the mainstream of the Danube below the dam (Mühlbauer & Zauner, 2010, unpublished report)

3.2.6 Vertical-slot passes

Vertical-slot passes are technical fish passes in which slope-processing occurs over constant height differences between two pools, thus reducing the kinetic and potential energy within each pool. The single pools are connected by vertical slots (ranging from top to bottom) which are usually situated on the same side (see Figure 32). In most cases, the entire fish pass consists of concrete but could also be made of wood. This type allows a mean slope of 1:8 and therefore represents a suitable solution for limited space. Advantages of this fish pass type are the low spatial demands and the possibility to construct an optimal entry under spatial restrictions. However, the construction is more expensive when compared to nature-like fish passes and this fish pass type requires more maintenance. Furthermore, the fish pass itself does not represent a suitable habitat for fish (BMLFUW, 2012).

An important parameter is the slot width (w_s) that determines the minimum cross section and therefore the discharge and flow velocity. The minimum slot width (w_s) depends on the body width (W_{fish}) of the size-decisive fish and is calculated as 3 x (W_{fish}). The pool length (L_p) represents the distance between two partitioning walls and should be higher than 3 x L_{fish} (fish length). (L_p) is used to determine the pool-width (W_p = ¾ of L_p) (see Figure 33). The minimum depth (D_{min}) should be > 0.6 m (0.5 m for small rivers) (BMLFUW, 2012).

Figure 32: Vertical-slot fish pass at Greinsfurth Hydropower Plant on the River Ybbs (© Mielach)

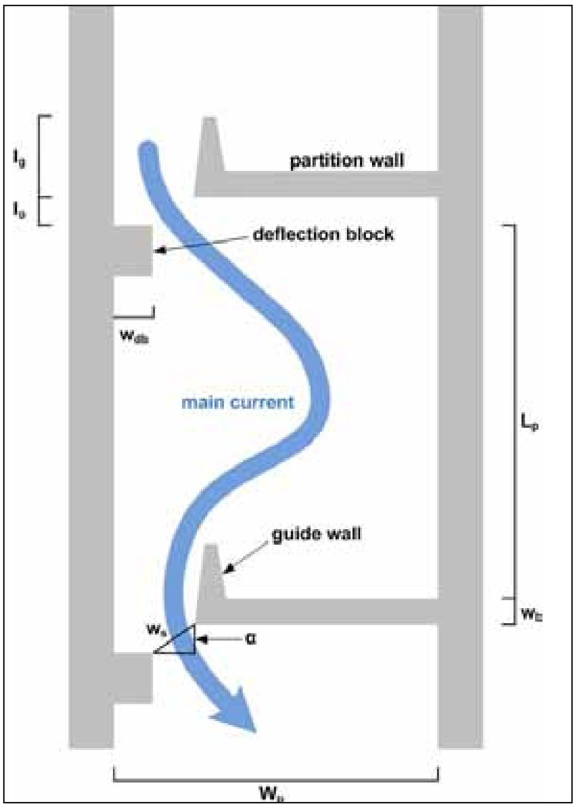

Figure 33: Schematic design of a vertical slot (adapted from DWA, 2010)

The maximum acceptable energy dissipation should be related to the fish species of the respective river type. The slots usually include a hydraulic steering device to ensure an oscillating main current that uses the entire pool volume for a low-turbulence energy transformation (Heimerl & Hagmeyer, 2005; Heimerl *et al.*, 2008). As shown in Figure 33:

- The deflection block prevents a linear, accelerating flow through the adjacent slots (hydraulic short-circuit), leading the flow into the corner between the side wall and the partition wall. The angle of deflection (α) should be between 20° (for small fish passes, Gelber, 1991) and 45° (Larinier, 1992; Rajaratnam *et al.,* 1986).

- An upstream hook-shaped extension (guide wall) ensures a consistent inflow without transverse flows, leading the main current back to the slot, supporting the energy dissipation.

The dimension of these two extensions should be in accordance with the slot width (see Table 15 in Annex; Larinier *et al.,* 2002b; Katopodis, 1992).

The bottom should be continuously covered with rough substrate to reduce the flow velocity towards the bottom (see Chapter 3.1.3.3).

Although vertical-slot passes can cope with small fluctuations in water level (up- and downstream), the discharge and hydraulic conditions change with variation of the water level and thus should be considered in defining geometric dimensions (Mayr, 2007).

An advantage of the vertical-slot fish passes is that the hydraulic parameters can be easily calculated. Furthermore, the migration corridors within the slots serve both benthic and water column fish species (Seifert, 2012).

With regard to the Mekong giant catfish, the vertical-slot dimensions for 200 and 300 cm long fish are provided in Table 5. The slot widths for the respective sizes were taken from Chapter 3.1.3.1. As mentioned in the previous chapter, the calculation of these values is only a rough estimation.

Table 5: Estimated vertical-slot dimensions (cm) with regard to the Mekong giant catfish

Formula	Results for Mekong giant catfish	
	L_{fish} = 300 cm	L_{fish} = 200 cm
Slot width $w_s = 1 * w_s$	**123 cm**	**84 cm**
Pool length L_p = 8.10 to 8.33 * w_s 1)	996 – 1,025 cm	680 – 700 cm
Guide wall length l_g = 1.78 to 2.00 * w_s	219 – 246 cm	150 – 168 cm
Offset length l_o = 0.41 to 0.83 * w_s	50 – 102 cm	34 – 70 cm
Width of the deflection block w_{db} = 1.15 to 1.49 * w_s	142 – 183 cm	97 – 125 cm

3.2.6.1 Lajeado Dam, Tocantins River

Vertical-slot fish passes were already applied in large rivers such as the Lajeado Dam in the Tocantins River (Brazil). The fish pass is 874 m long, 5 m wide, 1.5 m deep and processes a height of 36.8 m. The fish pass includes 92 pools with surface (0.5 x 1.0 m) and bottom slots (0.8 x 0.8 m). Although this fish pass is defined as a vertical-slot fish pass, the design with surface and bottom slots could also be considered as a weir-orifice fish pass. Within the fish pass, five still-water resting pools are included. The first is located 134 m from the first weir and is 14.4 x 17 m large. The remaining resting pools are 10 x 10 m large and located at 278,440,595 and 725 m from the first weir. The fish pass has a discharge of ~3.3 m³/s, a mean flow velocity of 0.44 m/s, a mean maximum velocity of 2.3 m/s (Agostinho *et al.,* 2012; Agostinho *et al.,* 2007a, b).

Agostinho *et al.* (2007a) report that 81 of 130 species were caught in the fish pass. Approximately 75% of migratory species caught downstream from the fish pass (i.e. 32 species) were found in the fish pass. The fish pass is moderately selective and favours rheophilic species. A drawback of the fish pass, however, is the limited functionality because the entrance of the fish pass is above the low-flow level of the river (Agostinho *et al.,* 2007a).

3.2.6.2 Iffezheim, Rhine River

A new fish pass was completed in 2000 at the Iffezheim Hydropower Plant on the Rhine River, Germany (EnBW Kraftwerke AG, 2009) and covers a height difference of 11 m with a slope of 6.7%. The fish pass is located in the middle of the weir. The vertical-slot fish pass with 37 pools (L = 4.5 m, W = 3.3 m, H = 1.5 m, slot width = 45 cm) has three entrances meeting in a dispersing basin (Figure 34). Upstream from the dispersing basin, the discharge is ~1.2 m^3/s. An attraction flow turbine introduces additional water (≤ 11.8 m^3/s) into the dispersing basin. The total attraction flow therefore accounts for 11 – 13 m^3/s which is ~1.0 – 1.3% of the average flow of the Rhine River (1,000 m^3/s). Two of the entries are located in the middle and close to the turbine outlets for species that prefer higher flow velocities while the third entry is located near the shoreline and suitable for weaker fish (Degel, 2010).

From 2001 to 2010, the fish pass monitoring with video and traps showed that 38 fish species were able to pass successfully. The species spectrum included long-distance migrants such as the Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*) and European eel (*Anguilla anguilla*) as well as potamodromous and short-distance migrants. The number of fish ranged from 13,077 (2002) to 27,039 individuals (2004). In total, 154 Wels catfish (*Silurus glanis*) ascended the fish pass resulting in an average annual rate of 15 fish. However, the high slope is considered a disadvantage because it contributes to turbulent flow (energy dissipation = 180 W/m^3) and results in abrasion of fish scales (Degel, 2010).

3.2.6.3 Gambsheim, Rhine River

In 2006, a similar fish pass was built at the Gambsheim Hydropower Plant, located 25 km upstream from Iffezheim. Compared with the fish pass at Iffezheim, the level difference between pools was reduced from 30 cm to 25 cm, thereby reducing the slope (5.7 %) of the fish pass and the dissipation energy in the pools. Monitoring revealed that the number of fish passed ranged from 30,184 (2009) to 64,546 individuals (2006). These figures are 1.7 – 3.7 times higher than in Iffezheim. Overall, 138 Wels catfish were recorded, equalling an average annual rate of 28 fish (Degel, 2010).

3.2.6.4 Geesthacht Fish Pass, Elbe River

The fish pass is located 142 km upstream from the mouth of the Elbe River at the Geesthacht weir where the Elbe has a mean flow of 728 m^3/s. The flow regulation weir creates an impoundment of 31.4 km long. A vertical-slot fish pass was built to ensure access to reproduction habitats for Atlantic salmon (*Salmo salar*), sea trout (*Salmo trutta*) and Atlantic sturgeon (*Acipenser oxyrinchus*) to in the upper reaches of the Elbe. A focus was given to the restoration of sturgeon populations that were already extinct in the Elbe River.

The Elbe sturgeon can reach a length of 3 m and weigh 130 kg, thus serving as a comparison to the large fish species of the Mekong River. The fish pass dimensions are designed according to the size of this species (Geesthacht-Elbe s.a.).

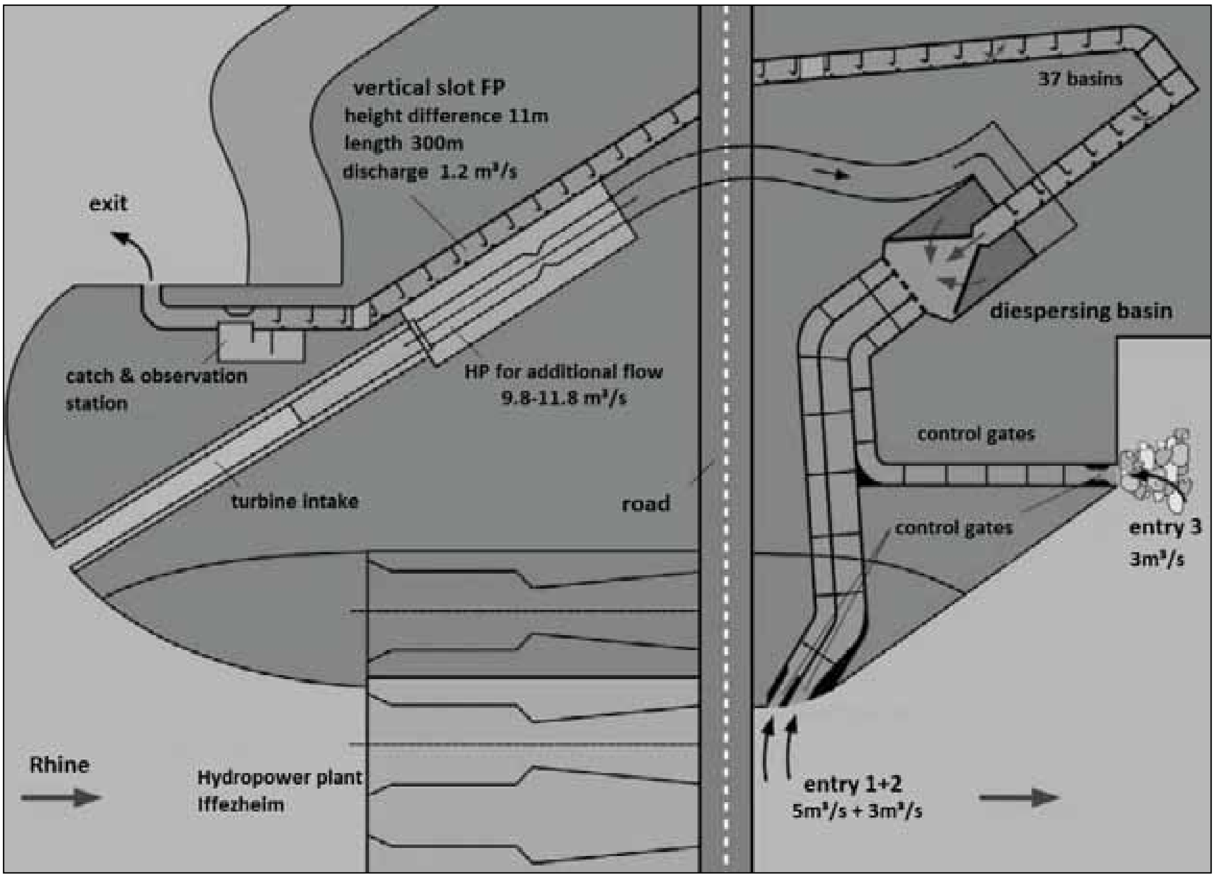

Figure 34: Functional principle of Iffezheim Fish Pass on the Rhine River (adapted from Degel, 2010 & DWA, 2010)

The fish pass is 550 m long and covers a height difference of up to 4 m. Fish are directed towards the entry of the fish pass by five gutters in the weir. The attraction flow helps the fish find the entrance which is located directly at the bottom of the weir. The fish pass consists of 45 large pools (length = 9 m, width = 16 m, minimum depth = 1.75 m) with head differences of < 10 cm. The pools are connected by two slots with a width of 1.2 m each. Within the fish pass, six additional flow inlets are regulated by float controls to ensure sufficient attraction flow. The maximum flow of the fish pass is 15 m^3/s which represents 2% of the mean flow of the Elbe (Vattenfall Europe AG).

Monitoring in the first 12 months after completion (2010) shows passage of more than 300,000 individuals out of 43 fish species. Successful passage of small-sized fish species, including the three-spined stickleback (*Gasterosteus aculeatus*, > 100,000 individuals), large-sized diadromous fish, including the Atlantic salmon (*Salmo salar*) and sea trout (*Salmo trutta*), and potamodromous species, including the European catfish (*Silurus glanis*) and sander (*Sander lucioperca*), proves that the fish pass is not size- and species-selective. Therefore, the fish pass is rated as fully functional (Adam *et al.,* 2012; see also http://www.schwevers.de/Konf-Teil2.html). By January 2012, a total of 500,000 individuals had passed the fish pass with daily peaks of 25,000 individuals, including a 3 m long sturgeon.

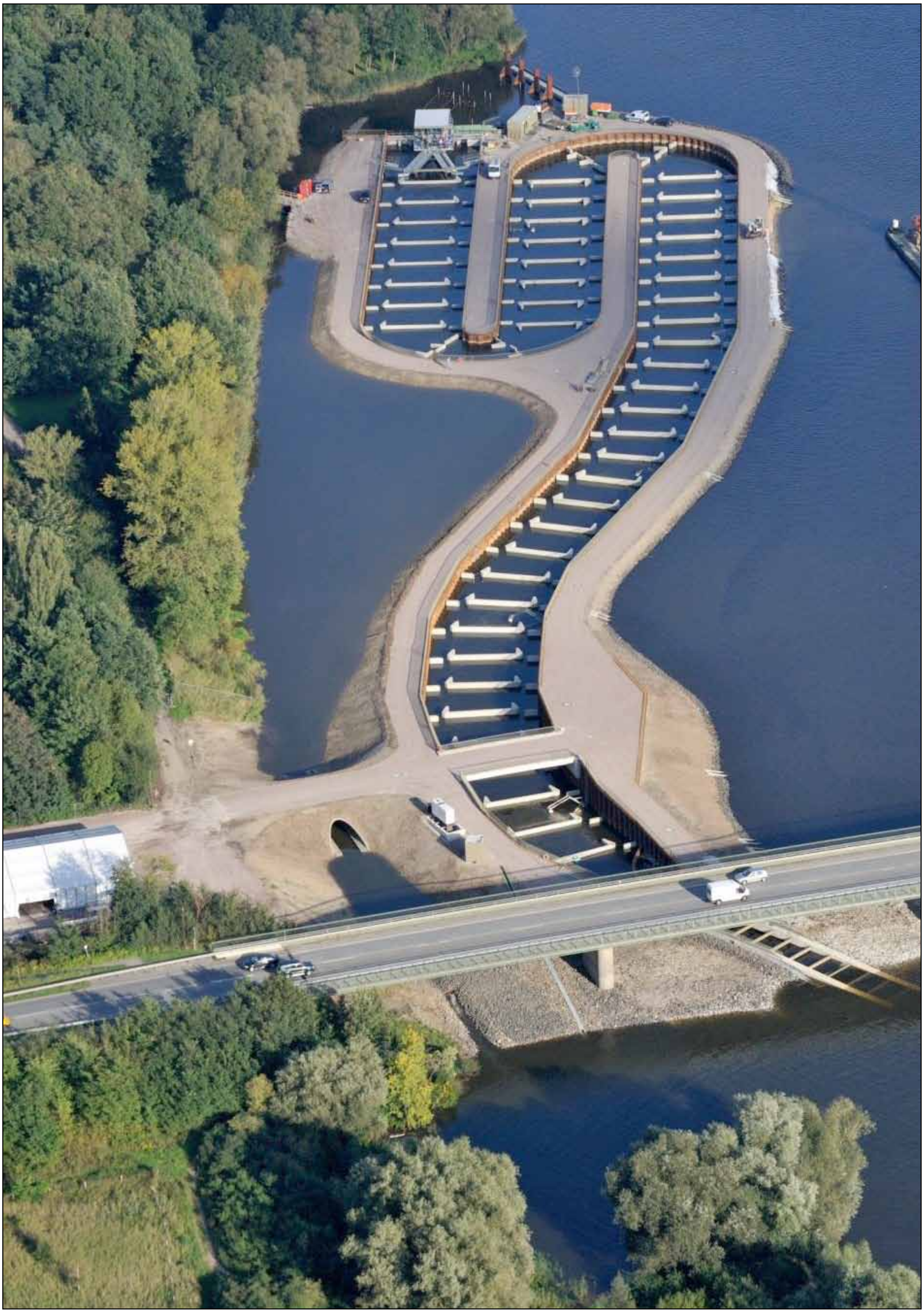

Figure 35: Geesthacht Fish Pass on the Elbe River (Geesthacht-Elbe s.a.)

3.2.6.5 Yangtang Fish Pass, Mishui River

Chen *et al.* (2012) reviewed the status of fish passes in China and concluded that the main types are vertical-slot passes and near-natural passes. For dams at different heights, the depths of fish passes are generally 2.5 – 3.0 m with flow velocities of 0.6 – 1.2 m/s. To overcome challenges in research, design, construction and management of fish passes, design criteria and fundamental and interdisciplinary research should be improved.

In 1958, the first fish ladder in China was built at the Qililong Hydropower Station on the Fuchun River in Zhejiang Province. It was constructed with a maximum hydraulic head of 18 m. In the 1960s and 1970s, over 40 fish pass facilities were built across the eastern Chinese provinces, including Jiangsu, Anhui, and Heilongjiang. Most of these fishways were built on low head dams of less than 10 m. Monitoring showed that the fish passes seldomly worked well and thus they were eventually abandoned. The most effective fishway in China is assumed to be the Yangtang Fishway that was built in 1981 as part of a low head hydropower station in Hunan Province. However, it is currently out of service due to sedimentation problems (Cheng & Gang, 2012).

Zhili *et al.* (1990) describe the Yangtang Fish Pass on the Mishui River in which 45 species and more than 580,000 fish passed every year. The effectiveness of the fish pass was monitored appropriately with 5,000 hours of observation per year. The effect of the fish pass appears to have been significant: statistics of fish harvest showed that the annual fish output in the upstream part of the Mishui River increased 3.5 times compared with previous years before the fishway was built. The fish pass was specifically designed to pass very small fish with very low turbulence in pools and low drops (about 0.05 m) between pools. The attraction flow (16 m^3/s) and the collection gallery above the turbines played an essential role in the effectiveness of the facility. The fish pass was one of the few examples of a well-designed fish pass that is adapted to native species and is monitored appropriately in a developing country.

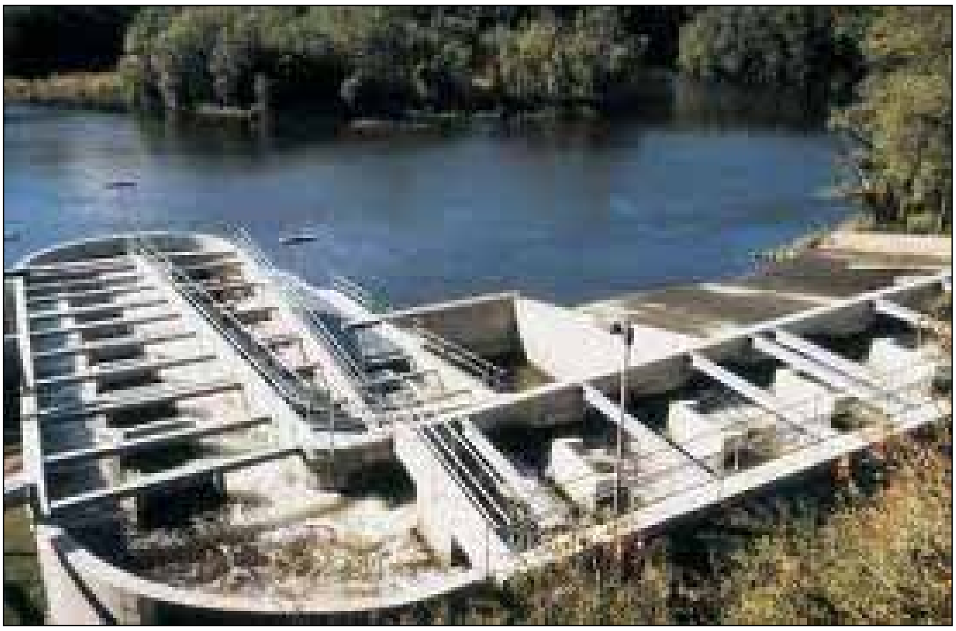

Figure 36: Yangtang Fishway at the Mishui River (www.fao.org)

3.2.6.6 Sariakandi Fish Pass, Bangali River

In Bangladesh, most hydraulic structures have been constructed without considering the physiology, ecology and migratory behaviour of different aquatic species. As a result, the benefit from these hydraulic structures did not meet the desired goal. The concept of fish passes is relatively new in Bangladesh. To date, two fish passes (i.e. Sariakandi Fish Pass at Bangali River, Kawadighi Haor at Monu River in Moulovibazar) and two fish-friendly structures (i.e. Lohajong River at Tangail, Morichardanra in Chapainawabganj) have been constructed (Ghosh, 2012).

The Bangladesh Water Development Board (BWDB) reconstructed the Sariakandi fish pass in 1999 - 2001 on the Belai River, which connects the Jamuna River (west bank) and the Bangali River (east bank), at Debdanga in Kutubpur Union in Sariakandi Upazilla. The structural design of the Sariakandi Fish Pass is a vertical-slot pass: the total length of the structure is 92.4 m and the width is 15 m. There are 3 separate and parallel passages. There are 3 vents (with gate) and 16 pools in each vent. The gate size is 6.42 m × 0.82 m (each), the height of the slot opening is 0.7 m, and the dimensions of the pool are 4.8 m long and 4.2 m wide (http://en.bdfish.org/2010/09/sariakandi-fishpass-fish-friendly-structure-bangladesh/). De *et al.* (2011) investigated the impact of the Sariakandi Fish Pass on fisheries diversity of the Bangali River, Bogra, Bangladesh. In order to facilitate the fish migration between the rivers Jamuna and Bangali, the Sariakandi Fish Pass was established in 2001 at Sariakandi Upazila, Bogra. Data were collected directly from fishermen, fish traders and organisations involved in this field. A total of 12 fish species comprising 8 families were recorded in the Bangali River before establishing a fish pass whereas 59 fin fish species and 9 non-fin fishes were recorded in the Bangali River after fish pass construction. These findings indicate that the fish pass has a positive impact on fisheries diversity of the Bangali River. Another study by Ghosh (2012) revealed that carp-type fish species dominated during the monsoon. Carp-type fish migrate in a higher velocity in comparison to catfish. Of note, some problems were found in the operation and management of the fish pass.

Figure 37: Sariakandi Fish Pass on the Bangali River, Bangladesh (www.bdfish.org/)

3.2.7 Denil fish passes

According to Katopodis & Williams (2012) and DWA (2010), Denil fish passes were applied for heads up to 15 m, lengths up to 227 m and slopes up to 25%. Some of the largest Denil fish passes were installed in Maine, USA (Decker, 1967). Although Denil passes were successfully installed at many lower head dams, their application to large dams is considered difficult and unsuitable. They provide migration for selected species and therefore can not support the passage of a heterogeneous fish community. In addition, Katopodis & Williams (2012) discuss that this fish pass type might not be suitable for large hydropower dams.

According to the DWA (2010), the Denil pass has the following disadvantages:

- Highly sensitive to upstream level fluctuations (max. 0.2 m);
- High maintenance effort (due to floating debris);
- Only suitable for short stretches; and
- Limited width and depth prevent the passage of large species.

This type of fish pass is unsuitable for the Mekong River because the fish pass should accommodate level fluctuations seen in the Mekong (dry and wet season), process high heads and allow the passage of multiple species.

3.2.8 Shipping locks and fish locks

Shipping locks can support the reconnection of continuity. However, they usually are not located according to the requirements of perceptible fish passes. For security reasons, shipping locks are mostly located in areas with low-flow velocity and therefore outside of the migration corridor of most species. The guiding current is only temporarily present and the lock is selectively opened if traffic occurs (DWA, 2010). In turn, fish migration often occurs randomly because shipping locks are usually zones with calm conditions and attraction flow is missing (Travade & Larinier, 2002). Thus, shipping locks can only supplement other fish passes (Zitek *et al.,* 2007).

Fish locks are similar to shipping locks. Fish locks were designed by an engineer named Borland and are also called Borland locks or Borland lifts (Aitken *et al.,* 1966). However, Borland locks are especially designed for migrating salmonids. This fish pass represents a connection of the head- and the tailrace water that strong swimmers can use to migrate upstream by using their own power. Given this technical feature, this type is unsuitable for the Mekong. There are also other types of fish locks (e.g. Pavlov lock or Deelder lock) where fish do not have to actively process the height difference.

In general, a fish lock includes a chamber with an up- and downstream lock. Four phases can be distinguished (DWA, 2010):

- **Entering phase:** the lower lock is open and the water level equals the downstream water level. The upper lock is opened partially to introduce attraction flow, which guides the fish into the chamber where they accumulate. Herding devices can be used to crowd the fish into and out of the transportation tank especially for large chambers (Clay, 1995).

- **Fill-up phase:** After some time, the lower lock is closed and more water enters from upstream until the water level in the chamber equals the upstream water level.

- **Exit phase:** The upper lock is opened and the lower lock is partially opened to generate an attraction flow which leads the fish further upstream.

- **Emptying phase:** After a certain time, the upper lock is closed again and the chamber is emptied again, until the level equals the downstream water level. Then, the cycle starts again.

One cycle can last 30 minutes to four hours (Pavlov, 1989; Larinier *et al.,* 1994; Redeker & Stephen, 2006; Travade & Larinier, 2002), depending on the actual requirements. A small frequency allows the passage of more fish. In seasons with low migration activity, the interval can be reduced. The first and third phase should be long enough for fish to orientate and find their way in and out of the chamber (DWA, 2010).

Fish locks have been built on barriers all over the world (Clay, 1995 in Baumgarnter & Harris, 2007). Fish locks transport fish automatically which means that fish do not have to put much effort into the upstream migration. However, fish have to be attracted to enter the fish lock and to continue their migration upstream (Clay, 1995 in Baumgartner & Harris, 2007).

Fish locks are selective because they are more suitable for indifferent species while rheophilic species prefer common fish passes. Furthermore, their functionality is limited over time as the lock can either collect or release fish, but not both at the same time.

Overall, fish locks are considered inefficient and might only serve as alternative passage for particular species such as sturgeons (Larinier & Travade, 2002) or other large fish species. A special type of fish lock is the Deelder lock (named after Deelder, 1958) which was first constructed on the Meuse River in Belgium. It consists of two chambers separated by an internal weir and is easy to construct, operate and adapt to existing fishways (Baumgartner & Harris, 2007).

According to Stuart *et al.* (2007), possible technical improvements for fish locks are:

- Entrances, both close to the spillway and the outlets (attraction flow);

- Consideration of increased tail and headwater range (higher operational activity);

- Continuous attraction flow (for entire cycle);

- Automatically adjusted attraction flow (with regard to tailwater level);

- Attraction flow with high water quality (form the surface);

- Improvements of the exit that allows the attraction of downstream migrating fish without passing back upstream migrating fish.

An example of a fish lock at large dams is located at the Salto Grande Dam (Uruguay River). It transports fish over 30 m height difference whereby one cycle lasts ~55 min. Although 36 of 48 species entered the lock, target migratory species were rare. The attraction flow of 0.5 m/s might not be strong enough to attract rheophilic species (Agostinho *et al.,* 2002; Oldani & Baigún, 2002). According to Stuart *et al.* (2007), fish locks have a high potential for tropical rivers with low minimum flows and low biomass. Therefore, they might not be suitable for the Mekong River and its abundant species diversity.

3.2.9 Fish siphons

This fish pass type is insufficiently discussed in scientific literature. Furthermore, no records of fish siphons applied to large rivers are known. Therefore, this type will not be discussed further.

3.2.10 Trap and truck

This approach traps migrating fish and trucks them up- or downstream where they are released. This type might be useful in large rivers where no satisfying technical solution for fish migration exists so far and for fish migration that occurs regularly and within a short time period (e.g. eel, salmon and sturgeon). This approach is used for eel in the Main and Mosel rivers (Germany). Trap and truck is supported by systems that detect fish migration periods. They have the advantage of verifying their functionality (monitoring data) and overcoming several barriers with one solution. Trap and truck systems are highly limited, especially for the upstream migration of a large fish biomass. Costs are high and permanently recurring. Professionals are required to guarantee safe handling and transportation. Trap and truck systems could be used to transport selected large fish species that might not be able to pass fish passes. In such cases, catch facilities should be included which allow the catch of the selected species. Potential of poaching should be limited.

3.2.11 Fish lifts

According to Croze *et al.* (2008), fish lifts represent one of the most cost-efficient solutions for high dams. As in this case, fish are transported upstream with exogenous energy (no effort for fish) and the solution is applicable for all heads (Lucas & Baras, 2001; Travade & Larinier, 2002). Fish lifts were constructed all over the world (Oldani & Baigún, 2002; Sanots *et al.,* 2002) with a focus on Acipenseridae (Pavlov, 1989; Kynard, 1998) and *Alosa* species (Dalley, 1980).

In contrast to fish locks, fish lifts transport fish in a separate container, not in a water-filled channel. Fish are guided into a chamber by means of attraction flow. The size of the chamber depends on the size and number of migrating fish. Larinier *et al.* (1994) suggests approximately 15 l/kg fish. The following dimensions are suggested for large fish species such as sturgeons (Larinier *et al.,* 1994; Pavlov, 1989; in DWA, 2010).

Table 6: Chamber dimensions for fish lifts (DWA, 2010)

Key species	Length	Width	Height	Volume
Sturgeon	up to > 50 m	> 5 m	several m	~ 1,000 m³

A pipe introduces the additional attraction flow. Larinier *et al.* (2005) recommend an attraction flow of 10 – 20% of the turbine flow for the fish lift at the Baigts power plant. The flow velocity should not be too high so that fish are able to gather. Larinier *et al.* (1994) suggest 0.3 – 0.6 m/s. To prevent fish from leaving, fish traps should be included. A movable grid (crowder) can be used to prevent fish from leaving and to densify them towards the transport container. This transport container includes a grid net and a bottom tub to supply sufficient water for the transport (6 l/kg fish). The dimensions should be at least 1.5 – 1 m with a minimum depth of 0.2 – 0.3 m (higher for larger fish species or fish species migrating in groups) (DWA, 2010; Larinier *et al.,* 1994). A power winch is used for the upstream transport. Upstream, fish are released by tilting the container or by opening a bottom gate. The duration of one cycle lasts between 10 minutes to four hours and depends on the number of migrating fish. In comparison to fish locks, the up- and downstream transport as well as the exit phase are much shorter (DWA, 2010).

Examples of fish lifts in tropical rivers include the Santa Clara Reservoir (Mucuri River, Brazil), the Yacyreta Dam (Paraná River, Argentine/Paraguay) and the Funil Dam (Rio Grande, Brazil).

According to Pompeu & Martinez (2007), the fish pass installed in Santa Clara Dam (Muncuri River, Brazil) is a combination of fish lift and trap and truck system. During the reproductive period of 2003 – 2004 (~5 months), the fish pass passed approximately 70,000 individuals, accounting for 32 species (Oldani *et al.,* 2007). Sixty-six percent of the downstream fish richness was able to pass. The efficiency for migratory species was ~7%. Nevertheless, Oldani *et al.* (2007) conclude that the overall efficiency was low with a mean of 106 fish per cycle and 40% of cycles without fish transportation. Furthermore, Pompeu & Martinez (2007) report regular interruption of the fish pass.

At Yacyretá Dam, two lifts have been operating since 1990 but provisions for two additional lifts are also installed (Clay, 1995). One entire cycle takes 60 minutes whereby the travel over the 21 m height difference takes only 7 minutes up- and downstream. The remaining time is used to attract fish. The entrance is 11.2 m wide with a closable gate. Each lift has a capacity of 15 m³/s. According to Oldani & Baigún (2002), the two lifts at Paraná River passed an average of 14,000 kg/day during migration peaks. Nevertheless, this amount represents only 2% of the migratory biomass (Oldani *et al.,* 2007).

Fish lifts usually require a high maintenance effort and experiences show that they do not operate continuously. During investigations at the Yacyretá Dam (Paraná River) from 1995 – 1998, the fish lift was inactive 30 – 38% of the time (Oldani & Baigún, 2002). Pompeu & Martinez (2007) also report regular interruption of the fish lift at the Santa Clara Dam (Mucuri River).

3.3 Applicability of various upstream migration fish pass types for the mainstream Mekong River

It will not be possible to use only one fish pass type of the above mentioned options directly for the Mekong River. However, the research on the functionality of various fish pass types on large rivers can be used to help assess the applicability of fish pass types for the mainstem Mekong taking into account the additional challenges on the Mekong.

A comprehensive assessment of the applicability of of the available fish passes requires assessment of the current biological monitoring of the fish assemblages of concern to determine the type, number and biological characteristics of fish that are to be passed. The potential efficiency of a fish pass in the Mekong context can be estimated by comparing the characteristics of the Mekong migratory fish with those passing the fish passes in other regions (see Chapter 5). Unfortunately, only few fish passes have been biologically monitored in large rivers with high fish diversity and very few have been tested for quantitative efficiency (Table 7).

In general, fish pass functioning relies on the state-of-the-art design criteria included in the construction of the fish pass. While the fish pass type might be appropriate for a specific situation, poor construction can cause reduced or insufficient functioning.

The aforementioned case studies suggest that **nature-like and vertical-slot fish passes** are equally appropriate for large rivers. Both are able to pass a high proportion of species present in the river. The number of fish passed varies between a few thousand (Danube) and several hundred thousand (Elbe). A lower slope of the fish pass (0.7%), larger size, higher fish pass flow and more attraction flow (2% of mean flow) enable more fish to pass and favour small species and age classes (Elbe). To date, the Geesthacht Fish Pass on the Elbe River is the largest fish pass in terms of pool size and is designed for sturgeons (pool length 9 m, width 16 m). Although the fish pass is 550 m long, it only covers a height difference of up to 4 m. A fish pass of similar design for a 30 m high Mekong mainstream dam would result in a 1,800 m long vertical-slot fish pass, a dimension that has never been built. The design would include a head difference of 10 cm between pools. Many open questions are associated with such a long fish pass. First, the spatial demand is huge for such a fish pass. Second, the costs associated with such a large fish pass are very high as the costs of the Geesthacht Fish Pass included £20 million for a head of only 4 m. A more affordable option is a nature-like channel but examples with the desired dimensions do not exist.

Data on large fish are limited to the Rhine and Elbe case studies. The number of European catfish passing fish passes on the Rhine is low with ~15 to 28 fish/year. However, comparative data of the stock size in the river are not available. In the Elbe, a single three-metre long sturgeon passed the Geesthacht Fish Pass, thereby indicating full functionality for large fish. These results demonstrate that large species are able to successfully pass fish passes when designed properly. Therefore, it can be assumed that large fish species of the Mekong, representing more than 25 % of the total catch, may use fish passes if appropriate fish pass dimensions and flows are provided. However, due to the few existing examples of large fish passage, effective quantitative passage of large species is still questionable.

The monitoring results reveal that **pool and weir fish passes** are species selective and favour fish with high swimming capabilities (Paraná). Furthermore, the size of the orifices limit the size of fish that can pass and orifices are likely to be clogged by woody debris if not supervised regularly and maintained properly. As a high proportion of the commercially important fish species of the Mekong is both small or large this fish pass type is not recommended for the Mekong.

Shipping locks are located in areas of low-flow velocity thereby making it difficult for fish to be attracted. The lock operation is not adjusted to the needs of fish and therefore do not function efficiently for fish migration. Fish locks are similar to shipping locks but intentionally operated for fish migration. Attraction flow is used to guide fish into and out of the lock chamber. A disadvantage is that they operate intermittently. Based on limited experiences, **fish locks** are considered species selective and inefficient. Fish locks, therefore, might only serve as alternative passage for particular species such as sturgeons and are only recommended as a complement to other fish pass solutions. Experience shows that **fish lifts** usually require extensive maintenance and do not operate continuously thereby resulting in low efficiency. They are recommended only as a complement to other fish pass solutions. **Trap and truck** systems could be used to transport selected large fish species which might not be able to pass fish passes but are ineffective for large fish biomass.

A **large bypass system** circumventing parts or the entire reservoir with a nature-like channel as currently planned for the Danube could also be suitable for the Mekong River. In order to provide passage for a high number of fish, the bypass channel needs to receive a significant proportion of the Mekong's discharge. This solution is only suitable, however, if the required space is available. Furthermore, it has to be tested if this fish pass solution is also suitable for the dry season. For narrow sections and gorges, conventional fish passes are the only suitable solution.

Table 7: Comparison of selected case studies (H_{tot} = head, L = length, W = width, D = depth, Q = flow)

Case study	River and mean flow	FP type	Monitoring	Weaknesses
Canal da Piracema	Paraná: 10,000 m³/s	Various: nature-like and pool and weir H_{tot} = 120 m L = 10 km W = 4 – 12 m D = 0.5 – 5 m Q = 12 m³/s Attraction flow = 0.12% Slope = 1.5 – 6%	21,987 ind.; 116 sp.; 17 out of 19 long-distant (in FP)	High selectivity due to high-flow velocities
Iffezheim FP	Rhine: 1,000 m³/s	Vertical-slot: H_{tot} = 11 m L = ~170 m W = 3.3 m D = 1.5 m Q = 1,2 – 11m³/s (up to 11.8 m³/s with turbine) Attraction flow = ≤1.3% Slope = 6.7%	13,077 ind. (2002); 27,039 ind. (2004); 38 species passed successfully; ~15 catfish/year	High turbulence leading to fish scale abrasion; efficiency low compared to river size

Table 7 (continued): Comparison of selected case studies (H_{tot} = head, L = length, W = width, D = depth, Q = flow)

Gambsheim FP	Rhine: 1,000 m³/s	Vertical-slot: Same as Iffezheim FP, but level difference between pools = 25 instead of 30 cm Attraction flow = ≤1.3% Slope 5.7 %	30,184 Ind. (2009); 64,546 Ind. (2006); ~28 catfish/year	Efficiency low compared to river size
Freudenau FP	Danube: 1,850 m³/s	Nature-like bypass: H_{tot} = 8.7 m L = 1,000 m W = 4 – 15 m D = ~1 – 1.5 m Q = 1.5 – 3.6 m³/s Attraction flow = ≤0.2% Slope = 0.9%	10,801 ind.; 38 sp. used FP (most species and age classes passed)	Less suitability for riverine species; not located on the side of the turbine outlet; efficiency low compared to river size
Melk FP	Danube 1,850 m³/s	Nature-like bypass: H_{tot} = 11.8 m L = 1,040 m W = 12 m D = ~1 – 1.5 m Q = 1 – 3.2 m³/s Attraction flow = ≤0.2% Slope = 1.1%	2,250 ind./100 m; 42 species (all species, guilds and age classes) were able to pass	Less suitability for riverine species; not located on the side of the turbine outlet; efficiency low compared to river size
Geesthacht FP	Elbe: 728 m³/s	Vertical-slot: H_{tot} = 4 m L = 550 m W = 16 m D >1.75 m Q = 15 m ³/s Attraction flow = 2% Slope = 0.7%	> 300,000 ind. (1st yr.); 43 sp., all age-classes; daily peaks of 25,000 ind.; Sturgeon greater than 3 m passed	None identified to date

Table 8: Comparison of upstream fish pass solutions

Upstream FP types	Case studies	Advantages	Disadvantages	Applicability for the Mekong
Nature-like bypass channel	Canal da Piracema (Paraná), FP Freudenau and FP Melk (Danube), Marchfeld channel (Rußbach, Danube)	Adequate for multiple species; effective if large enough, suitable habitat	Sensitive to upstream level variations; high spatial demands	Case studies for large rivers are rare but this type should be applicable if designed large enough and sufficient space is available.
Pool/weir pass	Porto Primavera Dam, Itaipú Reservoir (Paraná)	Less space necessary	Sensitive to upstream level variations; species selective: favours species with high swimming capabilities	Due to the selectivity, this type is not recommended for multi-species situations.
Bypass system	Danube (planned)	High transfer capacity; suitable habitat; partial substitute of lost fluvial habitat; can be used to overcome several barriers concurrently; high cost-benefit ratio	Sensitive to upstream level variations; optimal position of entry (near the dam) difficult with regard to low slope and high length of the FP; high discharge required; high spatial demands, no experiences available	Should be applicable for the Mekong if sufficient space is available.

Table 8 (continued): Comparison of upstream fish pass solutions

Upstream FP types	Case studies	Advantages	Disadvantages	Applicability for the Mekong
Denil FP		Suitable for salmonids; suitable for low head dams and short stretches	Sensitive to upstream level fluctuations; high maintenance effort; unsuitable for large dams; favours species with high swimming capabilities; not suitable for large species	Not suitable for the Mekong with its large dams and diverse fish community
Vertical-slot FP	FP Iffezheim/ FP Gambsheim/ (Rhine), FP Geesthacht (Elbe)	Comparable low spatial demands, possibility to construct an optimally located entry under spatial restrictions; suitable for a diverse fish community; hydraulic parameters can be easily calculated	More expensive than nature-like constructions; higher maintenance effort; no suitable habitat; no experiences available for large, high dams in tropical rivers	Suitable if morphometric values and hydraulic parameters are designed with regard to the local characteristics and fish community.
Shipping locks		No or low additional effort/costs	Usually at locations with low-flow velocity and therefore no/limited attraction flow; no continuous operation	Not suitable
Fish locks	Salto Grande dam (Uruguay River)	Flexible design allows construction at different dam types; suitable passage for selected species; potential for tropical rivers with low biomass	Capacity depends on cycle time and volume; no permanent attraction flow/ passage; more suitable for selected/indifferent species; inefficient if not operated regularly	Suitable if designed and operated properly; risk of selectivity remains. Therefore, only recommended in addition to other types.
Trap & Truck	Santa Clara Dam - Muncuri River	Can be used everywhere, especially when other systems fail; can be used to overcome several barriers; functionality can be easily verified	Not suitable for high biomass; high operation costs; fish might lose orientation; highly relies on present infrastructure	Only suitable as an interim solution for specific cases or species; not suitable as a permanent solution
Fish lifts/ Elevators		Used for high heights	High costs for construction, operation and maintenance; fish might be stressed and lose orientation; capacity depends on cycle time and volume; usually no permanent attraction flow and operation	Only suitable in combination with other FP systems.

4 Downstream migration and fish protection

4.1 General considerations

Methods for the restoration of downstream connectivity are much less advanced than for upstream passage (Williams *et al.,* 2012) because re-establishment of connectivity started with upstream migrations. Downstream migration has only been addressed in recent years.

Since downstream migration occurs with the flow, fish have less time to evaluate flow conditions in their environment. In this case, the migration corridor depends on the species and age class. For example, Chinook salmon (*Oncorhynchus tshawytscha*) prefer to migrate close to the shoreline when they are < 1 year old and change their migration path to the middle of the thalweg and areas with highest flow when they are > 1 year old. Sometimes, juvenile salmon are observed migrating tail first (facing upstream and moving backwards) in the current (Johnson *et al.,* 2000; Kemp *et al.,* 2005; Kemp *et al.,* 2006; Enders *et al.,* 2009).

It is increasingly recognised that facilities are needed to support both up- and downstream migration to restore overall connectivity. Downstream migration is significant within the fish life cycle. Therefore, significant fish losses may result if the continuity is not restored in both directions (Nok, 2009). Reduced survival rates of downstream-moving fish lead to increased efforts to actively or passively hinder fish from entering turbines (Williams *et al.,* 2012).

As discussed in Chapter 2.1, downstream migrations occur especially after reproduction or entail drift of fry and juveniles. However, detailed information about downstream migration and the behaviour of fish is still lacking. Downstream migration occurs either close to the surface (e.g. juveniles), close to the bottom or within the water column. Therefore, downstream fish passes (DFPs) should include options for surface, water column and bottom migration. Similar to upstream migration aids, facilities for downstream migration should be connected to the downstream migration corridor (Jäger *et al.,* 2010). For example, fish tend to gather in the forebay of weirs thereby requiring additional DFPs because most upstream fish passes cannot be used for downstream migration (AG-FAH, 2011).

Downstream migrating fish also pass through turbines and may be harmed or killed. The main challenge of downstream migration is to prevent fish from entering turbines and to guide them to an appropriate alternative for downstream passage. Measures for fish protection should therefore be included in all existing hydropower plants.

DFPs, fish-friendly turbines, adaptations of the operational mode of spill flow (Ĉada *et al.* 1997; Holzner, 2000) or modifications of the hydropower plant management are methods to enable downstream migration (AG-FAH, 2011).

4.2 Facilities for fish protection

Several approaches can be used for fish protection. However, since they only protect fish without offering downstream migration possibilities, they have to be combined with DFPs. The following sections showcase possible solutions for fish protection.

Existing fish pass solutions do not prevent drifting eggs and larvae from passing the dam through the turbines or the spillway (Cowx *et al.*, 2015; Agostinho *et al.,* 2002). For example, at the Itaipú Dam (Paranà River, Brazil/Paraguay), larvae are able to drift through the reservoir and reach the dam. However, their migration through turbines or spillways lead to high mortality and reduces the number of larvae downstream from the dam (Agostinho *et al.,* 2002).

4.2.1 Special turbines

Turbines can cause damage or mortality due to (Agostinho *et al.,* 2002):

- Contact with fixed/mobile equipment;
- Sudden pressure changes (incl. exposure to low pressure conditions);
- Extreme turbulence (e.g. amputation); and/or
- Cavitation.

For high-pressure plants, mortality can be up to 100% when fish pass through turbines. In contrast, low-pressure plants experience varying mortality or damage rate due to various factors, including the diameter of the rotor, distance between the rotor blades, rotation speed and pressure differences during turbine passage. To avoid clamping of fish, the distance between the blades and the turbine coat should be less than 3 mm (AG-FAH, 2011).

Death or serious injuries can be caused by pressure or velocity changes, shearing effects, collision with turbine or dam structures, grinding, turbulence and abrasion (Wittinger *et al.,* 1995; Larinier & Travade, 2002). Examples for special turbines are presented in Chapter 4.3.5.

Turbine passage can cause losses of 10 – 40% of juveniles and up to 100% for large fish, especially if they are passing several consecutive dams (Turnpenny, 1998; Holzner, 2000).

So far, it is not possible to prevent all fish from entering the turbines. Solutions are currently unavailable for juveniles that drift downstream passively. “Fish-friendly” turbines should be considered as a standard equipment for hydropower plants.

The consequences of unsuccessful downstream drift are discussed in Chapter 6.6 while Chapter 5.3.5 includes more detailed information on fish-friendly turbines.

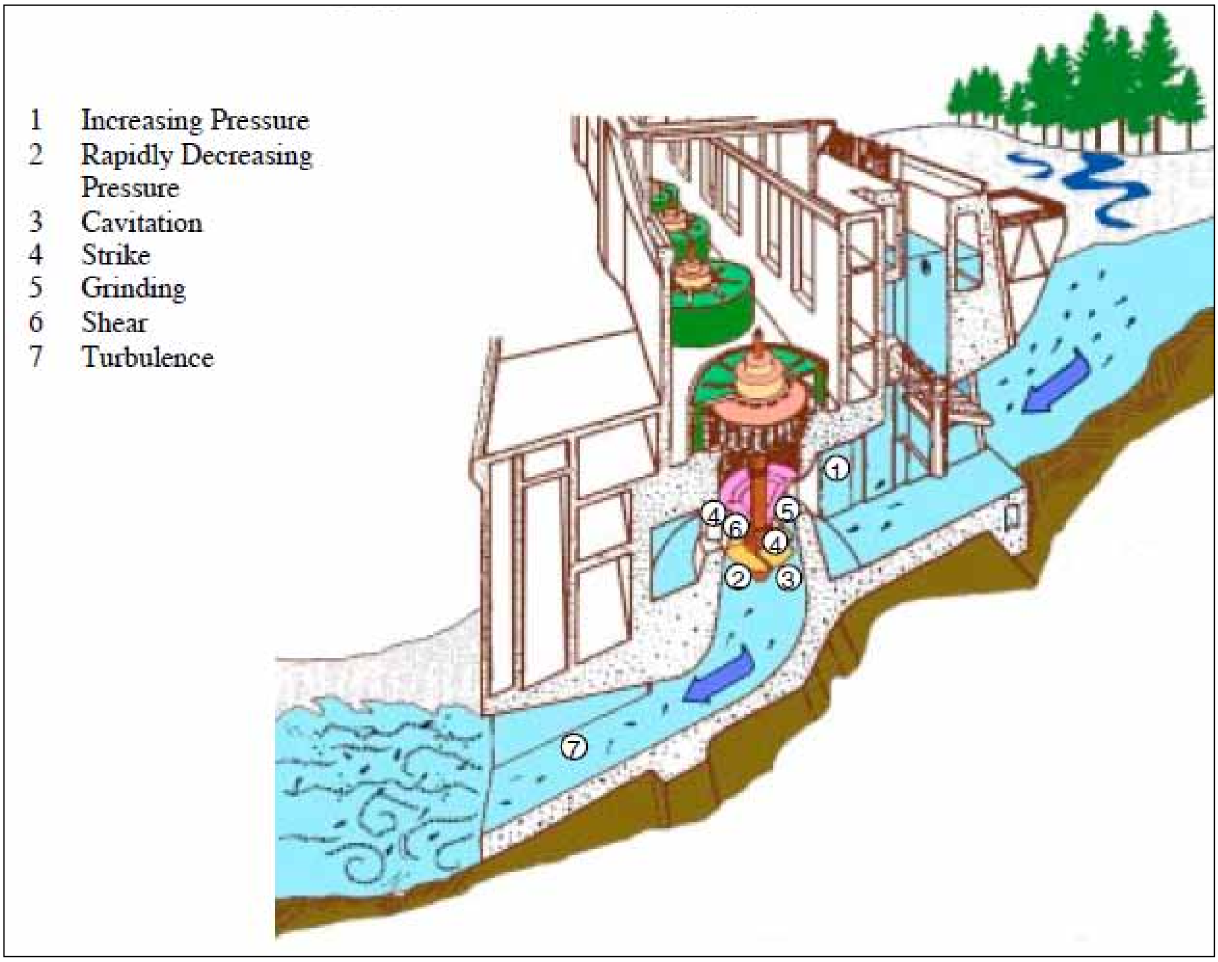

Figure 38: Schematic diagram of locations within a turbine system where fish injury mechanisms are believed to occur (Odeh, 1999; modified from Cada *et al.,* 1997)

4.2.2 Behavioural barriers

Behavioural barriers are facilities producing a stimulus for fish (repulsive or attractive), which are usually used to prevent the fish from entering the turbines. Examples include (BAFU, 2012):

- Electrical screens; efficiency limited to 15% (Gosset & Travade, 1999);
- Bubble screens;
- Sound screens (lacking experience);
- Fixed/mobile chain screens;
- Light screens (attractive or repellent); and
- Surface guide walls.

Surface guide walls are only suitable for species migrating close to the surface. For example, a guide wall is installed at the Bellows Falls Power Station (Connecticut River, USA) which extends 9 m deep into the water column with an angle of 40° (Larinier & Travade, 2002). As guide walls are only suitable for surface-migrating fish, they must be combined with other solutions.

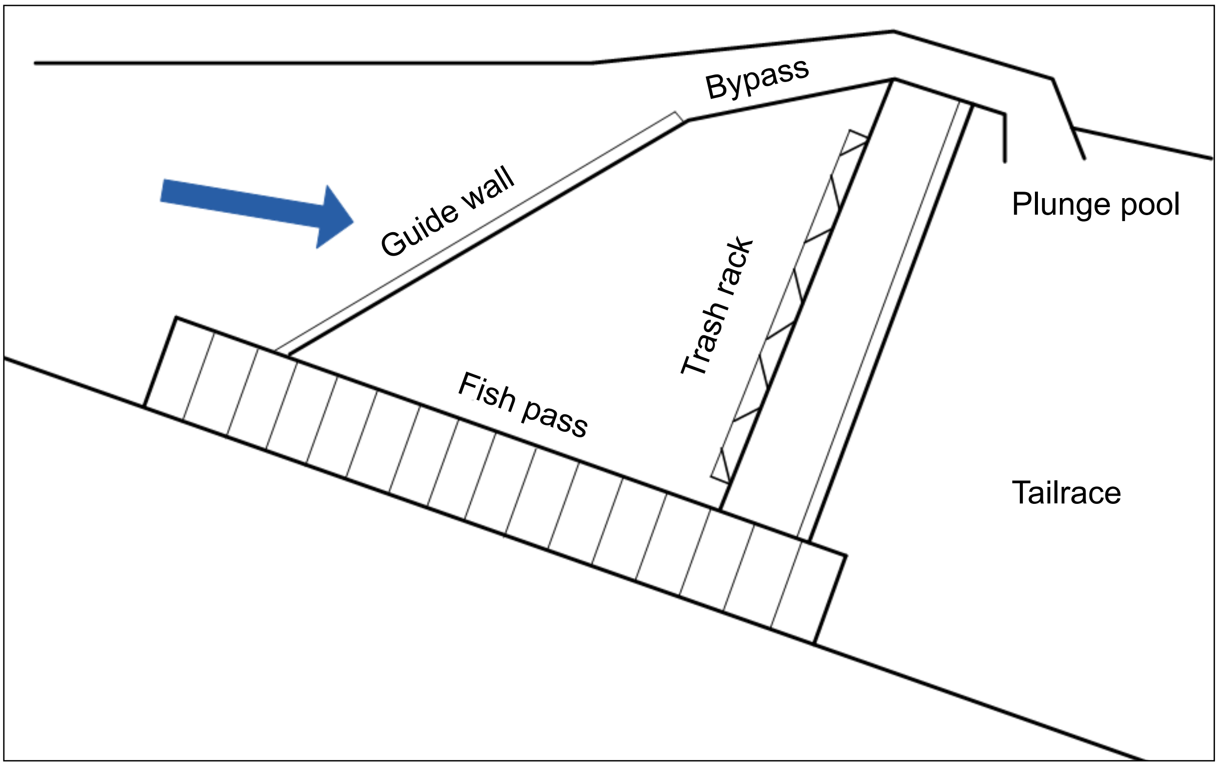

Figure 39: Guide wall at Bellows Falls Power Station (adapted from Larinier & Travade, 2002; based on Odeh & Orvis, 1998)

- Louvre screens consist of vertical slats with right angles towards the flow to introduce current vortices and guide fish to a bypass (ASCE, 1995 in Larinier & Travade, 2002). They have been widely used in the USA at flows of up to 140 m³/s. However, they have been gradually replaced because their efficiency is too low (60 – 90%) for the protection of juveniles when compared with physical barriers (Larinier & Travade, 2002).

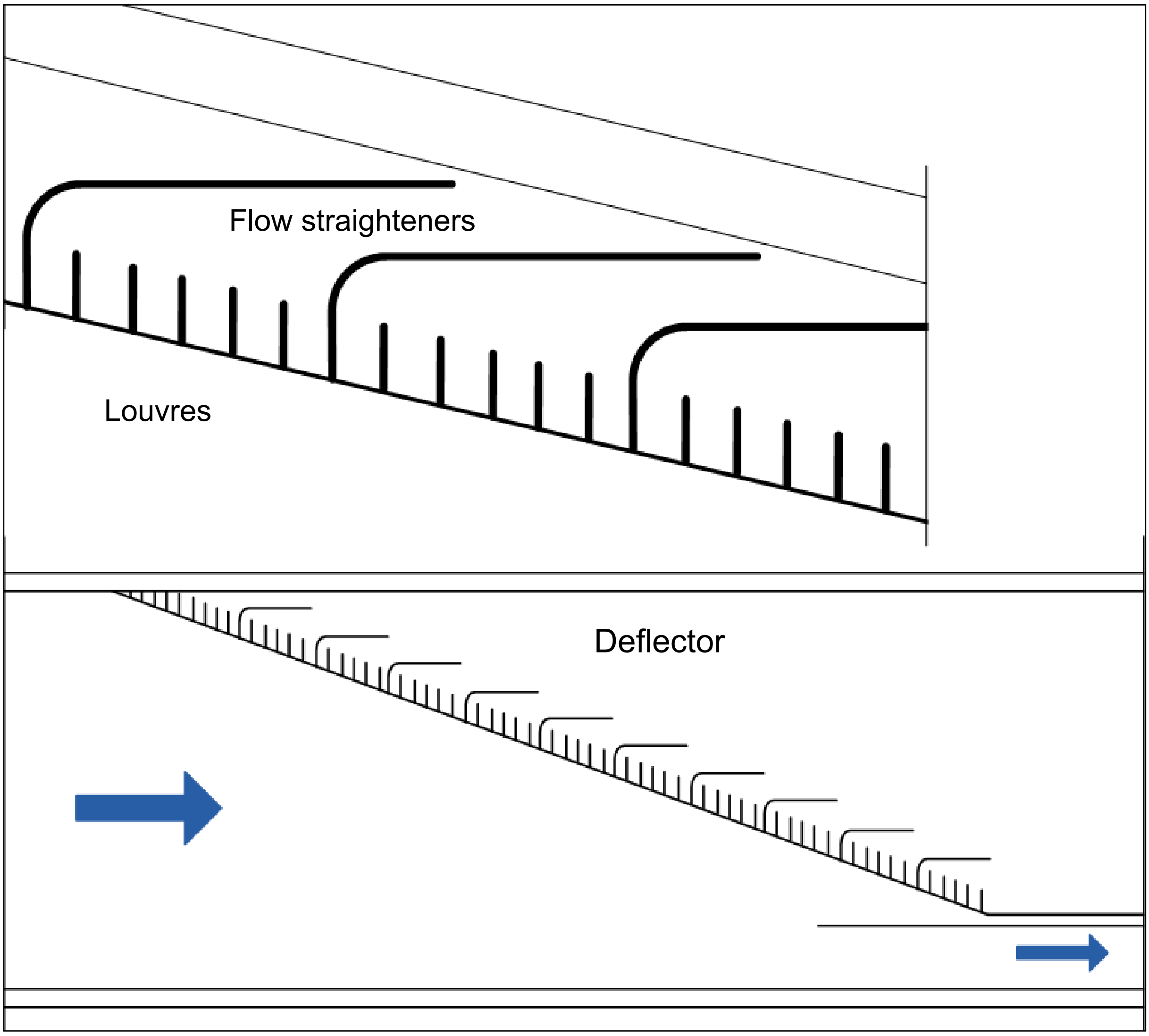

Figure 40: Louvre screens (Larinier & Travade, 2002)

In Europe, experiences with behavioural barriers are not convincing and their application is limited to flow velocities less than 0.3 m/s (Gosset & Travade, 1999). The reactions of fish to behavioural barriers are not entirely understood. For the Mekong, knowledge of fish behaviour facing such barriers is missing. According to Williams *et al.* (2012), physical barriers are more effective than behavioural barriers and thus the latter are not discussed further in this report.

4.2.3 Physical barriers

Screens act as physical barriers and mechanical filters. To provide effective protection, the clearance of screens (bars spacing) should be selected with regard to the fish community and should not exceed 20 mm (Dumont, 2005; Larinier & Travade, 2002; DWA, 2005). The approaching flow velocity (i.e. in the vertical profile in front of the screen) should not exceed the critical swimming speed of fish and should be less than 0.25 – 0.5 m/s. Physical barriers lead to hydraulic losses which cause reduced energy production. The losses depend on the geometry of the screen (e.g. distance between bars, profile of the bars) and flow velocity.

Screens should be positioned in a way that guide fish towards bypasses. Fish usually gather in the pointed angles of oblique weirs thereby indicating a suitable position for the bypasses. The angle between the flow and the screen is usually below 45° but is also ~20° in some cases. The angle also causes a certain amount of flow to be transported parallel to the screen (Larinier & Travade, 2002).

4.2.3.1 Fine screens

Screens with bar spacings of ≤ 20 mm are required to prevent downstream migration of fish (through turbines) from a length of 16 – 21 cm (depending on the species; Holzner, 2000). The bar spacing or clearance should be ~10% of the length of the fish length it is designed to exclude (Larinier & Travade, 2002). Physical barriers with a bar distance of 10 – 15 mm will exclude most fish but a special rake with less than 10 mm of bar spacing is required to prevent juveniles and very small fish from entering turbines. However, such screens are not applicable for large rivers as they currently can handle only flows <100 m^3/s (Dumont, 2008).

4.2.3.2 Wedge-wire screens

This screen consists of a row of tight lying bars (3 – 10 mm) shaped like a triangle. The screens are sloped towards the flow. Advantages include the smooth surface that prevents injuries of fish and favours their escape, and the v-shape that reduces the risk of clogging. While wedge-wire screens are suitable solutions for fish protection, the hydraulic losses are very high (BAFU, 2012). Experiences show that they can only be used for discharges up to 10 – 20 m^3/s while suitable solutions for larger rivers are still missing (Dumont *et al.,* 2005).

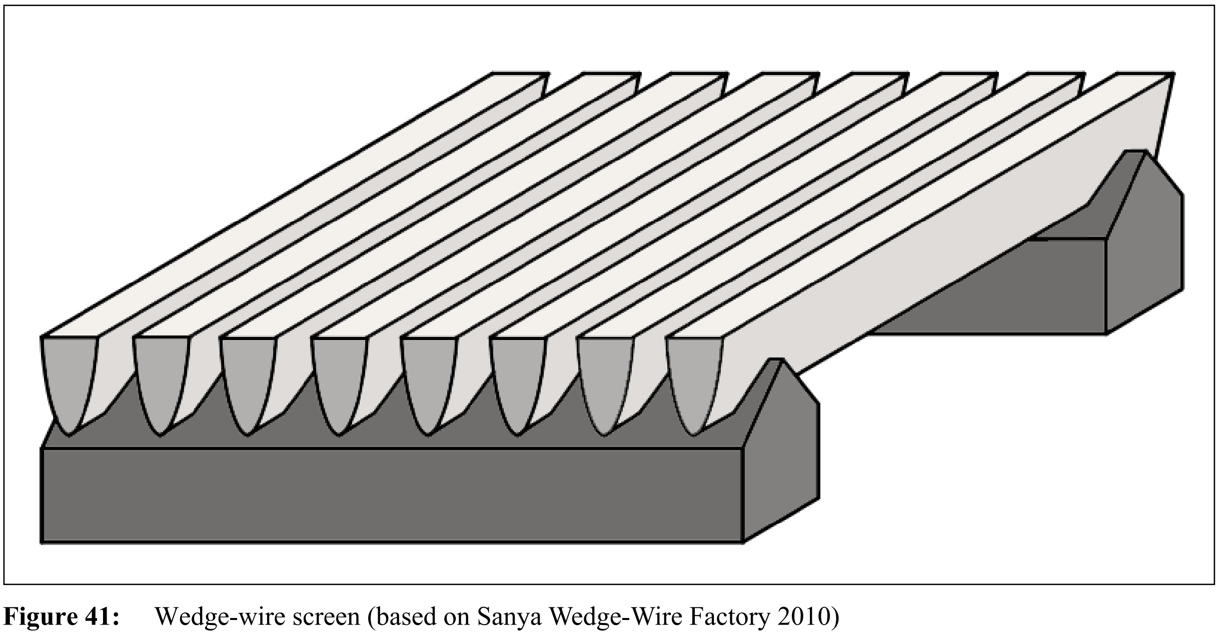

Figure 41: Wedge-wire screen (based on Sanya Wedge-Wire Factory 2010)

4.2.3.3 Special screens

Fine screens can be replaced by circulating shields in the form of perforated plates or weir grids in which the size of the holes depends on the size of fish to be protected. There are different types (BAFU, 2012):

- Stationary screens are constructed from a perforated metal plate aligned in a vertical or inclined direction.
- Travelling screens rotate at varying speeds depending on the amount of suspended debris. The diameter of openings is 1 – 6 mm. They can be complemented by facilities that collect fish and transport them downstream.
- Drum screens are similar to travelling screens, but in the form of a rotating drum (diameter 0.8 – 1.5 m for small, up to 6 m for larger HPPs). The distance between the bars is usually 3 – 6 mm.

These special screens have been developed in the USA and experience for Europe and Asia is not available yet. Furthermore, experience is not available for large rivers.

4.3 Selected facilities for downstream migration

The following chapters present some pathways for downstream migration of fish, including adults, juveniles and larvae. For larvae, which have limited control over their migration, two aspects are important: (1) the passability of the reservoir and (2) the passability of the dam (Agostinho *et al.,* 2002).

Larinier (2007) reports that more water is required for downstream than upstream migration (i.e. 2 – 12% of the actual discharge). However, adjustments may be required depending on site characteristics (e.g. location, hydraulic conditions, trash rack characteristics) (Larinier & Travade, 2002).

4.3.1 Downstream migration via upstream migration facilities

Fish passes for upstream migration are usually ineffective for downstream migration because the behaviour of downstream-migrating fish does not often lead them towards the fish pass exit. Agostinho *et al.* (2007b, 2011) address the inefficiency of most fish passes to support the downstream movement of adults and juveniles in tropical rivers. However, downstream migration is sometimes reported through fish passes designed for upstream migration. For example, Makrakis *et al.* (2007b) report bidirectional movements of several small non-migratory species and four out of seven migratory species. Furthermore, observations through a window showed that fish in the fish pass on the Ourinhos Dam (Paranapanema River) migrate up- and downstream in the fish pass. However, it is unclear if the fish moving downstream entered the fish pass from upstream (Arcifa & Esguícero, 2012).

4.3.2 Surface-orientated bypasses

Surface passage describes a pathway where fish migrating near the surface such as salmon smolt are passed downstream via bypass systems (Ferguson *et al.,* 1998). Surface passage is a cost-effective route with regard to the amount of water released per fish. However, in multi-species environments only a small proportion of the total downstream migration is supported. Another issue is predation downstream from the weir where the disoriented fish are released back to the river (Schilt, 2007).

Bypasses should be located close to the areas where fish concentrate (i.e. close to the weir or at a physical barrier towards the turbines). Bypasses located sideways are usually hard to trace, and therefore allow only partial passage. Fish have to be picked up where they usually gather in the forebay or they should be guided by screens towards the bypass system.

For juvenile salmonids, the bypass should have a rectangular entrance with a minimum dimension of 0.4 – 0.5 m for width and depth (Larinier & Travade, 2002). The dimensions should be adapted for the dimensions and expected biomass of downstream migrating fish. The bypass has to be connected to downstream transfer facilities. Also trash racks can be used in combination with bypasses, whereby the bypass entrances should be placed close to the trash rack face and on the side where fish gather (Larinier & Travade, 2002).

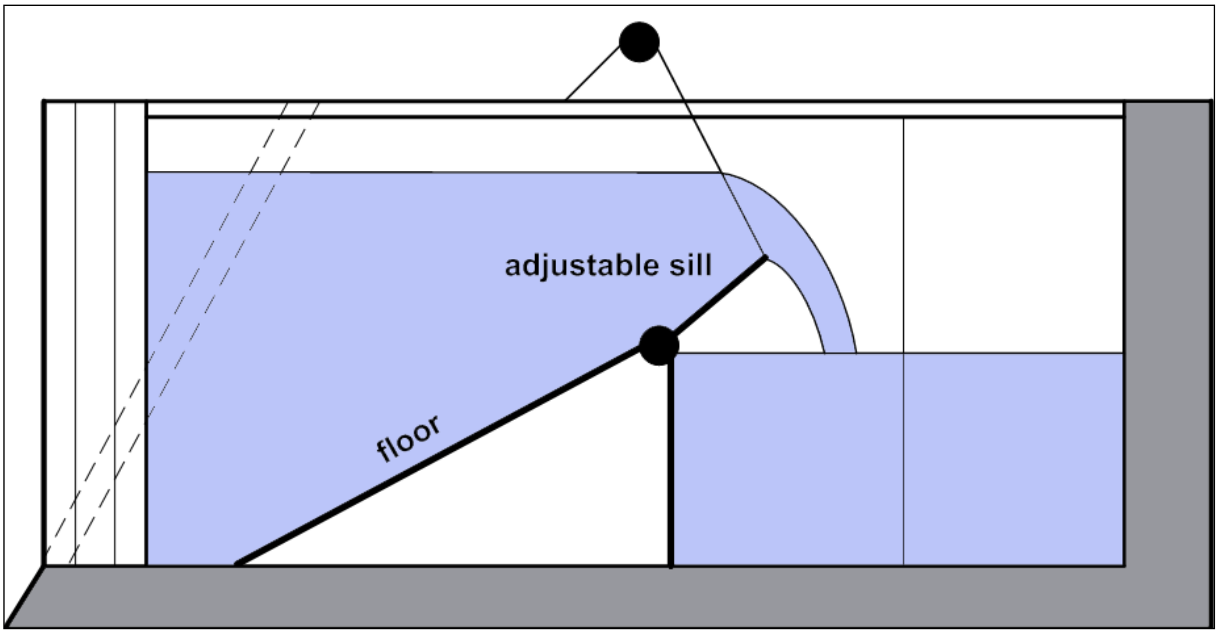

Figure 42: Conceptual design of a downstream bypass. The flow direction is from left to right. The bypass leads fish into an existing upstream fish pass or directly into the tailwater. (adapted from Larinier & Travade, 2002)

The functionality of such a bypass depends highly on its hydraulic conditions (i.e. depth, flow, velocity, acceleration) and the reaction of fish to these characteristics (ASCE, 1995; Larinier & Travade, 1999). Larinier (2007) reports that salmonids accept this DFP if the following conditions are met: positioned close to the screen, downstream flow is at least 40 cm deep, mean flow velocity is 0.4 – 0.6 m/s, and flowing section is at least 2 – 3 m long. It is possible to lead the downstream migrating fish from the bypass into an existing upstream fish pass or directly into the tailwater (Jens *et al.,* 1997; Travade & Larinier, 2007).

These systems are still under development (Dumont, 2008; Hassinger, 2011) and solutions for large rivers with multiple species are lacking.

4.3.3 Spillway passages

In general, spill flows discharge water that exceeds the capacity of the turbines during high flows. However, spill flows are also intentionally used to bypass downstream-migrating fish. The magnitude spilled can be regulated by gates that release water at the surface or bottom, depending on the type of gates. While spillway passage is considered the most effective passage route for juvenile salmonids, disadvantages exist such as increased mortality (Schilt, 2007) and supersaturation of dissolved gas (see Chapter 6.7).

Spillway mortality depends on the height and design of the spillways and varies from 0.2 – 99%. The Columbia River the (Bonneville, McNary and John Day dams) with spillways of ~30 m height presented mortality rates between 0 – 4%. However, mortality rates between 8 – 37% were estimated for the Glines Dam (60 m height) and Lower Elwha Dam (30 m height) on the Elwha River (Bell & Delacy, 1972; Ruggles, 1980; Ruggles & Murray, 1983). Factors causing mortality are abrasion against the surface, sudden pressure changes, rapid current changes (shearing effects) or supersaturation (Ruggles, 1980; Beiningen & Ebel, 1970; Bouck, 1980; Crunkilton *et al.*, 1980; Lutz, 1995; Backmann & Evans, 2002; Backmann *et al.,* 2002). Furthermore, spillway passage can reduce swimming performance, causes disorientation (Sciewe, 1974) and concentrates downstream passage which can favour predation (Schilt, 2007; Larinier & Travade, 2002).

Arnekleiv *et al.* (2007) showed that the majority of salmon smolt and kelt used short periods of surface water release (partially or fully opened weirs) to migrate downstream through the spillways. During their investigations, surface spill flows with water columns of 12 – 36 cm were used for downstream migration while the submerged turbine shafts or deep water releases were neglected.

Experience of spillway passage for large fish is scarce. For example, Parsley *et al.* (2007) reports successful passage of sturgeons via bottom gates at the Dalles Dam (Columbia River).

Surface spill flow can serve as a migratory pathway if the water depth is ¼ of the fall height and at least 0.9 m (DWA, 2005). Bell and Delacy (1972) showed that fish could be injured if the velocity exceeds 15 – 16 m/s. This critical velocity is reached after a free fall of 30 – 40 m (for 15 – 16 cm long fish) or 13 m (for > 60 cm long fish). Fish that are less than 10 – 13 cm long are not harmed if their velocity remains below the critical thresholds (i.e. 15 – 16 m/s). However, BAFU (2012) states that the free fall should not exceed 2.5 m. A release below the surface is not recommended since fish might be harmed. Further research is necessary to formulate recommendations for the Mekong River.

4.3.4 Trap and truck

This system, as explained for upstream migration (Chapter 3.2.10), is also suitable for downstream migration.

Trap and truck systems have been applied since 1981 to catch juvenile salmonids in several dams (Columbia River and Snake River) and to transport them safely downstream (Ward *et al.,* 1997). The fish can be released into the tailwater or transported over longer distances to bypass a chain of reservoirs.

For example, this system was used to collect juvenile salmon at the 95 m high Upper Baker Dam (Washington). Approximately 20% of the HP generation capacity (28 m^3/s) was used to attract fish into a collector which captured up to 87% of marked sockeye salmon (*Oncorhynchus nerka*) and coho salmon (*Oncorhynchus kisutch)* (Verretto, personal communication in Ferguson *et al.,* 2011).

Trap and truck systems could be used only for juveniles or larvae because it might not be possible to logistically cover the high biomass occurring in the Mekong River. In this case, more investigation is needed if species are able to find their way afterwards or if they suffer from a permanent or temporarily loss of orientation. Given that technology is unavailable to collect the fish in front of the turbines in such large rivers, this solution is not applicable. A major issue to consider is the mortality due to handling, especially if netted. Many species lose their scales readily thereby causing infections and increased mortality.

4.3.5 Fish-compatible turbines

Based on several investigations (Monten, 1985; Larinier & Dartiguelongue, 1989; Hadderingh & Bakker, 1998; EPRI, 1992), it is assumed that all turbines impair fish to a certain degree. Turbine passage can cause injuries and even death due to rapid extreme pressure changes, cavitation, shear stress, turbulence, strike or grinding (Ĉada, 1990; USACE, 1995; Ĉada *et al.,* 1997). The likelihood of impact caused by physical structures and pressure effects depends on the size of the fish. While up to 100% of adult fish can be affected, usually less than 5% of ichthyoplankton is affected (Ĉada, 1990). Large Kaplan turbines may be the most “fish-friendly” conventional turbines and show an average survival rate of 88% (Bickford & Skalski, 2000). For the Mekong River, the mortality of certain turbine types should be investigated.

Adaptations of turbine geometry, the operational mode and management of the hydropower plant with regard to key species are possible solutions to mitigate turbine impacts. For example, Voit Hydro Inc. develops fish-friendly turbines by modifying existing turbine types (Franke *et al.,* 1997). Fish-friendly turbines should consider the following recommendations (Ĉada *et al.,* 1999; Odeh, 1999):

- **Kaplan turbines:** (1) operation at high efficiency to prevent cavitation, (2) remove gaps in the turbine system (modify shape of the hub and discharge ring from the cylindrical-spherical-conical shape to all spherical), (3) eliminate wicket gate overhang to reduce shear stress, (4) proper placement of wicket gates and use of hydraulically smooth stay vane, (5) use of environmentally friendly lubricating guilds and greases, (6) keep surfaces smooth to reduce abrasion injuries, (7) use of advanced control systems for efficient operation, (8) redesign draft tube piers to be hydraulically smooth.

- **Francis turbines:** (1) use turbines with low blade number, (2) use blades with thicker edges, (3) reduce wicket gate overhang, (4) use of greaseless and self-lubricating wicket gate bushings, (5) smooth surfaces, (6) operation mode with adjustable speeds, (7) application of advances turbine control system, (8) minimisation of pressure changes.

The following list provides additional examples of special turbines that are designed to improve safe passage for fish:

- **Turbine VLH (very low head):** application for height differences of 1.4 – 3.2 m and flows of 10 – 26 m^3/s (www.vlh-turbine.com). The turbine is used in France, Italy, Germany and Poland. Monitoring of eel and salmon smolt introduced directly in the turbine measured a survival rate of 92.3%. However, this turbine requires testing over longer periods with different fish species to allow general conclusions.

- **Screw turbine:** application for height differences of 1 – 10 m and flows of 0.5 – 5.5 m^3/s (NPTEC GmbH, 2011). Although the producer claims that this turbine is fish-friendly, scientific proof is not available yet.

- **Alden turbine (Cook *et al.*, 2000):** applicable for height differences from 20 – 30 m and flows > 30 m^3/s. The turbine looks like a corkscrew (Energy.gov, 2011), has three blades, no gaps, is large and rotates slowly while energy production does not suffer. The turbine was successfully tested by the Alden Laboratory in 2001 and 2002 to show its biological functionality (see also PowerEngineering, 2010). According to EPRI (2011), the predicted fish survival rate is 98.4% for 20 cm long fish.

- **Archimedean Screw:** is thought to be fish-friendly due to its low rotation speed (28 – 30 rpm) and no significant shear forces or pressure changes. Several studies showed a low rate of fish harmed by this type (depending on the fish species). A case study by Schmalz (2010) shows that three species remained unharmed (roach, tench and bream) and 92% of all remaining species were unharmed. However, he argues that large gaps between the turbine and its case may cause fish injuries and sharp edges of blades should be avoided. Application of Archimedean Screw is limited to low-head dams.

- **Advanced hydropower turbines (AHTs):** at Wanapun Dam (Columbia River), ten turbines were replaced by so-called advanced hydropower turbines to increase power generation and improve fish passage security. However, significant differences in blade-strike injuries do not exist between conventional and advanced turbine types (Deng *et al.,* 2011).

In summary, further investigations are required to prove if new designs or operational modifications can increase turbine-passage survival. To date, scientists are optimistic that ongoing development will lead to turbine designs with reduced damage to large fish.

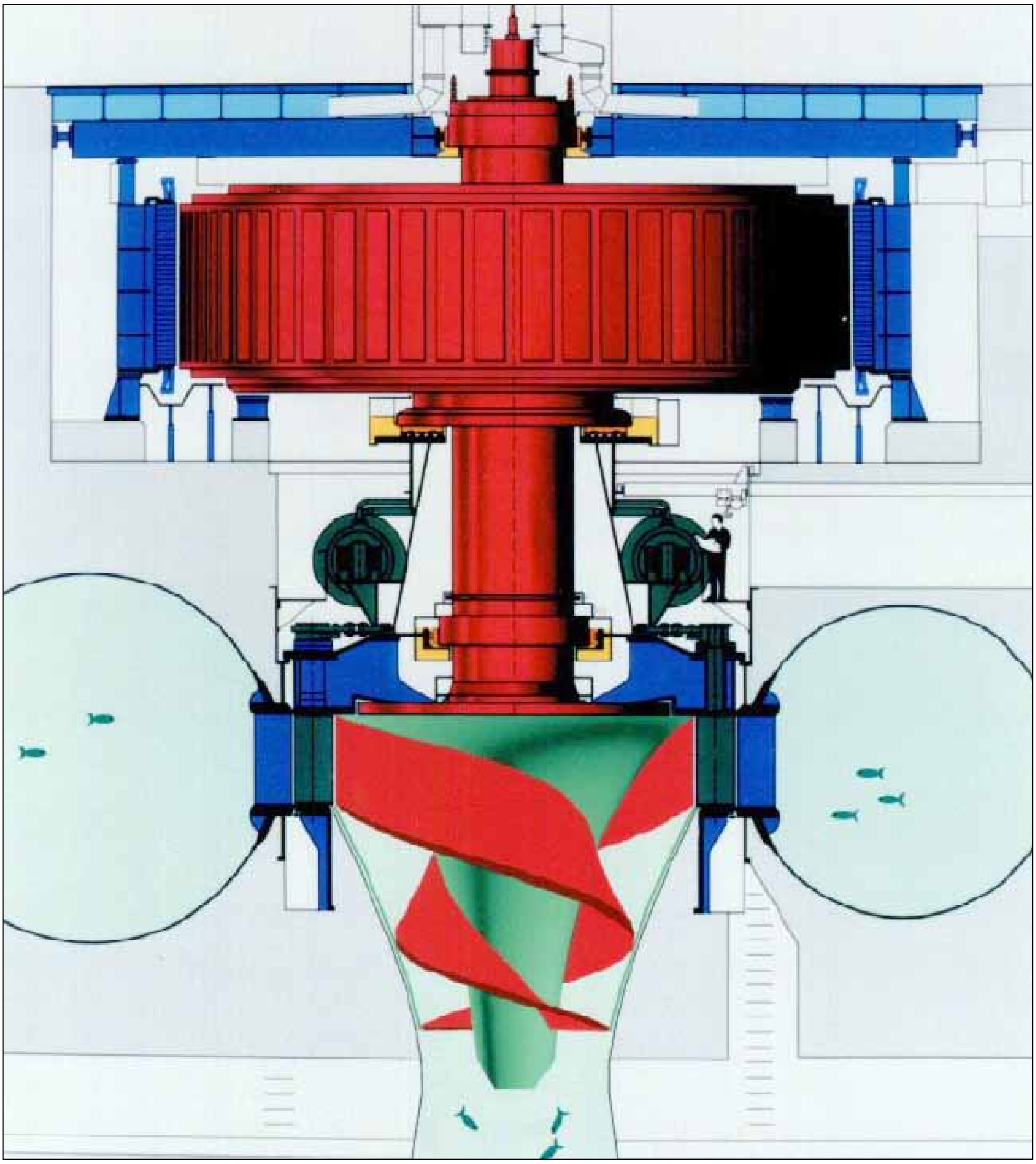

Figure 43: Schematic of the Alden Research Laboratory/Northern Research and Engineering Corporation fish-friendly turbine (Odeh, 1999; Courtesy Alden Research Laboratory Inc.)

5 Monitoring and assessment of the functionality of fish passes

Monitoring of fish passes reveals insights into their functionality. The monitoring will show if the observed fish passage is in accordance with the expectations and assumptions made prior to the construction, i.e. expected species diversity and amount of fish. The evaluation of a fish pass solely based on abiotic data (e.g. slope, discharge, fall height) without consideration of actual fish migrations is not adequate.

Full ecological functionality is only ensured if all (potentially) occurring species (autochthonous fish fauna) and age classes are always (> 300 days per year) able to migrate without qualitative and quantitative restrictions. Depending on the scope of assessment, species relevant for a fishery might be assigned more importance than other species. In general, the evaluation of the functionality of a fish pass can be based on one of the following two approaches (Gumpinger, 2001; Woschitz *et al.,* 2003):

- **Evaluation based on indirect parameters (abiotic parameters):** This evaluation method was frequently applied in the past by comparing easily measured parameters (e.g. slope, hydraulic parameters, morphometric dimensions and attraction flow) with reference values obtained from functional fish passes or guidelines. Although this method is fast, some parameters cannot be easily measured and comparable values may be missing. Although abiotic parameters can serve as valuable supplements for the evaluation of a fish pass, an ecologial evaluation of its functionality is the reliable option.

- **Evaluation based on fish-ecological investigations:** Several approaches such as expert opinion, fish trap investigation or counting windows are possible. However, it is important to select a method that can be evaluated through qualitative and quantitative methods. It is therefore insufficient to evaluate only the number of fish which are currently in a fish pass (e.g. by electro-fishing) because this does not provide evidence that a fish pass is passable.

Especially for the Mekong, where knowledge concerning fish behaviour and requirements is still limited, fish-ecological investigations are mandatory.

Optical evaluations via video monitoring in counting windows may work automatically. The evaluations can take place for long periods and provide reliable results. However, they are only suitable if the visibility allows the detection of both species and age class of migrating species which is unlikely due to the frequent high turbidity in the Mekong River.

Telemetric surveys (via transponders) provide good data for the migration behaviour of fish. Fish can be caught and equipped with a transponder to evaluate if and where fish are able to migrate up- or downstream. However, this evaluation approach is very expensive because a large number of fish is required to provide significant data.

Fish traps allow the qualitative and quantitative evaluation of up- and downstream migrations. If additional data on the actual fish stock are available, migrating fish can be related to the overall migration potential (Jungwirth *et al.,* 1994; Eberstaller *et al.*, 1998; Eberstaller *et al.,* 2001). This is also the case if fish stock data are investigated as a first step. Compared to other approaches, this method seems to be most effective and suitable. Therefore, Woschitz *et al.* (2003) suggest the application of fish traps in combination with quantitative fish stock evaluations.

The length of investigation is advised to be one year or more. Since the length of time might not be feasible, the investigation should take place at least before and during the reproduction periods of the key species and the subsequent downstream migration of juveniles or drift of larvae. It is also desirable to detect a wide spectrum of fish with regard to swimming behaviour, size and age under different discharge situations.

Although the investigation should be performed quickly after completion of a fish pass, conducting an assessment after one year is suitable to provide enough time for the ecosystem to compensate for negative effects caused by construction activities. However, for large rivers such as the Mekong, investigations could start as soon as a fish pass starts operating and continue for several years. Monitoring should be carried out periodically to evaluate possible changes over time. In turn, it might be possible to address certain detected deficits of the fish pass when identified.

For upstream fish passes, there should be at least one fish trap at the exit of the fish pass (upstream end). However, if an additional fish trap is included at the entry of a fish pass (downstream end), this inclusion can provide rich data on the perceptibility of the fish pass. Several evaluations along the fish pass should be included for long fish passes with different characteristics, including slope, flow velocity, and dimension. If single segments are less passable than the rest of the fish pass, these segments can jeopardise the entire functionality of the fish pass.

Downstream migrations, whether active or passive, may take place through the turbines, opened weirs, spillways or downstream fish passes. Investigations on downstream migration are expensive and only a few examples exist (e.g. in Europe).

Nature-like fish passes and bypass systems may provide permanent habitats for fish communities. Several investigations are required to evaluate the quality of habitat for particular species and life stages, including its suitability for reproduction.

Along with biological data, abiotic data (e.g. discharge, temperature, water quality) are valuable data that can be used for the interpretation of results. These data might also be favourable for the investigation of migration triggers in the Mekong River. In addition to the discharge in the river, the discharge in the fish pass should be monitored throughout the year.

The following biological criteria for the evaluation of efficiency are recommended (adapted from Eberstaller *et al.,* 1998; Eberstaller *et al.,* 2001):

- Qualitative upstream fish migration: species diversity, species traits (long, medium and short distance migratory species), life stages (adults, juveniles);
- Quantitative upstream fish migration: number and proportion of fish passed;

- Qualitative downstream fish migration: species diversity, species traits (long, medium and short distance migratory species), life stages (adults, juveniles, larvae);
- Quantitative downstream fish migration: number and proportion of fish passed; and
- Habitat suitability of nature-like fish passes and bypass systems.

To assess qualitative and qualitative efficiency of a fish pass, the proportion of fish successfully passed is used. This requires a comparison of the number of fish intending to migrate (monitored downstream and upstream from the dam) with the number of fish passing the fish pass (monitored in the fish pass).

At a larger scale, the *effectiveness* of a fish pass is assessed by estimating the extent to which the fish pass contributes to the functioning of viable fish populations. Highly efficient fish passes may not be effective if other impacts impede viable populations. The assessment of viable fish populations requires definition of a baseline level (reference value). The baseline may refer to historic conditions without major human alterations, pre-damming conditions or post-damming conditions with altered fish assemblages. The baseline set by the EU WFD is the *high ecological status* as defined by *minor or no anthropogenic alterations*. The environmental objective is the good ecological status as defined by a low level of distortion, resulting in slight changes in species composition and abundance. The environmental objectives are lower (good ecological potential) in so-called heavily modified water bodies (e.g. dammed river sections) where the objective is also to maintain viable fish populations (European Commission, 2000).

6 Other impacts on fish associated with large dams

Hydropower development can cause various environmental impacts. The integrity of fish populations relies to a high degree on the availability of essential, mostly spatially separated habitat patches within the river network. The preservation of favourable areas for life cycle completion might be of higher importance than the construction of functional fish passes (Suzuki *et al.,* 2011). Dams may result in impacts that are related to the reservoir and upstream and downstream river sections (Schmutz & Jungwirth 1999; WCD, 2000; Jackson & Marmulla, 2001). This chapter provides a brief introduction to the most important impacts. The environmental conditions are changed in reservoirs as a consequence of reduced flow velocities and deposited sediments and nutrients. The lack of sediment in downstream sections may affect the hydromorpholgical dynamics and habitat conditions. Depending on the size of the reservoir, the downstream flow might be modified on a diurnal or seasonal basis. In spite of fish passes, the life cycle of fish might be affected by dams if fish are attracted to ecological traps. Furthermore, predation below dams, where fish often congregate and gas supersaturationare specific problems associated with dams. The impacts of dams increase in cases of multiple dams in a cascade.

For the Mekong, except for some cases, limited information is available on impacts of current and planned dams. The severity of negative impacts is likely to depend on the following features: (1) the size of the dam, (2) the size of the dammed watercourse and (3) the location of the dam relative to fish-migration routes, valuable habitats, amount of submerged floodplains and settlement patterns (Hortle, 2009b). While some data are reported for the Pak Mun Dam (e.g. Roberts, 1993, 2001; Schouten *et al.,* 2000; Foran & Manorom, 2009; Jutagate *et al.,* in press), further investigation is necessary to fully understand the impacts.

While tolerant species with a short life cycle may adapt to new conditions after dam construction, riverine specialist species will be affected by many well-known or still unexplored factors such as changes of migration triggers (Kang *et al.,* 2009). Knowledge of life history strategies is essential to assess potential impacts of dams. Some knowledge is already available on the respective life histories but more information should be gathered (Kang *et al.,* 2009).

6.1 Impacts of the reservoir size and depth

Hydropower dams alter hydromorphological conditions by inundating rivers upstream from the dam. Storage capacity depends on the size of the reservoir. Retention time of the water is linked to the amount of flow passing through the reservoir. Large reservoirs with high water-retention time resemble lakes and, likewise, deeper reservoirs are likely to be vertically stratified. Run-of-the-river plants create impoundments with low retention time and therefore represent an intermediate type of water body that is neither a lake nor a river. During low-flow conditions, they function like lakes. In contrast, during floods, they resume characteristics of running waters that may impede the establishment of both limnophilic and rheophilic fish communities (Welcomme & Marmulla, 2008).

The impacts of dams are partly related to the size of the reservoir created by the dam. In general, the greater size of the dam increasingly alters the hydromorphological conditions. However, impacts depend also on the local conditions of the dam. The size of the reservoir is a result of the topography (e.g. river slope) and the height of the dam. Reservoirs inundate fluvial habitats and floodplains, reduce flow velocity, increase depth and therefore change the entire characteristics of the river. Mainstream dams in the LMB would be >30 m high and form reservoirs 75 – 200 km long (Roberts, 1995) thereby transforming large reaches of the Mekong into slow-moving water (Hortle, 2009b).

There is strong evidence that dams and associated reservoirs impact fish populations (e.g. Penczak *et al.,* 2012). Dams form new lentic or semi-lentic environments upstream from the dam where the rheophilic riverine fish communities become dominated by eurytopic and limnophilic species (Welcomme & Marmulla, 2008). As a rule, abundance and richness of riverine species decrease as a result of absence of riverine habitats or deterioration of feeding and spawning habitats (de Brito Ribeiro *et al.,* 1995; Kruk & Penczak, 2003). On the other hand, generalist fish species adapt to the altered conditions and may become more abundant (Welcomme & Marmulla, 2008).
In addition to the habitat, other characteristics such as turbidity and temperature might be modified. Viravong *et al.* (1994) report an inverse relationship between migration activity and water temperatures. Thus, temperature changes caused by large reservoirs may impact the migration of certain species. Furthermore, entire cascades of reservoirs can cause the absence of reproduction habitats, including those up- and downstream from the barrier.

Spawning occurs mostly during rainy periods with higher turbid flows. Passively transported ichthyoplankton enters the floodplains where juveniles find shelter and favourable conditions for feeding (Agostinho & Zalewski, 1995; Lowe-McConnell, 1999). It is assumed that egg and larvae are less visible during turbid flows and therefore better protected against predation (Agostinho *et al.,* 2002 in Pompeu *et al.,* 2011). The transparency in the reservoir makes eggs and larvae more prone to predation and reduces their survival (Agostinho *et al.,* 2007b).

If the flow velocity in the reservoir is below a specific threshold for species and age (see also Chapter 2.1.3) fish lose their positive rheoactive orientation (DWA, 2010). As such, the flow velocity in the migration corridor should be larger than the rheoactive velocity. In contrast, Agostinho *et al.* (2002) argue that orientation for upstream migration is not always impacted and fish might benefit from lentic conditions by faster upstream migration.

Nevertheless, depending on the size and characteristic of the reservoir, ichthyoplankton may be unable to pass the reservoir during their passive drift (Agostinho & Gomes, 1997b; Agostinho *et al.,* 2007b; Agostinho *et al.,* 2007c). Agostinho *et al.* (2007b) reports that the impact of a reservoir on downstream passage of fish and larvae may depend on the size of the reservoir. Lower impacts may be associated with small reservoirs and with low residence time. While some larvae were detected downstream from Santa Clara Reservoir (7.5 km²), Funil Reservoir (38.32 km², 4 days residence time) and Itutinga-Camargos Reservoir (75.08 km² and 24 days residence time) the Upper Rio Grande River appears to have conditions that limit the passage of ichthyoplankton (Suzuki *et al.,* 2011).

In an analysis of fish larvae and eggs in Funil, Itutinga and Camargos reservoirs, Suzuki *et al.* (2011) identified that ichthyoplankton was abundant upstream from the reservoir but immediately absent downstream from the dam. This was especially true at the Funil Reservoir where a fish pass supports the upstream migration while downstream migration is highly impacted and counteracts recruitment success.

The lentic conditions in a reservoir reduce the mobility of ichthyoplankton whereby eggs might sink to the bottom of the reservoir and suffocate due to low oxygenation (Agostinho *et al.,* 2007b). In turn, the recruitment on both sides of dams can be impaired (Agostinho *et al.,* 2007b). A common management strategy to reduce the impact is stocking though this is not considered a sustainable solution in the long term (Pompeu *et al.,* 2011; see also Chapter 6.1).

Mekong experience: The initial Xayaburi Design Report (2010) and Xayaburi EIA Report (2010) recognise the need for downstream migration to complete life cycles. However, review by the Expert Panel during the PNPCA[2] process revealed that key issues remained to be addressed, including those related to reduced current velocity and disruption to the hydrodynamics of the river. It is estimated that flow velocity in the reservoir will be reduced from ~0.9 to 0.1 m/s and is likely to cause disruption of the life cycles of many species.

The fish larval drift project carried out by the MRC in 2010 in the Xayaburi Hydropower Project area identified 87 species and 22 families drifting in large numbers during the wet season. The mean drift rate was estimated at up to 5.9 million fish per day, including 5 million fish larvae, thereby underlining the importance of drift as a mechanism for downstream dispersal (Hortle *et al.,* 2015). Another MRC drift study conducted in 2009 focused on downstream parts of the Mekong River (Cowx *et al.,* 2015). The study suggests that the fish community structure and population dynamics are likely to be altered as reservoirs act as a sink for downstream drifting eggs and larvae thereby inevitably disrupting downstream dispersal of ichthyoplankton and juvenile life stages.

Mitigation of the impact of reservoirs: Mitigation of the impacts listed above is site specific and they are not easily mitigated. Clearly, the presence of effective upstream and downstream fish passage goes some way towards ameliorating certain impacts as detailed in the preceding sections. However, further actions will be necessary in order to minimise these impacts.

6.2 Ecological traps

In spite of fish passes, harmful effects are possible if fish are attracted to ecological traps. For example, fish may be attracted to pass upstream into reservoirs which do not have spawning habitats available due to other development constraints (Agostinho *et al.*, 2002, 2007a, c; Fernandez *et al.*, 2004; Oldani *et al.,* 2007; Makrakis *et al.,* 2007b; Pelicice & Agostinho, 2008; Schlaepfer *et al.,* 2002; Battin, 2004). This would be the case with cascades of reservoirs that may result in the absence

[2] MRC's Procedure for Notification, Prior Consultation and Agreement for the Xayaburi project was carried out in 2011

of reproduction habitats along long river sections; ascending fish might enter these areas that are unsuitable for spawning (Pelicice & Agostinho, 2008).

According to Carolsfeld *et al.* (2004), the following conditions lead to ecological traps, especially for neotropical migratory species:

- Attracting forces lead fish upstream through a fish pass;
- A fish pass and dam may cause upstream (unidirectional) migratory movements (no downstream migration possible);
- Environmental conditions above the dam exhibit poor conditions for reproduction (absence of spawning grounds, nursery areas);
- Conditions below the dam would be more suitable for spawning and recruitment than upstream from the dam.

If these conditions are fulfilled, fish are prone to migrate into ecological traps. This outcome leads to reduced viability and can thus threaten entire populations (Pelicice & Agostinho, 2008; Schlaepfer *et al.,* 2002; Battin, 2004).

However, rheophilic fish entering a reservoir usually continue their migration further upstream. They are trapped only if they cannot reach suitable reproduction habitats, say, within tributaries. Of course, if fish swim up to another dam that does not have access to passage they will gather downstream from the dam and reproduction is endangered (Pelicice & Agostinho, 2008).

Antonio *et al.* (2007) analysed the blockage of migration routes caused by dam construction (e.g. Porto Primavera Dam in the Paraná River) and found that some species are able to respond to barriers. *P. lineatus* was released up- and downstream from the dam. Half of the downstream-released fish found alternative migration options in tributaries of the Paraná River after contacting the dam. Upstream-released fish moved mostly upstream except for some disoriented individuals that passed the dam downstream (Antonio *et al.,* 2007). Therefore, the knowledge of the location of spawning and nursery areas is critical to effectively detecting ecological traps.

Another ecological trap occurs if ichthyoplankton are not able to pass downstream. This is likely if breeding areas are located upstream from a dam and nursery areas are located downstream (Pompeu *et al.,* 2011). Larvae and eggs rely on the current for passive drift. If they enter the lentic reservoirs that are upstream from dams, they might not be transported further downstream or even sink to the ground of the reservoir and suffocate.

Apart from other impacts, the operational regime of dams varies greatly; fluctuating flows from hydroelectric releases are particularly damaging as are accidental or emergency releases (Wyatt & Baird, 2007). Hydropeaking, an operational regime that provides energy during peak demand, is known to be very harmful for fish. During peak flows, juvenile fish are flushed downstream. During downramping, fish are stranded at riverbanks, in side arms and in floodplains (Heggenes, 1988; Higgins & Bradford, 1996; Irvine *et al.,* 2009; Young *et al.,* 2011).

Damming for inter-basin diversions is also likely to be damaging for river fisheries because the flow of the dammed river is cut off, thereby resulting in reduced flow downstream from the dam. Recent interbasin schemes include Nam Theun to Hinboun, Nam Theun 2 to Se Bang Fai and both Nam Song and Nam Leuk to Nam Ngum (Hortle, 2009b).

Large, deep dams such as those built in China and those proposed on the mainstream and on some tributaries are likely to yield some productivity but may not compensate for lost productivity on floodplains. This is likely the case because the water held in such reservoirs covers a relatively small area and such dams stratify with nutrients depleted as seston settles below a thermocline that develops at ~10 – 20 m depth (Sitthichaikasem, 1990; Hortle, 2009b).

6.3 Sedimentation

Dams also interrupt the natural sediment transport and cause deposition within the reservoir. This reduces the reservoir capacity thereby affecting operation and significantly impacting the ecosystem (MRC, 2009).

Fu *et al.* (2008) examined Manwan Dam from its completion in 1993 to 2003 and concluded that storage capacity was reduced by more than 20% in 11 years (witholds ~21 x 106 m^3/a; 227.6 – 241.2 x 106 m^3 from 1993 – 2003). However, due to accelerated soil erosion in the Lancang River Basin (e.g. deforestation, steep slope cultivation), the impact downstream is still under discussion (Liu *et al.,* 2013). However, the long-term mean annual sediment load of the mouth of the Mekong River (~145 x 106 t/a) is likely to decrease in the future (Liu *et al.,* 2013).

The system will transport less sediment downstream if several dams block the continuity of the Mekong River. The natural sediment transport is interrupted, sediments deposit in the reservoir (reduced flow velocity and barrier) and the downstream section can suffer from depletion. This can cause erosion of the banks and channel bed as well as a second step down-cutting of the bed. For the Mekong, this would result in loss of large bed forms including gravel bars and increased bank erosion in alluvial sections. Habitat alteration can significantly impact reproduction and other factors such as production of benthic invertebrates (MRC, 2009).

Therefore, each barrier has to include sediment management (e.g. sediment routing, sediment bypass, sediment flushing) that is selected after detailed evaluation of possible ecological consequences of the alternative. Sediment or turbidity transport can also act as a trigger for migrations and therefore alterations can lead to reproduction losses. In general, the release of sediment should mimic the natural timing of sediment transport in the respective river to minimise impacts (MRC, 2009).

6.4 Hydrological modifications

In addition to interruption of continuity, dams can alter the hydrology and the timing and magnitude of floods. Several species rely on higher flows during the monsoon season to move towards the floodplains for spawning. Dam construction can thus impact adaptations to pulse floods (Ferguson *et al.,* 2011). Since nearly all of the fishery catch at the Khone Falls consists of taxa that are sensitive to discharge, flow modifications can have a dramatic effect on the fish harvest and possibly for the entire LMB (Baran, 2006).

Higher flows trigger upstream migration. Since dams will regulate the flow of the Mekong River, they may create conditions that reduce higher flows and do not induce spawning migrations. In addition, changes in water temperature may influence the migration triggers (Baran, 2006).

In addition, negative effects on downstream fisheries include the direct effects on productivity caused by trapping of nutrients and detritus, release of hypolimnetic water which may be anoxic and toxic due to the presence of hydrogen sulphide, and rapid downstream fluctuations in water level caused by hydroelectric releases (Hortle, 2009b).

6.5 Predation

Some predatory fish respond to changed conditions and may become more common in reservoirs or downstream from dams. In the Mekong Basin, these are snakeheads (Channidae) and featherbacks (Notopteridae) (Hortle pers. comm.). Predatory birds such as egrets and cormorants also accumulate downstream from dams to feed on fish. Reservoirs, in turn, may create areas of high mortality (Koed *et al.,* 2002).

Upstream migrating fish often congregate below barriers (Agostinho *et al.* 1993, Agostinho *et al.,* 2007c; Baumgartner, 2007; Pompeu & Martinez, 2006; Agostinho *et al.,* 2007b). In these areas, fish are exposed to a high predation pressure. Fish passes allow fish to continue their migration and reduce the aggregation of fish below a dam. However, given the high concentration of fish and the limited spatial habitat in a fish pass, predators might be attracted to fish passes. Therefore, intensified predation and injuries are expected in and around fish passes (McLaughlin *et al.,* in press). In an investigation of predation pressure in a fish pass, Agostinho *et al.* (2012) demonstrated that large piscivorous fish (> 40 cm) were found near the fish pass entrance and that their presence might be a barrier for fish. This situation can therefore reduce the efficiency of the fish pass. Furthermore, injuries and exhaustion alter the behaviour of fish as evidenced in the fish pass (Sazima & Machado, 1990) which may lead to a higher risk of attacks by predators upstream from the fish pass (Agostinho *et al.,* 2012).

It is assumed that the design of the fish pass at the Porto Primavera Dam (Paraná River) favours predation. Agostinho *et al.* (2007a) discussed similar problems for the Lajeado Dam. Predation on salmon smolt below bypass systems is also known for the Columbia River (Muir & Williams, 2012).

6.6 Multiple dam passage

Even if fish passes are available, a delay in migration is observed for several species such as the Atlantic salmon (*Salmo salar*, Karppinen *et al.,* 2002), barbel (*Barbus barbus*, Lucas & Frear 1997), American shad (*Alosa sapidissima*, Moser *et al.,* 2000), sea lamprey (*Petromyzon marinus*, Haro & Kynard 1997), paddlefish (*Polyodon spathula*, Zigler *et al.,* 2004) and Pacific salmonids (*Oncorhynchus* spp.) of the Columbia River Basin (Williams, 1998; Keefer *et al.,* 2004). The delay can increase with multiple dam passage (Caudill *et al.,* 2007) and can cause high energy losses that impede the fish from completing spawning (Geist *et al.,* 2000).

Salmon of the Columbia River returning to the Snake River drainages have to pass four dams on the lower Columbia River and most of them also pass four dams on the lower Snake River. Fish returning to the Columbia River upstream from the confluence with the Snake River have to pass four to nine dams.

Caudill *et al.* (2007) investigated the migrations of 18,286 returning adult salmonids during seven migration seasons (1996 - 2003) in the Columbia River system. Analyses showed that most adults passed each dam within two days after entering the tailrace of the dam and eventually were able to spawn (Keefer *et al.,* 2004, 2005). But many specimens (1.4 – 13.7% in each run) needed more than five days (and up to weeks) to pass a single dam. Fish with long passing times were often unsuccessful in reproduction.

When fish migrate upstream, they have to pass the tailrace (1 – 2 km before the dam) with turbulent flows coming from the turbines and spillways. Within these flows, fish have to find the entrance to the fish pass quickly which greatly depends on the characteristics of the attraction flow and the location of the fish pass. If fish cannot find the entrance quickly, they lose valuable time searching for alternative migration routes. Once they find the entrance, they still have to pass the fish passes which are up to 1,300 m long in the Columbia River. However, it is assumed that the difficult passage over the tailrace and the fish pass is compensated by low-velocity conditions within the reservoirs upstream from the dam (Keefer *et al.,* 2004; Naughton *et al.,* 2005). Therefore, species rapidly finding the entrance of fish passes and successfully passing them might not take longer to reach their reproduction habitats than they would under undisturbed conditions.

Besides hydraulics at fish pass entry, high-flow levels (turbines and spill flow, Caudill *et al.,* 2006a), fallback behavior (Boggs *et al.,* 2004) and temperature (Caudill *et al.,* 2006b; Goniea *et al.,* 2006; High *et al.,* 2006) might influence the time spent in the tailrace and fish passes.

Dams also disrupt the connectivity between spawning and rearing habitats (Muir & Williams, 2012). When Raymond (1979) discovered that survival of Chinook salmon smolt passing through dams was very low (average of 22% from 1966 - 1980) and even worse during dry years (e.g. 1973, 1977), mitigation measures were introduced to improve the downstream passage (Williams & Matthews, 1995). These included the installation of screened bypass systems at most mainstream dams, spill management (Williams *et al.,* 2005) and, more recently, surface-passage structures (Johnson & Dauble, 2006). These measures showed favourable improvements (Muir & Williams, 2012). According to Welch *et al.* (2008), survival rates have been restored to historic levels. Nevertheless, the time required for downstream travel exceeds historic values which causes a later entry into the ocean than historically observed (Muir *et al.,* 2006; Scheuerell *et al.,* 2009). A delayed entry of juveniles into the oceans (Scheuerell *et al.,* 2009) or other rearing habitats located downstream leaves fish with a negative energy balance (Muir & Williams *et al.,* 2012).

6.7 Gas supersaturation and gas bubble disease

Gas bubble disease (GBD) is caused by supersaturated levels of total dissolved gas in the water. Lesions in the fish are caused by the accumulation of gas bubbles in blood vasculature and tissues. Either supersaturation of oxygen or nitrogen can result GBD though the total dissolved gas (TDG) is more important than individual gases or varying combined gas ratios. Supersaturation occurs when water contains more dissolved gas than it can normally hold in a solution at a given temperature and atmospheric pressure. Artificially supersaturated water occurs in plunge pools from dams where the gravity head forces gas into the solution (www.adfg.alaska.gov).

Figure 44: Visible gas bubbles in vasculature of operculum and eye as observed in acute gas bubble disease (www.adfg.alaska.gov)

Energy dissipation structures, spill rates and operation patterns are the main factors causing TDG supersaturation in large dams (Qu *et al.,* 2011).

Table 9: Examples of total dissolved gas (TDG) levels in large dams in China (Qu *et al.*, 2011)

Case No.	Project	Location of the observed section	Energy dissipation	Spill rate (m^3/s)	Power flow (m^3/s)	TDG level (%)
1	Three Gorges	4,000 m downstream the dam	Ski-jump energy dissipation	20,200	15,600	138.0
2	Ertan	3,000 m downstream the dam	Ski-jump energy dissipation	3706	1,809	140.0
3	Zipingpu	Rainbow Bridge downstream the dam	Ski-jump energy dissipation	340	0	114.9
4	Manwan	Downstream stilling basin export	Ski-jump energy dissipation	1,810	1,927	124.0
5	Dachaoshan	Bridge downstream the dam	Ski-jump energy dissipation	830	2,120	116.0
6	Gongzui	Gongdian Bridge downstream the dam	Surface flow energy dissipation	2,642	1,580	142.5
7	Tongjiezi	Stilling basin export	Underflow energy dissipation	317	1,920	138.7

Lab experiments on the effects of gas supersaturation on lethality and avoidance responses in juvenile rock carp (*Procypris rabaudi* Tchang) show that these fish can survive in water with a supersaturated level of up to 115% of TDG. Juvenile rock carp avoid and die in water with higher levels (Huang *et al.*, 2010). However, field studies indicate lower critical levels. Ryan *et al*. (2000) developed a model to predict the extent of GBD signs by using observations of GBD in large samples of non-salmonids and invertebrates collected from the Snake and Columbia Rivers and observations in net-pen holding experiments. They developed a mathematical equivalence model for TDG saturation duration and level of exposure that was strongly correlated with the prevalence of GBD signs ($r^2 = 0.79$). Signs of GBD were rare when TDG did not exceed 120% of saturation. Severity of GBD signs provided weak or variable relationships with the TDG data and was not used for the model. They concluded that the model reliably predicted the extent to which fish displayed external GBD signs when TDG exceeds 120%. Recent literature indicates TDG supersaturation in the Canal da Piracema (Weitkamp, 2008).

7 Conclusions and future research priorities

Hydropower plants lead to alteration of the aquatic ecosystem. The disruption of river continuity is considered the main cause of impact to aquatic organisms, especially migratory fish. The impact will most likely increase with ongoing hydropower exploitation. In order to mitigate the effect of hydropower plants on aquatic organisms, fish passes should be considered for all existing and planned hydropower plants as referenced in the MRC's Preliminary Design Guidance (MRC, 2009). This does, however, require a sound understanding of the fish passage types available as well as their efficiency and effectiveness under certain aquatic, ecological and biological conditions.

This report has sought to summarise recent research on fish pass solutions for both upstream and downstream migration, with a particular emphasis on the lessons learned from around the world and their applicability to the Mekong River. It thereby provides guidance to consultants and practitioners in the Mekong River Basin (as well as in other rivers facing similar challenges) about the current state of research concerning fish passage through large dams. This ultimate aim is to initiate research and further study towards developing effective mitigation measures for large dams in the Mekong River.

7.1 Challenges for fish passage in the Mekong and research priorities

With more than 800 documented fish species, the Mekong has the second highest diversity of species after the Amazon River. In particular, the Mekong provides habitats for at least seven species of large fishes such as the Mekong giant catfish. The literature research carried out in this study highlighted the following points:

- Detailed information on the Mekong fishery is limited and needs continued and ongoing attention to improve baseline information on species ecology, migration behaviour and biomass movements.
- It is estimated that there are more than 150 migratory species important for capture fisheries, and 58 species (i.e. 744,000 tonnes) are considered as highly vulnerable (Barlow *et al.,* 2008; Halls & Kshatriya, 2009).
- Migratory species account for about 40% of the fisheries yield in the LMB (Halls, 2010).
- Fish migration in the LMB is currently known to involve complex habitat shifts between multiple regions of the basin.
- So-called "white fish" migrate within the mainstream river and into the floodplains during the wet season whereas "black fish" and "grey fish" demonstrate restricted migratory behaviour.

- Mekong fish species migrate for several purposes, including spawning, feeding, and refuge (deep pools), in both directions – upstream and downstream.
- Migration takes place throughout the year and throughout the life cycle of fish (i.e. as larvae, juveniles, sub-adults and adults). Migration peaks occur at the onset and during the wet season.
- The Mekong supports very high fish productivity compared to other inland fishery regions in the world with an estimated harvest of between 755,000 t/year and 2.5 million t/year. The estimated fish productivity of the Mekong represents a market sale value of between US$3 billion to US$6.5 billion/year (Hogan, 2011).
- Taking into account secondary industries, such as fish processing and marketing, the total economic value for the Mekong's fisheries is between US$5.6 billion and US$9.4 billion/year, contributing significantly to the region's economy (Dugan, 2008).
- It is estimated that mainstream dam development in the LMB could potentially result in losses of 0.3 – 1.0 million tonnes of fish per year, and a higher impact is expected from dams built in the lower compared to the upper basin (MRC, 2011c).

Knowledge concerning the effective design of fish passes for large tropical rivers remains limited. Data and information are available largely on South American rivers (which are of particular interest for this study due to their diverse fish fauna and high productivity – similarly to the Mekong River), North America and Europe. For the Mekong River Basin, only few case studies on fish passes exist.

At the same time, multiple challenges for effective fish passes exist, especially with regard to the large scale of required fish passes, the migration of large species, migration peaks with high biomass, and the high diversity of species – all constituting different requirements for fish passes. The following main challenges with the application of fish passage in the Mekong have been highlighted:

- **Testing of available technology for Mekong dams:** Globally, different types of upstream fish passes have been developed in recent decades. Technologies vary in terms of conceptual design, spatial demands and the applicability for single or multiple species (e.g. eel ladders vs. nature-like fish passes). So far, however, most existing fish passes have been built in small or medium-sized dams. For large dams, many challenges remain, including for those constructed in multi-species tropical rivers.
- **High species diversity:** Different species will have different requirements for fish passage and different responses to upstream and downstream conditions. For large multi-species rivers, vertical-slot fish passes and nature-like bypass channels are likely to provide the best solutions but further research is required to test this application in the Mekong context.
- **Perceptibility:** fish pass efficiency depends on fish finding the entrance to the passage and this includes questions relating to the entrance of the fish pass and the attraction flow.

- **Passability:** For the passability of a fish pass, especially for various species, the fish pass has to be large enough to accommodate large species, numerous fish and large amounts of biomass but also small fish with low swimming abilities.

- **Downstream passage:** Solutions for **downstream migration** are largely lacking for large, multi-species rivers. Potential downstream pathways are turbines, spill flows or fish passes designed for downstream migration. The protection of fish is thereby the critical consideration in the design of downstream migration pathways – especially with regard to preventing turbine injuries, but also taking into consideration the drift of larval fish. The challenge is to avoid impingement of fish by turbines and to guide fish efficiently to downstream bypass systems.

- **Seasonal variation in water level:** fish pass solutions in the Mekong River must adapt to the seasonal variations in the discharge and water level. Seasonal variations of tailwater levels may exceed 10 m in the Mekong River. Fish passes have to accommodate these variations by providing different entrances at different water levels.

In order to tackle the above challenges, it will be necessary to undertake research in the Mekong to understand how existing knowledge must be adapted to the local conditions and what potential new technologies may need to be developed. The table below indicates the research priorities and current status.

Table 10: Major challenges for fish passage at Mekong mainstream dams, potential solutions and their status

Challenges	Potential solutions	Status	Research priotities
Effective FP designs are not tested for large tropical rivers	• Test existing technologies on Mekong species and conditions.	• Insufficient knowledge	• Research Baseline Information on ecology of key fish species and fishery important species including migratory patterns and behaviour. • Carry out field tests at existing facilities of new dams on adopted technology (with developers). • Consider new designs that may improve effectiveness. • Test the efficiency of fish passes at the river system and fish population level including situations with multiple dams.
High species diversity	• Multiple FP for species with different migratory requirements • Appropriate selection of functioning FP types (e.g. vertical slot, nature-like bypass channels, bypass systems)	• Technologies available but applications missing	• Monitor fish species diversity of migratory fish in the river system. • Monitor and assess fish pass effectiveness for multiple species at existing facilities.
High number of migrating fish	• Multiple and larger FP	• Technologies available but applications missing	• Analyse spatio-temporal dynamics and quantify the amount and of migratory fish in the river system. • Test fish passes of different dimensions at existing facilities. • Test the effect of multiple, complementary fish passes at existing facilities.
Large fish species (> 100 cm)	• Larger FP	• Technologies available but few applications	• Monitor migratory routes of large fish in the river and at existing fish passes (including telemetry studies).
Small fish species important for fisheries (< 20 cm)	• Low-flow velocities, low turbulences, FP length > 2 km	• Technologies available but few applications	• Monitor migratory routes of small fish in the river and at existing fish passes (including telemetry and hydroacustic studies).
Attracting fish to FP entrance	• Multiple entrances (e.g. mid-channel, shore line, close to the bottom, mid-water, surface) • Attraction flow minimum of 1 – 5% of competing flow	• Technologies available but applications missing	• Study hydromorphological and hydraulic conditions below existing dams. • Study the detailed migratory behaviour of fish below existing dams. • Experiment with different amount of attraction flow and settings of entrances at existing facilities.
Seasonal variation of water level (>10 m)	• Multiple adjustable FP entrances and exits	• Technologies available but applications missing	• As above • Test effectiveness under conditions of varing water levels and settings of entrances at existing facilities.
Downstream migration	• Development of new technologies for large tropical rivers including new screens, optimised spill flows, and fish friendly turbines	• Technologies missing	• Monitor and analyse downstream fish migration in the river system, in reservoirs and above dams. • Carry out a feasibility study to analyse the options of screen technologies for large tropical rivers. • Analyse the effectiveness of varying spill flows at existing facilities. • Test the effectiveness of fish friendly turbines at existing facilities.

7.1.1 Next steps

In spite of the knowledge of fish pass outlined above, a number of challenges and open research questions persist that need to be answered in order to develop effective mitigation options for fish passage through dams on the Mekong mainstream.

This report seeks to provide a comprehensive review of current knowledge globally in the area of large dam fish passage. It will set a foundation for and initiate steps towards the various aforementioned research questions on fish passes based on both general theoretical considerations as well as lessons learned from large (tropical) rivers, while demonstrating the applicability of fish passes to the Mekong mainstream dams.

The MRC will take up the recommendations on research priorities in upcoming studies to further the understanding of the risk management of the impacts of hydropower dams on this vital Mekong resource.

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Table 11: Characteristics of selected fish species important for Lower Mekong Basin fishery including endemism, IUCN status, and body length (cm)

English name	Latin name	Max. length	Poulsen *et at.*, 2004	Baran *et al.*, 2005	Halls *et al.* (2003)				IUCN list status
					DFMP	LTMP	FADMP	average % of catch weight	
	Amblyrhynchichthys micracanthus	19			x	x		0.3	Lease concern
Goonch	*Bagarius yarrelli*	200	x	x		x		1.5	Near threatened
Two head carp	*Bangana behri*	60	x	x				0.2	Vulnerable
Boeseman croaker, Small-scale croaker	*Boesemania microlepis*	100	x		x			1	Near threatened
Giant barb	*Catlocarpio siamensis*	300						0	Critically endangered
Clown featherback	*Chitala ornata*	100	x					0.4	Least concern
Small scale mud carp, Small scale river carp	*Cirrhinus microlepis*	65	x	x	x			0.5	Vulnerable
	Cosmochilus harmandi	100		x	x		x	4.4	Least concern
Soldier river barb	*Cyclocheilichthys enoplus*	74	x	x	x			0.7	Least concern
Eye-Spot barb	*Hampala dispar**	35	x					0.3	Least concern
Hampala barb, Barred barb	*Hampala macrolepidota*	70	x					0.5	Least concern
Catfish	***Helicophagus leptorhynchus***	79	x					2.2	Not investigated
Suthi River Catfish	*Hemibagrus filamentus*	60	x						Data deficient
Asian redtail catfish	*Hemibagrus nemurus*	65		x		x		2.7	Least concern
	Hemisilurus mekongensis	80		x		x		0.3	Least concern
	Henicorhynchus cryptopogon	15		x					Not evaluated
	Henicorhynchus lineatus	15		x					Least concern
Siamese mud carp	***Henicorhynchus lobatus****	15	x		x		x	3.4	Least concern
	Henicorhynchus ornatipinnis	9.5		x				0	Least concern
Siamese mud carp	***Henicorhynchus siamensis***	20	x	x	x	x	x	5.9	Least concern
Black sharkminnow	***Labeo chrysophekadion***	90	x	x	x	x	x	4.1	Least concern
	Labiobarbus leptocheilus	30		x				0.3	Least concern
	Labiobarbus lineatus	11			x			1.1	Least concern
	Lobocheilos cryptopogon	15			x				Not evaluated

Table 11 (continued): Characteristics of selected fish species important for Lower Mekong Basin fishery including endemism, IUCN status, and body length (cm)

English name	Latin name	Max. length	Poulsen *et at.*, 2004	Baran *et al.*, 2005	Halls *et al.* (2003)				IUCN list status
					DFMP	LTMP	FADMP	average % of catch weight	
Sabretoothed thryssa	*Lycothrissa crocodilus*	30	x					0.1	Least concern
Striped river barb	***Mekongina erythrospila****	45	x	x				0.2	Least concern
	Micronema apogon	130	x						Least concern
Bronze featherback	*Notopterus notopterus*	60	x					1	Least concern
	Osteochilus hasseltii	32	x						Least concern
Bonylip barb, Nilem carp	*Osteochilus vittatus*	32	x	x					Least concern
Giant Mekong catfish	*Pangasianodon gigas**	300	x					0.1	Critically endangered
Striped catfish, Sutchi River Catfish	*Pangasianodon hypophthalmus*	150	x		x			0.2	Endangered
Bocourt's catfish	*Pangasius bocourti*	120	x	x		x		0.3	Least concern
Sharp-nosed catfish	***Pangasius conchophilus***	120	x	x	x	x	x	3.3	Least concern
Elongate catfish	*Pangasius elongatus*	100	x					0.5	Data deficient
Krempf's catfish	*Pangasius krempfi*	120	x	x					Vulnerable
Spot pangasius, Red-finned catfish	***Pangasius larnaudii***	130	x	x	x	x		0.5	Least concern
Long-barbel catfish	*Pangasius macronema*	30	x	x		x		1.7	Least concern
Red-finned catfish	*Pangasius pleurotaenia*	35	x	x	x			0.5	Least concern
Giant pangasius, Giant catfish	*Pangasius sanitwongsei*	300	x						Critically endangered
	Paralaubuca barroni	15			x			0.1	Least concern
Pelagic river carp	***Paralaubuca typus***	18	x	x				0.8	Least concern
Silver sheatfish	*Phalacronotus apogon*	130					x	2.6	Least concern
Red sheatfish	*Phalacronotus bleekeri*	60	x					1	Least concern
Goldfin tinfoil barb	*Poropuntius malcolmi*	50					x	2.4	Least concern
Isok barb, Jullien's barb	*Probarbus jullieni*	165	x	x				0.8	Endangered
Thicklip barb	*Probarbus labeamajor**	150	x					0.3	Endangered
Silver barb	*Puntioplites falcifer**	35	x	x			x	2.5	Least concern
Smith's barb	*Puntioplites proctozystron*	30			x			1.2	Least concern
Laotian shad	*Tenualosa thibaudeaui**	30	x	x				0	Vulnerable
Wallago, Giant sheatfish	*Wallago attu*	200	x			x	x	2.1	Near threatened
Redtail botia, Redtail loach	***Yasuhikotakia modesta***	25	x	x	x			0.6	Least concern

Latin name: * endemic to the Mekong; bold letters = detailed explanation included in report

DFMP (Dai Fishery Monitoring Programme, Tonle Sap, Cambodia, 1994-2010); LTMP (Lee Trap Monitoring Programme, Khone Falls, Lao PDR, 1994-2010); FADMP (Fish Abundance and Diversity Monitoring Programme, 40 sites across the LMB, 2003-2010);

Table 12: Important species for fishery, species distribution in the Lower Mekong Basin and important sections/months (where available) based on Poulsen *et al.* (2004)

Latin name	Lower Mekong	Important section/areas	1	2	3	4	5	6	7	8	9	10	11	12
Amblyrhynchichthys micracanthus														
Bagarius yarrelli	Basinwide (except Delta)													
Bangana behri	Basinwide	Se San/Sre Pok/Se Kong, Mekong around Stung Treng												
Boesemania microlepis	Middle-lower	Khone Falls, Cambodia, Viet Nam												
Catlocarpio siamensis	Basinwide	Cambodia, Viet Nam, Tonle Sap												
Chitala ornata	Basinwide													
Cirrhinus microlepis	Basinwide	Tonle Sap, Middle Mekong												
Cosmochilus harmandi														
Cyclocheilichthys enoplus	Basinwide	Tonle Sap, Khone Falls												
*Hampala dispar**	Basinwide													
Hampala macrolepidota	Basinwide													
Helicophagus leptorhynchus	Basinwide	Middle Mekong												
Hemibagrus filamentus	Basinwide	Khone Falls												
Hemibagrus nemurus														
Hemisilurus mekongensis														
Henicorhynchus cryptopogon														
Henicorhynchus lineatus														
Henicorhynchus lobatus*	Basinwide	Lower Mekong Basin, Tonle Sap												
Henicorhynchus ornatipinnis														
Henicorhynchus siamensis	Basinwide	Lower Mekong Basin, Tonle Sap												
Labeo chrysophekadion	Basinwide													
Labiobarbus leptocheilus														
Labiobarbus lineatus														
Lobocheilos cryptopogon														
Lycothrissa crocodilus	Lower mekong	Estuary												
Mekongina erythrospila*	Basinwide	Lao-Cambodia, Se San, Sre Pok, Se Kong												
Micronema apogon	Basinwide	Cambodia												
Notopterus notopterus	Basinwide	Tonle Sap												
Osteochilus hasseltii	Basinwide	Nam Ngum Reservoir												
Osteochilus vittatus		Nam Ngum Reservoir												
*Pangasianodon gigas**	Basinwide	Lao-Thai border												

Table 12 (continued): Important species for fishery, species distribution in the Lower Mekong Basin and important sections/months (where available) based on Poulsen *et al.* (2004)

Latin name	Lower Mekong	Important section/areas	1	2	3	4	5	6	7	8	9	10	11	12
Pangasianodon hypophthalmus	Basinwide	An Giang and Dong Thap provinces of Viet Nam, southern Cambodia, Tonle Sap, Khone Falls, middle and upper Mekong												
Pangasius bocourti	Basinwide	Khone Falls, middle Mekong												
Pangasius conchophilus	Basinwide	Khone Falls, Cambodia												
Pangasius elongatus	Basinwide (rare in middle Mekong)	Khone Falls												
Pangasius krempfi	Basinwide	Khone Falls, Tonle Sap												
Pangasius larnaudii	Basinwide													
Pangasius macronema	Basinwide													
Pangasius pleurotaenia	Basinwide (most common in middle Mekong)	Khone Falls, Tonle Sap												
Pangasius sanitwongsei	Basinwide													
Paralaubuca barroni														
Paralaubuca typus	Basinwide	Ban Hang Khone, Tonle Sap, Stung Treng, Kratie												
Phalacronotus apogon														
Phalacronotus bleekeri	Basinwide	Cambodia												
Poropuntius malcolmi														
Probarbus jullieni	Basinwide	Ban Hang Khone, Middle Mekong												
*Probarbus labeamajor**	Basinwide (also reservoirs)	Ban Hang Khone												
*Puntioplites falcifer**		Nam Ngum Reservoir												
Puntioplites proctozystron														
*Tenualosa thibaudeaui**	Basinwide	Khone Falls, Cambodia, middle Mekong from Pakse to Vientiane												
Wallago attu	Basinwide (also reservoirs)	Viet Nam and Cambodia												
Yasuhikotakia modesta	Basinwide	Ban Hang Khone												

Latin name: * endemic to the Mekong; bold letters = detailed explanation included in report

Table 13: Rheoactive velocities for selected species and age classes/sizes

Species	Age class/ size	Rheoactive velocity [m/s]	Source
Bullhead, stone loach, Eurasian minnow, stickleback	Juveniles	0.15	Adam & Schwevers, 1997
Brown trout, grayling, Eurasian dace	≤ 12 cm	0.15	Adam & Schwevers, 1997
Most cyprinids, salmonids and other families, adults of small fish species (Eurasian minnow, stone loach)	Juveniles	0.15	Seifert 2012
Most cyprinids (barbel, nase, European chub), salmonids (brown trout, grayling) and other families	Adults	0.20	Seifert, 2012
Most species	Adults	0.20	Pavlov, 1989
Barbel. European chub, Eurasian dace	Adults	0.20	Adam *et al.*, 1999
Anadromous salmonids	Adults	> 0.30	Pavlov, 1989
Danube salmon	Adults	> 0.30	Seifert, 2012

Table 14: Morphometric criteria and threshold values (based on DWA 2010 (draft), BMLFUW 2012, AG-FAH 2012)

Parameter	Application	Thresholds for size-decisive fish species
Pools		
Min. hydraulic depth (D_{min})	General	$2.5 \cdot H_{fish}$ [1]
	For technical pool FPs	>50 – 60 cm[3]
	For nature-like bypasses	>70 to 120 cm (170 for Danube)[3]
Min. pool length (L_p)	For technical/pool FPs/ rough bypasses	$3 \cdot L_{fish}$ [1, 2]
Min. pool width (W_p)	For technical pool FPs/ rough bypasses	50 to 67% of L_p [1]
	For technical pool FPs/ rough bypasses	$2 \cdot L_{fish}$ [1, 2]
Bottlenecks and transition zones		
Min. hydraulic depth of sluices (d_s)	General	$2 \cdot H_{fish}$ [1, 4] ($2.5 \cdot H_{fish}$ for grayling)[4]
	Nature-like bypasses	$2.5 \cdot H_{fish}$ and > 0.2 m[2]
	Nature-like pool passes/ ramps	2/3 of D_{min} (= 2/3 of 2.5 H_{fish})[2]
Min. width of sluices (w_s)	General	$3 \cdot W_{fish}$ [1, 2] and > 0.15 m[2]
	For nature-like constructions (pool pass/bypass)	Larger: 1.25 to 1.5 • ($3 \cdot W_{fish}$)[3]

[1] DWA (2010)
[2] BMLFUW (2012)
[3] AG-FAH (2011)
[4] Gebler (2009)

Table 15: Dimensions of a vertical slot in relation to the slot width (s) (based on Larinier *et al.,* 2002; Katopodis, 1992 in DWA, 2010), see Figure 33

	Factor x
Slot width $w_s = x * w_s$	1.00
Pool length $L_p = x * w^s$ [1)]	8.10 – 8.33
Guide wall length (incl. width of partition wall) $l_g = x * w_s$	1.78 – 2.00
Offset length $l_o = x * w_s$	0.41 – 0.83
Width of the deflection block $w_{db} = x * w_s$	1.15 – 1.49
	Angle
Lateral offset angle α • For small FPs • In general (Larinier, 1992 and Rajaratnam, 1986)	> 20° 30 – 40°

[1)] Insofar as the size-decisive fish or the energy dissipation do not require larger dimensions

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