Mekong River Fish Ecology Information Gap Assessment and Capacity Building in Laos

Final Report and Recommendations
Prepared for the Living Aquatic Resources Research Center

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Acronyms and Abbreviations[1]

ACIAR	Australian Centre for International Agricultural Research, Canberra
AFS	American Fisheries Society
CGIAR	Consultative Group for International Agricultural Research
CPUE	catch-per-unit-effort
DOI	United States Department of the Interior
DLF	Department of Livestock and Fisheries, MAF, Laos
FAO	Food and Agriculture Organization of the United Nations
DOI-ITAP	DOI International Technical Assistance Program
LARReC	Living Aquatic Resources Research Center, NAFRI, MAF, Vientiane
LMB	Lower Mekong River Basin
MAF	Ministry of Agriculture and Forestry, Laos
MRC	Mekong River Commission, Phnom Penh and Vientiane
mtDNA	mitochondrial DNA
NAFRI	National Agricultural and Forestry Research Institute, Laos
NAUFWP	National Association of University Fisheries and Wildlife Programs (United States)
NCTC	National Conservation Training Center (USFWS)
NGO	non-governmental organization
NUOL	National University of Laos, Vientiane
PNNL	Pacific Northwest National Laboratory, United States Department of Energy, Richland, Washington
SEAFDEC	Southeast Asian Fisheries Development Centre, Bangkok
SIM	Smart Infrastructure for the Mekong Program, DOI-ITAP
spp.	species (plural)
USFWS	United States Fish and Wildlife Service
USAID	United States Agency for International Development

Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

[1]Cities listed are the locations of the headquarters offices; many agencies/institutions have regional offices located elsewhere.

Executive Summary

This report was prepared by the United States Department of the Interior - International Technical Assistance Program (DOI-ITAP) under the framework of Smart Infrastructure for the Mekong, a U.S. Government inter-agency program supported by USAID. DOI-ITAP developed this report in response to a request from the Lao People's Democratic Republic Ministry of Agriculture and Forestry, Living Aquatic Resources Research Center (LARReC), to evaluate the current state of knowledge of important commercial and subsistence fish species in the Mekong River and its tributaries.

This report combines the analysis and recommendations of three teams of scientists who visited Laos in 2015. It provides a summary of the existing state of knowledge on the life history and ecology, population genetics, and migratory behavior of Mekong River fishes, identifies knowledge gaps, and offers suggestions to assist LARReC in crafting a long-term research and management agenda. The overarching goal is to better inform future sustainable hydropower development, fish passage threshold development, and sustainable fish harvest in Laos.

In the areas of research, monitoring, operations and management, and capacity building, the report provides 18 recommendations as listed below:

Research

1. Expand fish passage research at Pak Peung wetland and apply lessons learned to other wetlands.
2. Develop and implement a study to evaluate relative effectiveness of fish passage facilities at mainstem dams on the Mekong River in Laos.
3. Assess the effects of habitat alteration upstream and downstream of hydropower facilities (for example, larval drift, predator/prey dynamics) to inform the potential impacts of future mainstem dams.
4. Develop a prioritization plan for improving connectivity of habitats between the Mekong River and its tributaries.
5. Select one fish species to use as a prototype for the design and implementation of a genetic population structure study.
6. Develop a proactive program to identify spawning areas and spawning seasons of selected species (for example, *Pangasius* spp.).

Monitoring

7. Establish a long-term monitoring program on the mainstem Mekong River.
8. Collect baseline information on genetic structure of selected fish species to monitor genetic changes over time that occur as a result of fishing, climate change, and intentional or accidental release of hatchery reared fish.

Operations and Management

9. Invite coordination between ministries and departments to identify fisheries information needs and develop opportunities for collaboration and communication.
10. Establish a forum to coordinate information from non-governmental fishery research activities in Laos.

11. Establish fish passage technical working groups to collaboratively develop and implement a fish passage monitoring plan for Xayaburi, Don Sahong, and other planned mainstem dams.
12. Obtain regulatory approval for LARReC and other governmental departments to use otherwise unauthorized fisheries sampling methods for research, monitoring, and evaluation activities.
13. Establish and maintain a LARReC website.
14. Investigate public education opportunities for LARReC activities and fishery resources.

Capacity Building

15. Provide one- to two-week genetics workshops in Laos.
16. Provide short- and mid-term genetics training programs for Lao students at institutions in the United States.
17. Develop basic-to-intermediate technical ability in geographic information systems (GIS), databases, and statistical analyses to enable LARReC staff to independently collect, organize, archive, and analyze fishery data.
18. Develop a strategy to fund fisheries research and capacity building.

1. Background

The Mekong River Fish Biology Information Gap Assessment and Capacity Building activity was undertaken by the United States Department of the Interior - International Technical Assistance Program (DOI-ITAP). The activity was implemented under the framework of the Smart Infrastructure for the Mekong program, supported by USAID. This assessment was designed to assist the Living Aquatic Resources Research Center (LARReC) of the Ministry of Agriculture and Forestry in the Lao People's Democratic Republic in describing the existing state of knowledge of the life history and ecology, population genetics, and migratory behavior of Mekong River fishes, to identify knowledge gaps, and to craft a long-term research agenda. The desired research agenda would better inform future sustainable hydropower development, fish passage threshold development, and sustainable fish harvest.

The activity included assessments of existing science and knowledge gaps in the areas of fish migration (January 2015), fish ecology (June 2015), and fish genetics (November 2015) and capacity building for Lao scientists. Under this component of the activity, three months of advanced training in fisheries science in the United States was provided for one Lao scientist from LARReC and another scientist from National University of Laos (NUOL).

This report is based on a pre- and post-trip review of literature, including many published articles and less widely available "gray" reports. While in Laos, the three teams conducted interviews with 85 Lao governmental and non-governmental experts and policymakers (multiple individuals were contacted by more than one team).

2. Existing Knowledge and Data Gaps

2.1 Physical Setting

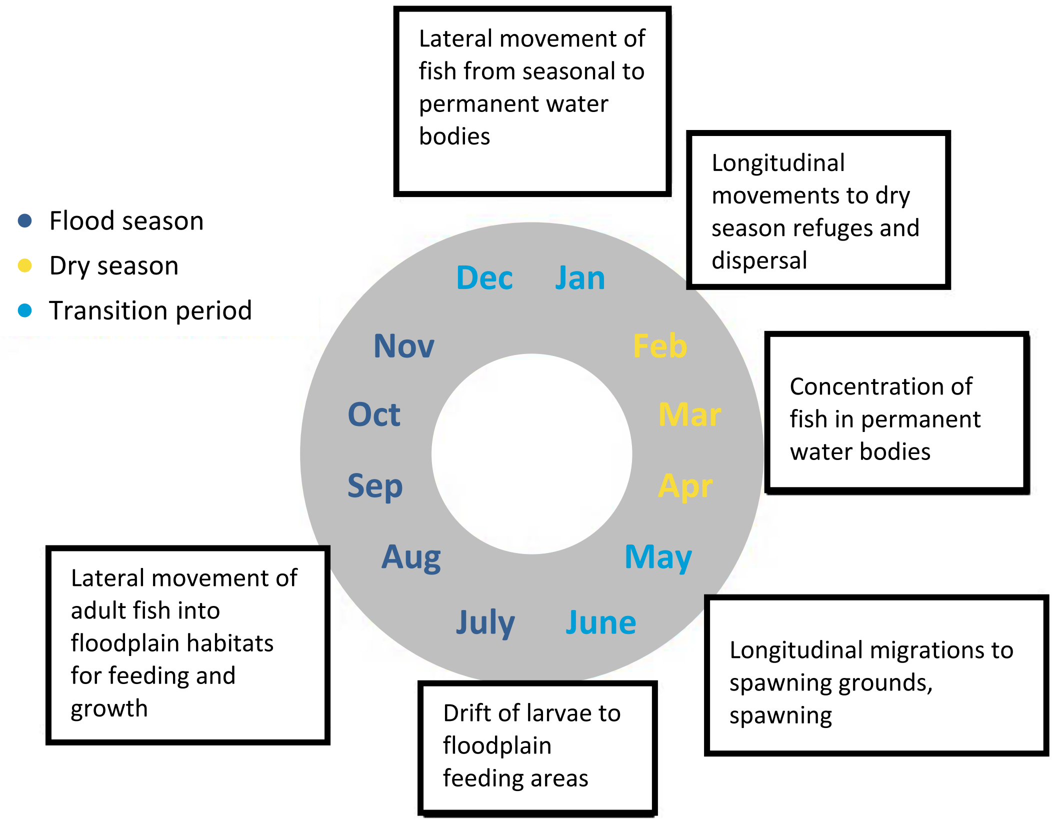
The Mekong River basin is recognized as one of the great rivers of the world, and many publications include detailed descriptions of the physical setting. Detailed overviews of the hydrology, physiography, geology, and climate are provided by MRC (2005) and Rainboth et al. (2012).

The Mekong River is approximately 4,909 km long, with the upper 2,198 km flowing through China (known there as the Lancang River) and the lower 2,711 km passing through Myanmar, Laos, Thailand, Cambodia, and Vietnam; the latter portion is typically referred to as the lower Mekong basin (LMB). Surface area of the entire Mekong basin is approximately 810,000 km^2. The basin is variously ranked as tenth or twelfth in the world by average annual freshwater discharge (470 km^3/year; citations vary due to some authors assigning certain tributary rivers separate rank). In terms of sediment discharge (160×10^6 metric tons/year) the Mekong is commonly ranked ninth among the world's largest rivers.

Two of the most notable features of the lowermost region of the LMB are the Tonle Sap Great Lake and its connection to the Mekong River via the Tonle Sap River in the Cambodian floodplain, where flow is seasonally bi-directional, and the extensive Mekong Delta at the river's terminus in southern Vietnam. In Laos the river is commonly divided into a northern mountainous reach and the southern lowlands (Vientiane to Pakse), where hydrology changes extensively due to physiography and the contribution of major tributaries. Khone Falls in Champasak Province, southern Laos, is a major physical feature of the lower Mekong and a biogeographic barrier to certain fish (for example, marine invaders). Khone Falls is thus an aggregation point for many migratory species and home to a significant number of fisheries (Roberts and Baird 1995; Baran et al. 2005).

Broad-scale habitat types within the Mekong River basin can be divided into wetlands, tributaries, and mainstem habitats. In general, wetlands, which include floodplains and wet-season rice fields, are important habitats for spawning and rearing of many fish species. Wetlands are seasonal habitats, created during the monsoon season, and are rich in nutrients, food, and shelter (Poulsen et al. 2002b). The majority of wetland habitats in Laos are located along tributaries of the Mekong River near Vientiane and downstream towards the Cambodian border. Tributaries of the Mekong River are used for spawning and rearing, and as migratory corridors between critical habitats. The lifecycle and migration pattern of Mekong river fish is summarized in Figure 1.

Figure 1. Generalized life cycle and migration pattern of Mekong River fishes

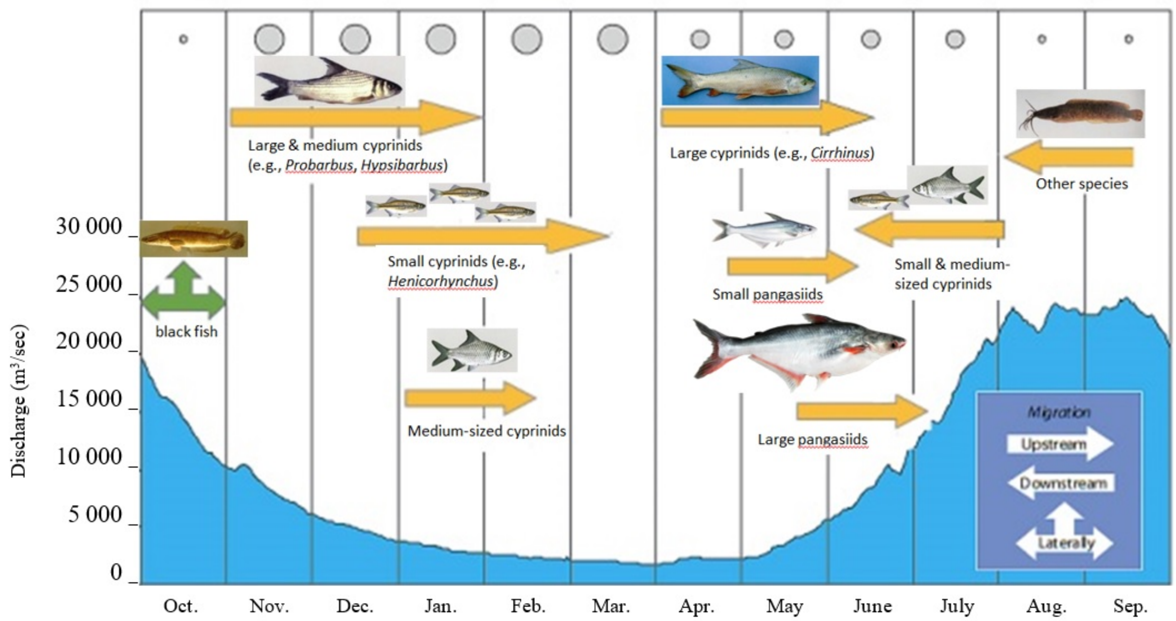


Source: Modified from Sverdrup-Jensen (2002).

For many species, spawning areas in tributaries are thought to be associated with rapids and pools (Poulsen and Valbo-Jorgensen 2000; Poulsen et al. 2002b; Poulsen et al. 2004). Some fish species spend their entire life cycle within a tributary, migrating between spawning and rearing habitats within the main channel. Some migrate between the tributary channel and associated floodplain (wetland) habitats, and others use tributaries to migrate from the mainstem Mekong River to spawning habitats within the tributary or wetlands.

The mainstem Mekong River is an important migratory corridor and provides spawning habitat for many fish species, while deep pool areas in the mainstem also serve as critically important dry season refuges (Poulsen et al. 2002a; Zalinge et al. 2002; MRC-TAB 2005; Halls et al. 2013a). Similar to tributaries, spawning habitats in the mainstem are believed to be associated with rapids and pools. Many Mekong River fishes are thought to migrate long distances in the mainstem in order to spawn, feed, and seek refuge (Phonvisay 2013), and the migration cycles have a strong seasonal component associated with rainfall and hydroperiod (Figure 2).

Figure 2. Variation in migratory patterns of various types of fishes in the Khone Falls area of the Mekong basin, southern Laos



Note: Hydroperiod indicated in blue (scale on left), discharge as cubic meters per second); and relative fishing pressure (shaded circles at top, as catch-per-unit effort).
Source: Modified from Baran (2006).

In tropical lowland areas, fish are commonly divided into categories based on their migratory patterns. “White fish” use floodplain habitats but make long-distance migrations in main river channels, “black fish” are found primarily in floodplain habitats, and “gray fish” breed and feed in floodplain habitats, but favor riverine habitats during the dry season (Valbo-Jorgensen et al. 2009).

2.2 Aquatic Faunal Diversity

The diversity of freshwater species within the Mekong River basin is exceeded only by the Amazon and possibly the Congo rivers, both of which have much larger drainage basins. Moreover, endemism of fishes in the Mekong is high, especially in headwater systems and the upper portion of the basin (Kang et al. 2009). Prior to 2002, estimates of fish species richness in the Mekong ranged from between about 450 and 1,200 (Dudgeon 2012), whereas subsequent estimates place the number as high as 1,700 species (Sverdrup-Jensen 2002; Coates et al. 2003). Kottelat (2001) stated that about 700 species are documented to occur in the basin, without providing sources or distinguishing strictly freshwater forms from brackish and marine species. Kottelat et al. (2012) indicated there were about 500 species in the basin but noted that "several hundred species are still to be discovered" and that some known species are likely taxonomic complexes.

In one of the most comprehensive taxonomic assessments, 890 freshwater fish species were recorded for the Mekong basin and at least 200 euryhaline or marine species were predicted to occur in the extensive estuary of the Mekong Delta (Rainboth et al. 2012). Given the species richness of marine and estuarine fishes in the South China Sea and Gulf of Thailand, the number of species is likely to be even greater than the 200+ estimated by Rainboth et al. (2012). Moreover, new freshwater species are continually being discovered as under-explored areas are increasingly surveyed, particularly in remote highland areas, and as taxonomists conduct revisionary studies, describe new species, and apply non-traditional approaches (for example, molecular systematics). Thus, most current estimates are likely to under-represent the actual number of extant species. Rainboth et al. (2012) speculated that the "Greater Mekong Ecosystem" may support a minimum of 3,275 freshwater, estuarine, coastal and marine fish species.

In another landmark monograph, Kottelat (2013) recognized 3,108 native inland fish species in fresh waters, mangroves, and estuaries within the all-encompassing Southeast Asia region extending from the Irrawaddy River (Myanmar) through Indochina and the Philippines, although some of the taxonomic conclusions in that publication were questioned by Eschmeyer and Fricke (2016). Within the Mekong basin, the Sekong, Sesan, and Srepok watersheds ("3S" system) is thought to harbor 42 percent of fish biodiversity for the entire basin and has at least 17 endemic species, although the surface area of these watersheds constitutes only about 10 percent of the basin (Baran and Guerin 2012).

At present, an accurate estimate of the number of freshwater and euryhaline fish species occurring in Laos is unavailable. Estimates are that about 480 species occur in the country, of which at least 22 are nonindigenous (Kottelat 2001; Phonvisay 2013); between 1996 and 2000 alone the number reported in the literature increased a remarkable 111percent, from 220 to 465 (Kottelat 2000, 2001; Kottelat et al. 2012). There are predicted to be many undescribed and likely endemic fish species in mountainous areas of northern Laos. This tremendous ichthyofaunal diversity makes fishery management and ecological research a challenge. In addition to having a rich freshwater fish fauna, the Mekong River basin is a biodiversity hotspot for other aquatic and semi-aquatic organisms, including freshwater and wetland plants (Lansdown 2012), mollusks (Strong et al. 2008; Köhler et al. 2012), crustaceans (Cumberlidge et al. 2012), odonates (Reels et al. 2012) and lesser known insects (IUCN 2013), and amphibians (Giam et al. 2010).

2.3 Population Genetics

The Mekong River is one of the longest and most species-rich rivers in the world. Nevertheless, there is little information in the scientific literature on genetic diversity and population structure of Mekong River fishes. There appear to be only 20 pertinent papers on this topic, none of which appear to have Lao authors. The majority of these publications are genetic investigations of various Asian catfish species in the Pangasiidae family. Seven of these focus exclusively or primarily on the Mekong giant catfish (*Pangasianodon gigas*), considered one of the largest freshwater fish in the world with confirmed reports up to 2.7 m and 293 kg. Interestingly, none of the author or institution affiliations listed for these papers include Laos. Similarly, while in Laos, we did not find any individuals with significant genetic expertise, and did not uncover any additional reports, gray literature, or even works published in other languages giving genetics anything beyond superficial treatment.

With few exceptions, the genetic analyses described in the literature are quite basic and of variable quality. This is not meant to disparage the researchers involved, as there are technological, financial and logistical difficulties of working in the Mekong River region. In many cases the authors themselves note the need to expand sample collections, genetic markers and the sophistication of analyses and characterize the conclusions as tentative or as working hypotheses. In most cases, mitochondrial DNA (mtDNA) markers are used exclusively, which limits or even biases the inferences drawn from the data (Ballard and Whitlock 2004). This is especially true when testing hypotheses about fine scale population structure and relative levels of genetic diversity, which are stated goals in many papers. Finally, in many of the papers, sampling design is poor, statistical analyses are simplistic, and conclusions drawn go well beyond the data at hand. Therefore, many of the conclusions drawn in these papers should be questioned and regarded as starting points or working hypotheses from which to design more comprehensive studies.

Pouyaud et al. (2000) contributed significantly to the phylogeny of Pangasiidae with a phylogenetic assessment of more than 20 species using allozyme and mtDNA data. Similarly, Jondeung et al. (2007) published the complete mtDNA sequence of the Mekong giant catfish in their phylogenetic analyses of Mekong giant catfish and 15 of 33 families of Siluriformes. However, Jondeung et al. (2007) caution that their results should be considered tentative as several important families were not included in the analyses.

Three papers provide details for microsatellite markers developed specifically for Mekong giant catfish. Na-Nakorn et al. (2006a) present 10 novel microsatellite loci developed from Mekong giant catfish. Ngamsiri et al. (2006) and Ohashi et al. (2006) also report on the development of microsatellites from Mekong giant catfish. However, they claim to have developed six of the exact same microsatellite markers, even though both papers report them as novel developments and neither paper cites the other (all five authors from Ohashi et al. [2006] are co-authors on Ngamsiri et al. [2006]). Finally, Hogan and May (2002) report on 27 novel microsatellite markers developed from pooled DNA from three Pangasiidae species (*Pangasius larnaudei*, *Pangasius conchophilus* and *Pangasius pleurotaenia*); interestingly, they do not report results for tests of these primers on Mekong giant catfish.

Na-Nakorn et al. (2006b) and Ngamsiri et al. (2007) are the only papers in the literature that focus primarily on genetic diversity and population structure of Mekong giant catfish. Both studies analyzed a limited number of samples from the wild in Thailand and Cambodia (N=1-15). Once again, these papers each have five of seven authors in common and appear to use many of the same samples. Na-Nakorn et al. (2006b) analyzed a 570 base pair region of the mtDNA genome, while Ngamsiri et al. (2007) analyzed a different 384 base pair segment mtDNA along with 10 microsatellite loci reported in Ngamsiri et al. (2006). The markers and number of samples used in these studies limit inferences that can be drawn, but in general these papers find little evidence for population structure across large geographic distances (~1,200 km). The results regarding overall levels of genetic diversity are not concordant: Na-Nakorn et al. (2006) stated that their results "support the conclusion that the Mekong giant catfish is critically endangered", while Ngamsiri et al. (2007) concluded that the species "might be more robust than currently thought". However, given the small samples sizes and markers used, conclusions drawn from these studies should be interpreted with caution.

Three of the most comprehensive and rigorous genetic studies in the Mekong River basin were published in 2006 and focused on the sutchi (or striped) catfish (*Pangasianodon hypophthalmus*; So et al. 2006a,b,c). The sutchi catfish is quite large (reaching up to 130 cm and 44 kg), but it is significantly smaller and far more common than the Mekong giant catfish. In these three studies, the authors used both microsatellite markers and variation in mtDNA sequences to assess the population structure and genetic diversity for both adults and larvae from at least 10 different locations below Khone Falls. All three studies (So et al. 2006a,b,c) report relatively high levels of genetic diversity and low levels of population structure for collections as many as 1,230 km apart. So et al. (2006a) reported evidence for up to three genetically differentiated populations from adult samples, and So et al. (2006b) reported evidence for several different spawning groups involving discrete spawning events when assaying larval samples during peak downstream drift. A common theme in all three studies was the assertion that maintenance of migration routes and natural flow patterns in the Mekong River basin is important for the long-term viability of the species. Similarly, Ha et al. (2009) found no evidence of population structure among four hatchery and two wild populations in Vietnam using a different suite of five microsatellite loci.

The giant pangasius (*Pangasius sanitwongsei*) is another large Asian catfish growing up to 300 kg, second in size only to the Mekong giant catfish. In the last study of the Pangasiidae family, Na-Nakorn et al. (2009) used seven microsatellite loci developed by Na-Nakorn et al. (2006a) to assess population structure among 66 adult samples collected from five locations along the Mekong River (including cages and ponds stocked with fingerlings from the Mekong River). They reported low genetic diversity and high levels of population structure and concluded that at least two populations of giant pangasius were present in the range of the samples analyzed.

The remaining papers reported on genetic analyses for a variety of other species from multiple genera. The family Cyprinidae is considered the largest fish family with over 3,000 valid species representing roughly 10% of all fish species in the world and 25% of all freshwater fish species. It is also the largest family of freshwater fish in the Mekong River with over 200 species. Even so, there appear to be only two genetic studies of cyprinids from the Mekong River. The studies provide some useful comparisons of similar genetic studies focused on two morphologically similar congeners. The studies have three authors in common and used nearly identical mtDNA markers as well as several of the same sampling locations (including Mekong River drainage sites in Laos, Thailand, Cambodia and Vietnam) to investigate two small but abundant and morphologically similar species. Hurwood et al. (2008) investigated diversity from 136 samples *of Henicorhynchus lobatus* collected from 10 locations (sample sizes ranged from 6 to 26) in the Mekong River drainage (including Laos, Thailand, Cambodia and Vietnam) and an outgroup location in the Chao Phraya River, Thailand. Adamson et al. (2009) assayed 217 *Henicorhynchus siamensis* (one of the most abundant species in the Mekong River) from 13 locations in the Mekong River drainage and an outgroup location in the Khlong River drainage, also in Thailand.

Two papers detail genetic investigations for the seven-line barb (*Probarbus jullieni*). Sukumasavin et al. 2004 described the development of microsatellite markers for this species. Bhassu and Rashid (2009) use seven of these microsatellite markers (in addition to morphometric measurements) to test for differentiation between wild fish from Malaysia and fish from a research facility in Thailand. Not surprisingly, they concluded that these collections represented two distinct populations.

The three remaining papers share the same lead author and have several other authors in common. Takagi et al. (2006) used mtDNA sequence variation to assess genetic differentiation among bronze featherback (*Notopterus notopterus*) collections from the Mekong River and Tonle Sap Lake. They concluded the existence of at least two populations of bronze featherback, one around Tonle Sap Lake and the other along the Mekong River. However, they noted that their data indicated there may be at least three populations in the Mekong River and suggested further investigation. Takagi et al. (2011a) assessed genetic variation among four collections (two each from Laos and Cambodia) of peacock eel (*Macrognathus siamensis*) by sequencing 1,047 base pairs of mtDNA. They reported strong evidence for population differentiation between the samples from Laos and Cambodia. Finally, in a similar study using the same mtDNA markers, the same authors assessed genetic variation in the climbing perch (*Anabas testudineus*) among six Mekong River collections in Cambodia and two in Laos. They report higher levels of differentiation in the climbing perch samples, with at least four genetically differentiated populations in the Mekong River.

Several common themes regarding the major influences on genetic diversity and population structure were noted by many of the authors in the aforementioned papers. First, the Mekong River drainage has experienced significant geomorphological and hydrological change in the recent evolutionary past, which has major influence on the contemporary population structure and gene flow. In addition, many current natural and human-made hydrological migration barriers exist, and many more of the latter are planned. Foremost among the natural impediments to migration are the Khone Falls in Laos and Tonle Sap Lake in Cambodia, both of which exhibit major influence on the migration patterns and population structure of many Mekong River species. Existing and planned dams along the Mekong main stem and its tributaries are cause for concern, as they will likely alter the natural migration and life history for hundreds of species, resulting in increased isolation of discrete populations. Several of the papers advocate for freshwater protected areas (refuge for sedentary stocks) to benefit migratory species, as well as seasonal protection to conserve spawning individuals and breeding locations and mitigate the negative consequences of dams in the drainage.

2.4 Fisheries Value

Southeast Asia and especially the LMB has the most productive inland fishery in the world. The Mekong River provides food security for more than 60 million people. Fisheries are of vital economic, social, and cultural interest to all countries of the region (Sverdrup-Jensen 2002; Zalinge et al. 2004; Baran et al. 2007). Fish and other aquatic animals are the principal animal protein source for human residents of the region, with estimates of per capita consumption ranging from less than 20 kg per year for people in mountainous areas to 70 kg per year for people living near the Tonle Sap region of Cambodia.

In the LMB over 2.5 million metric tons of wild fish are caught annually at a value of about US$2.5 billion–US$3 billion (Barlow et al. 2008), thus representing about one quarter of global freshwater fish catch. Additionally, burgeoning aquaculture in the region contributes substantially to production of fisheries, as does exploitation of reservoir stocks. Combined, these two sources account for at least 0.5 million metric tons annually (Sverdrup-Jensen 2002). The actual economic value of fisheries in the LMB is much greater when adding largely undocumented assets, such as the production and sale of fishing equipment, employment in the fisheries sector involving capture, transport, processing and sale, infrastructure development, and a myriad of other indirect benefits at the local and regional level. Other aquatic animals including mussels, snails, crabs, shrimps, frogs, and turtles are also important food resources but are generally overlooked in fisheries assessments (Phonvisay 2013).

For years the Mekong River Commission (MRC) and other entities have routinely monitored and estimated fisheries production and harvest based on a combination of capture fisheries of wild stocks and aquaculture production. In recent years, estimates of total fisheries production have often been revised upward as household surveys and improved or expanded methods of data collection and analysis are implemented. However, in some cases declining catches of wild fish (as harvest per fisher) are reported, possibly reflecting discrepancies between official catch statistics and those based on more rigorous scientific studies (Baran et al. 2007).

2.5 Threats to Aquatic Fauna of the Mekong

General threats to the fauna and flora of the Mekong basin are largely the same as for lotic systems globally—especially tropical and subtropical floodplain rivers. The major threats to freshwater fauna, as summarized in many publications (Dudgeon 1992, 1999, 2011, 2012; Kottelat and Whitten 1996; Lazarus et al. 2006; Helfman 2007; Kang et al. 2009), include

- Land-use change and habitat loss
- Barriers to fish passage and altered hydrology, including water diversion (for example, interbasin transfers), flow variability, levee construction, and activities associated with rice cultivation
- Overfishing
- Altered sediment transport, sediment sequestration

- Pollution, including organic matter, nutrients, and industrial contaminants (often bound to sediments)
- Nonnative species
- Climate change

An extensive body of literature exists on threats to fishes and their habitats in the Mekong basin. The abbreviated summary of major threats presented here is intended to highlight the breadth and depth of ecological problems facing fish populations in the region. If the extent of these threats and their rate of increase continues, Mekong fisheries are not currently regarded as sustainable in the long term. An informative, interactive web-based learning toolkit that provides more in-depth detail about threats throughout the Mekong basin is available at: http://www.mekong.riverawarenesskit.com/html/rak_frameset.html.

2.5.1 Land Use and Habitat Loss

Land-use changes in the Mekong basin are primarily caused by deforestation and agriculture, and by urbanization and mining to a lesser extent. Loss of terrestrial habitats due to deforestation currently occurs at a higher rate in Southeast Asia relative to other tropical regions, with an especially dramatic loss in forest cover between 1970 and 1990 (Achard et al. 2002; Bradshaw et al. 2009; Dudgeon 2012). In recent years there have been large-scale land conversions in Yunnan Province (China), Myanmar, Laos, Cambodia, and northeastern Thailand that have resulted in major changes to landscapes, especially associated with rubber plantations and industrial agriculture (Kottelat et al. 2012).

Aside from direct loss of habitat for some aquatic species, land transformation associated with these human activities has incidental impacts, including alteration of the timing and amount of runoff or stream flow and increased input of inorganic sediments, organic matter, and contaminants. Conversion of land from natural conditions through forestry and agricultural practices is often accompanied by changes in riparian areas associated with levee construction, bank engineering, and other modifications that may alter connections between rivers, lakes, and wetlands that are naturally inundated during the wet season. Previously shaded stream or river sections may be exposed to sunlight, resulting in warmer water temperatures and the proliferation of algae. Subtler changes can occur if food webs are altered or there are changes in primary productivity, such as a shift away from detrital input from terrestrial sources to aquatic autotroph production. Cumulatively, the impacts of these types of land-use changes on aquatic systems results in loss of habitat complexity or heterogeneity, declines in biodiversity, and altered conditions that favor generalist or more tolerant or invasive species.

2.5.2 Barriers to Fish Passage

For migratory fish species, a primary factor in the proper functioning of the ecosystem is the ability to access critical habitats at the appropriate time (Poulsen et al. 2002b). To ensure the overall health of migratory fish populations, it is vital to maintain connectivity between critical habitats. In Laos this is an important issue. Physical barriers include existing or planned dams on tributaries, levees blocking free access between the Mekong River and its floodplains, and dams on the mainstem Mekong River. Collectively, these barriers may reduce the productivity of fisheries by restricting access to critical habitats.

Within Laos, several mainstem Mekong River dams are proposed, with one currently under construction at Xayaburi and another, Don Sahong, in the final stages of planning. A great deal of attention has been focused on the potential impacts that mainstem dams might have on migratory fish species in the Mekong River. Dams can impact fish directly by obstructing migration and fragmenting habitats, as well as indirectly by altering the hydrologic cycle that fish have adapted to over generations (Phomikong et al. 2014).

Several authors have estimated potential impacts of mainstem dams on migratory fish species in the lower Mekong River basin (for example, Baran and Myschowoda 2009, Halls and Kshatriya 2009, Dugan et al. 2010, Ferguson et al. 2011, Ziv et al. 2012). Most of these assessments conclude that migratory species will be impacted; however, the biological data on many migratory species are inadequate to fully assess the impacts of mainstem dams (Baran and Myschowoda 2009).

In addition to mainstem hydropower development, tributary dams and levee systems along floodplain wetlands can impact migratory fish populations by fragmenting habitats and altering hydrologic conditions (Ziv et al. 2012, Phomikong et al. 2014). Tributary rivers provide spawning and rearing habitats for many migratory species and wetlands serve as important rearing, feeding, and refuge areas for many species (Phonvisay 2013). Tributary rivers appear to provide important habitats for medium and large species of cyprinids, as well as Pangasiid catfish, however more research is needed to clearly define the role of tributaries in the life cycle of many species in the Mekong River basin (Halls et al. 2013a). Maintaining connectivity between critical habitats within the Mekong River basin is necessary to sustain most migratory fish species (Poulsen et al. 2002b).

The most common mitigation action to reduce impacts to fish species from the construction of dams is to provide upstream and downstream passage through the construction of fishways with or without operational changes (FERC 2004). In other large river systems in North America and Europe, mitigation measures have been partially successful, and have relied on decades of research and development (Enders et al. 2009; Ferguson et al. 2006).

For the proposed mainstem Mekong River hydropower projects, fish passage has been identified as a necessary component of the design of the facilities. The Xayaburi hydropower project located on the Mekong River downstream of Luang Prabang is the first of several planned mainstem hydropower projects in Laos. The dam will include a partial fishway and fish lift to provide upstream passage, while downstream passage is anticipated through the project’s spillway, a system of passageways in the powerhouse, and through the turbines. During the construction phase of the Xayaburi hydropower project, before the fish passage facilities are operational, upstream fish passage is planned through the navigation locks and downstream passage is planned through the locks and spillway. The planned Don Sahong hydropower project will block all upstream and downstream fish migrations in the river channel of construction, so adjacent river channels will be relied on for fish passage.

The effectiveness of proposed mitigation measures at mainstem dams on the Mekong River is unknown. The diversity of migratory species in the Mekong River, as well as the relatively limited information on swimming abilities, timing of migrations, and critical habitats for many species complicates efforts to design effective fish passage facilities. In addition, even if passage facilities are designed based on extensive hydraulic engineering and biological science to cover a wide range of environmental conditions and fish behaviors, unanticipated issues or complications often arise once the designs are implemented (OTA 1995).

Monitoring and assessment of fish passage facilities (once they are built) is necessary to ensure that the facilities are operating as intended, as well as to provide information with which to design future fish passage facilities (Baumgartner et al. 2014). Fish passage facilities that are based strictly on engineering models and priorities that do not take into account fish behavior and biology often fail to efficiently pass fish. In many locations in Europe, North America, and South America, improvements to fish passage efficiency were gained only after engineers, biologists, and government agencies worked together to quantitatively assess fish passage and work toward common goals (Martins da Silva et al. 2012).

Regular modifications to the operation or structures at the dam and its fish passage facilities will likely be necessary to optimize the effectiveness of fish passage at Xayaburi Dam and other hydropower projects. Significant long-term investments in research and monitoring programs will likely be necessary as well, to adequately determine the effectiveness of fish passage facilities at the mainstem Mekong River dams (Dugan 2008).

Tributary dams in Laos do not currently have upstream fish passage provisions. The migratory impacts of dams built high in the watersheds may be limited by the relatively short section of river upstream. However, numerous new dams are being proposed and these would likely be located lower in the tributary areas where impacts to migration could be substantial (Ziv et al. 2012, Halls et al. 2013b). In addition, diversions and barriers along floodplains and wetlands can have significant impacts on some species (Baumgartner et al. 2010). The lateral migration of fish from the mainstem and tributaries into highly productive floodplains is an important life history strategy for many species (Poulsen and Valbo-Jorgensen 2000). The same concepts regarding fish passage, both upstream and downstream, apply to tributary and floodplain barriers, but often at a smaller scale.

Hydropower development along the mainstem Mekong River and its tributaries is moving forward at a rapid pace (Dugan et al. 2010). While the planned projects will boost the region’s economy, the full impact of dams on important migratory fish species is unknown (Baran and Myschowoda 2009). The rapid pace of development in the region also poses a challenge for the various Lao ministries and governmental departments. Individual companies are proposing each mainstem hydropower project, and coordination between project proposals is lacking. Currently, the Lao Government is relying on the technical knowledge of the hydropower developers to ensure fish passage at each project and to assess potential impacts to fishery resources. The Environment Department of the Lao Ministry of Energy and Mines and LARReC expressed a desire to increase governmental capacity and coordination between agencies to better assess hydropower development. The ability to independently review hydropower project proposals and assess potential impacts to fishery resources is a desired capability for the Lao Government. The LARReC will play an important role in developing this capability.

2.5.3 Overfishing

Overexploitation of fisheries stocks in the Mekong River basin is inadequately studied. There are perceptions that fisheries production, namely wild-captured stocks, have been declining in recent years. However, data from the Tonle Sap system in Cambodia indicate that from 1940-1995 the catch approximately doubled, but the human population of the region tripled; thus, catch per fisher was lower even though total biomass harvested was greater than in the past (Baran et al. 2001; Baran and Myschowoda 2008). As the human population expands in the Mekong basin, overfishing is likely to become an increasingly pervasive threat, due, in part, to the open access nature of the fishery and to a general lack of controls over the resource and weak enforcement of fisheries laws (Baran 2005).

The most notable and best documented examples of overfished species in the Mekong basin occurred in areas of China (Kang et al. 2009), while in the LMB overfishing impacted large-bodied species (Allan et al. 2005; Dudgeon 2011). One of the Mekong's most iconic species, the Mekong Giant Catfish (*Pangasianodon gigas*), has been greatly overfished and is dangerously close to extinction. A trend of declining catch with sustained high fishing pressure is evident in the Mekong for several other large fish species, all considered imperiled, including the Striped Catfish (*Pangasianodon hypophthalmus*), Giant Pangasius (*Pangasius sanitwongsei*), Isok Barb (*Probarbus jullieni*), Giant Barb (*Catlocarpio siamensis*), and Freshwater Whipray (*Himantura polylepis*). These large migratory species are especially susceptible to overfishing because they are long-lived and reach sexual maturity relatively late. Furthermore, use of different regions or habitats of the river basin at different life-history stages increases their vulnerability due to barriers to migration, increased chance of capture, and potential exposure to degraded water quality conditions. In the region of Khone Falls, apparent overfishing of the Isok Barb and the Thicklip Barb (*Probarbus labeamajor*) — species that reach 70 kg and 1.5 m long — has resulted in a shift to the capture of smaller species (Baird 2006).

2.5.4 Sediment Transport

Alteration of sediment transport in the Mekong basin has substantial ecological consequences, including direct physical changes to habitats, effects on life-history of individual species, and population or community-level impacts. Most existing and projected changes to sedimentation in the basin are attributable to hydropower development (particularly sequestration behind dams), but increasing deforestation and other land-use changes are also contributing to changes in sediment dynamics.

The issue of sediment deprivation in the Mekong basin is considered to be the greatest overall threat to fishery production and is the focus of extensive technical assessment and outreach to inform governmental and non-governmental entities, such as efforts by the Natural Heritage Institute (Box 1). Sediments in rivers occur in a suspended state and as bedload. Suspended sediment consists of fine particulate organic and inorganic matter (such as sands, clay, and silt) that is carried in the water column with long residence time and settling at lower velocities. Bedload sediment consists of coarse material (such as gravel or pebbles) that is transported near the substrate and accumulates in a loose, unconsolidated form at the bottom of a water body.

Construction of dams on the Mekong mainstem has already greatly reduced sediment loads in the LMB and this trend is anticipated to increase in the future. An estimated 45-50 percent of total sediment load of the basin is predicted to be trapped when all mainstem dams planned in China are completed (Kummu et al. 2010; Wang et al. 2011; MRC Secretariat 2011). If most or all dams planned for the Mekong mainstem and tributaries in Laos are built, there may be an estimated 75 percent reduction in baseline sediment loads for the basin, with a large portion of sediments eventually settling out in the ~100 km reservoir impounded by the Xayaburi Dam (Dudgeon 2011; MRC Secretariat 2011; Pukinskis 2013; ICEM 2010).

Box 1. Technical assessments of sedimentation and hydropower development in the Mekong basin associated with "A Climate Resilient Mekong Activity" by the Natural Heritage Institute, with funding from USAID

Baran, E., and E. Guerin. 2012. Dams, changes in sediment load and impact on fish resources in the Mekong: approach and way forward. Unpublished report.

—. 2012. Fish bioecology in relation to sediments in the Mekong and in tropical rivers. Unpublished report.

—. 2012. Influence of sediment load on Mekong floodplain and coastal fisheries: state of knowledge and research options. Unpublished report.

Baran, E., and J. Nasielski. 2011. Reservoir sediment flushing and fish resources. Unpublished report.

Baran, E., E. Guerin and S. Saray. 2012. Features of high fish productivity in the Mekong basin: Case of 32 biodiversity hotspots. Unpublished report.

Golder and Associates. 2013. Maximizing sediment passage through dams on the Xe Kong River, Laos. Unpublished report.

—. 2013. Technical memorandum on options for sediment passage through Lower Se San 2 Dam. Unpublished report.

—. 2013. Technical memorandum on options for sediment passage through Sambor Dam. Unpublished report.

—. 2013. Technical memorandum on preliminary assessment of sediment management at Mekong River and its tributaries: case for Buon Tua Srah and Buon Kuop Dam in Vietnam. Unpublished report.

Kondolf, G.M., Y.X. Gao, G.W. Annandale, G.L. Morris, E.H. Jiang, J.H. Zhang, Y.T. Cao, P. Carling, K.D. Fu, Q.C. Guo, R. Hotchkiss, C. Peteuil, T. Sumi, H.W. Wang, Z.M. Wang, Z.L. Wei, B.S. Wu, C.P. Wu and C.T. Yang. 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future 2(5):256-280.

McKinney, D.C. 2011. HEC ResSim model of Lancang cascade dams. Unpublished report.

Rubin, Z.K., G.M. Kondolf and P.A. Carling. 2015. Anticipated geomorphic impacts from Mekong basin dam construction. International Journal of River Basin Management 13(1):105-121.

Thomas, G.A. 2010. Technical concept paper: Reoptimization of dams in the Mekong/Lancang river basin to safeguard livelihoods and aquatic ecosystems. Unpublished report.

Wild, T.B., and D.P. Loucks. 2013. *SedSim* model: A simulation model for the preliminary screening of sediment transport and management in river basins, Version 3.0: documentation and user's manual (Department of Civil and Environmental Engineering, Cornell University, Ithaca, New York). Unpublished report.

Note: See http://www.global-dam-re-operation.org/where-we-work/southeast-asia.html.

Trapped sediments and the nutrients bound to them has already led to an estimated 15-35 percent reduction in nutrient supply over pre-dam levels, and this reduction is predicted to increase to 20-40 percent, with a worst-case scenario of up to 70 percent, if all mainstem and tributary dams are constructed (Dudgeon 2011). Diminished delivery of nutrient-rich sediments to down-river areas, particularly floodplain habitats such as the Tonle Sap, and the Mekong Delta (see Manh et al. 2014), lowers primary productivity and has cascading consequences on fish recruitment and production. Another consequence of sediment sequestration behind dams is downstream bank erosion and channel incision, leading to changes in river geomorphology that further exacerbate alterations to flow and dynamics of sediment deposition. Channel incision contributes to disconnections between channel and floodplain habitats. To mitigate for sediment sequestration in Mekong reservoirs, dams are typically engineered and operated to periodically flush or scour sediments (Baran and Nasielski 2011).

There is an extensive body of literature concerning the impact of sediment and nutrient concentrations resulting from reservoir flushing or organic pollution on fish communities, but fewer studies on the effects of reduced sediments or nutrients (Baran and Guerin 2012). The role of sediments in the ecology of individual species varies extensively and changes in sediment loads may have direct or indirect effects on respiration, nutrition, reproduction, migration, and habitat at different life-history stages.

The organic component of sediments directly influences aquatic oxygen levels, and turbidity also affects plant growth and, therefore, photosynthesis and primary productivity. Sediment fluxes may influence reproduction, and in some cases habitat for reproduction, particularly for benthic species. Changes in turbidity or water color at the beginning of the rainy season act as a trigger for some of the long-distance migratory species (Baran 2006; MRC-TAB 2007). Moreover, fish migrations have a significant role in the transfer and distribution of nutrients; thus, the interruption of migration movements and changes in sediment delivery has the potential for large-scale effects across the entire Mekong basin. Given the complex interrelationships between sediment dynamics and fish life histories, this is an area where large gaps in knowledge exist. Research in this area would better inform management of fishery resources.

2.5.5 Pollution

Pollution from urban, industrial, agricultural, and mining sources is variable throughout the LMB. In comparison to the Yangtze River basin in China (see Kang et al. 2009), the LMB currently is not affected by severe widespread or trans-boundary pollution problems (Dudgeon 2011). However, localized areas have degraded water quality conditions, especially near urban areas of Thailand and rural, agricultural, and urban areas of Vietnam, including the Mekong Delta.

The MRC established a water quality monitoring network (WQMN) in 1985, consisting of 90 stations distributed throughout the mainstem and tributaries of the lower Mekong River. The number of stations sampled has varied over the years since the inception of the program. Based on data from 1985 to 2005 (or the subset of 2000-2005), conditions were generally considered to be of good to moderate quality with the exception of the Mekong Delta (MRC 2008b). The principal water quality issues are salinity (associated with both saltwater intrusion and irrigation regimes), acidification (generally resulting from oxidation of sulfate soils), and eutrophication (increases in total nitrogen and phosphorus). Primary sources of pollutants were discharge from urban areas, including human sewage, industrial wastewater, and runoff from agriculture, the latter associated with increased use of fertilizers and pesticides. Increasing populations of water buffalo (*Bubalis bubalis*) also have negative effects, not only by destroying river banks and shallow habitats, but also by contributing to organic loading and oxygen depletion from their excrement (Kottelat et al. 2012).

From 2004 to 2008 the MRC conducted a biomonitoring program at sites throughout the LMB using indicator organisms (diatoms, zooplankton, littoral and benthic macroinvertebrates) and ecological metrics to assess environmental health of the aquatic environment (MRC 2008a; Dao et al. 2010; MRC 2010). Some sites were impaired, but water quality at most sites was scored moderate to good; however, degradation of sites as measured by the aquatic communities may have been associated with bank erosion and changes in sediments. As the human population expands in the LMB and anthropogenic stressors increase, water pollution from different sources is also expected to increase and have greater effects on fishery resources in the future.

2.5.6 Nonnative Species

The introduction and spread of nonnative species and biotic homogenization is recognized as one of the major threats to freshwater faunas worldwide (Rahel 2002; Dudgeon et al. 2006). In many freshwater systems, nonnative fish species have been implicated in the decline and extirpation of local fish populations and other aquatic organisms (Light and Marchetti 2007), although in others systems their establishment has had little perceptible effect (Moyle and Light 1996). Where they do have an impact, nonnative aquatic species — especially fishes — can affect native aquatic communities through a variety of ecological mechanisms, including competition and predation (displacement), establishment in ecological niches created by the decline of native species (replacement), introduction and transmission of diseases, and hybridization. Also, some nonnative species can exert an indirect effect through the alteration of the physical habitat, such that it becomes unfavorable for native species; for example, habitat alteration, bioturbation, and increased siltation by Common Carp (*Cyprinus carpio*) and Armored Catfishes (Loricariidae, especially *Pterygoplichthys* spp.) in Australia, the United States, and elsewhere (Weber and Brown 2009; Dudgeon 2012).

A number of ecological hypotheses have been proposed to explain variations in the establishment and impact of invasive species, and they may not be mutually exclusive (Catford et al. 2009). The biotic resistance theory (originally proposed by Elton 1958) posits that habitats containing many native species with robust populations are less likely to be invaded. The corollary to this is biotic resistance to invaders where most of the available niches are already occupied or most life-history strategies are already present. It has also been demonstrated that fish communities with predators are less likely to be invaded (Baltz and Moyle 1993).

The environmental resistance hypothesis holds that the establishment and spread of nonnatives is hindered by important physical characteristics of the system, for example the timing of floods, which can limit recruitment (Fausch et al. 2001). Propagule pressure, expressed as the frequency and magnitude of introductions, is also hypothesized to influence establishment and spread of nonnative species (Lockwood et al. 2005).

Welcomme and Vidthayanon (2003) reviewed nonnative fish introductions in the Mekong River basin and evaluated the introduction of Nile Tilapia (*Oreochromis niloticus*), Mossambique Tilapia (*O. mossambicus*), and Common Carp (*Cyprinus carpio*), species that are often considered as pests outside of their native ranges. The authors concluded that there was generally little evidence of substantial, widespread negative effects from nonnative species on native Mekong River fish populations. However, the authors noted that this situation should not be considered static, and it is very likely that the threat of invasion from nonnative aquatic species will increase dramatically in the coming decades. Five nonnative fish species, mostly carps and tilapia, were listed by Dudgeon (2012) as occurring in Laos.

In general, any stressors that alter the habitats and reduce the populations of native fishes will provide new opportunities for nonnative species. For example, planned construction of hydroelectric dams on the mainstem Mekong River and tributaries will not only reduce the abundance of migratory species (and reduce biotic resistance) but will also alter natural flow regimes and create novel slack-water habitats in impoundments that may foster the establishment and spread of nonnative fishes (and reduce environmental resistance). Overfishing of native fishes can generally lower the biotic resistance to nonnatives, and the dramatic reduction of large-bodied predators, such as the Mekong Giant Catfish, may be particularly important if their presence contributes to biotic resistance. Nonnative fishes (for example, tilapia) are widely used in aquaculture, and the growth of that sector increases the probability of fish escaping from net pens or ponds into streams and rivers (and increasing propagule pressure). Stocking of fish in natural or man-made habitats is often done to supplement local food resources, but without careful consideration of the species stocked and the recipient habitat(s) there can be risk of spread and impact on native species (Welcomme and Vidthayanon 2003).

2.5.7 Climate Change

The earth's climate is warming, and continued emissions of greenhouse gases is projected to result in further warming and have potentially irreversible impacts to ecosystems (IPCC 2014); these changes are expected to strongly affect freshwater biodiversity in the coming century (Strayer and Dudgeon 2010). Global mean surface temperatures are projected to increase between 1.1^{o}C -2.6^{o}C compared to 1986-2015, assuming moderate emissions of greenhouse gases (Representative Concentration Pathway 4.5 scenario of IPCC 2014). Globally, heat waves and extreme precipitation events will likely be more frequent and intense, oceans are predicted to warm and acidify, and sea levels are predicted to rise.

Temperature increases coupled with changes in precipitation are expected to significantly affect the hydrologic regimes of river systems, including the Mekong River (Gosling et al. 2011; USAID 2013; Arias et al. 2014). Substantial increases in air temperature are predicted for the Mekong River basin during all seasons across a range of emission scenarios, climate models, and statistical methods (Eastham et al. 2008; Keskinen et al. 2010; Huang et al. 2014); the rate of warming is expected to vary spatially (USAID 2013).

Future projections for precipitation and river discharge in the Mekong River basin vary slightly depending on methodology (Keskinen et al. 2010; Gosling et al. 2011; Kingston et al. 2011) or sub-basin (Shrestha et al. 2013). In general, however, the expected change will be for greater annual precipitation (especially in central Laos), increased seasonal variability in precipitation (wetter wet seasons, drier dry seasons) in southern areas of the LMB, and a larger flood pulse (Dudgeon 2011; USAID 2013).

Climate change could influence freshwater fishery resources in LMB and in Laos through a host of direct and indirect ecological effects, ranging from changes in physical habitats to alteration of food webs (see reviews by Ficke et al. 2007; Cochrane et al. 2009; Bach et al. 2014). Increased water temperatures may present physiological challenges to fishes and other poikilothermic aquatic species, which could affect their growth, susceptibility to disease, and ultimately, their survival. Unfortunately, there are few data about the thermal preferences and tolerances of Mekong River fishes (USAID 2014). In general, changes in river temperatures could lead to range shifts as more temperature-sensitive (stenothermal) species seek cooler water in upstream reaches or at higher elevations and, concurrently, species with greater thermal tolerances (eurythermal) — often nonindigenous species — expand their distributions. Reduced dissolved oxygen concentrations coupled with increased water temperature may also alter the distribution of fishes and other aquatic organisms where differences in tolerances exist between species or guilds.

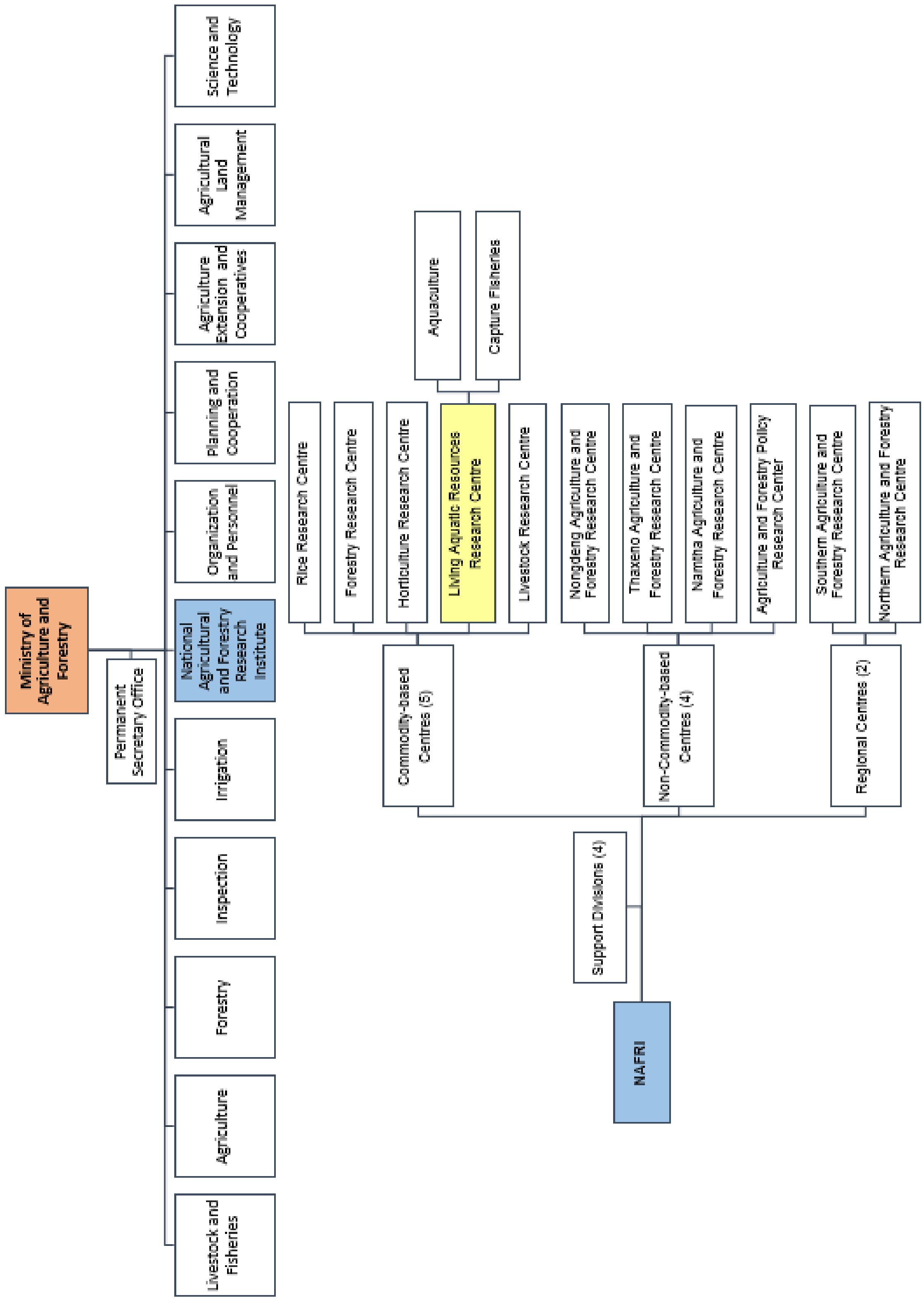
Hydrologic changes could also affect the phenology of migration and spawning cycles of many fish species (Cochrane et al. 2009), which may depend on specific hydrologic cues, such as increasing or decreasing discharge (Baran 2006). If droughts become more severe or long-lasting, then seasonal dewatering could deprive fish of access to important spawning or rearing habitats, for example in floodplains. Thermal and hydrologic changes and possible shifts in sediment flux (Shrestha et al. 2013) resulting from climate change could affect fish populations by changing food webs and production at lower trophic levels (reviewed by Schindler 2001).

Ultimately, climate change is expected to substantially affect at least some of the capture fisheries on which residents of the Mekong River basin depend for food security (USAID 2014). However, it must be noted there is uncertainty in the timing, magnitude, and possibly even the direction of these effects, given both the lack of basic ecological information about many fish species in the basin and how climate will affect them, and the fact that climate change will interact with most or all of the other stressors or threats described in preceding sections.

3. Overview of LARReC

The Living Aquatic Resources Research Center (LARReC) is one of 11 research centers within the National Agricultural and Forestry Research Institute (NAFRI), which is one of 11 departments within the Ministry of Agriculture and Forestry (MAF) of the Lao Government. NAFRI was established in 1999 and restructured in 2007 to consolidate agricultural, fisheries, and forestry research nationwide. Figure 3 depicts the Organizational structure of MAF, with NAFRI, LARReC, and associated Departments of Aquaculture and Capture Fisheries.

Figure 3. Organizational structure of the Lao Ministry of Agriculture and Forestry



NAFRI has four main functions: (1) to conduct adaptive research; (2) to develop methods, tools, and information packages; (3) to provide policy feedback; and (4) to coordinate and manage research. Research responsibilities separate NAFRI from other departments within the MAF, and LARReC is responsible for fisheries research while the Department of Livestock and Fisheries (DLF) is responsible for management and regulatory actions. However, LARReC and DLF work together to implement science-based approaches to resource management. The research focus of LARReC is directed by the NAFRI Strategic Plan (NAFRI 2004, 2015).

3.1 Existing Capacity

LARReC consists of an Aquaculture Research unit (36 staff employees) and a Capture Fisheries Research unit (eight employees), with Lieng Khamsyvilay currently serving as Director and Douangkham Singhanouvong as Deputy Director. The Capture Fisheries Research unit conducts research on wild fish stocks and its staff members have either considerable fishery experience or a background in related fields. Much of the data collected and field work conducted by LARReC is based on log books of local fishers, fish-landing catches, surveys and household questionnaires, and traditional or local ecological knowledge, all common approaches to obtaining data throughout the region.

LARReC maintains fruitful collaborations and receives funding primarily from groups outside the Lao Government. Collaborations include those with the National University of Laos (NUOL), LaTrobe University in Melbourne, Australia, and the Pacific Northwest National Laboratory (PNNL; United States Department of Energy, Richland, Washington). Most funding for LARReC research has traditionally come from the Mekong River Commission (MRC), the Australian Centre for International Agricultural Research (ACIAR), and the Southeast Asian Fisheries Development Centre (SEAFDEC).

In-country interviews were conducted with LARReC staff members to identify their needs, concerns and aspirations. One of the principal issues of LARReC staff members was the desire to be less reliant on outside groups for funds, analysis, and reporting. Lack of institutional and human resource capacity to implement scientifically sound and advanced applied research is the main constraint currently facing LARReC (Phonvisay 2005). Capacity-building areas of interest expressed by LARReC staff members ranged in scope from greater expertise using Microsoft Access and Excel to performing in-house data analyses and assessments. These areas include

- Training on data collection and analysis
- Database management (Microsoft Access, Excel)
- Less reliance on MRC for analysis and publishing
- Capability to do in-house Fishery Impact Assessments
- Capability to provide for planning of hydropower development
- Linking research with other institutions, such as Inland Fisheries Research and Development Institute (IFReDI) in Cambodia

3.2 Existing Research and Projects

As part of the MRC Fishery Monitoring Program, LARReC has historically sampled capture fisheries at a number of sites along the Mekong River; over the years, the number of sites varied from 3 to 15. At each site, fish are sampled using various gear and the number and species of fish are recorded. This project was funded by MRC as part of an effort to standardize sampling throughout the lower basin. LARReC staff sent field data to MRC for analysis and consolidation to be used in MRC reports, such as "Integrated Analysis of Data from the MRC Fisheries Monitoring Programs in the Lower Mekong Basin" (Halls et al. 2013b). Future funding from MRC for this project is uncertain, and much of the recently collected data has not been analyzed and reported back to LARReC (by MRC) in a timely fashion. As MRC support for fishery resource monitoring in the LMB wanes, there is increasing pressure on the line agencies of Cambodia, Laos, Thailand, and Vietnam (formal members of MRC) to assume the costs and logistics of continuing data collection at the fixed sampling sites. In the case of Laos, the lack of sufficient financial support, infrastructure, and well-trained staff jeopardizes continuation of the long-term fishery assessment program (for example, D. Singhanouvong stated that data collection at some of the sites ceased in 2013).

An associated MRC-coordinated project is the lee trap fishery monitoring program at Khone Falls in southern Laos.[2] The goal of the project is to estimate the abundance and biomass of fish migrating through the Khone Falls area each year. In addition, LARReC has been involved in several studies of fish passage, including work at an experimental fish ladder at the Pak Peung wetland near Paksan. The information collected through these and other projects has provided valuable baseline information on fish distribution, fish migrations in the LMB, and fish passage design criteria (for example, Baumgartner et al. 2012; Halls et al. 2013b).

The weakness of fisheries development and management in Laos is related in part to problems associated with methodology and approaches of obtaining capture-fishery data, which have not been collected in a systematic and comprehensive manner at the national level (Coates 2002). Some of the constraints pertaining to fisheries development identified by Phonvisay (2005) include

- Insufficient scientific knowledge on riverine ecology, biodiversity, and cultural values of the resources, resulting in an inability to accurately address or confirm the status of fisheries in the country;
- Inadequate physical infrastructure within the fishery sector;
- Inadequate research, extension, and development support;
- Lack of research and development in aquaculture, especially flexible and appropriate design in farming system approaches (including choice of species, water source, feed and nutrition, etc.); and
- Lack of sustainable and viable strategies for effective and efficient management of aquatic resources that would support long-term stability of the local livelihood of communities.

[2] Lee traps are specialized large filtering gear targeting downstream-migrating fish.

In addition to issues pertaining to collecting data on capture fisheries, limitations on statistical analysis and interpretation are a substantial barrier to understanding and effectively managing aquatic resources in Laos. As stated by Souvannaphanh et al. (2003):

> "…statistical data and information on the economic significance of the fisheries sector is difficult to obtain because of the limitation of financial support, limitation of human resources and knowledge of fishery scientists in statistics. A lack of information and statistical data on inland fisheries has undermined their importance and the subsequent management of the resources. With a growing population, it is important to maintain the contributions of inland fisheries to food security and to increase production. Concerted action is required in this regard. There is a need to improve the collection of statistical data that can be interpreted in economic, scientific and ecological terms for use in planning and development."

As MRC undergoes changes in staffing, funding, and direction relative to its regional role in the assessment of fisheries resources, LARReC faces the critical need to improve its internal capacity to collect, analyze, and interpret capture fishery data in a robust framework.

4. Recommendations

4.1 Research

Habitat Connectivity

Physical barriers to migration are one of the primary factors threatening sustainable fisheries in Laos. Existing barriers prevent or limit connectivity between the Mekong River and critical habitats used for spawning and rearing in wetlands and tributary rivers, and numerous future barriers, including dams on the Mekong River, are in the planning phase. The following recommendations address wetland, tributary, and mainstem habitats.

- **Recommendation 1**: Expand fish passage research at Pak Peung wetland and apply lessons learned to other wetlands.

  The results of the research on the existing upstream fish passage at Pak Peung wetland are very encouraging and support expansion of the design to other sites. Additional study is needed, however, to determine the rate of passage of various species, rather than simply the number of species and individuals ascending the structure. Such an analysis, commonly called event time analysis, could identify ways to improve the already promising design, such as factors restricting fish entering or ascending the fish pass at specific areas. It is recommended to undertake such an analysis prior to expanding the fish passage design to other sites. In the meantime, a prioritization, such as the one by Marsden et al. (2014), should be conducted or updated to select fruitful sites for fish passage construction. A study could be designed to use passive integrated transponder (PIT) tagged fish to inform upstream and downstream passage.

Resources needed: With technical support from DOI-ITAP experts, an informative study based on event time methods could be conducted over one or two migration seasons. These studies are normally conducted using fish with individual marks, such as PIT, radio, or acoustic tags so that the presence of fish near and within the fish pass can be identified. PIT tag technology is particularly well suited for use at this site, but other tools, such as acoustic cameras, could also be used to examine fish behaviors in specific areas (see Appendix 1 and 2).

- **Recommendation 2**: Evaluate the relative effectiveness of existing fish passage facilities at mainstem dams on the Mekong River in Laos.

The presence of dams on the Mekong River will likely have a serious impact on habitat connectivity. For example, while the design of Xayaburi Dam includes several features to provide upstream and downstream fish migration, their success with Mekong River species is essentially unknown. Don Sahong and Xayaburi dams, as the first of many planned dams on the Mekong River in Laos, should be used to the greatest extent possible to inform how they affect fish migration so that passage at these and future sites can be optimized to provide sustainable hydropower and fisheries. Information required to determine the efficacy of fish passage optimally includes knowledge of route-specific passage and survival probabilities, from which overall dam passage survival can be estimated (Skalski et al. 2002, Halls and Kshatriya 2009). These data can be used to identify areas that meet or fall short of passage goals, which can then be addressed on a route-specific or an operational framework. Designing and conducting studies of fish has to this point been the sole responsibility of the dam companies (specifically at Xayaburi Dam, but this is likely true of Don Sahong Dam as well). The Lao Government, presumably LARReC, should have a role in such matters; as outlined a pathway in the section "Operations and Management."

Resources needed: Thorough studies of fish passage at dams with multiple passage routes often take many years. The species richness of the Mekong River and the current lack of information about how Mekong River fishes respond to specific fish passage provisions will add to the complexity of such studies, and will require prioritization of the species or guilds studied. Such studies often require complex study designs and analytical methods, which should be developed though collaboration with a Technical Working Group (see the section "Operations and Management"). The methods used for studies of route-specific passage at dams are often more elaborate than those that may be suitable at the fish passage at Pak Peung, often requiring the use of active tags to determine route-specific passage. Passive methods such as hydroacoustics or acoustic cameras could be used for some aspects of an assessment (see Appendix 2). The DOI-ITAP project on Fish Friendly Hydropower could be extended to this effort.

- **Recommendation 3:** Assess habitat alteration upstream and downstream of existing mainstem hydropower facilities (for example, larval drift, predator/prey dynamics) to inform the potential impacts of future dams.

Migration barriers, and dams in particular, cause a variety of changes to the natural environment that affect the local flora and fauna. Reservoirs created by dams, whether they are run-of-river or for storage purposes, alter water velocities, depths, and water quality relative to pre-impoundment conditions (Cowx et al. 2015). Dams also alter downstream conditions, such as total discharge, water velocities, water temperatures, total dissolved gases and solids. These changes commonly alter fish assemblages and predator-prey relations. The importance of downstream drift of eggs, larvae, and juvenile fish (collectively, ichthyoplankton) to the recruitment and production of many Mekong River fish species makes the reduction in magnitude and timing of water velocities in reservoirs a substantial risk to sustainable fisheries. Ichthyoplankton drift studies conducted before and after impoundment will be essential to determine the impacts of dam development and could be used to help guide future design, operation, and mitigation of mainstem dams.

Resources needed: Cowx et al. (2015) provide methods and shortcomings for a comprehensive study of ichthyoplankton in the Mekong River. Such a study (or studies) would take at least one year of sampling effort, and would ideally span multiple years to capture different environmental conditions.

- **Recommendation 4:** Develop a prioritization plan for improving connectivity of habitats within tributaries of the Mekong River.

Most existing barriers to fish migration are on tributary rivers, yet there are no known provisions for fish passage at these sites The most prevalent barriers on tributaries are dams for hydropower or irrigation uses, but there are also many other barriers such as those caused by culverts at road crossings. Given the large number of these barriers, the reestablishment of habitat connectivity within the tributary corridors has the potential to reap great benefits. A database of the present and planned barriers should be compiled as a tool for prioritizing work to provide fish passage at barriers on tributary rivers.

Resources needed: Spatially-referenced databases of this kind are not uncommon and in Laos one has already been compiled for prioritizing restoration of connectivity among some wetland areas (Marsden et al. 2014). The time frame to develop the database will depend on the available information, but could probably be completed for some watersheds in 1-2 years. The types of data required include location, type, height and age of the barrier, the fishery or other important biological resources that would be provided passage, the type and quality of habitat that would be made available, the relative importance of inaccessible habitat to human food security, and the estimated cost to provide connectivity. A ranking of the importance of these variables could then be used to prioritize the barriers in terms of costs and benefits.

Ecology

Understanding the genetic population structure of fishes of the Mekong River basin would provide important information on the ecology and historical and current patterns of fish migration. Defining the spatial genetic stock structure of fish species will enable testing for effects of fragmentation due to dams, and will facilitate management in anticipation of hydrological changes from climate change and dams.

To make effective and strategic management decisions, it is critical to understand population structure and basic life-history characteristics of individual species; such parameters include knowledge about barriers to gene exchange, migratory and movement patterns, reproductive biology (such as spawning location, spawning season, fecundity, larval development and drift), trophic category, and habitat associations.

- **Recommendation 5:** Select one fish species for use as a prototype in the design and implementation of a genetic population structure study.

  The use of one species as a prototype will provide training for Lao scientists, proof of concept about what can be learned by population genetic studies (or conversely, what mistakes in management might occur if such studies were not completed), and would establish a protocol that could be applied to other species. Jullien's barb (*Probarbus jullieni*) is classified as an endangered species by the International Union for Conservation of Nature (IUCN) and it is a prized food fish, thus it may be an appropriate prototype. Importantly, several spawning locations have been identified which would greatly facilitate genetic sampling for population structure analyses. Furthermore, over 3 million fry are raised and released annually on National Fish Release Day in Laos. Such massive stockings could have unintended harmful consequences. For example, moving fish from one stream to another could result in loss of geographic genetic differentiation; stocking large numbers of progeny from a few parental fish could also result in reduction of local genetic variation.

  <u>Resources needed:</u> A Lao scientist could complete the genotyping associated with this project at a United States facility; one location could be the United States Fish and Wildlife Service (USFWS) Genetics Lab in Anchorage, Alaska, where technical experts could oversee the work. This project would depend upon appropriate sampling. Ideally, some 50 samples would be taken from several known spawning areas in Laos. Appropriate genetic markers (microsatellite primer sequences) are already available in the published literature (Sukumasavin et al. 2004; Bhassua and Abd Rashid 2009). This project would take one researcher approximately one year.

- **Recommendation 6:** Develop a proactive program to identify spawning areas and spawning season of selected species (for example, *Pangasius* spp.).

  Limited data exist about spatial and temporal spawning of many mainstem and tributary fishes commonly exploited for food in Laos. Existing data on target species should be compiled and systematically planned studies should be developed to collect additional information with the goal of identifying critical spawning areas, timing of spawning, and other relevant data using appropriate techniques (tagging, mark-recapture, telemetry, local ecological knowledge, and fisher surveys).

  <u>Resources needed</u>: These activities can be achieved in a collaborative framework with other organizations (such as MRC and FISHBIO) that are involved in similar efforts.

4.2 Monitoring

A continuous long-term data set is invaluable for assessing population trends and relating any changes to management interventions, environmental stressors, or human impacts, such as changes in fishing regulations, climate change, or hydroelectric dam construction.

- **Recommendation 7:** Establish a long-term monitoring program on the mainstem Mekong River.

The 15-site program that was recently discontinued could be used as the basis for the long-term program, but should be peer reviewed and updated to facilitate standardization of capture data and ensure data quality, both of which are necessary for a robust analysis and inference from catch-per-unit-effort (CPUE) data.

Resources needed: Biologists with expertise in experimental design and analysis of fish stock analysis (especially CPUE) should review the existing protocol used to collect the capture fishery data, as well as the existing database, and provide specific guidance for improvement and enhancement. Such expertise is readily available within DOI or other agencies of the U.S. Government, such as the National Oceanic and Atmospheric Administration (NOAA) Fisheries. LARReC should continue to develop their in-house expertise in database management. The structure and format of the existing database will likely require updating to accommodate changes to the previous sampling protocol and data collected at the 15 sites following peer review. LARReC staff should take a more active role in data collection, via direct sampling, and LARReC may need to acquire sampling equipment (nets, field computers) and supplies (data sheets, vials or filter paper for fin clips). Re-establishing a long-term monitoring program that replaces or builds on the previous 15-site program should be considered a high priority that requires immediate, ongoing attention. Once the sampling design has been established, data collection costs should be low to moderate assuming that fishers will provide in-kind labor by capturing fish and bringing them to a landing area for data collection. Costs may increase if LARReC takes a more active role in acquisition of raw data, such as direct sampling using nets or electrofishing, but this may be an acceptable expense if it helps standardize the dataset and validate capture rates for the local fishers.

Genetic Monitoring

- **Recommendation 8:** Collect baseline information on the genetic structure of selected fish species and develop a fish tissue sample archive to monitor genetic changes over time that occur as a result of fishing, climate change, intentional release of hatchery reared fish, and accidental release from aquaculture facilities.

This would require identifying a group of several species as targets of genetic monitoring to look at within- and between-population genetic structure over time. Samples would have to be collected and archived.

Resources needed: Procedures for collecting, storing, and archiving genetic tissue samples (fin clips, etc.) would ideally involve an electronic database developed with programs such as Microsoft Access. Genetic samples should be stored in a safe place under appropriate supervision and responsibility. The long-term objective is to eventually analyze these samples using appropriate molecular genetic analysis following the protocols developed using the Jullien’s barb.

4.3 Operations and Management

Coordination

- **Recommendation 9:** Invite coordination between Lao ministries and departments to identify fisheries information needs and develop opportunities for collaboration and communication.

With rapid development of hydropower, fisheries, and other natural resources in Laos, the information needs of managers at the department and ministry level are increasing. Establishing a forum for communication among the technical staff at the various natural resource departments could help identify common information needs, reduce the potential for duplication of efforts, encourage information sharing, and facilitate coordinated government fishery research, environmental review, and environmental mitigation activities across the country. The planned Trans-Pacific Fish Passage Conference that LARReC is co-hosting with NUOL in November 2016 would be a good forum for this type of coordination.

- **Recommendation 10:** Establish a forum to coordinate information from nongovernmental fishery research activities in Laos.

There are several fishery research activities ongoing in Laos by NGOs and universities. Establishing a central forum, for example by hosting an annual workshop where researchers can present information on their current and planned activities, would foster communication and increase information exchange among all interested parties.

- **Recommendation 11:** Establish fish passage technical working groups to collaboratively develop and implement fish passage monitoring plans for Xayaburi, Don Sahong, and other planned mainstem dams.

The development of fish passage technical working groups for the mainstem hydropower projects would foster communication and collaboration between the various departments of the Lao Government concerned with fish passage and the developers/operators of the project. The technical working groups could consist of technical staff from the Ministry of Energy and Mines, LARReC, NUOL, other relevant government departments, and the developer/operator of the hydropower project. The technical working groups should identify research and monitoring needs at each project, review the results of the individual monitoring programs, and provide recommendations to managers on ways to optimize fish passage and hydropower production. Regular meetings and coordination through the working groups would enable timely exchange of information and the development of adaptive management principles (Baumgartner et al. 2014), and foster a collaborative approach to achieving sustainable fisheries, hydropower, and flood control.

- **Recommendation 12:** Obtain regulatory approval for LARReC, and other government departments to implement fisheries sampling methods needed for research, monitoring, and evaluation activities.

Fisheries regulations that limit harvest methods and locations are an important management tool for achieving conservation and sustainable harvest goals. Some regulations, however, may limit the ability of LARReC to efficiently conduct important, scientifically-defensible research and monitoring activities. For example, electrofishing, or the use of lee traps, might be the most efficient way to sample and monitor important fish species in some locations. Having a process in place whereby LARReC could seek approval for specific exemptions to harvest regulations for research and monitoring purposes as occur in many other countries would enable LARReC to implement a broader range of research activities.

Outreach and education

- **Recommendation 13:** Establish and maintain a LARReC website.

Rapid and effective dissemination of information using a variety of technological applications is essential for communicating in today's modern digital age. LARReC and NUOL currently provide limited information online about their fishery programs, but this situation could be remedied with relative ease and at low cost. An improved web presence would enhance knowledge about these programs and reach a broader audience, including other government agencies within Laos as well as external governments, NGOs, academic institutions, the general public, and potential collaborators and funding entities.

- **Recommendation 14:** Investigate public education opportunities for LARReC activities and fishery resources.

In addition to developing a dynamic web presence, LARReC and NUOL would benefit by producing and promoting other educational materials to highlight the importance of sustainable fisheries and food security in Laos and throughout the greater Mekong region. Other types of educational materials could include a variety of media that would reach broad audiences, such as posters, traveling exhibits, videos, short television documentaries, billboards, and smartphone applications. Outreach directed to the general public and to youth (through school programs, for example) would have maximum impact by reaching constituents who are under-represented in government and academia, and would motivate more people to pursue education and training in science and natural-resource management.

4.5 Capacity Building

Many of the fisheries issues facing Laos are highly complex, wide-ranging, and long-term in nature. To address these issues, the number of staff with advanced technical and scientific capabilities will likely need to be increased. LARReC and NUOL have collaborated with universities in Australia and other countries, as well as the DOI-ITAP program, to provide scientific and technical assistance. These efforts should continue with the ultimate goal of raising the technical capacity of LARReC staff. A short-term strategy would be to hire outside staff with the desired scientific and technical capabilities. The longer-term strategy should be to continue to educate and train Lao biologists, for example at the bachelor’s and master’s level through NUOL, as well as in advanced degree programs in the United States or other countries. Table 1 lists institutions with respected graduate programs in fish ecology that could serve as templates for curriculum development at NUOL. Representative areas of expertise in other fisheries disciplines are also noted in the table, although most programs are broad based and the diversity of faculty members generally provides many areas of expertise. Although it can be costly, specialized training, even in advance of an identified need to apply that training, may facilitate exposure to new ideas and long-term benefits that justify the investment of financial and other resources. Core training should be emphasized.

Table 1. Sample of institutions of higher learning in the United States with well-recognized graduate programs in fish ecology

Institution	Program/Department	Website	Relevant expertise in other sub-disciplines
Auburn University	Fisheries and Allied Aquacultures	http://www.ag.auburn.edu/fish/	Aquaculture, fish health
University of California (Davis)	Wildlife, Fish and Conservation Biology	http://wfcb.ucdavis.edu/	
Colorado State University	Fish, Wildlife and Conservation Biology	warnercnr.colostate.edu/fwcb-home	Quantitative, human dimensions
University of Florida	Fisheries and Aquatic Sciences	http://sfrc.ufl.edu/fish/	Quantitative, aquatic animal health
Southern Illinois University	Center for Fisheries, Aquaculture and Aquatic Sciences	http://fisheries.siu.edu	Quantitative, aquaculture, physiology, genetics
Louisiana State University	Fisheries and Aquaculture	http://www.rnr.lsu.edu/	Aquaculture, international fisheries
Michigan State University	Fisheries and Wildlife	www.fw.msu.edu	Quantitative, human dimensions
University of Missouri (Columbia)	Fisheries and Wildlife	http://snr.missouri.edu/fw/	Large river ecology
Montana State University	Fish and Wildlife Management and/or Conservation Biology and Ecology Program	www.montana.edu/ecology/fwlprogram.html or www.montana.edu/ecology/cbeprogram.html	Quantitative
Oregon State University	Fisheries and Wildlife	http://fw.oregonstate.edu/content/graduate	Fisheries and wildlife administration
University of Rhode Island	Fisheries, Animal and Veterinary Sciences	http://web.uri.edu/favs/	Aquaculture
Virginia Polytechnic Institute and State University	Fish and Wildlife Conservation	http://www.fishwild.vt.edu/about.htm	Quantitative, human dimensions
University of Washington	Fisheries and Aquatic Sciences	fish.uw.edu	Fish stock assessment, taxonomy and systematics
University of Wisconsin	Fisheries and Water Resources	http://www.uwsp.edu/water/Pages/default.aspx	Hydrology

- **Recommendation 15:** Provide one- to two-week genetic workshops in Laos. DOI-ITAP staff are available to direct these workshops.

- **Recommendation 16:** Provide short- and mid-term genetics training programs for Lao students at U.S. institutions, for example the University of Montana and the USFWS Genetics Lab in Alaska, and potentially in neighboring countries.

- **Recommendation 17:** Develop basic-to-intermediate technical ability in geographic information systems (GIS), databases, and statistical analyses so that LARReC staff can independently collect, organize, archive, and analyze fishery data.

The USFWS National Conservation Training Center (NCTC) offers a suite of week-long courses covering these topics for students with a bachelor's or master's degree. The courses provide conceptual and technical instruction as well as opportunities to learn through practical examples, including the participant's own (or their institution's) datasets. English proficiency is important for participants to derive maximum benefit from the NCTC courses because they tend to be fast paced. The costs are comparatively low, and would include travel and per diem to send participants from Laos to the United States after qualified candidates have been identified.

A series of short-term, Laos-based technical workshops could provide targeted instruction to LARReC staff. Some benefits to this approach are that the training could reach a larger audience within LARReC compared to sending one or a few staff to NCTC courses; the content could be tailored to address topics of direct interest to LARReC; the pace of instruction could be scaled commensurate with students receiving instruction in a second language or translators could be provided, and cooperators from other government ministries (the Department of Livestock and Fisheries, Ministry of Energy and Mines) could also attend. A pool of qualified technical experts is available in the United States through DOI-ITAP (and elsewhere).

- **Recommendation 18:** Develop a strategy to secure funding to support fisheries research and capacity building. As part of this strategy, LARReC should seek to increase its ability to develop research proposals, identify grant and funding opportunities, and apply for funding from appropriate sources.

Works Cited

Achard, F., H.D. Eva, H.J. Stibig, P. Mayaux, J. Gallego, T. Richards and J.P. Malingreau. 2002. Determination of deforestation rates of the world's humid tropical forests. Science 297(5583):999-1002.

Adams, N.S., J.W. Beeman and J.H. Eiler (eds). 2012. Telemetry techniques: a user guide for fisheries research. American Fisheries Society, Bethesda Maryland.

Adamson, E.A.S., D.A. Hurwood, A.M. Baker and P.B. Mather. 2009. Population subdivision in Siamese mud carp *Henicorhynchus siamensis* in the Mekong River basin: implications for management. Journal of Fish Biology, 75, 1371-1392.

Allan, J.D., R. Abell, Z. Hogan, C. Revenga, B.W. Taylor, R.L. Welcomme and K. Winemiller. 2005. Overfishing of inland waters. Bioscience 55(12):1041-1051.

Aquacoustics. 2010. Semi-automated DIDSON data analysis for the assessment of Kenai Chinook salmon. Field manual by Aquacoustics, Sterling, Alaska. http://www.aquacoustics.com/proj_Didson-automation.html (accessed August 2013).

Arias, M.E., T.A. Cochrane, M. Kummu, H. Lauri, G.W. Holtgrieve, J. Koponen and T. Piman**.** 2014. Impacts of hydropower and climate change on drivers of ecological productivity of Southeast Asia's most important wetland. Ecological Modelling 272:252-263.

Bach, H., P. Glennie, R.Taylor, T.J. Clausen, F. Holzwarth, K.M. Jensen, A. Meija and S. Schmeier. 2014. Cooperation for water, energy and food security in transboundary basins under changing climate. Mekong River Commission, Vientiane.

Baird, I.G. 2006. *Probarbus jullieni* and *Probarbus labeamajor*: the management and conservation of two of the largest fish species in the Mekong River in southern Laos. Aquatic Conservation: Marine and Freshwater Ecosystems 16(5):517-532.

Ballard, J.W.O., and M.C. Whitlock. 2004. The incomplete natural history of mitochondria. Molecular Ecology, 13, 729-744.

Baltz, D.M., and P.B. Moyle. 1993. Invasion resistance to introduced species by a native assemblage of California stream fishes. Ecological Applications 3(2):246-255.

Baran, E. 2005. Cambodian inland fisheries: facts, figures and context. WorldFish Center Contribution No. 175. Phnom Penh.

Baran, E. 2006. Fish migration triggers in the Lower Mekong Basin and other tropical freshwater systems. MRC Technical Paper No. 14. Mekong River Commission, Vientiane, 56 p.

Baran, E., I.G. Baird and G. Cans. 2005. Fisheries bioecology at the Khone Falls (Mekong River, southern Laos). WorldFish Center, Penang, Malaysia, 84 p.

Baran, E., and E. Guerin. 2012. Fish bioecology in relation to sediments in the Mekong and in tropical rivers. Report for the Project "A climate resilient Mekong: maintaining the flows that nourish life," Natural Heritage Institute and WorldFish Center, Phnom Penh.

Baran, E., T. Jantunen and C.K. Chong. 2007. Values of inland fisheries in the Mekong River basin. *In:* A.E. Neiland and C. Béné (eds.), Tropical river fisheries valuation: background papers to a global synthesis. WorldFish Center Studies and Reviews No. 31, WorldFish Center, Penang, Malaysia and Phnom Penh.

Baran, E., and C. Myschowoda. 2008. Have fish catches been declining in the Mekong river basin?, p. 55-64. *In:* M. Kummu, M. Keskinen and O. Varis (eds.), Modern myths of the Mekong: a critical review of water and development concepts, principles and policies. Water and Development Publications, Helsinki University of Technology, Helsinki.

Baran, E., and C. Myschowoda. 2009. Dams and fisheries in the Mekong Basin. Aquatic Ecosystem Health and Management 12(3):227-234.

Baran, E., and J. Nasielski. 2011. Reservoir sediment flushing and fish resources. A climate resilient Mekong: maintaining the flows that nourish life. Natural Heritage Institute, San Francisco, California.

Baran, E., N.v. Zalinge and N.P. Bun. 2001. Floods, floodplains and fish production in the Mekong Basin: present and past trends. *In:* A. Ali (ed.), Proceedings of the Second Asian Wetlands Symposium, 27-30 August. Penerbit Universiti Sains Malaysia, Pulau, Penang, Malaysia.

Barlow, C., E. Baran, A.S. Halls and M. Kshatriya. 2008. How much of the Mekong fish catch is at risk from mainstream dam development? Catch and Culture 14(3):15-20.

Baumgartner, L.J., T. Marsden, D. Singhanouvong, O. Phonekhampheng, I.G. Stuart and G. Thorncraft. 2012. Using an experimental in situ fishway to provide key design criteria for lateral fish passage in tropical rivers: a case study from the Mekong river, central Lao PDR River Research and Applications 28(8):1217-1229.

Baumgartner, L., G. Thorncraft, T. Marsden, O. Phonekhampeng, D. Singhanouvong, I. Stewart, and U. Suntomratana. 2010. Development of fish passage criteria for floodplain species of Central Laos. Report by Australian Centre for International Agricultural Research, project numbers FIS/2007/076 and FIS/2006/183.

Baumgartner, L., B. Zampatti, M. Jones, I. Stuart and M. Mallen-Cooper, M. 2014. Fish passage in the Murray-Darling basin, Australia: not just an upstream battle. Ecological Management and Restoration 15:28-39.

Beeman, J.W., A.C. Braatz, H.C. Hansel, S.D Fielding, P.V. Haner, S.G. Hansen, D.J. Shurtleff, J.M. Sprando and D.W. Rondorf. 2010. Approach, passage, and survival of juvenile salmonids at Little Goose Dam, Washington: Post-construction evaluation of a temporary spillway weir, 2009. United States Geological Survey Open-File Report 2010-1224. http://pubs.usgs.gov/of/2010/1224/.

Beeman, J.W., H.C. Hansel, A.C. Hansen, S.D. Evans, P.V. Haner, T.W. Hatton, E.E. Kofoot, J.M. Sprando and C.D. Smith. 2014. Behavior and dam passage of juvenile Chinook salmon and juvenile steelhead at Detroit Reservoir and Dam, Oregon, March 2012-February 2013. United States Geological Survey Open-File Report 2014-1144. http://dx.doi.org/10.3133/ofr20141144.

Bhassu, S., and Z. Abd Rashid. 2009. Molecular and Morphological Approaches in Discrimination of Endangered *Probarbus jullieni* of Malaysia and Thailand Stocks. Animal Genetics, 1092-1097.

Boswell, K.M., M.P. Wilson and J.H. Cowan, Jr. 2008. A semiautomated approach to estimating fish size, abundance, and behavior from dual-frequency identification sonar (DIDSON) data. North American Journal of Fisheries Management 28:799-807.

Bradshaw, C.J.A., N.S. Sodhi and B.W. Brook. 2009. Tropical turmoil: a biodiversity tragedy in progress. Frontiers in Ecology and the Environment 7(2):79-87.

Castro-Santos, T., and A. Haro. 2003. Quantifying migratory delay: a new application of survival analysis methods. Canadian Journal of Fisheries and Aquatic Sciences 60:986-996.

Castro-Santos, T., and A. Haro. 2010. Fish guidance and passage at barriers. p. 62-89. *In:* P. Domenici and B.G. Kapoor (eds.), Fish Locomotion: An Eco-Ethological Perspective, Edited by, Science Publishers, Enfield, New Hampshire, 549 p.

Castro-Santos, T., and R.W. Perry. 2012. Time-to-event analysis as a framework for quantifying fish passage performance. p. 427-452. *In:* N.S. Adams, J.W. Beeman and J.H. Eiler (eds.), Telemetry techniques: a user guide for fisheries research. American Fisheries Society, Bethesda, Maryland.

Catford, J.A., R. Jansson and C. Nilsson. 2009. Reducing redundancy in invasion ecology by integrating hypotheses into a single theoretical framework. Diversity and distributions 15(1):22-40.

Coates, D. 2002. Inland capture fishery statistics of southeast Asia: current status and information needs. Asia-Pacific Fishery Commission, Bangkok. RAP Publication 2002/11:1-114.

Coates, D., P. Ouch, U. Suntornratana and N.T. Tung. 2003. Biodiversity and fisheries in the Lower Mekong Basin. Mekong Development Series No. 2, Mekong River Commission. Phnom Penh.

Cochrane, K., C. De Young, D. Soto and T. Bahri (eds.). 2009. Climate change implications for fisheries and aquaculture: overview of current scientific knowledge. FAO Fisheries and Aquaculture Technical Paper 530. Rome, 212 p.

Connolly, P.J., I.G. Jezorek, K.D. Martens and E.F. Prentice. 2008. Measuring the performance of two stationary interrogation systems for detecting downstream and upstream movement of PIT-tagged salmonids. North American Journal of Fisheries Management 28:402-407. Available at http://dx.doi.org/10.1577/M07-008.1.

Cowx, I.G., W. Kamonrat, N. Sukumasavin, R. Sirimongkolthawon, S. Suksri and N. Phila. 2015. Larval and Juvenile Fish Communities of the Lower Mekong Basin. MRC Technical Paper No. 49. Mekong River Commission, Phnom Penh. 100 p. ISSN: 1683-1489.

Cumberlidge, N., P.K.L. Ng and D.C.J. Yeo. 2012. Freshwater crabs of the Indo-Burma hotspot: diversity, distribution, and conservation, p. 102-113. *In:* D.J. Allen, K.G. Smith and W.R.T. Darwall (eds.), The status and distribution of freshwater biodiversity in Indo-Burma. International Union for Conservation of Nature, Cambridge, United Kingdom and Gland, Switzerland.

Dao, H.G., T. Kunpradid, C. Vongsombath, T.B.L. Do and S. Prum. 2010. Report on the 2008 biomonitoring survey of the lower Mekong River and selected tributaries. MRC Technical Paper No. 27. Mekong River Commission, Vientiane, 69 p.

Dudgeon, D. 1992. Endangered ecosystems: a review of the conservation status of tropical Asian rivers. Hydrobiologia 248(3):167-191.

Dudgeon, D. 1999. Tropical Asian streams: zoobenthos, ecology and conservation. Hong Kong University Press, Hong Kong, China. 830 p.

Dudgeon, D. 2011. Asian river fishes in the Anthropocene: threats and conservation challenges in an era of rapid environmental change. Journal of Fish Biology 79(6):1487-1524.

Dudgeon, D. 2012. Threats to freshwater biodiversity globally and in the Indo-Burma biodiversity hotspot, p. 1-28. *In:* D.J. Allen, K.G. Smith and W.R.T. Darwall (eds.), The status and distribution of freshwater biodiversity in Indo-Burma. International Union for Conservation of Nature, Cambridge, United Kingdom and Gland, Switzerland.

Dudgeon, D., A.H. Arthington, M.O. Gessner, Z.I. Kawabata, D.J. Knowler, C. Lévêque, R.J. Naiman, A.H. Prieur-Richard, D. Soto and M.L.J. Stiassny. 2006. Freshwater biodiversity: importance, threats, status and conservation challenges. Biological Reviews 81(2):163-182.

Dugan, P. 2008. Mainstream dams as barriers to fish migration: international learning and implications for the Mekong. Catch and Culture 14(3): 9-15. Mekong River Commission, Vientiane.

Dugan, P.J., C. Barlow, A.A. Agostinho, E. Baran, G.F. Cada, D.Q. Chen, I.G. Cowx, J.W. Ferguson, T. Jutagate, M. Mallen-Cooper, G. Marmulla, J. Nestler, M. Petrere, R.L. Welcomme and K.O. Winemiller. 2010. Fish migration, dams, and loss of ecosystem services in the Mekong Basin. Ambio 39(4):344-348.

Eastham, J., F. Mpelasoka, M. Mainuddin, C. Ticehurst, P. Dyce, G. Hodgson, R. Ali and M. Kirby. 2008. Mekong river basin water resources assessment: impacts of climate change. CSIRO: Water for a Healthy Country Flagship Report Series ISSN:1835-095X, National Research Flagship, Canberra.

Elton, C.S. 1958. The ecology of invasions by animals and plants. The University of Chicago Press, Chicago, Illinois. 181 p.

Enders, E.C., M.H. Gessel and J.G. Williams. 2009. Development of successful fish passage structures for downstream migrants requires knowledge of their behavioral responses to accelerating flow. Canadian Journal of Fisheries and Aquatic Sciences 66:2109-2117.

Eschmeyer, W.N., and R. Fricke. 2016. Catalog of fishes: genera, species, references. http://research.calacademy.org/redirect?url=http://researcharchive.calacademy.org/research/ichthyology/catalog/fishcatmain.asp.

Fausch, K.D., Y. Taniguchi, S. Nakano, G.D. Grossman and C.R. Townsend. 2001. Flood disturbance regimes influence rainbow trout invasion success among five holarctic regions. Ecological Applications 11(5):1438-1455.

FERC (Federal Energy Regulatory Commission). 2004. Evaluation of mitigation effectiveness at hydropower projects: Fish passage. Office of Energy Projects, Washington, D.C.

Ferguson, J.W., R.F. Absolon, T.J. Carlson and B.J. Sanford. 2006. Evidence of delayed mortality on juvenile Pacific salmon passing through turbines at Columbia River dams. Transactions of the American Fisheries Society 135:139-150.

Ferguson, J.W., M. Healey, P. Dugan and C. Barlow. 2011. Potential effects of dams on migratory fish in the Mekong River: lessons from salmon in the Fraser and Columbia rivers. Environmental Management 47(1):141-159.

Ficke, A.D., C.A. Myrick and L.J. Hansen. 2007. Potential impacts of global climate change on freshwater fisheries. Reviews in Fish Biology and Fisheries 17(4):581-613.

Giam, X.L., T.H. Ng, V. Yap and H.T.W. Tan. 2010. The extent of undiscovered species in Southeast Asia. Biodiversity and Conservation 19(4):943-954.

Gosling, S.N., R.G. Taylor, N.W. Arnell and M.C. Todd. 2011. A comparative analysis of projected impacts of climate change on river runoff from global and catchment-scale hydrological models. Hydrology and Earth System Sciences 15(1):279-294.

Ha, H.P., T.T.T. Nguyen, S. Poompuang and U. Na-Nakorn. 2009. Microsatellites revealed no genetic differentiation between hatchery and contemporary wild populations of striped catfish, *Pangasianodon hypothalamus* (Sauvage 1878) in Vietnam. Aquaculture, 291, 154-160.

Halls, A.S., I. Conlan, W. Wisesjindawat, K. Phouthavongs, S. Viravong, S. Chan and V.A. Vu. 2013a. Atlas of deep pools of the lower Mekong River and some of its tributaries. MRC Technical Paper No. 31, Mekong River Commission, Phnom Penh, 69 p.

Halls, A.S., and M. Kshatriya. 2009. Modelling the cumulative barrier and passage effects of mainstream hydropower dams on migratory fish populations in the Lower Mekong Basin. MRC Technical Paper No. 25. Mekong River Commission, Vientiane, 104 p.

Halls, A.S., B.R. Paxton, B.R., N. Hall, N., K.G. Hortle, N. So, T. Chea, P. Chheng, S. Putrea, S. Lieng, N. Peng Bun, N. Pengby, S. Chan, V.A. Vu, N.D. Nguyen, V.T. Doan, V. Sinthavong, S. Douangkham, S. Vannaxay, S. Renu, U. Suntornratana, T. Tiwarat and S. Boonsong. 2013b. Integrated analysis of data from MRC fisheries monitoring programmes in the lower Mekong basin. MRC Technical Paper No. 33. Mekong River Commission, Phnom Penh, 130 p.

Helfman, G.S. 2007. Chapter 6: Dams, impoundments, and other hydrological alterations, p. 130-157. *In:* G.S. Helfman (ed.), Fish conservation: a guide to understanding and restoring global aquatic biodiversity and fishery resources. Island Press, Washington, D.C.

Hightower, J.E., K.J. Magowan, L.M. Brown and D.A. Fox. 2013. Reliability of fish size estimates obtained from imaging sonar. Journal of Fish and Wildlife Management 4:86-96; e1944-687X. doi: 10.3996/102011-JFWM-061.

Hogan, Z., and B.P. May. 2002. Twenty-seven new microsatellites for the migratory Asian catfish family Pangasiidae. Molecular Ecology Notes, 2, 38-41.

Huang, Y., F.Y. Wang, Y. Li and T.J. Cai**.** 2014. Multi-model ensemble simulation and projection in the climate change in the Mekong River Basin. Part I: temperature. Environmental Monitoring and Assessment 186(11):7513-7523.

Hurwood, D.A., E.A.S. Adamson and P.B. Mather. 2008. Evidence for strong genetic structure in a regionally important, highly vagile cyprinid (*Henicorhynchus lobatus*) in the Mekong River Basin. Ecology of Freshwater Fish, 17, 273-283.

Hosmer, D.W., and S. Lemeshow. 1999. Applied survival analysis—Regression modeling of time to event data. Wiley, New York.

ICEM Australia (International Center for Environmental Management). 2010. MRC Strategic Environmental Assessment (SEA) of hydropower development on the Mekong mainstream, Hanoi. Glen Iris, Victoria, Australia.

IPCC (International Panel on Climate Change). Core Writing Team: R.K. Pachauri and L.A. Meyer. 2014. Synthesis report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change.

IUCN (International Union for Conservation of Nature). 2013. Ecological survey of the Mekong River between Louangphabang and Vientiane cities, Lao PDR. IUCN, Vientiane, 239 p.

Jonduang, A., P. Sangthong and R. Zardoya. 2007. The complete mitochondrial DNA sequence of the Mekong giant catfish (*Pangasianodon gigas*), and the phylogenetic relationships among Siluriformes. Gene, 387, 49-57.

Kang, B., D.M. He, L. Perrett, H.Y. Wang, W.X. Hu, W.D. Deng and Y.F. Wu. 2009. Fish and fisheries in the Upper Mekong: Current assessment of the fish community, threats and conservation. Reviews in Fish Biology and Fisheries 19(4):465-480.

Keskinen, M., S. Chinvanno, M. Kummu, P. Nuorteva, A. Snidvongs, O. Varis and K. Vastila. 2010. Climate change and water resources in the Lower Mekong River Basin: putting adaptation into the context. Journal of Water and Climate Change 1(2):103-117.

Kingston, D.G., J.R. Thompson and G. Kite. 2011. Uncertainty in climate change projections of discharge for the Mekong River Basin. Hydrology and Earth System Sciences 15(5):1459-1471.

Köhler, F., M. Seddon, A.E. Bogan, D.V. Tu, P. Sri-Aroon and D. Allen. 2012. The status and distribution of freshwater molluscs of the Indo-Burma region, p. 66-89. *In:* D.J. Allen, K.G. Smith and W.R.T. Darwall (eds.), The status and distribution of freshwater biodiversity in Indo-Burma. International Union for Conservation of Nature, Cambridge, United Kingdom and Gland, Switzerland.

Kottelat, M. 2000. Diagnoses of a new genus and 64 new species of fishes from Laos (Teleostei: Cyprinidae, Balitoridae, Bagridae, Syngnathidae, Chaudhuriidae and Tetraodontidae). Journal of South Asian Natural History 51(1):37-82.

Kottelat, M. 2001. Fishes of Laos. WTE Publications (Pte) Ltd., Colombo, Sri Lanka. 198 p.

Kottelat, M. 2013. The fishes of the inland waters of southeast Asia: a catalogue and core bibliography of the fishes known to occur in freshwaters, mangroves and estuaries. Raffles Bulletin of Zoology suppl. 27:1-663.

Kottelat, M., I.G. Baird, S.O. Kullander, H.H. Ng, L.R. Parenti, W.J. Rainboth and C. Vidthayanon. 2012. The status and distribution of freshwater fishes of Indo-Burma, p. 38-65. *In:* D.J. Allen, K.G. Smith and W.R.T. Darwall (eds.), The status and distribution of freshwater biodiversity in Indo-Burma. International Union for Conservation of Nature, Cambridge, United Kingdom and Gland, Switzerland. 158 p.

Kottelat, M., and T. Whitten. 1996. Freshwater biodiversity in Asia: with special reference to fish. World Bank Technical Paper No. 343, Washington, D.C.

Kummu, M., X.X. Lu, J.J. Wang and O. Varis. 2010. Basin-wide sediment trapping efficiency of emerging reservoirs along the Mekong. Geomorphology 119(3-4):181-197.

Lansdown. 2012. The conservation of aquatic and wetland plants in the Indo-Burma region, p. 114-133. *In:* D.J. Allen, K.G. Smith and W.R.T. Darwall (eds.), The status and distribution of freshwater biodiversity in Indo-Burma. International Union for Conservation of Nature, Cambridge, United Kingdom and Gland, Switzerland. 158 p.

Lazarus, K., P. Dubeau, C. Bambaradeniya, R. Friend and L. Sylavong. 2006. An uncertain future: Biodiversity and livelihoods along the Mekong River in northern Lao PDR. IUCN, Bangkok and Gland, Switzerland, 49 p.

Liedtke, T.L., L.P Gee and J.W. Beeman. 2012. A standard operating procedure for the surgical implantation of transmitters in juvenile salmonids. United States Geological Survey Open File Report 2012-1267. http://pubs.usgs.gov/of/2012/1267.

Light, T., and M.P. Marchetti. 2007. Distinguishing between invasions and habitat changes as drivers of diversity loss among California's freshwater fishes. Conservation Biology 21(2):434-446.

Lockwood, J.L., P. Cassey and T. Blackburn. 2005. The role of propagule pressure in explaining species invasions. Trends in Ecology and Evolution 20(5):223-228.

Manh, N.V., N.V. Dung, N.N. Hung, B. Merz and H. Apel. 2014. Large-scale suspended sediment transport and sediment deposition in the Mekong Delta. Hydrology and Earth System Sciences 18(8):3033-3053.

Marsden, T., M. Moore, A. O'Brien, J. McPherson, L. Baumgartner, C. Peterken and G. Thorncraft. 2014. Prioritising barriers to upstream fish passage for remediation works: Xe Champhone Catchment, Lao PDR. Unpublished report, Australasian Fish Passage Services, 49 p.

Martins da Silva, L.M., L.B. Nogueira, B.P. Maia and L. Borges de Resende. 2012. Fish passage post-construction issues: analysis of distribution, attraction and passage efficiency metrics at Baguari Dam fish ladder to approach the problem. Neotropical Ichthyology 10(4):751-762.

McMichael, G.A., M.B. Eppard, T.J. Carlson, J.A. Carter, B.D. Ebberts, R.S. Brown, M. Weiland, G.R. Ploskey, R.A. Harnish and Z.D. Deng. 2010. The juvenile salmon acoustic telemetry system—A new tool. Fisheries 35:9-22.

Moyle, P.B., and T. Light. 1996. Biological invasions of fresh water: empirical rules and assembly theory. Biological Conservation 78(1):149-161.

MRC-TAB (Mekong River Commission, Technical Advisory Body). 2005. Deep pools as dry season habitats in the Mekong River basin. Mekong Fisheries Management Recommendation No. 3. Mekong River Commission, Vientiane, 7 p.

MRC-TAB (Mekong River Commission, Technical Advisory Body for Fisheries Management). 2007. Fish migration triggers the lower Mekong basin. Mekong Fisheries Management Recommendation No. 6. Mekong River Commission, Vientiane.

MRC (Mekong River Commission). 2008a. Biomonitoring of the lower Mekong River and selected tributaries, 2004-2007. MRC Technical Paper No. 20. Mekong River Commission, Vientiane, 77 p.

MRC (Mekong River Commission). 2008b. An assessment of water quality in the Lower Mekong Basin. MRC Technical Paper No. 19. Mekong River Commission, Vientiane, 70 p.

MRC (Mekong River Commission). 2010. Biomonitoring methods for the Lower Mekong Basin. Vientiane, 65 p.

MRC (Mekong River Commission) Secretariat. 2011. Prior consultation project review report, proposed Xayaburi Dam project-Mekong River. Phnom Penh, 99 p.

Na-Nakorn, U., K. Sriphairoj, S. Sukmanomon, S. Poompuang and K. Kamonrat. 2006a. Polymorphic microsatellite primers developed from DNA of the endangered Mekong giant catfish, *Pangasianodon gigas* (Chevey) and cross-species amplification in three species of Pangasius. Molecular Ecology Notes, 6, 1174-1176.

Na-Nakorn, U., S. Sukmanomon, M. Nakajima, N. Taniguchi, W. Kamonrat, S. Poompuang and T.T.T. Nguyen. 2006b. MtDNA diversity of the critically endangered Mekong giant catfish (*Pangasianodon gigas* Chevey, 1913) and closely related species: implications for conservation. Animal Conservation, 9, 483-494.

Na-Nakorn, U., S. Sukmanomon, S. Poompuang, P. Saelim, N. Taniguchi and M. Nakajima. 2009. Genetic diversity of the Vulnerable *Pangasius sanitwongsei* using Microsatellite DNA and 16S rRNA. Kasetsart University Fisheries Research Bulletin 33(2):24-40.

NAFRI (National Agriculture and Forestry Research Institute). 2004. Strategic plan 2005-2010. Lao Ministry of Agriculture and Forestry, National Agriculture and Forestry Research Institute.

NAFRI (National Agriculture and Forestry Research Institute). 2015. Agriculture and Forestry Research Strategy 2015 and Vision up to 2030. Lao Ministry of Agriculture and Forestry, NAFRI, http://web.nafri.org.la/index.php/en/2014-03-25-07-05-49/nafri-stratgic-plan.

Ngamsiri, T., M. Nakajima, S. Sukanomon, N. Sukumasavin, W. Kamonrat, U. Na-Nakorn and N. Taniguchi. 2007. Genetic diversity of wild Mekong giant catfish *Pangasianodon gigas* collected from Thailand and Cambodia. Fisheries Science, 73, 792-799.

Ngamsiri, T., Y. Ohashi, N. Sukumasavin, M. Nakajima, U. Na-Nakorn and N. Taniguchi. 2006. Characterization of microsatellite DNA markers in a critically endangered species Mekong giant catfish, *Pangasianodon gigas*. Molecular Ecology Notes, 6, 313–315.

Office of Technology Assessment (OTA). 1995. Fish passage technologies: protection at hydropower facilities. OTA-ENV-641 U.S. Government Printing Office, Washington, D.C.

Ohashi, Y., M. Nakajima, N. Sukumasavin, U. Na-Nakorn and N. Taniguchi. 2006. Isolation and characterization of microsatellite DNA markers in endangered Mekong giant catfish *Pangasianodon gigas*. Fisheries Science, 72, 1066-1071.

Phomikong, P., M. Fukushima, B. Sricharoendham, S. Nohara and T. Jutagate. 2014. Diversity and community structure of fishes in regulated versus unregulated tributaries of the Mekong River. River Research and Applications DOI: 10.1002/rra.2816.

Phonvisay, A. 2005. In institutional analysis of LARReC on economic and market-related research. Unpublished Master of Applied Science, University of Sydney, Sydney, Australia. 88 p.

Phonvisay, S. 2013. An introduction to the fisheries of Lao PDR. Mekong River Commission, Mekong Development Series No. 6:1-62.

PIT Tag Steering Committee. 2014. PIT tag marking procedures manual. Pacific States Marine Fisheries Commission, Portland, Oregon. Available at http://www.ptagis.org/resources/document-library/ptagis-program-documents

Poulsen, A.F., K.G. Hortle, J. Valbo-Jorgensen, S. Chan, C.K. Chhuon, S. Viravong, K. Bouakhamvongsa, U. Suntornratana, N. Yoorong, T.T. Nguyen and B.Q. Tran. 2004. Distribution and ecology of some important riverine fish species of the Mekong River basin. MRC Technical Paper No. 10. Mekong River Commission, Phnom Penh, 116 p.

Poulsen, A.F., O. Poeu, S. Viravong, U. Suntornratana and N.T. Tung. 2002a. Deep pools as dry season fish habitats in the Mekong River basin. MRC Technical Paper No. 4. Mekong River Commission, Phnom Penh, 22 p.

Poulsen, A.F., O. Poeu, S. Viravong, U. Suntornratana and N.T. Tung. 2002b. Fish migrations of the Lower Mekong River Basin: implications for development, planning and environmental management. MRC Technical Paper No. 8. Mekong River Commission, Phnom Penh, 62 p.

Poulsen, A.F., and J. Valbo-Jorgensen. 2000. Fish migrations and spawning habits in the Mekong mainstream: a survey using local knowledge (basinwide). Assessment of Mekong Fisheries: Fish Migrations and Spawning and the Impact of Water Management Project. AMFC Technical Report, Mekong River Commission, Vientiane.

Pouyaud, L., G.G. Teugels, R. Gustiano and M. Legendre. 2000. Contribution to the phyogeny of Pangasiis catfishes based on allozymes and mitochondrial DNA. Journal of Fish Biology, 56, 1509-1538.

Pukinskis, I. 2013. Mekong sediment basics. State of Knowledge Series 2, CGIAR Challenge Program on Water and Food. Vientiane, 6 p.

Rahel, F.J. 2002. Homogenization of freshwater faunas. Annual Review of Ecology and Systematics 33:291-315.

Rainboth, W.J., C. Vidthayanon and M.D. Yen. 2012. Fishes of the greater Mekong ecosystem with species list and photographic atlas. Museum of Zoology, University of Michigan, Miscellanous Publications No. 201, 294 p.

Reels, G., R. Dow, M. Hämäläinen and D.M. Cuong. 2012. The status and distribution of dragonflies and damselflies (Odonata) in the Indo-Burma region, p. 90-101. *In:* D.J. Allen, K.G. Smith and W.R.T. Darwall (eds.), The status and distribution of freshwater biodiversity in Indo-Burma. International Union for Conservation of Nature, Cambridge, United Kingdom and Gland, Switzerland.

Roberts, T.R., and I.G. Baird. 1995. Traditional fisheries and fish ecology on the Mekong River at Rhone waterfalls in southern Laos. Natural History Bulletin of the Siam Society 43:219-262.

Roscoe, D.W., and S.G. Hinch. 2010. Effectiveness monitoring of fish passage facilities: historical trends, geographic patterns and future directions. Fish and Fisheries 11:12-33.

Schindler, D.W. 2001. The cumulative effects of climate warming and other human stresses on Canadian freshwaters in the new millennium. Canadian Journal of Fisheries and Aquatic Sciences 58(1):18-29.

Shrestha, B., M.S. Babel, S. Maskey, A. van Griensven, S. Uhlenbrook, A. Green and I. Akkharath. 2013. Impact of climate change on sediment yield in the Mekong River basin: a case study of the Nam Ou basin, Lao PDR. Hydrology and Earth System Sciences 17(1):1-20.

Skalski, J.R., R. Townsend, J. Lady, A.E. Giorgi, J.R. Stevenson and R.S. McDonald. 2002. Estimating route-specific passage and survival probabilities at a hydroelectric project from smolt radiotelemetry studies. Canadian Journal of Fisheries and Aquatic Sciences 59:1385-1393.

So, N., G.E. Maes and F.A.M. Volckaert. 2006a. High genetic diversity in cryptic populations of the migratory sutchi catfish *Pangasianodon hypophthalmus* in the Mekong River. Heredity, 96, 166-174.

So, N., G.E. Maes and F.A.M. Volckaert. 2006b. Intra-annual genetic variation in the downstream larval drift of sutchi catfish (*Pangasianodon hypophthalmus*) in the Mekong River. Biological Journal of the Linnean Society, 89, 719-728.

So, N., J.K.J. Van Houdt and F.A.M. Volckaert. 2006c. Genetic diversity and population history of the migratory catfishes *Pangasianodon hypophthalmus* and *Pagasius bocourti* in the Cambodia Mekong River. Fisheries Science, 72, 469-476.

Souvannaphanh, B., S. Chanphendxay and X. Choulamany. 2003. Status of inland fisheries statistics in Lao PDR, p. 27-32. *In:* T. Clayton, S. Funge-Smith, D. Bartley and C. Barlow (eds.), New approaches for the improvement of inland capture fishery statistics in the Mekong basin. FAO (Food and Agriculture Organization of the United Nations), MRC (Mekong River Commission), Government of Thailand, Government of the Netherlands, RAP Publication 2003/01, Udon Thani, Thailand.

Strayer, D.L., and D. Dudgeon. 2010. Freshwater biodiversity conservation: recent progress and future challenges. Journal of the North American Benthological Society 29(1):344-358.

Strong, E.E., O. Gargominy, W.F. Ponder and P. Bouchet. 2008. Global diversity of gastropods (Gastropoda; Mollusca) in freshwater. Hydrobiologia 595(1):149-166.

Sukumasavin, N., M. Nakajima and N. Taniguchi. 2004. Identification and Characterization of Microsatellite DNA Markers Developed in an Endangered Cyprinid of the Mekong River, the Seven Line Barb (*Probarbus jullieni*). Molecular Ecology Notes, 4, 465-467.

Sverdrup-Jensen, S. 2002. Fisheries in the lower Mekong basin: status and perspectives. MRC Technical Paper No. 6. Mekong River Commission, Phnom Penh, 103 p.

Takagi, A.P., S. Ishikawa, T. Nao, S. Hort, M. Nakatani, M. Nishida and H. Kurokura. 2006. Genetic differentiation of the bronze featherback *Notopterus notopterus* between Mekong River and Tonle Sap Lake populations by mitochondrial DNA analysis. Fisheries Science, 72, 750-754.

Takagi A.P., S. Ishikawa, T. Nao, S.L. Song, S. Hort, K. Thammavong, B. Saphakdy, A. Phomsouvanhm, M. Nishida and H. Kurokura. 2011. Population structure of the climbing perch, *Anabas testudineus*, in the lower Mekong River basin. Fisheries Management and Ecology, 18, 145-153.

Takagi A.P., S. Ishikawa, T. Nao, S.L. Song, S. Hort, K. Thammavong, B. Saphakdy, A. Phomsouvanhm, M. Nishida and H. Kurokura. 2011. Genetic differentiation of *Macrognathus siamensis* within the Mekong River between Laos and Cambodia. Journal of Applied Ichthyology, 27, 1150-1154.

USAID (U.S. Agency for International Development). 2013. USAID Mekong ARCC climate change impact and adaptation study for the Lower Mekong Basin: main report. Bangkok (available online at www.mekongarcc.net/resource), 279 p.

USAID (U.S. Agency for International Development). 2014. USAID Mekong ARCC climate change impact and adaptation study for the Lower Mekong Basin on fisheries. Bangkok (available online at www.mekongarcc.net/resource), 147 p.

Valbo-Jorgensen, J., and A.F. Poulsen. 2000. Using local knowledge as a research tool in the study of river fish biology: experiences from the Mekong. Environment, Development and Sustainability 2(3-4):253-376.

Valbo-Jorgensen, J., D. Coates and K. Hortle. 2009. Fish diversity on the Mekong River Basin, p. 161-196. *In:* I.A. Campbell (ed.), The Mekong: Biophysical environment of an international river. Academic Press, New York.

Wang, J.J., X.X. Lu and M. Kummu. 2011. Sediment load estimates and variations in the lower Mekong River. River Research and Applications 27(1):33-46.

Weber, M.J., and M.L. Brown. 2009. Effects of common carp on aquatic ecosystems 80 years after "carp as a dominant": ecological insights for fisheries management. Reviews in Fisheries Science 17(4):524-537.

Welcomme, R., and C. Vidthayanon. 2003. The impacts of introductions and stockings of exotic species in the Mekong basin and policies for their control. MRC Technical Paper No. 9. Mekong River Commission, Phnom Penh, 38 p.

Zalinge, N.v., P. Degen, C. Pongsri, S. Nuov, J.G. Jensen, V.H. Nguyen and X. Choulamany. 2004. The Mekong River system, p. 335-357. *In:* R. Welcomme and T. Peter (eds.), Proceedings of the second international symposium on the management of large rivers for fisheries, vol. 1, FAO Regional Office for Asia and the Pacific, Bangkok. RAP Publication 2004/16.

Zalinge, N.v., L. Sopha, N.P. Bun, H. Kong and J.V. Joergensen. 2002. Status of the Mekong *Pangasianodon hypophthalmus* resources, with special reference to the stock shared between Cambodia and Viet Nam. MRC Technical Paper No. 1. Mekong River Commission, Phnom Penh, 29 p.

Ziv, G., E. Baran, S. Nam, I. Rodriguez-Iturbe and S.A. Levin. 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. Proceedings of the National Academy of Sciences of the United States of America 109(15):5609-5614.

Zydelewski, G.B., G. Horton, T. Dubreuil, B. Letcher, S. Casey and J. Zydelewski. 2006. Remote monitoring of fish in small streams. Fisheries 31(10): 492-502.

Appendix 1. Design and Evaluation of Fish Passes

Fish passes have been evaluated using a variety of methods, but the most useful go beyond simply quantifying fish using the devices by identifying mechanisms of success or failure. In a review of fish pass assessments, Roscoe and Hinch (2010) noted which assessments answered one or more questions, including efficiency (how well they work), mechanisms (why they do or do not work), consequences (impacts to fish or people dependent on them), and fish physiology (to help explain problems). In addition, Castro-Santos and Haro (2003) suggested the use of time-to-event analytical methods (also called survival analysis) to study the timing and rates of passage. Time-to-event methods are uniquely suited to analyses of fish passage, because they were designed to deal with the issues of skewness and censoring typical in data based on the timing of events (Hosmer and Lemeshow 1999). The methods also incorporate the number at risk of an event (how many fish are available for a passage event) which scales the estimates by the numbers available for an event (the “risk set”). Castro-Santos and Haro (2003) also noted the broad applicability of these methods, which are often used for evaluations of drug treatments in human medicine.

The following theoretical example illustrates the benefit of basing inferences on a risk set: suppose the efficiencies of two prototype downstream passage systems (designs A and B) at Pak Peung wetland are being measured by counting fish numbers passing downstream at the fishway exits. The results show that fishway design A had twice the number of fish exiting than fishway design B. Now consider the number of fish near the upstream side of the fishways during the tests (these are the risk sets, or number of subjects available for a passage event). Suppose that during the tests there were two times as many fish at the upstream side of design A as there were at design B. Passage efficiency is the number passing divided by the number available to pass, thus, design B is equal to design A. This example shows the need to account for the risk set to evaluate the efficiency of each design. Castro-Santos and Perry (2012) provide a more detailed description and example of this important topic.

Determining the mechanisms of passage success or failure is also aided by assessing the timing and rates of passage by zones such as areas nearby a fish pass entrance or those near, within, and downstream from a passage route (Sweeney et al. 2007, Castro-Santos and Haro 2010; Figure 2). These types of analytical methods can be very useful in measuring passage efficiency, and also in diagnosing migration and passage problems, quantifying factors affecting passage rates, and providing science-based solutions (Castro-Santos and Perry 2012). Dividing the study area into logical zones is also useful for defining and estimating passage parameters for different risk sets, such as those available to enter a reservoir or to pass the dam once near it (see Beeman et al. 2010 and 2014 for examples).

Appendix 2. Fish Marking and Monitoring

Rigorous evaluations of fish passage depend on knowing the movements of individual fish. This is commonly accomplished using uniquely coded passive or active tags affixed to the animal, using passive integrated transponder (PIT) tags and active tags (radio or acoustic telemetry). Other means are also used to a lesser extent, ranging in complexity from Floy tags, to tags communicating with satellites, to genetic markers.

Information about fish monitoring methods can be obtained through peer-reviewed literature, reports, and books, as well as at meetings, such as the International Conference on Fish Telemetry (http://2015icft.org/). It can be beneficial to attend conferences with tagging and tracking workshops. Most meetings and peer-reviewed literature are in English, so the ability to understand both spoken and written English is important when accessing these resources. The literature on these topics is extensive and many resources are accessible online. Some examples include literature about fish marking techniques (Liedtke et al. 2012, PIT Tag Steering Committee 2014), animal telemetry systems (Zydelewski et al. 2006, Connolly et al. 2008, Adams et al. 2012, Hightower et al. 2013) and experimental design and analysis (Hosmer and Lemeshow 1999, Skalski et al. 2002). The book Telemetry Techniques published by the American Fisheries Society contains useful information about many aspects of radio and acoustic telemetry methods and was written as a guide for those applying the tools in research studies (Adams et al. 2012).

There are a variety of commercial sources of animal telemetry equipment including passive and active systems and acoustic cameras. PIT tags are a passive telemetry system, as the power to send the tag transmission resides with the detection system rather than the tag. PIT tags, antennas and tag readers are manufactured by several companies, including Biomark (www.biomark.com) and Oregon RFID (www.oregonrfid.com). PIT equipment operates in a half-duplex mode or a full-duplex mode, with some antennas available to monitor both types. Half duplex systems have a larger read range and simpler antenna design than full duplex systems, but generally have larger tags and slower read responses (See http://www.oregonrfid.com/index.php?main_page=page&id=31). Researchers can construct economical pass-through and pass-over antennas (Figure A1) (Zydelewski et al. 2006).

PIT tags have the advantages of small size (commonly 12 mm long, but other sizes are available), low tag cost (approximately US$4 or 34,000 Kip), long life (unlimited), and a large number of unique codes. The primary disadvantage is a short read range (several centimeters to about a meter, depending on the tag size, system type and tag orientation).

Figure A1. Economical pass-through (left) and pass-over (middle and right) full duplex PIT tag antennas

Note: Antennas constructed by DOI researchers. Antennas not visible in the photo on the right due to turbid water. Photo credit: Brian Hayes and John Beeman, United States Geological Survey.

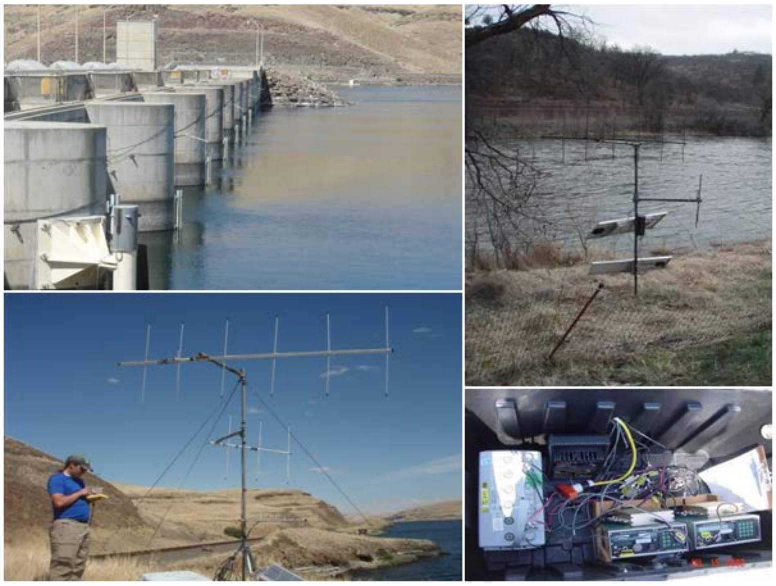
Active telemetry systems carry their own power sources and include radio and acoustic types (Adams et al. 2012). Radio telemetry operates with transmission frequencies in the range of 30 to about 200 million Hertz (MHz) whereas acoustic telemetry operates at frequencies between about 69 and 400 thousand Hertz (kHz). The advantages of radio telemetry include the transmission of signals through water, the water-air interface, and the air; detecting transmissions in the air is often much easier than using underwater equipment. Nevertheless, there are disadvantages to using radio telemetry. A trailing tag antenna is typically required and transmission through water depends on the water conductivity (which is best in shallow fresh water). Finally, the cost of radio telemetry systems is high.

Acoustic telemetry functions without an antenna and is better able to transmit signals through water (much less dependent on conductivity than radio frequencies). Yet acoustic systems are unable to pass the water-air interface and are sensitive to ambient low-frequency noise and reflected signals. Acoustic telemetry also carries a high system cost.

Both active systems rely on batteries in the tags to power their transmissions and tag life is a tradeoff between strength of the transmitted signal, how often the transmissions are made, and tag size. There is some advantage in size, life, and tag weight for acoustic telemetry over radio telemetry, but in most cases the tags are of similar dimensions for a given tag life. The smallest radio or acoustic tags used for fishery research currently weigh a few hundred milligrams in air.

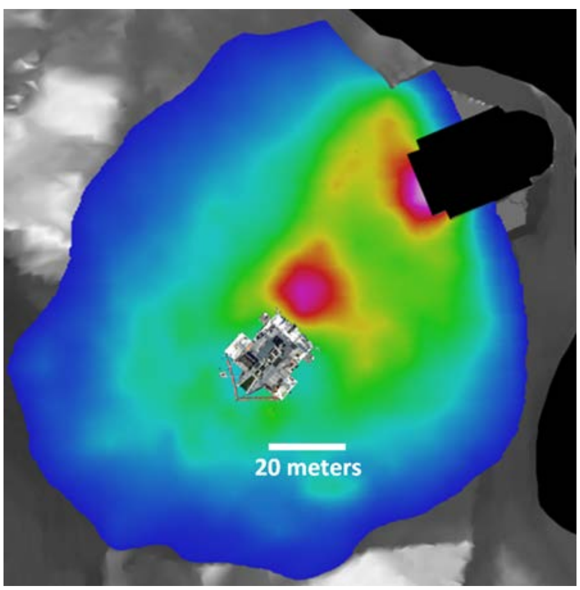
Tags of both types of active systems cost about US$200–US$500 and detection systems commonly cost several thousand dollars per receiver and often require many receivers. Radio and acoustic telemetry systems are very complex and are usually purchased from commercial vendors. Both automated and manually-operated systems are common (Figure A2). A summary of fish position data from an acoustic telemetry system is shown in Figure A3. Common vendors of fishery telemetry systems include (in alphabetical order) Advanced Telemetry Systems (www.atstrack.com), HTI (www.htisonar.com), Lotek Wireless (www.lotekwireless.com), Sigma Eight (www.sigmaeight.ca), Sonotronics (www.sonotronics.com), and Vemco (www.vemco.com). Advanced Telemetry Systems and Lotek Wireless also offer equipment meeting specifications of the Juvenile Salmon Acoustic Telemetry System developed by the United States Army Corps of Engineers (see McMichael et al. 2010), which includes a very small transmitter with long life compared to other systems.

Figure A2. Radio telemetry antennas configured in automated detection systems



Note: Manual systems are often the individual parts of the automated systems, such as a single antenna and receiver.
Photo credit: United States Geological Survey.

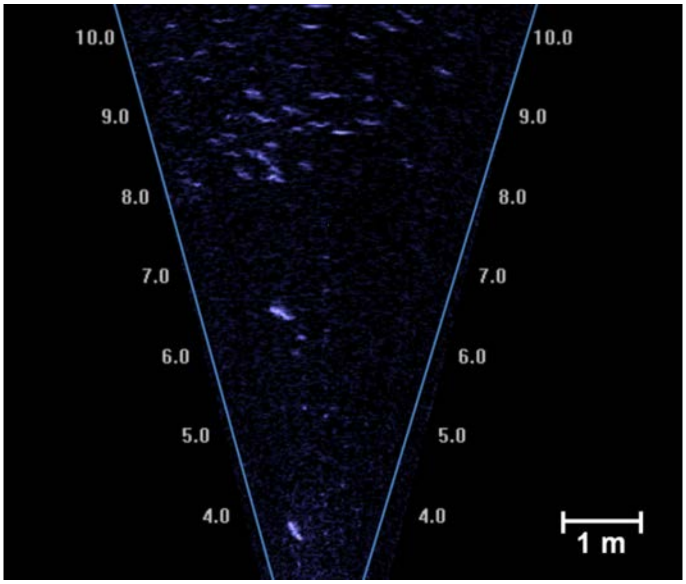
Figure A3. Acoustic telemetry plot of the probability of presence of tagged fish



Note: Image depicts experimental fish collector (object near center) and an outlet of a dam (black object). Warmer colors indicate greater probabilities of presence.
Source: United States Geological Survey.

Acoustic cameras are also used to remotely study fish. Acoustic cameras use sound rather than light to construct an image. The advantages of acoustic cameras in fisheries science include the ability to “see” through turbid waters and darkness and to collect information about untagged fish without affecting their behavior. Data from acoustic cameras are often best used to describe general behaviors such as schooling. Figure A4 shows the typical fan-shaped viewing angle of an acoustic camera picture. It depicts a school of small fish and two larger individuals nearby. Numbers indicate range in meters from the camera. The two largest fish (near the 4.0 and 6.5 meter range) are about 350 mm long; others are 150-220 mm long. Perhaps the greatest disadvantage of the technology is the inability to determine the species of all individual targets and the inability to detect when individuals pass repeatedly through the camera’s view. For this reason, acoustic cameras cannot accurately estimate population size. If 1,000 individuals pass through the camera’s view, it is not possible to know if the count represents one time each or if 100 individuals left the field of view and returned 10 times.

Figure A4. Fish in the view of a dual frequency identification sonar (DIDSON) acoustic camera



Source: United States Geological Survey.

Acoustic cameras have been used to measure and identify the species of large fish (usually fish several hundred centimeters long), but identification of fish less than about 20 centimeters long is less precise due to the relation between operating frequency and the ability to get adequate images from small targets (this depends on the operating frequency; see Hightower et al. 2013 for one case study). Despite the potential for abundance and measurement errors, acoustic cameras can be very useful to assess general behaviors, especially if data processing is automated (Boswell et al. 2008, Aquacoustics 2010). Common acoustic cameras include the dual frequency identification sonar (DIDSON) and ARIS cameras, both available from Sound Metrics (www.soundmetrics.com). Both cameras are quite expensive; one ARIS camera with a camera rotator costs about US$90,000 (7.65 billion Kip). The data can also be time consuming to summarize, which can add to the total costs of use.