VOLUME 2
Sustainable Hydropower
Development Plan:
Sections 1-10

SUSTAINABLE HYDROPOWER MASTER PLAN FOR THE XE KONG BASIN IN LAO PDR

FINAL REPORT

A component of

Hydropower Development Alternatives for the Mekong Basin: Maintaining the Flows that Nourish Life

Submitted to
Government of Lao PDR

Submitted by
Natural Heritage Institute, San Francisco, California
In Association with the National University of Lao

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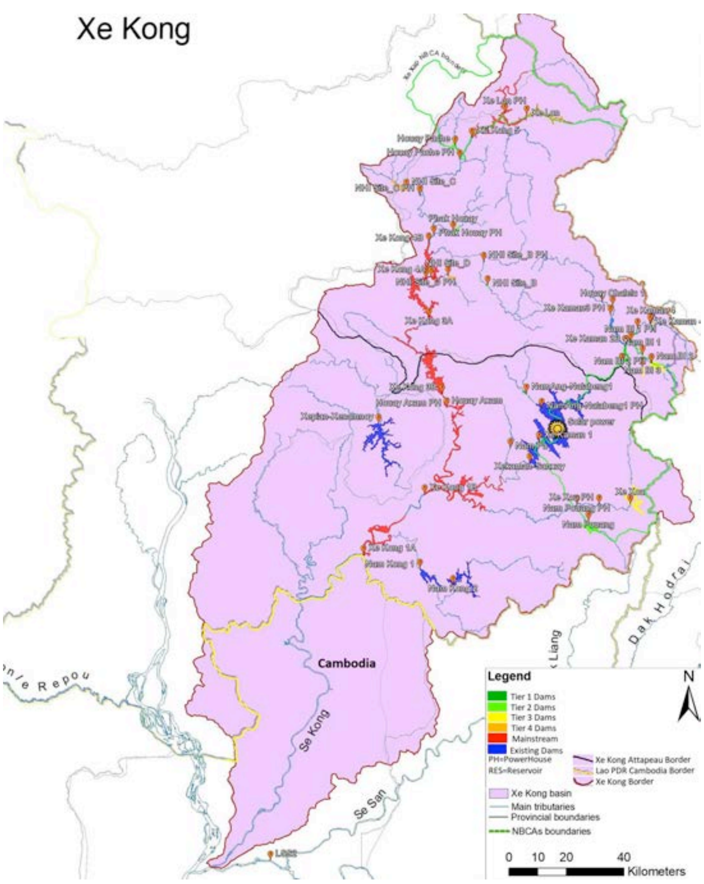

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Sustainable Hydropower Master Plan for the Xe Kong Basin in Lao PDR

Final Report

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Acronyms

3S	Xe Kong, Se San and Sre Pok Rivers, known collectively as the "3S" rivers
ADB	Asian Development Bank
AIT	Asian Institute of Technology
ASEAN	Association of Southeast Asia Nations
BOO	Build-Operate-Own projects
BOS	Balance of System
BOT	Build-Operate Transfer projects
CA	Concession Agreement
CAPEX	Capital Expenditure (or upfront capital expenditure)
CFD	Computational Fluid Dynamics
CIA	Cumulative Impact Assessment
CIAGs	Cumulative Impact Assessment Guidelines
CIP	Committee for Investment Promotion and Management
CIR	Capacity Inflow Ratio
COD	Commercial Operation Date
CPU	Catch Per Unit
CPUE	Catch Per Unit Effort
DEB	Department of Energy Business
DEPP	Department of Energy Policy and Planning
DNEI	Department of Natural Resources and Environment Inspection
DNREP	Department of Natural Resources and Environmental Policy
DWR	Department of Water Resources
ECAFE	Economic Commission for Asia and the Far East
ECC	Environmental Compliance Certificate
EDL	Électricité du Laos
EIA	Environmental Impact Assessment
EMDP	Ethnic Minority Development Plan
EMMP	Environmental Management and Monitoring Plan
EPA	Environmental Protection Agency of the United States
EPC	Engineering Procurement and Construction
EPCI	Equity Project Cost Investment
EPRI	Electric Power Research Institute (of the US)
ESIA	Environmental and Social Impact Assessment
ESMMP	Environmental and Social Management and Monitoring Plan

EVN	Électricité du Vietnam; and same acronym refers to energy demand curve
FI	Flood Index
FS	Feasibility Study
FTCC	Floating Tracking Cooling Concentrator
GHI	Global Horizontal Irradiance
GL	Gigaliters
GMS	Greater Mekong System
GoL	Government of Lao PDR
GWh	Gigawatt hours
GWh/y	Gigawatt hours per year
HIA	Health Impact Assessment
HPD	Hydropower Development
HSAP	Hydropower Sustainability Assessment Protocol (of IHA)
HWL	High Water Level
IADB	Inter-American Development Bank
IC	Insurance Cost
IDC	Interest During Construction
IEE	Initial Environmental Examination
IEI	Inverter Warranty Extension Investment
IFC	International Finance Corporation
IFI	International Finance Institutions
IFReDI	Inland Fisheries Research and Development Institute
IHA	International Hydropower Association
IMA	Inter-Ministerial Committee
IP	Ingress Protection
IP65	International classification for the ingress protection
IPP	Independent Power Producer
IRD	Irradiance
IRENA	International Renewable Energy Agency
ITRPV	International Technology Roadmap of Photovoltaic
JICA	Japanese International Development Agency
JMA	Japan Meteorological Agency
Km	Kilometers
kPA	Kilopascal, a unit of pressure
kWac	kilowatt AC power
kWp	Kilowatt peak (peak power)

LAC	Limits of Acceptable Change
LAK	Lao Kip (currency of Lao PDR)
LEK	Local Ecological Knowledge
LEPTS	Lao Electrical Power Technical Standards
LMB	Lower Mekong Basin
LMS	Lower Migratory System
LSS2	Lower Se San 2
LTCR	Long-Term Capacity Ratio
m	Meters
m^3/s	Meters per second
mill m^3	Million meters cubed (for total reservoir volume)
MAF	Ministry of Agriculture and Forestry
MDS	Multi-Dimensional Scaling
MEM	Ministry of Energy and Mines
MIGA	Multilateral Investment Guarantee Agency
MMS	Middle Migratory System
MoNRE	Ministry of Natural Resources and Environment
MoF	Ministry of Finance
MOU	Memorandum of Understanding
MPI	Ministry of Planning and Investment
MR	Mutilation Ratio (a component of a blade strike model)
MRF	Multiple Reference Frame
MRC	Mekong River Commission
MRCS	Mekong River Commission Secretariat
MSSS	Maximum Sustainable Swimming Speed
MTBF	Mean Time Between Failures
Mt/yr	Metric ton per year
MW	Megawatts
MWac	Megawatt AC power
MWp	Megawatt peak
NBCA	National Biodiversity Conservation Areas
NDR	Nominal Discount Rate
NHI	Natural Heritage Institute
NTEC	Nam Theun 2 Electricity Consortium
NTFPs	Non-Timber Forest Products
NUoL	National University of Lao

OAAs	Other Aquatic Animals
O&M	Operation & Management/ Operating & Maintenance Cost
PAPs	Project-Affected Persons
PDA	Project Development Agreement
PDEM	Provincial Department of Energy and Mines
PDPI	Provincial Department of Planning and Investment
PDPVII	The Power Development Plan VII
PID-free	The PV module is free from Potential-Induced Degradation
PPA	Power Purchasing Agreement
PPP	Public-Private Partnerships
PR	Performance Ratio
PSHD	Policy on Sustainable Hydropower Development in Lao PDR
PV	Photo Voltaic
RAP	Resettlement Action Plan
RC	Resettlement Committee
rpm	revolutions per minute
RSCP	River System Coordination Plan
R&R	Resettlement and Relocation
SDR	System Degradation Rate
SERIS	Solar Energy Research Institute of Singapore
SESO	The Standard Environmental and Social Obligations
SHA	Shareholder Agreement
SIA	Social Impact Assessment
SOP	Social Action Plan
SR	Scoping Report
SSY	Suspended Sediment Yield
ST	Stung Treng monitoring site
SWAT	Soil and Water Assessment Tool
TbEIA	Transboundary Environmental and Social Impact Assessment
TF	Total Flow
ToR	Terms of Reference
TP	Tax Payment
TWL	Tail Water Levels
UN	United Nations
UPS	Upper Migratory System
W/m	Watts per cubic meter, such as the measurement for Turbulence

Wp	Watt-peak
XK1	Xe Kaman 1 Hydropower project

1. Purpose and Approach of the Master Plan: Implementation of Policy on Sustainable Hydropower Development in Lao PDR

Lao PDR is now the most experienced nation in Southeast Asia in hydropower development. At present, 21 hydropower dams larger than 15 MW are operating, and 26 more are under construction. For these facilities, irreversible choices regarding siting and design have already been made; only the operations can be altered. Yet, as of mid-2015, here are about 85 additional hydropower facilities larger than 15 MW that have been approved or are being planned and studied (www.poweringprogress.org/new/power-projects, published June 9, 2015 by Lao PDR Ministry of Energy and Mines). As to all of the potential future facilities, the choices regarding the siting, design and operation are yet to be determined by the Government of Lao PDR (GoL).

The Natural Heritage Institute (NHI) offers this "Master Plan" for future hydropower development in the Xe Kong River Basin to assist and guide the GoL in implementing its recent Policy on Sustainable Hydropower Development, as ratified by the National Assembly and decreed by the Prime Minister on January 12, 2015. The crafting of this Master Plan was conducted under an Operations Permit issued by the Ministry of Foreign Affairs, pursuant to a charter agreed with the Ministry of Energy and Mines (MEM), a Memorandum of Understanding with the National University of Lao (NUoL) and ongoing consultation with all of the agencies of the GoL that exercise authority over hydropower development, natural resources management, river basin planning, and fisheries administration.

To provide a roadmap for implementation of the new policy on Sustainable Hydropower Development, it is necessary to start with an understanding of what the policy is and what it is not. This policy commands several ministries to further develop the hydropower resources of Lao PDR in a manner that avoids and mitigates their negative impacts and, to foster that result, requires developers to assess the impacts including their cumulative and transboundary aspects.

The January 2015 policy builds on and reorients the previous policy articulated in 2005, which states:

> **"ecological sustainability relies upon the avoidance of irreversible environmental impacts such as the loss of biodiversity or disruption of ecological cycles."**

We should pause to note the remarkable feature of this policy statement by a country at an early stage of economic development and with a history of privation of its people that might well predispose it to a purely utilitarian view of how to develop its natural assets. Yet, instead of articulating ecological sustainability primarily in terms of food sufficiency or livelihoods, we see here a commendably farsighted policy rooted in the intrinsic value of biodiversity and ecological integrity.

That substantive standard is reiterated in the Guidelines for Implementation of the 2015 Policy (see http://www.poweringprogress.org/new/images/PDF/Guideline/Guideline.pdf), which also broadens the concept of sustainable hydropower to include the economic and technical aspects[1]. However, the main injunctions of the "Policy Guidelines for the Implementation of the Policy on Sustainable Hydropower Development in Lao PDR" are stated as goals and procedures rather than criteria or attributes for determining sustainability of a project:

> §5.1a **The Government** agencies are to ensure that potential negative impacts on the environment and social system are prevented or mitigated.
>
> §5.3b **Project developers** shall prevent and mitigate any potential risks to the natural resources and the environment in the design, construction and operation stages.
>
> §5.7 **All hydropower projects** shall undertake a comprehensive Environmental and Social Impact Assessment. For any project with large transboundary impacts, the EIA shall include a cumulative and transboundary impact assessment.
>
> §5.11 **Natural conserved habitat** losses due to hydropower development projects shall be avoided and mitigated as much as possible.[2]

Fundamentally, the Policy is a set of procedural instructions to the relevant organs of the national and provincial governments, and a set of goals or results to be achieved. It does not provide substantive criteria or standards for determining what attributes make a hydropower project sustainable or unsustainable. Nor does it really provide a process through which such criteria or standards can be developed and ratified. Therefore, the first step for this Sustainable Hydropower Master Plan is to provide a set of practical criteria and standards to operationalize the new policy together with the rationale that justifies them. That definition is provided in detail in Section 6 of this Master Plan. NHI submits that the recommended approach can be applied universally, not just in the Xe Kong basin, but throughout Lao PDR and, indeed, at the global scale.

The Ministry of Energy and Mines, and specifically the Department of Energy Policy and Planning (DEPP) is assigned the lead role for implementation of the policy, in close consultation with the other responsible agencies of the Government of Lao PDR (§5.b and §5.2b). The Ministry of Natural Resources and Environment (MoNRE) is assigned a particularly significant role (§5.7b). The Department of Environmental and Social Impact Assessment (ESIA) of MoNRE is charged with the responsibility for "ensuring that hydropower projects are fully in compliance with the [regulations on environmental and social impact assessment. Yet, notably, neither the Policy Guidelines nor the ESIA regulations specify which agency of the Government of Lao PDR is responsible for determining whether a proposed project is environmentally or socially "sustainable", the process for making that determination, or the substantive standard

[1] The Background section of the 2015 policy states: "Based on the experience in developing hydropower sustainably, the policy needs to be enhanced/improved as considering only environmental and social aspects may not be sufficient and it is therefore necessary to consider the economic and technical aspects as well".

[2] §5.11 "Natural conserved habitat area losses due to hydropower development projects shall be avoided and mitigated as much as possible. Where avoidance is not possible, it must be compensated and restored by the project developers as well as provide funding to help manage and effectively conserve the watershed area as well as nearby watersheds and other important conservation areas. [The developer m]ust also develop a sustainable biodiversity management plan, consider compensation or help mitigate the impact on the local natural resource base".

that is to be applied. Lack of specificity on this crucial responsibility is the greatest major omission of the Lao Policy.

Other notable features of the policy are discussed in Section 12 of this Master Plan. Some highlights are provided in the text box below:

Text Box 1-1. Notable features of the 2015 Policy on Sustainable Hydropower Development.

§5.1a Use of water for ecological maintenance is recognized as a legitimate water right.

§5.1a Multiple hydropower projects on a single river are to be developed in an integrated manner.

§5.1a All costs associated with environmental and social impact avoidance, mitigation, compensation or restoration are to be treated as project expenses to be borne by the project developer.

§5.1a The GoL will ensure integrity, accountability, and transparency of hydropower projects through compliance monitoring, reporting and information disclosure. §5.10 provides that "All hydropower development projects shall be undertaken on the basis of transparency and openness." § 5.10a notes that the ESIA regulations require "public disclosure of information related to the project developers, the social and environmental impact…" Notably, however, this injunction has not (yet) been applied to public access to environmental and social impact assessments which are still regarded by the Ministry of Natural Resources and Environment (MoNRE) as the property of the developers (who do, indeed, pay for their preparation as required by §5.7 of the Guidelines).[1]

§5.7 The environmental and social impact assessments will "include a risk assessment over the entire life-span of the [the] project, an analysis of alternatives for project structure and locations, including the no-project alternative, lessons learnt from previous projects, and cumulative impacts analysis at the basin and/or sub-basin levels. §5.7a) notes that the regulations of MoNRE require public participation during the preparation of the environmental and social impact assessments as well as disclosure of "public information". No definition of that term is provided, however. The requirement for assessment of alternative sites and designs of hydropower projects is particularly relevant to this Master Plan, which is essentially just that: an assessment of sustainable alternatives to proposed projects.

§5.2 Stakeholders are to be included in the process of planning, implementation and monitoring of projects. While the "stakeholders" are not defined explicitly, the term apparently includes at least the local affected peoples and government officials. §5.8 makes clear that persons subject to displacement and relocation have a right to consultation as "project-affected persons" (PAPs).

§5.1a and §5.14 Existing hydropower project will be reviewed to ensure that unsustainable aspects are adequately addressed (i.e., projects at any stage of development, including those for which feasibility studies have been conducted under existing MOUs are not exempt from the policy).

It is correct to observe that sustainability depends on more than just avoiding and mitigating adverse environmental and social impacts of hydropower project. Technical and economic sustainability must also be taken into account. Indeed, the Policy on Sustainable Hydropower Development makes this broader conception of sustainability explicit in stating:

> "Based on the experience in developing hydropower sustainably, the policy needs to be enhanced/improved as considering only environmental and social aspects may not be sufficient and it is therefore necessary to consider the economic and technical aspects as well."

While acknowledging the obvious validity of this point, this Master Plan concentrates on the environmental aspects of sustainability simply because those present the greatest challenge to the Government of Lao PDR in implementing this Policy. The technical and economic feasibility does not require much oversight by the Ministry of Energy and Mines, as projects that are technically or economically unsustainable are culled out by the project developers and investors themselves. It is highly unlikely that these actors will pursue project that proves to be infeasible from an engineering standpoint, and investors are highly unlikely to put their resources into a project that proves to be uneconomic. The one exception that may require more probing oversight is dam safety.

The social impacts are also not given much attention in this Master Plan, not because they are unimportant, but because they are considered at length in guidelines provided by other institutions such as the World Bank and the Asian Development Bank (ADB) in their "safeguards" policies.

Approach to Crafting the Master Plan

Logic and charter for the Master Plan

In the Mekong River Basin, the principal sustainability consideration in hydropower development is the avoidance of impairment of the exceptional productivity of its extraordinary fishery resource. This priceless resource is at risk unless dams are **sited, designed and operated** to maintain:

1) The passage of migratory fish both upstream and downstream, and the free-flowing conditions of their spawning and rearing habitats, so that they can complete their life-cycle;

2) The natural variability in the flow patterns that connect the river to its floodplains and provide the cues for fish migrations;

3) The flows of the sediment and associated nutrients that sustain the morphology and habitats downstream of the dams.

In summary, the functional definition of sustainable hydropower is simply the siting, design and operation of hydropower dams to avoid or counteract the three principle physical impairments that dams cause to the natural processes of rivers and their living elements. How this paradigm can be applied in practice is described in detail in Section 6 of this Master Plan.

In formulating this project in consultation with the Ministry of Energy and Mines, it was agreed that the Master Plan would be crafted to serve as the successor to the one previously prepared by the Japanese International Development Agency (JICA), with an updated approach to the goal of sustainable development. For reasons described at length below, the Xe Kong was selected as the focus of the Master Plan with a view toward explicating and demonstrating a template for sustainable development that could then be applied nationwide. In view of the types of biophysical threats that can make hydropower non-sustainable, which are explicated at length in Section 5, this Master Plan lays out a hydropower development for the Xe Kong basin that will:

- Avoid or minimize adverse impacts on migratory fish or unique habitats for resident endemic fish;
- Minimize capture and depletion of sediment flows;
- Keep the costs from deterring potential investors;
- Satisfy the hydropower production goals of the national government of Lao PDR for the hydropower potential within the Xe Kong basin.

This Master Plan satisfies that charter by presenting techniques and opportunities for:

- **siting** future hydropower dams in locations that do not inundate or block fish passage into the habitats that are most valuable for migratory fish breeding and rearing;
- **designing** the dams to efficiently pass sediments and nutrients; and
- **operating** the dams to maintain a semblance of the natural flow patterns, including the seasonal variability of flows, to enable the fish to access and use the high-value riverine and floodplain habitats.

In sum, this Master Plan illuminates a development pathway that will yield approximately the same level of hydropower production as the pending hydropower development proposals while still maintaining the social and environmental benefits of a healthy fishery, and will do so with financial costs attractive to potential investors and power customers. It presents a development plan that will provide an equivalent amount of power output as could be achieved from all of the dams under investigation on the mainstream of the Xe Kong by looking at sites that satisfy the sustainability principles and criteria both within the Xe Kong.

What the Master Plan is and is not

The Master Plan is not a feasibility study of the new sites that are identified as candidates for sustainable hydropower development. Some of the sites are already being investigated for feasibility by developers (see Section 7 of the Master Plan). The new sites were identified in a desk top study that included data on topography, hydrology and geology. But, no site visits were made by a team of experienced geotechnical experts (to assess ground conditions), construction engineers (to assess access and logistical challenges), or environmental experts, as would be necessary to conduct a full-fledged technical feasibility study. Some of the sites would present significant access challenges (although roughly comparable to those associated with the Xe Kong 5 project that is already under study.

Rather, the Master Plan is a reconnaissance level assessment of project sites, designs and operations that allows the alternatives to be ranked according to the degree to which they satisfy meaningful criteria of environmental sustainability as precursor to the conduct of an actual feasibility study. The value of the Master Plan is simply to advise the Government of Lao of the relative priority of sites for which it should invite full-fledged feasibility studies by interested developers. This approach, however, would work a rather radical change in the way that hydropower development proceeds today, as discussed below.

Process of internal review and vetting of the Master Plan

The Internal Review Draft of the Master Plan was delivered in September 2017 to all relevant ministries and units of the Government of Lao (GoL) at the national and provincial levels and to intergovernmental organizations who serve as technical advisors, to allow a four-month opportunity for review and comment before the final version was prepared and submitted at the end of January, 2018. All recipients were invited to schedule briefings for the receipt of comments.

On January 16, 2018, Vice Prime Minister, H.E. Sonexay Sypandon, graciously invited six vice ministers of the relevant agencies and their relevant department heads and technical staff to attend a briefing provided by NHI. Valuable feedback was obtained during this session.

The officials who were invited by the Vice Prime Minister and/or NHI to participate in the review process are listed below. Blue color denotes officials and agencies that requested and received a briefing; green color denotes officials and agencies that provided written comments. The valuable comments received during the review and vetting process are reflected in this final version of the Master Plan and described on the following pages.

- ✓ **Ministry of Energy and Mines**
  - Minister
  - Vice Minister
  - Permanent Secretary
  - Director General of Dept. of Energy Policy and Planning and technical staff
  - Director General of Dept. of Energy Business
  - Deputy Managing Director of Électricité du Laos (EDL)
  - Managing Director of EDL-Gen
  - Vice Managing Director of EDL-Gen
- ✓ **Ministry of Natural Resources and Environment**
  - Minister
  - Vice Minister
  - Director General of Dept. of Natural Resources and Environmental Policy
  - Deputy Director General of Dept. of Natural Resources and Environmental Policy and staff
  - Director General of Dept. of Water Resources
  - Deputy Director General of Dept. of Water Resources
- ✓ **Ministry of Planning and Investment**
  - Director General of Dept. of Investment Promotion
  - Deputy Director General of Dept. of investment Promotion and staff
- ✓ **Ministry of Agriculture and Forestry**
  - Vice Minister
  - Director General of Dept. of Forestry Management
  - Director General of National Agriculture and Forestry Research Institute
  - Director General of Living Aquatic Resources Research Institute
  - Director General of Department of Livestock and Fisheries

- ✓ **Ministry of Finance**
  - Vice Minister
- ✓ **Ministry of Education**
  - Minister
  - Vice Minister
  - President of National University of Lao and faculty of several departments
  - Vice President of National University of Lao
  - Faculty of Agriculture and Forestry
- ✓ **Sekong Provincial Office of Agriculture and Forestry**
  - Director General
- ✓ **Attapeu Provincial Office of Agriculture and Forestry**
  - Deputy Director General
- ✓ **World Bank**
- ✓ **International Finance Corporation**
  - Hydropower Developer's Working Group (organized under auspices of IFC)
- ✓ **Mekong River Commission**
  - Chief Executive Officer
  - Institute for Sustainable Hydropower

Comments received during the review and vetting process

The main points raised in the comments are listed below, together with an indication of how these are reflected in the final Master Plan:

1) The Master Plan is incomplete because it addresses only the environmental aspects of hydropower sustainability:

   Rejoinder: It is correct to state that the Policy on Sustainable Hydropower explicitly states that there are four dimensions of sustainability that must be taken into account in hydropower development. As noted above, the Policy observes that:

   > "Based on the experience in developing hydropower sustainably, the policy needs to be enhanced/ improved as considering only environmental and social aspects may not be sufficient and it is therefore necessary to consider the economic and technical aspects as well"

   However, it is not correct to state that the Master Plan ignores the technical and economic aspects. These are taken into consideration in the hydropower site suitability analysis, in the assessment of impacts of proposed hydropower projects in the basin, and in the feasibility study of the solar augmentation of existing reservoirs. It would be more accurate for these commenters to state that the technical and economic aspects (and, indeed, the environmental aspects), are treated at a reconnaissance level of analysis rather than at the depth that would be appropriate in a full-fledged feasibility study of specific project proposals. Again, that is intentional. As stated clearly above, the Master Plan is a basin wide planning document whose sole purpose is to assist the GoL in deciding what projects warrant conducting a technical and economic feasibility study. It is important not to confuse the purpose of a Master Plan with the purpose of a feasibility study.

It is also correct to point out that the Master Plan does not give equal treatment to the social aspects of the hydropower development alternatives. That is also intentional. Just as the Master Plan is not intended to be a full-fledged feasibility study, so also it is not a project-specific environmental and social impact assessment. That too will come once a decision is made, on the basis of the Master Plan, which projects should receive a MOU to go through the feasibility study and ESIA stages. Rather, the Master Plan includes a programmatic or planning level of environmental and social impact analysis. A comparison of the social costs and benefits of the sustainable alternatives is rather superficial simply because the main issue is relocation and resettlement of affected communities. It is obvious that the sustainable alternative sites are much less impactful than the proposed mainstream sites because they are in locations in the upper catchments that have a very sparse population. Indeed, many of them are roadless.

2) The mainstream projects have already invested significant funds to complete feasibility studies and environmental and social impact studies. All have received MOUs, and some have received Project Development Agreements (PDAs). Therefore, it is too late to cancel these projects.

   Rejoinder: The Master Plan does not recommend that these projects be "cancelled", but that they be assigned a lower priority for conferring a concession agreement than the (much) more sustainable alternatives presented. These projects should be considered a "last resort". Even among these projects, the Master Plan ranks them in terms of sustainability in descending order from the top to the bottom of the cascade.

   The legal entitlement of these mainstream projects to receive final approval and a concession agreement is treated at length in Section 12 of the Master Plan. Suffice it to point out here that neither MOUs nor PDAs confer on the developer a right to receive a concession agreement. These only assure that if the projects prove to be feasible <u>and</u> sustainable, the holders of those warrants have an exclusive and non-competitive right to build, own and operate the project. Notably, none of these projects are entitled to a Concession Agreement (CA) at the time of this writing because none of them have a power purchase agreement, a transmission arrangement, or a tariff agreement. Indeed, none of them have a currently valid Environmental Compliance Certificate (ECC), except the uppermost project which holds only a temporary ECC. More to the point, it is doubtful that any of these projects would qualify for a ECC if the environmental impact assessment requirements in the Policy were fully complied with.

3) The Master Plan proposes that the Ministry of Energy and Mines (MEM) and the Ministry of Natural Resources and Environment (MoNRE) assume a more proactive role in preparing master plans for sustainable hydropower development and, in the process, conduct comparative environmental assessments of the alternatives. That will require financial resources to acquire the necessary technical and economic capabilities. Therefore, implementation of this recommendation will require a funding mechanism.

   Rejoinder: A proposed funding mechanism is described in Section 12 of the Master Plan at pages 51-55.

4) In recommending a basin-wide planning approach to hydropower development, the Master Plan should include a process for selecting developers who have the intent and capability of pursuing an integrated approach for all projects for which optimal performance requires coordinated operations.

   Rejoinder: This is an important observation and has been incorporated into the implementation recommendations in Section 12.

5) The Master Plan lacks details on the character of the migratory fishery, such as the species, the points of origin of the fish migrations, etc.

   Rejoinder: Section 5 and its extensive Annexes contain the most complete compilation of the state of knowledge regarding the migratory fishery in the Xe Kong basin, including the movement of the fish from the Tonle Sap Great Lake. This includes data from field surveys, the MRC records, and exhaustive literature search, and zonation modeling of fish migrations into the basin. It is correct to point out that the state of knowledge is still incomplete and fragmentary. That is another reason why it is risky to construct dams in the migratory fish corridor, and an important rationale for assessing siting alternatives above existing barriers to fish migration.

6) The reduction in fish harvest that will occur due to the mainstream dams will be experienced mostly in Cambodia, which already captures a large fraction of the migratory fish that would otherwise access the Lao portion of the Xe Kong Basin.

   Rejoinder: The Policy is clear that the transboundary impacts in Cambodia are to be explicitly accounted for making the sustainability determination on the Lao hydropower projects. While it is true that the volume of fish migrations into the Lao portion of the basin would be larger if fish were not harvested in Cambodia, it is also true that the harvest in Cambodia and in Lao will be substantially reduced if the spawning reaches on the Xe Kong in Lao are obstructed.

7) There is potential to revise the mainstream dam projects to better mitigate their impacts and make them more sustainable.

   Rejoinder: NHI acknowledges that this is correct and, indeed, the Master Plan includes detailed discussion of improved mitigation that can be accomplished by redesigning the mainstream dams for fish passage (see Section 8) and sediment discharge (see Section 9). However, the residual concern is that the barriers that the reservoirs themselves will present to the passage of fish, eggs and larvae may not be mitigatable without reducing power generation to the point where the projects are no longer economically viable. See Sections 5, 8 and 10.

8) The loss of natural capture fisheries can be compensated by fish farming (aquaculture) on the reservoirs.

   Rejoinder: While it may be possible in the near term to produce equivalent biomass from fish farming, the quality and diversity of the fishery will decline over time.

Moreover, it is unlikely that even the equivalence of biomass can be maintained over the longer run. Perhaps more important, industrial fish farming does not replace the livelihoods lost by the reduction in the capture fishery. These points are elaborated in Section 8, pages 31-34.

9) In other river systems with many dams (e.g., the Danube with some 50 dams), the fishery remains robust.

   Rejoinder: The Mekong is radically different from the Danube with respect the migratory character of the fishery and its exceptional productivity. Moreover over, the notion that the Danube fishery has not been substantially impaired does not withstand scrutiny.

10) If the Xe Kong is developed, it will simply adjust with a different aquatic ecosystem that will replace the current one.

   Rejoinder: This is correct, but the replacement ecosystem will have much less species diversity and will likely produce much less commercially valuable fish.

11) With regard to the practicality and "sustainability" of the alternative of augmenting power generation at existing reservoirs (Xe Kaman 1, specifically) by integrating floating solar photovoltaic parks, several points were raised:

    a. Solar panels only last a few decades whereas hydropower dams last much longer.

       Rejoinder: Solar panels are guaranteed for 20-25 years, after which they must be replaced. The replacement costs have been factored into the levelized cost of power comparison with hydropower. The more important point here is that the GoL should assure in the contract terms and conditions for a concession agreement that the panels are replaced just before the facility is transferred to GoL ownership.

    b. Solar panels create recycling and disposal hazard because of the toxicity of the materials.

       Rejoinder: This problem is easily dealt with, as described on pages 50-52 of Section 11.

    c. The initial cost of solar is higher than hydropower.

       Rejoinder: the net economic benefits of the solar alternative are much better than the hydropower alternatives when all costs and benefits are taken into account, as shown in Section 11. The cost of solar is declining year on year, whereas the costs of hydropower are going up year on year.

    d. The intermittent nature of solar power makes it unmarketable.

Rejoinder: This is a problem for stand-along solar parks. It is not a problem for solar/hydro hybrid facilities. Indeed, the reliability of power from these facilities is considerably more reliable than hydropower standing alone.

e. VM Education:
   - Need analysis of fishery ecosystems after dam construction,
   - Concerned about disposal problem with solar cells,
   - The Master Plan focuses on fish only,
   - In previous times, Xe Kong fish were consumed by local people. Now, they are also exported,
   - Fishery declines are also caused by over-fishing.

f. Dept. of Forestry: concerned about erosion impacts and sediment from forest lands impacting watershed and biodiversity, e.g. roads built for hydro project will open up areas of forest not previously accessible. They want mitigation measures for forest lands erosion.

12) Although the Policy calls for the creation of an Inter-Ministerial Committee to implement the policy, it is not practical to rely on it to develop the sustainability standards. In reality, the ministers' attention will be too intermittent. It would be better to set up a special unit at the working level with the assignment to develop the standards and monitor compliance. It should be permanently, chaired by MEM and should include EDL.

Rejoinder: This comment has been incorporated in the Implementation Plan in Section 12.

How the Master Plan Will Reposition the Government of Lao PDR in the Hydropower Development Process

As described more fully in Section 12 of the Master Plan, the general trajectory for hydropower development in Lao PDR is as follows:

- Projects are initiated by foreign investors, sometimes with a Lao public or private equity stake, and proposed to the Lao Government for its approval.
- Application is made to the Ministry of Planning and Investment for a Memorandum of Understanding (MOU) conferring exclusive rights to conduct a feasibility study, which is then submitted to the MEM for review of the technical and financial merits. Importantly, these MOU's do not commit the GoL to ultimately permit the construction of the facility nor to any of the proposed siting, design or operational details. The MOUs require the developer to conduct an environmental impact assessment, which is submitted to the MoNRE for review.
- If MoNRE determines that the assessment complies with the procedural requirements, it issues a Certificate of Compliance.
- The developer then applies to MPI for a Project Development Agreement, which commits the parties to cooperate in the negotiation of the financial instruments, power purchase agreements, and other legal documents necessary to submit an application for

a concession agreement to build, own, operate and transfer the hydropower project. MEM is the agency that exercises the discretion whether to issue such concession agreements. The concession period lasts for approximately 25 years, at which point the projects may be transferred to the government of Lao PDR. In the main, the projects will export the power to foreign power companies in Thailand and Vietnam, subject to power purchase agreements that provide a revenue stream that guarantees a rate of return to the investors.

Notably, the role of the Lao Government in this process is entirely reactive. The siting, design and operations are proposed by the developers, who perform the feasibility analysis, the financial analysis, and the environmental impact assessments, all with cursory oversight by the government agencies, which generally lack the technical expertise to perform an independent review. Most notably, the development decisions are made without the benefit of a basin-wide or nation-wide survey of the comparative advantages or disadvantages of siting, design or operational alternatives.

This Master Plan for sustainable hydropower development will reverse that trajectory. Today, the GoL enters into a MOU with any developer who is willing to invest resources in a feasibility study for a site that the developer has selected, based on the same type of preliminary data that has been used in for site suitability analysis in this Master Plan. That MOU creates an exclusive right for the holder to carry out a detailed feasibility study and sets that holder on a course to have the exclusive right to build, own and operate a project at that location, should the feasibility study show technical and financial viability, and if the developer can find a customer for the power who is willing to enter into a Power Purchase Agreement (PPA) on terms that make the project "bankable". In other words, the developer chooses the location for the project and, to a large extent, the design and operations. To be sure, in the environmental assessment process, some consideration may be given to mitigation measures for fish and sediment. But the site, scale and optimal operations are largely fixed by the developer. The mitigation measures are designed to accommodate these parameters rather than the other way around.

By developing or (adopting) a Master Plan for sustainable hydropower development, the Government of Lao would take over the prerogative to define the sites, designs and operations for which it will issue MOUs for feasibility studies to interested developers on a competitive basis. Like under current practice, the feasibility study performs the on-site geotechnical investigation, engineering studies, site specific environmental impact assessment, modeling of power output, etc. The competition in awarding MOU's is over the comparative capabilities of the bidders to carry out the feasibility study rather than on the price terms.

In other words, under a Master Plan, nothing changes in the process except that the GoL decides what sites are up for grabs and specifies up front certain environmental performance criteria with respect to fish survival and sediment passage. Yet, this would radically change the course of development. It would make it quite unlikely that the potential hydropower sites that would have large impacts on the fishery would not be studied, much less built. This approach also poses much less of a burden on the GoL in implementing the policy mandate for sustainable hydropower development. All it has to do is apply a set of principles that are described in detail in the Master Plan to identify the sites, designs and operations that would be offered for detailed feasibility study. The Master Plan merely provides a basis for determining what MOU's for feasibility studies to invite, which is all that it is intended to do.

This change in current practice would position the to be the master of its own house in the economic development of its portion of the Mekong River System. This repositioning is consistent with the observation by the Asian Development Bank in its the review of the Lao power sector that the government of Lao recognizes that it could boost its revenue share significantly if it were to grant concessions for large hydropower projects on the basis of a competitive and transparent bidding process, rather than depend upon the existing developer- and investor-driven system[3]. Such a "top-down" development paradigm would also assist the potential investors in knowing where and when to invest their project development funds with some assurance that those investments will result in projects that satisfy the "sustainability" standard and can therefore be approved. A more rational, efficient, and beneficial hydropower development trajectory for Lao PDR is likely to emerge.

It may be observed that the Master Plan for the Xe Kong basin comes too late because the MOUs for the feasibility studies have already been issued under the current practices and the feasibility studies have already been completed. This issue is dealt with at length in Section 12 of the Master Plan. Suffice it to say here that only one of the projects that have completed a feasibility study have an active Environmental Compliance Certificate (ECC) as of this writing, and that one is only temporary. This means that there is yet an opportunity in the environmental and social impact approval process to reconsider the compliance of these projects with meaningful standards of environmental sustainability. The Policy now requires that the environmental impact studies consider *alternative sites,* which opens the door to consideration of whether the proposed site should be approved. We note that an alternative site assessment would look very much like this Master Plan, and, if objective and technically sound, might well conclude that alternative sites better satisfy the Policy on Sustainable Hydropower Development.

Once "test driven" in the Xe Kong basin, the Master Plan can then also serve as an exemplar and template for sustainable development that can be applied in the rest of the country and throughout the Mekong Basin.

The current process for planning and approving hydropower projects and how these would need to be changed to implement the Sustainable Hydropower Master Plan is discussed in Section 12 of the Master Plan, which is plan for its implementation.

Why focus on the Xe Kong sub-basin?

Today, the mainstream of the Xe Kong tributary is the last major undeveloped tributary in the Mekong River Basin, and its natural functions remain intact all the way from the headwaters at the Vietnam border[4], through southern Laos to the mainstream Mekong, through the

[3] ADB, Independent Evaluation Department: Sector Assistance Program Implementation for the Energy Sector in Lao People's Democratic Republic, October 2010, p.7.

[4] The Xe Kong River originates on the Vietnam side of the border, where it is called the A Sap. A diversion dam was constructed for hydropower generation in this reach that diverts most of the flow to a powerhouse located in the Bo River basin. However, this facility is so high in the catchment that it does not significantly affect the flows in the Lao portion of the river.

Cambodian floodplains and the Tonle Sap Great Lake, through the Vietnam Delta, to the South China Sea.[5] The rest of the Mekong River system basin has already been fundamentally altered by the seven mainstream dams in the Lancang headwaters in China, the mainstream dams in the Lao reach above the Khone Falls and by the pervasive siting of dams on all the other major tributaries (Figure 1-1).

Within the highly productive 3S sub-basin, the Lower Se San 2 dam in Cambodia now blocks passage of migratory fish into the Sre Pok and Se San tributaries, leaving only the main stem of the Xe Kong River unimpeded.

Therefore, in the context of the development that has already occurred, the Xe Kong River is the most important portion of the Mekong River system for unimpaired flow, sediment and nutrient contributions[6], and for sustaining migratory fish. Maintaining its extraordinary natural values in the course of hydropower development is therefore the most important challenge that the Government of Lao PDR faces today in implementing its Policy on Sustainable Hydropower Development.

[5] The only downstream obstruction in prospect is the Sambor hydropower dam on the mainstream Mekong in Cambodia. This dam would be built in a migratory fish corridor that carries the greatest density of adult fish and larvae on the planet. As originally proposed, the dam would destroy the Mekong migratory fishery. Fortunately, an alternative that would leave channels of the river unobstructed is being assessed by NHI under an agreement with the Royal Government of Cambodia that is likely to be adopted instead. That will keep the river free-flowing from the Xe Kong headwaters to the South China Sea.

[6] By one estimate, nearly 10% of the sediment and nutrient load of the entire system comes from the Xe Kong. Sediment and nutrient passage in this tributary will have the greatest benefit for the continued productivity of the Tonle Sap in Cambodia and the delta in Vietnam because there are no downstream dams to capture these materials. The habitats that are nourished by these materials from the Xe Kong produce the fish that migrate back up into this system to the great benefit of everyone, including the people of Lao PDR.

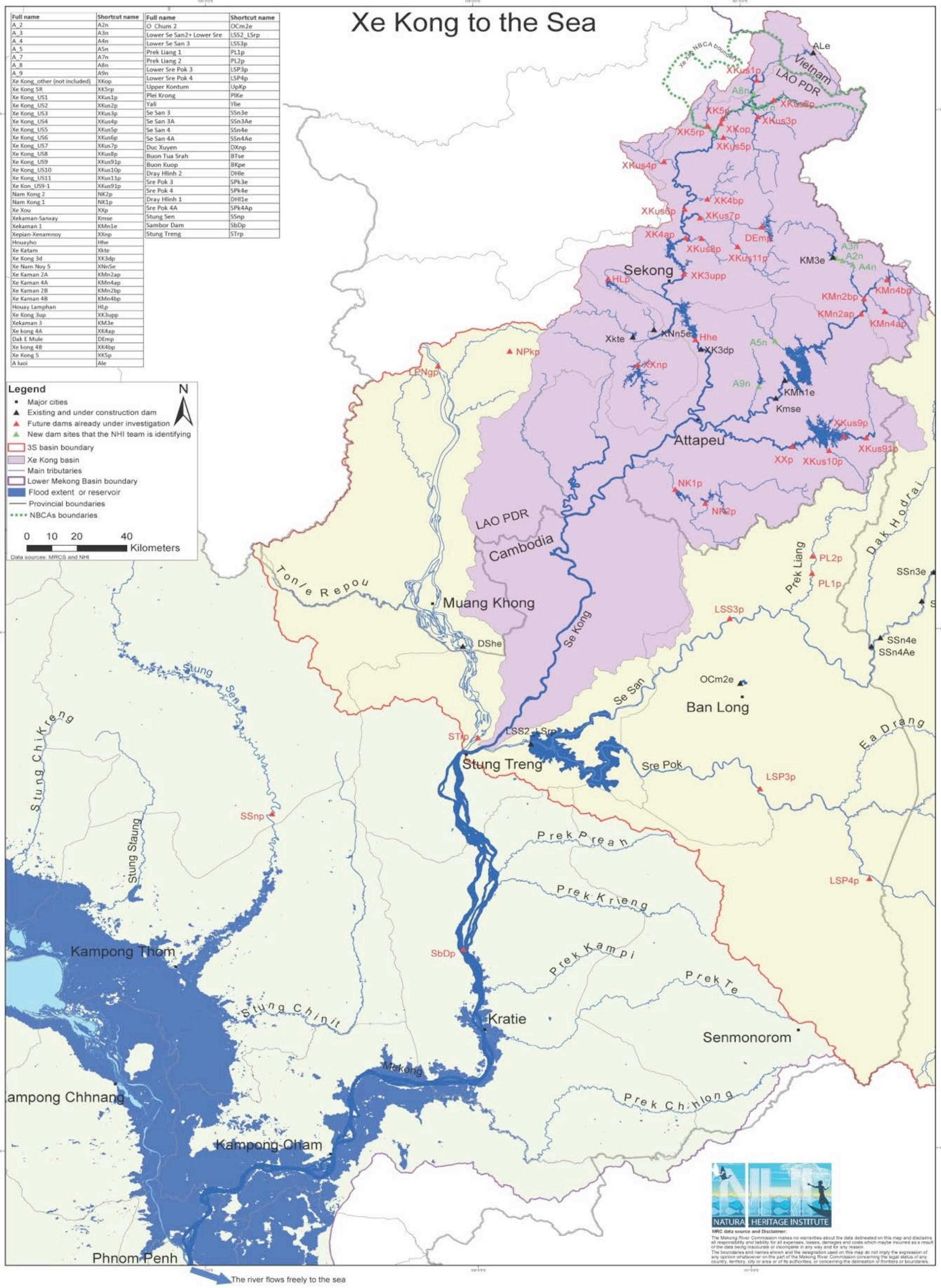

Figure 1-1. Map of Xe Kong to the sea with dams in the Mekong Basin.

How the Master Plan Improves Upon Previous Development Plans

There have been a series of hydropower development plans prepared for the Mekong River basin by outside experts over the years. Two or the earliest studies were prepared by the UN Economic Commission for Asia and the Far East (ECAFE), Bureau of Flood Control and Water Resources Development, in 1957, and around the same time the U.S. Bureau of Reclamation produced the *Reconnaissance Report: Lower Mekong River Basin* (1956). Soon thereafter, the United Nations (UN) sponsored the "Wheeler Report"[7] carried out by the U.S. Army Corps of Engineers (UN, 1958), and then the Ford Foundation supported a report by White *et al*. in 1962. More recently, each of the successive Mekong River Basin organs (the Mekong River Committee, then the Interim Mekong Committee, followed by the Mekong River Commission) have issued several "indicative studies" and "basin development plans", all of which targeted the Xe Kong portion of the river basin within Lao PDR for the most intensive development due to its conducive topography and abundant and well-watered river basins.

The first hydropower development study to focus specifically on in the Xe Kong basin in Lao PDR was the 1995 "Master Plan Study on Hydroelectric Power Development in the Se Kong Basin", prepared by the Japanese International Development Agency.[8] The JICA study encompassed the entire basin, and inventoried potential projects >10 MW as independent projects rather than as an integrated approach to power development. The study was conducted with topographic maps at the scale of 1/50,000 but without precise flow data for the specific sites. The study was conducted in two stages: (1) a study of hydropower potential, which identified 15 sites, three of which were on the mainstream; and (2) a pre-feasibility study of three selected projects; the Xenamnoi dams, the Xe Kaman 1 dam, and Xe Kong 4 dam were specifically featured. Of these, the first is operating, the second has just been constructed, and the third is still being planned. The JICA Master Plan also cites information from the 1984 report of the Mekong River Committee, which identified another potential project at the Xe Kong 5 dam site, which is still under active study under a MOU renewed most recently by the MPI on February 5, 2014. That scheme is described in Section 4 of this Master Plan.

The Xe Kong 4 scheme is a mainstream project that has undergone several alterations and is still under active investigation at two sites[9], under a MOU for a feasibility study that was reissued most recently by the Ministry of Planning and Investment (MPI) on November 6, 2015. This project is discussed in more detail in Section 4 of this Master Plan. This project was initially identified by the Mekong River Committee (the predecessor to the Mekong River Commission) in a 1984 study. As assessed by JICA, the Xe Kong 4 project would have an installed capacity of 443 MW and produce 1816 GWh/y and 137 m head.

The environmental impact assessments of the projects featured in the JICA Master Plan are scant at best:

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[7] At the time the report was produced, the U.S. Army Corps of Engineers was led by Raymond Wheeler.

[8] Master Plan Study on Hydroelectric Power Development in the Se Kong Basin in the Lao People's Democratic Republic, March 1995, by Japan International Cooperation Agency (JICA).

[9] The JICA study notes the presence of coal seams in the vicinity and, indeed, a major coal mine has since been developed at Ban Chakeui. Plans to expand that mine have resulted in the original Xe Kong #4 dam site being split into two, one above and one below the mine to avoid conflicts with it, and the entire village of Ban Kaleum has been relocated.

- **Flow characteristics:** The JICA Master Plan assumes that mainstream Xe Kong dams would be operated in a hydropeaking mode, and also would be operated to make seasonal and annual flows more uniform. Yet, the discussion of the environmental impacts of the flow alteration is cursory. In two paragraphs on page 11-13, the JICA Master Plan asserts that the operation of the dams would have a "favorable" effect on the downstream flow patterns by increasing the dry flows and decreasing the rainy season flows, exactly the opposite of what the migratory fish need. In passing, it does note that daily fluctuation in flows due to hydropeaking might "present a danger to people using boat transport, fishing, bathing, doing laundry and the like". In estimating power potential, the study assumes operations that would provide for minimum environmental flows during the driest months of two-thirds of mean monthly discharge (S-18).

- **Fish migrations:** Pages 11-16 acknowledge that the dams will affect spawning of migratory fish by hindering their ascent and descent, and that the projects "may therefore bring about a decline in their numbers". Yet, even this one sentence treatment of this issue is dismissed by citing the increase in fish yield from fish farming in the Nam Ngum reservoir.

- **Sediment flows:** Effects are discussed in four short paragraphs on page 11, and most of the information is incorrect. It states that the main impact of reservoirs on downstream channels is the scouring of the foundations of existing structures, which the Master Plan rates as negligible because of the paucity of bridges in the Xe Kong. Impacts from sediment changes due to dams on the Xe Kong on the Mekong River and its delta are also judged to be negligible because the catchment is only about 1% of the Mekong basin. Even the damping of the flood discharge is not deemed to have much effect on sediment transport. The JICA Master Plan is oblivious to the importance of the sediment and nutrient contribution for the maintenance of the Tonle Sap Great Lake and the Mekong Delta, which is discussed at some length in Sections 2 and 5 of this Master Plan.

In summary, the JICA Master Plan is now obsolete for two reasons: (1) it assessed dams that have now either already been constructed or for which the plans have now been substantially altered, and (2) its treatment of the main considerations for sustainability of hydropower development is quite inadequate. This merely shows how far the paradigm for sustainable hydropower development has evolved over the more than 20 years since that JICA Master Plan was rendered.

A few years after the JICA Master Plan was published, the Asian Development Bank sponsored a study by Halcrow on hydropower development potential in the Xe Kong and other basins[10]. Its objective was to carry out a preliminary analysis of 37 hydropower schemes then under consideration in the Se Kong, Se San and Nam Theun River basins and to assess and rank them on the basis of their relative socio-economic financial, environmental and social merit. Thirteen of the schemes were identified as meritorious[11] including seven in the Xe Kong basin: the Xe

[10] Summary of ADB Se Kong – Se San and Nam Theun River Basins Hydropower Study, Final Report (Halcrow, 1999).

[11] The net present value of these is positive at discount rates of 8% and 10% but marginally negative at 12%. The average supply costs (at a discount rate of 10%) is 3.40 UScents/kWh.

Katam, Houay Lamphan Gnai, Xe Kaman 3, Xe Kong 4, Nam Kong 1, Xe Kong 5, and Xe Kaman 1[12]. Of these 13, six were selected for further study, including in the Xe Kong basin, Xe Kaman 3 and Nam Kong 1. The first of these is already constructed, and the second has been awarded a concession agreement and the construction is about to begin at the time of this writing.

Regarding the environmental impacts of the selected project, Halcrow concludes that:

> "Although some dam projects could have severe negative impacts, such as route blockage for migrating fish, effective mitigation measures can be introduced in many cases. Upstream migration may be partly mitigated by the installation of a fish pass or fish lift. However, the success of such devices has yet to be proven on the Mekong. There is a need for fisheries and environmental specialists to carry out detailed baseline surveys well before any dam design process is underway to assess the impact on fisheries (Page 1.4.3)."

Sections 5 and 8 of this Master Plan call into question the assertion that the impacts of these dams on migratory fish can be mitigated due to the effects of the reservoir. For this reason, and because of the limited scope of the Halcrow assessment, its value is now questionable.

Expertise and Institutional Engagement

The scope and design of the Master Plan was devised in close consultation with the MEM, under the particular guidance of the former Vice Minister, and the former Director General of the Department of Energy Planning and Policy. However, at their request, this Master Plan was prepared independently of MEM so as to assure that it would be based purely upon scientific and technical considerations and would not be viewed as shaped by the policies. Accordingly, MEM makes no pre-commitment to the findings and conclusions until it has the opportunity to consider it on its merits and suggested that the project proceed under a MOU with a scientific research agency of the Government of Lao. The Natural Heritage Institute acceded to this prudential approach by executing a MOU with the National University of Lao, which has cooperated in some aspects of this study.

Relationship to agencies of the Lao Government

The Master Plan has also been shaped through consultations with the Ministry of Planning and Investment, Ministry of Natural Resources and Environment and the Ministry of Agriculture and Forestry. The project is official sanctioned by an Operations Permit issued by the Ministry of Foreign Affairs. The roles of the various agencies at the national and provincial levels in the execution of the project are set forth in Table 1-1 below:

[12] The study found that Xe Kong 4, Se Kaman 3 and Nam Kong 1 had a positive net present value, but Xe Kong 5 had a marginally negative value.

Table 1-1. Roster of Lao Government Agencies and their role in the Project

Agency	Ministry or Province	Role
Department of International Organizations	Ministry of Foreign Affairs	Permit issuance
Department of Energy Policy and Planning	Ministry of Energy and Mines	Involved since inception-project design in close consultation
Department of Investment Promotion	Ministry of Planning and Investment	Advise on status of MOUs
National University of Lao	Ministry of Education	Lead role in literature review and participating in workshop of foreign and local experts on Xe Kong fisheries
Living Aquatic Resources Research Center	Ministry of Agriculture and Forestry	Review and comment on fisheries assessment
Department of Livestock and Fisheries	Ministry of Agriculture and Forestry	Review and comment on fisheries assessment
Department of Environment and Social Impact Assessment	Ministry of Environment and Natural Resources	Sustainability criteria review
Department of Agriculture and Forestry	Sekong Province	Consultation, review and comment
Department of Planning and Investment	Sekong Province	Consultation, review and comment
Department of Agriculture and Forestry	Attapeu Province	Consultation, review and comment
Department of Planning and Investment	Attapeu Province	Consultation, review and comment

The project team

To satisfy the need for a high-level of specialized, technical expertise for the Master Plan, NHI assembled an international team of distinguished experts with a depth of experience covering the full range of disciplines needed. Technical inputs were also provided by the Ministry of Energy and Mines, the National University of Lao, the Living Aquatic Resources Research Center of the Ministry of Agriculture and Forestry, the Ministry of Planning and Investment, and the Ministry of Natural Resources and Environment. The Mekong River Commission is a "cooperating agency". The roster of NHI team of experts working on the project is attached as Annex 1.1. The scientific basis for the Master Plan was developed in a workshop of, and series of consultations with, Lao and foreign experts on the Xe Kong fishery. The findings and conclusions from that process are presented in Section 5 of this Master Plan. The roster of experts who contributed to the findings and conclusions is presented in Annex 5.2.

Funding for the Master Plan

While this work to assist in implementing the new Policy on Sustainable Hydropower is undertaken in consultation with and for the benefit of the Government of Lao and its people, these are not the "clients" of NHI in the traditional sense, nor is NHI a commercial consulting firm. Rather, NHI (www.n-h-i.org) is a non-profit, charitable, and non-governmental organization, whose mission is to restore and protect the natural functions that support water-dependent ecosystems and the services they provide to sustain and enrich human life. Since its inception, NHI has been working to recreate a world where rivers function like rivers again in harmony with human needs. We have done this work in major river systems throughout the US, and in Asia, Africa and Latin America, often focusing on trans-basin systems.

Funding for this work was not provided by the Government of Lao, and the work was not conducted under its command or control. Rather, the funds were provided from grants conferred by the United States Agency for International Development and two private foundations: The Mac Arthur Foundation and the Margaret A. Cargill Foundation. The content of the Master Plan is entirely the responsibility of the Natural Heritage Institute and does not necessarily reflect the views of the funders or the collaborating institutions in Lao PDR.

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2. Hydrology, Morphology and Sediment

Xe Kong River Basin

The Xe Kong, Se San, and Sre Pok drain the Ammanite Mountains of Laos and Vietnam (and including the Bolaven and Kon Tum plateaus), flow westward to converge just above their confluence with the mainstream Mekong River, upstream of the city of Stung Treng, Cambodia, about 500 km upstream of the Mekong Delta (Figure 2-1). Collectively, the three rivers are known as the "3S" rivers. They represent approximately 10% of the total Mekong drainage area of 795,000 km².

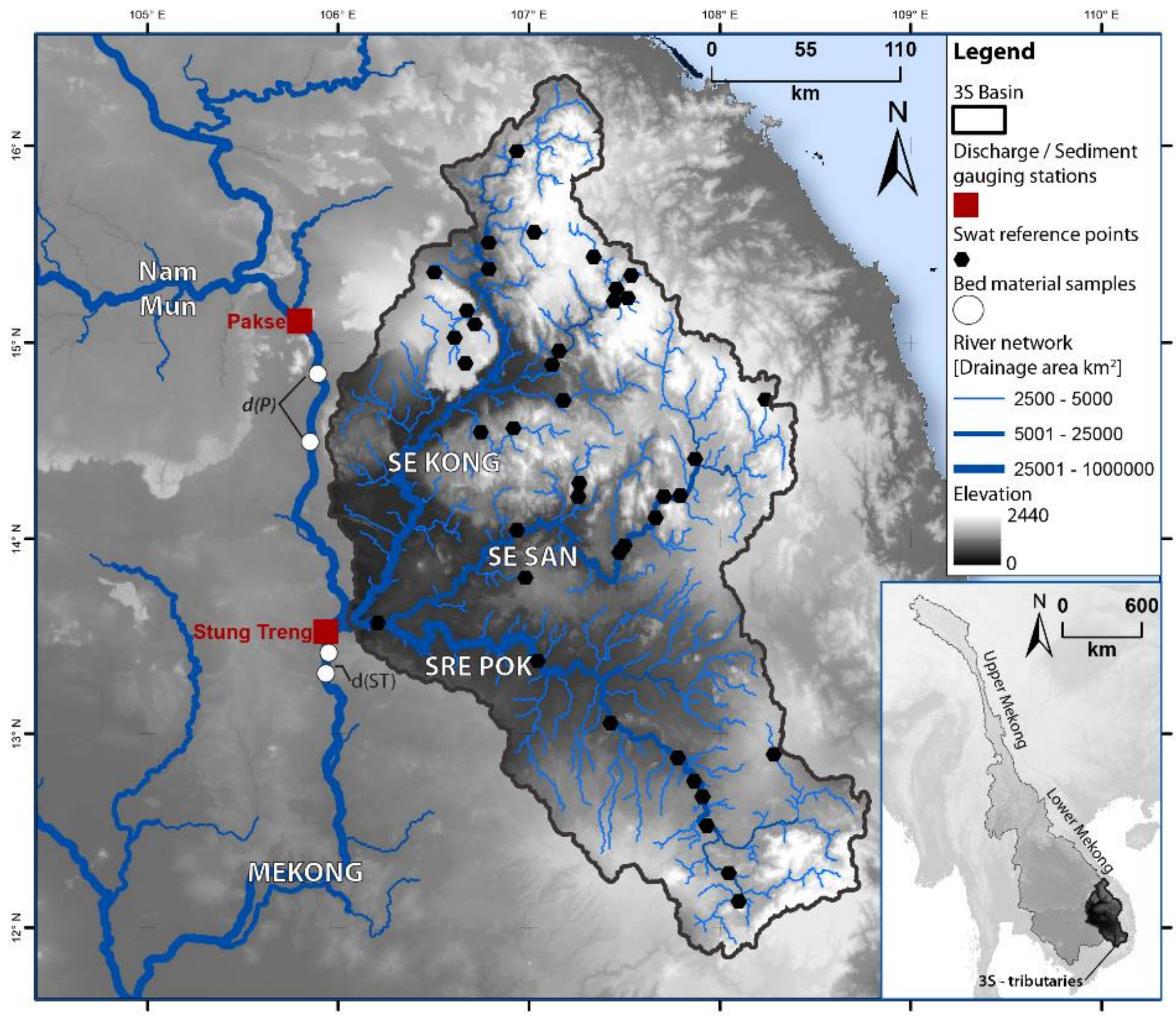

Figure 2-1. Overview of the 3S basin and its confluence with the lower Mekong and the entire Mekong basin (small panel). Locations of sediment gauges (red squares) (Koehnken, 2012a, 2012b), reference points of a hydrologic model (black hexagons, Piman et al. 2013).

The total river length of the Xe Kong is about a third of the total length of the 3S rivers (see Table 2-1). The Xe Kong River basin is characterised by a diverse range of topographical features ranging from mountainous to flat terrain. The fast-flowing streams in the north are characterised by rocky reaches creating rapids interspersed by deep pools. In the reach downstream of the proposed Xe Kong 5 dam site, there are 14 sets of rapids and 18 deep pools. The southern lower reaches (Attapeu Region) are broad floodplain areas (134 km downstream of Xe Kong 5 Dam site) characterized by slower flowing water, sandy substrate, few rapids and deep pools. Below the confluence with the Xe Kaman River, the river flows through a wide floodplain with few rapids and eight deep pools. In the Lao PDR part, the Xe Kong river differs from other Mekong tributaries as there is little flooded forest. There are two major NBCA's (National Biodiversity Conservation Areas) in the watershed, the Xe Xap of 1,499 km^2 (in the north; see Figure 2-2) and the Dong Amphan of 1,998 km^2 (in the east; see Figure 2-2).

Table 2-1. Comparison of watershed areas, river length and flooded forest areas of the Lower Mekong Basin (LMB) for the area above the Lower Se San2 (LSS2) hydropower dam and the Xe Kong River. For the Xe Kong River, only a part of the Stung Treng watershed is included. The Xe Kong River has 4.4% of the LMB area, 33.5% of the 3S river length and has 103km^2 flooded forest in Cambodia and only 33km^2 in Lao PDR.

Watershed Areas	**Km^2**	**% of Mekong Basin**	**% of the LMB**
Entire Mekong Basin (drainage area)	795,000		
Lower Mekong Basin (LMB)	665,740	83	
3S (Se San + Sre Pok + Xe Kong) Rivers	82,400	10.3	12
2S (Se San + Sre Pok) Rivers above LSS2	54,556	7	8.2
Above Sambor Hydropower Project (HP)	568,354	71.5	85.4
Below Sambor HP	97,386	12	14.6
Xe Kong (part of Stung Treng)	29,218	3.7	4.4
Cambodian Flooded Forest Area	**Km^2**	**% of Total Flooded Area**	
Total Cambodia area east of the Mekong	2,136		
Above LSS2 Hydropower Project	966	45	
Above Sambor HP	1,444	68	
Above Xe Kong in Cambodia	70	3	
Xe Kong Total Forest Area Flooded in Cambodia	103		
Xe Kong Total Forest Area Flooded in Lao PDR	33		
River Length	**Km**	**% of 3S Length**	
3S (Se San + Sre Pok + Xe Kong) Rivers	14,315		
2S (Se San + Sre Pok) Rivers	9,518	66.5	
Xe Kong River	4,797	33.5	
Se San River	2,681	19	
Sre Pok River	6,837	47.8	

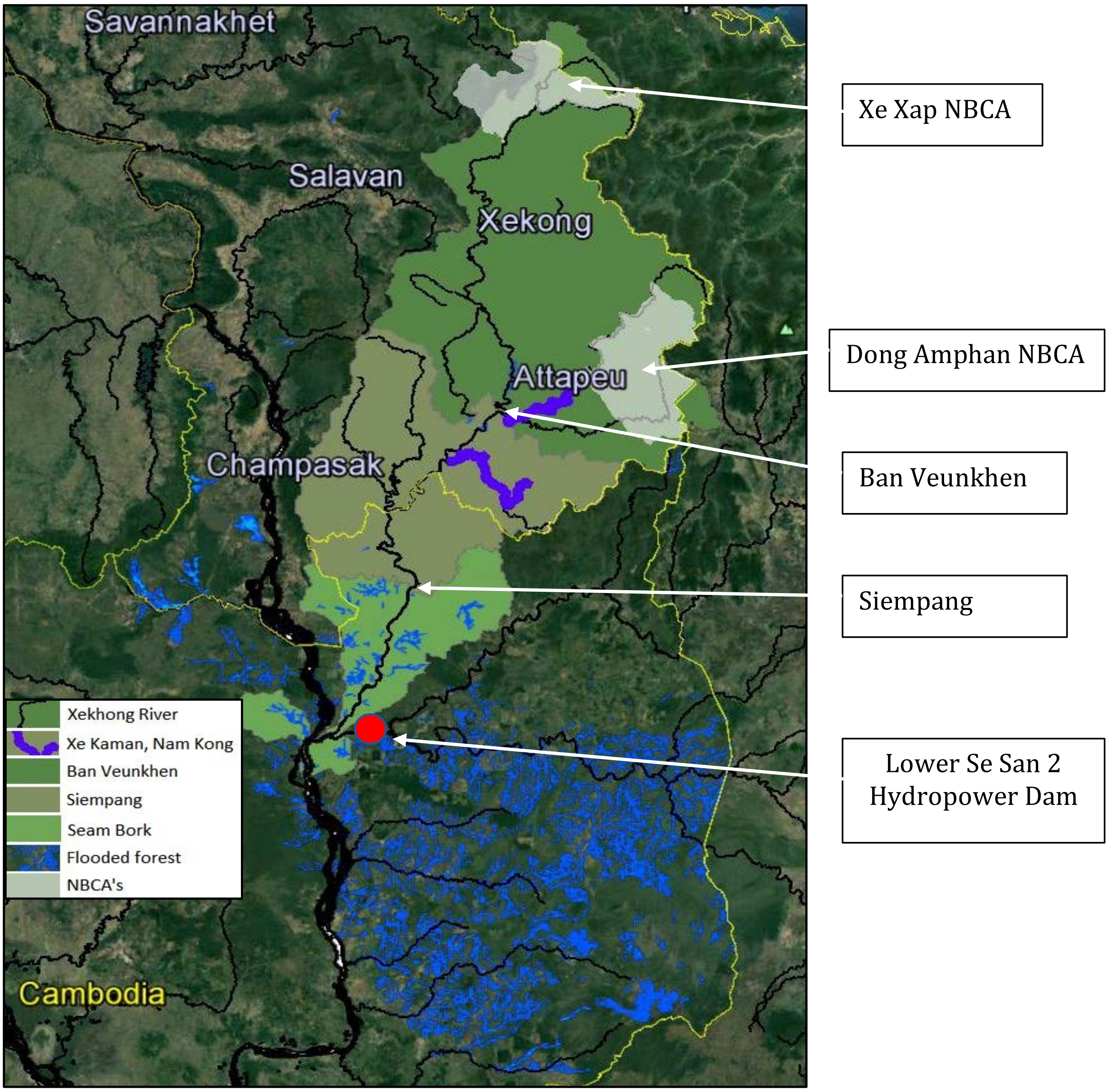

Figure 2-2. The Xe Kong River watershed with NBCA's and flooded forests; red dot indicates the location of the Lower Se San 2 hydropower dam. For flooded forest around Attapeu, see Figure 2-3.

Figure 2-3. Flooded forest areas in the Xe Kong basin covers only around 33 km^2. In the Cambodian part of the Xe Kong there are large flooded forest areas, see Figure 2-2.

The floodplain area of the Xe Kong River is substantial (see Figure 2-4 for extent in Xe Kong and Xe Kaman River, Attapeu Province) and likely one of the key factors contributing to its impressive fish productivity and diversity (Welcomme, 1995). It consists of seasonal and permanent wetlands, streams, forests, grasslands and rice paddies. High water levels during the rainy season provide a food-rich environment for spawning fish as well as productive soil for the cultivation of rice and other cash crops. Many fish species that spawn on the floodplain migrate seasonally over long distances into the headwaters of the river system (Poulsen and Viravong, 2001), suggesting that the extensive floodplain habitat has biological and socio-economic benefits for both upstream and downstream communities. Floodplains are unquestionably the engine of high fish production and rich biodiversity, and serve important ecological roles for the entire river basin (Coates, D *et al*., 2003). They support a significant fishery for both local and national demand. Conserving this habitat is essential for protecting biodiversity and providing food security for rural households. But for flooded forest, only 3% falls in the Xe Kong watershed, against 45% above the LSS2 dam in the Se San and Sre Pok sub-basins (see Table 2-1). And, flooded forest on the Xe Kong in Lao PDR counts for only 33km^2 around Attapeu or about 1.4% of the flooded forest east of the Mekong River. The Xe Kong River therefore differs from the Se San and the Sre Pok Rivers in its relative paucity of lowland flooded forests and by its steeper rapid/pool dominated reaches.

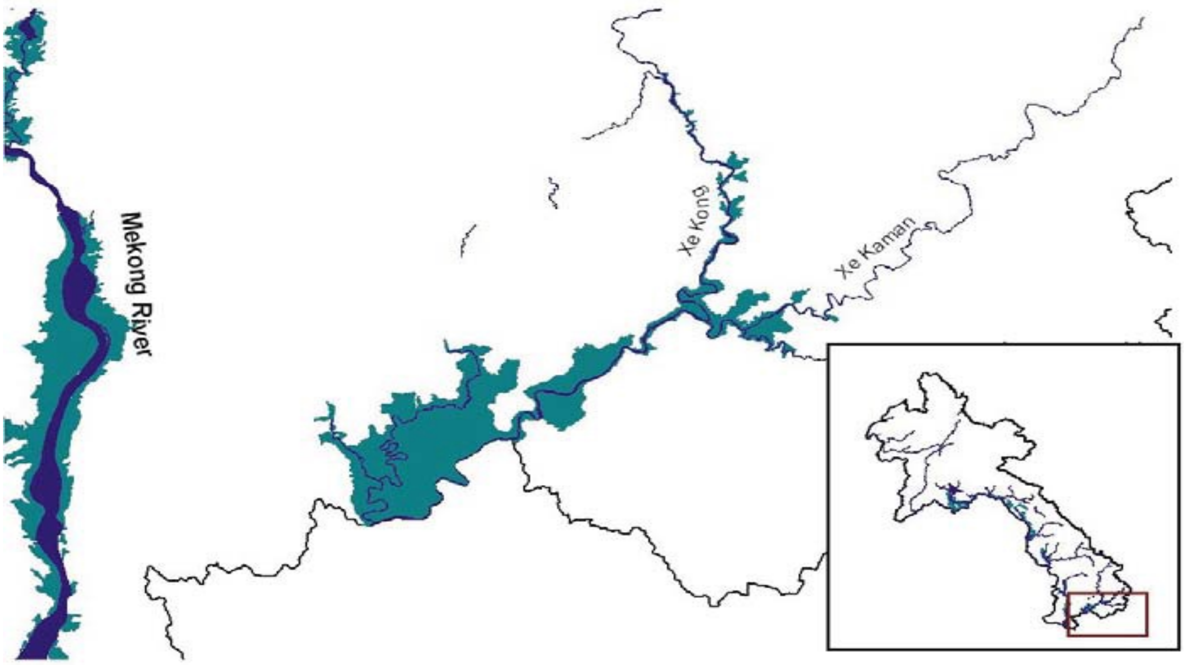

Figure 2-4. Extent of floodplains of the Xe Kong and Xe Kaman rivers - Attapeu Province. Source. *Mollot et al.,* 2003.

Xe Kong Hydrology

Water level and discharge

Data from two hydro meteorological stations was used to assess the hydrology of the Xe Kong River. One is in Lao PDR (430106 Ban Veunkhen (near Attapeu)) and one is in Cambodia (430102 Siempang). They cover the northern and the middle watershed of the river. As all hydropower development takes place above the Siempang station, the lower watershed below Siempang, which is not covered by a station, is not included, see Table 2-2 (Jensen, 2016).

Table 2-2. Hydro meteorological monitoring stations (See Figure 2-2).

No.	Station	River	Lat	Long	Country	Zero Gauge MSL (m)
430106	Ban Veunkhen	Sekong	14.81920	106.80566	Lao PDR	97.042
430102	Siempang	Sekong	14.11527	106.38777	Cambodia	48.000

(MSL: Kolak Datum =almost equal to Ha Tien).

The water level on the Xe Kong River fluctuates greatly, especially in the wet season, where it can change up to 12m in a few days (Figure 2-5).

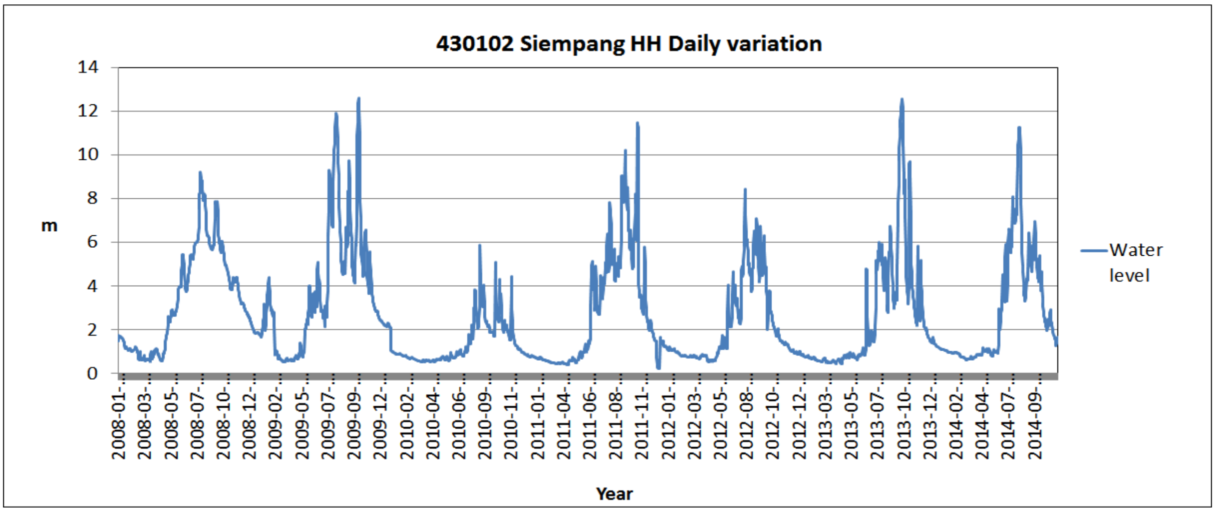

Figure 2-5. The water level at Siempang station from 2008 to October 2014. See MSL (Kolak) in Table 2-2.

The minimum water level in the period 2009-2015 was 0.54 m and the maximum 13.58 m. A similar large change in discharge was monitored at the Siempang station during this time period (Table 2-3). The average discharge at Siempang during the period 2001 to 2014 was around 43 km^3 per year.

Table 2-3. Xe Kong River discharge and water level at Siempang station.

	Average	Min	Max
Water level (2009-2015, m)	3.37	0.54	13.58
Discharge (2009-2015, m^3/s)	1,411	149	10,398

The large fluctuations during the wet season are due to northeast cyclones passing the Annamite mountains, precipitating heavily on the Lao PDR and Cambodian sides. The peak flow can be followed from the Ban Veunkhen station to the Siempang station, as the pattern of Ban Veunkhen is the same at Siempang and synchronized with the monsoon landfalls. The peaks arrive on average 10.4 days later at Siempang, giving an average velocity of 0.16 m/s on an average slope of 0.029% (Figure 2-6).

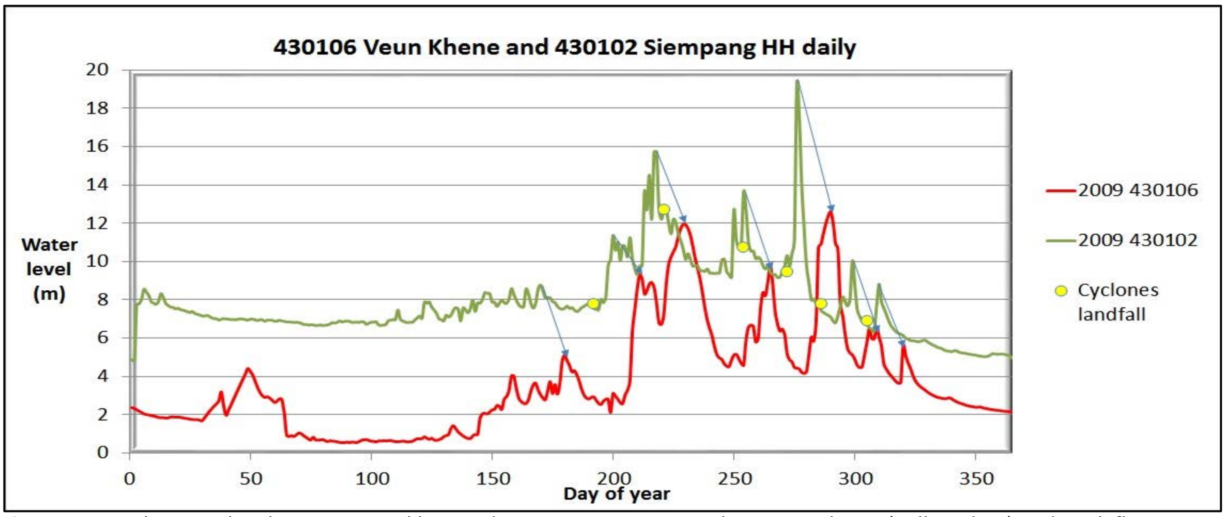

Figure 2-6. Daily water levels at Ban Veunkhen and Siempang year 2009, showing cyclones (Yellow dots) and peak flow delays. The fluctuations in water level are mainly due to cyclones creating heavy precipitation.

The water level in the dry season did not change in the period from 2001 to 2014, indicating that the small hydropower stations already constructed in 1999 and 2012 do not affect the discharge (Figure 2-7).

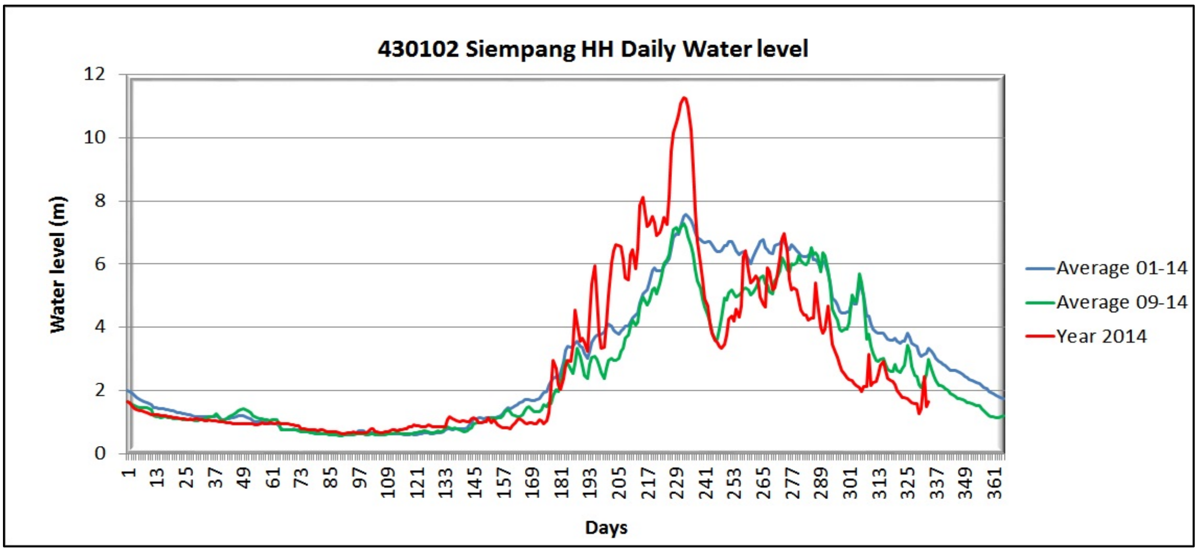

Figure 2-7. Daily average water level at Siempang 2001-2014, years 2009-2014 and year 2014 show same water level in the dry season; no change by hydropower operation is observed.

There are no daily fluctuations (peaking) visible in the wet season, also indicating that until 2014, hydropower did not affect the Xe Kong River flow (Figure 2-8).

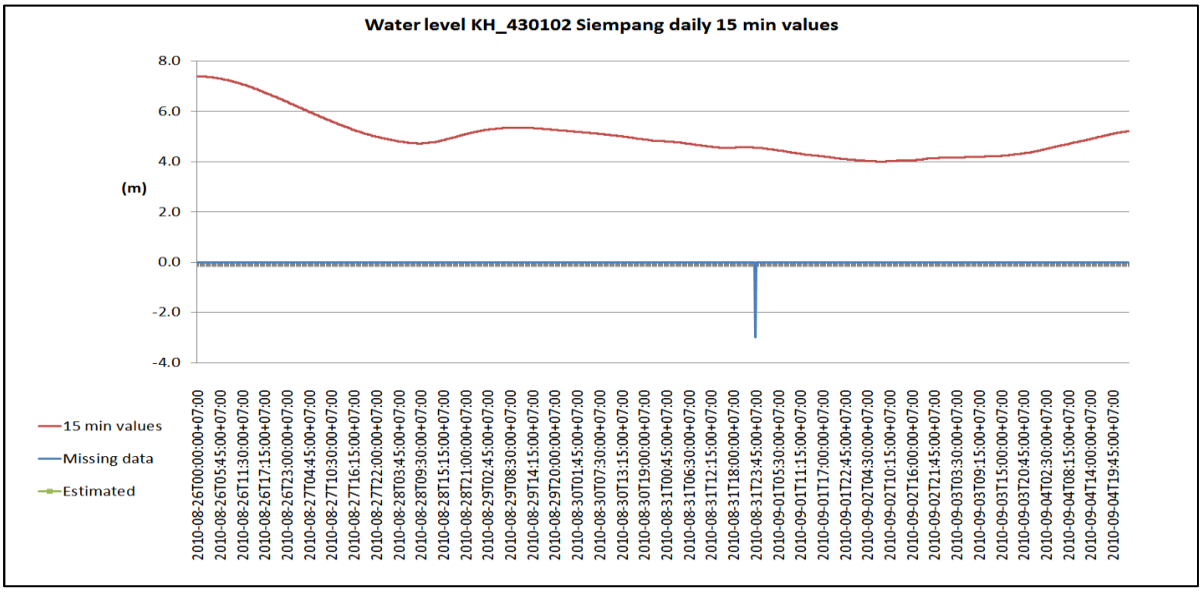

Figure 2-8. Minimum water levels from 26 August 2010 to 4 September 2010 show no daily peaking due to hydropower.

Flood frequency analysis

Data on flood levels (locally established gauges when water overflow the riverbanks) are not available for the 430106 Ban Veunkhen and 430102 Siempang stations. Based on the flooded forest lineation (Figure 2-4), the flood level is estimated to be 12m above local zero at Ban Veunkhen, because the water level of the flooded forest around Attapeu in flooded years exceeded this 12m water level. This level was experienced for 67 days during the years from 2001-2014 and reached a maximum of 19.2 m in 2009. The probability of exceeding the flood level of 12m is 1.2%, expressed in terms of days (see Figures 2-9 and 2-10). Flooding in these areas is a direct result of heavy monsoon precipitation or cyclones rather than from river overbank flow. Flooding takes place every year in the Cambodian part of the Xe Kong, see the extent of the flooded forest in Figure 2-2. The recurrence interval has uncertainty as only 13 years of data from 2001-2014 are available.

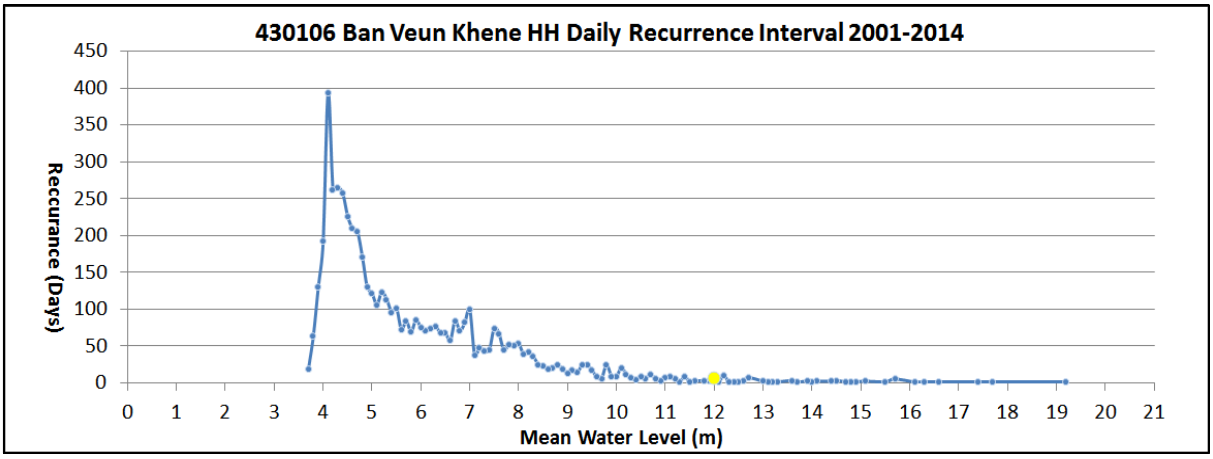

Figure 2-9. The probability of exceeding the estimated 12m flood level (yellow point) above local zero is 1.2%.

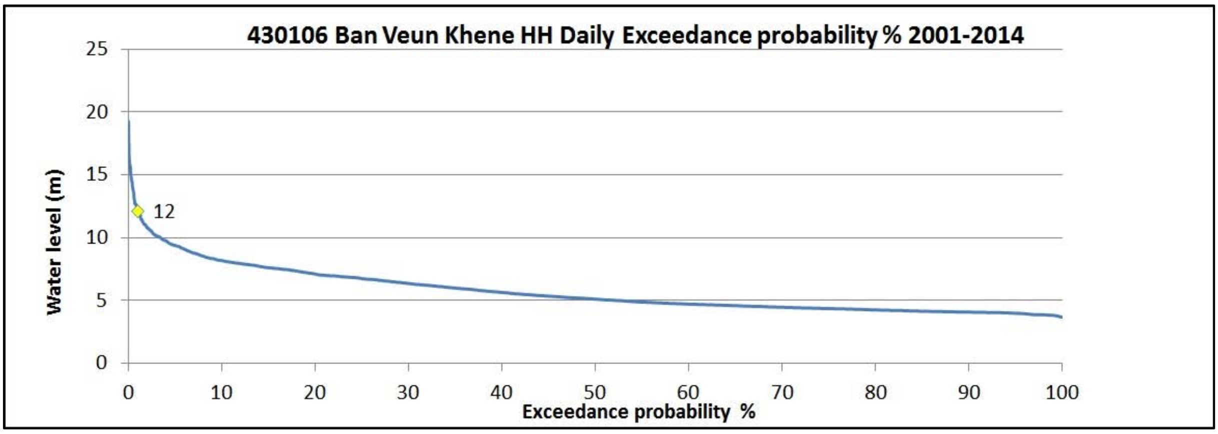

Figure 2-10. The number of days with water level higher than or equal to 12m (yellow point) in the period from 2001-2014 was 67 days or 1.2% of the days. Water level around 4m above local zero is most recurrent.

Geology and Geomorphology

The geology of the Xe Kong watershed is very complex (Figure 2-11). A simplified view is that the geomorphology is dominated by the high Bolaven plateau to the west and the Annamite mountain range along the border between Lao PDR and Vietnam. The Bolaven plateau rises to between 1000 and 1350 meters above sea level and the Annamite mountains heights exceed 1200 meters within the Xe Kong watershed. This provides for steep slopes, rapids and river valleys with high base rock banks (see Figures 2-12 and 2-13).

The Bolaven plateau consists of igneous rocks like Rhyolite, Andesite, Tuff and Basalt and the Annamite mountains primarily consists of Quartzite, Limestone, Shale, Sandstone and Siltstone. Gneiss, Schist and Marble is present in the southern part of the watershed. All three areas have outcrops of hard bedrock, but are also traversed by numerous fault lines (black lines on the map in Figure 2-11). Along the rivers smaller areas of unconsolidated sediments top the base rocks.

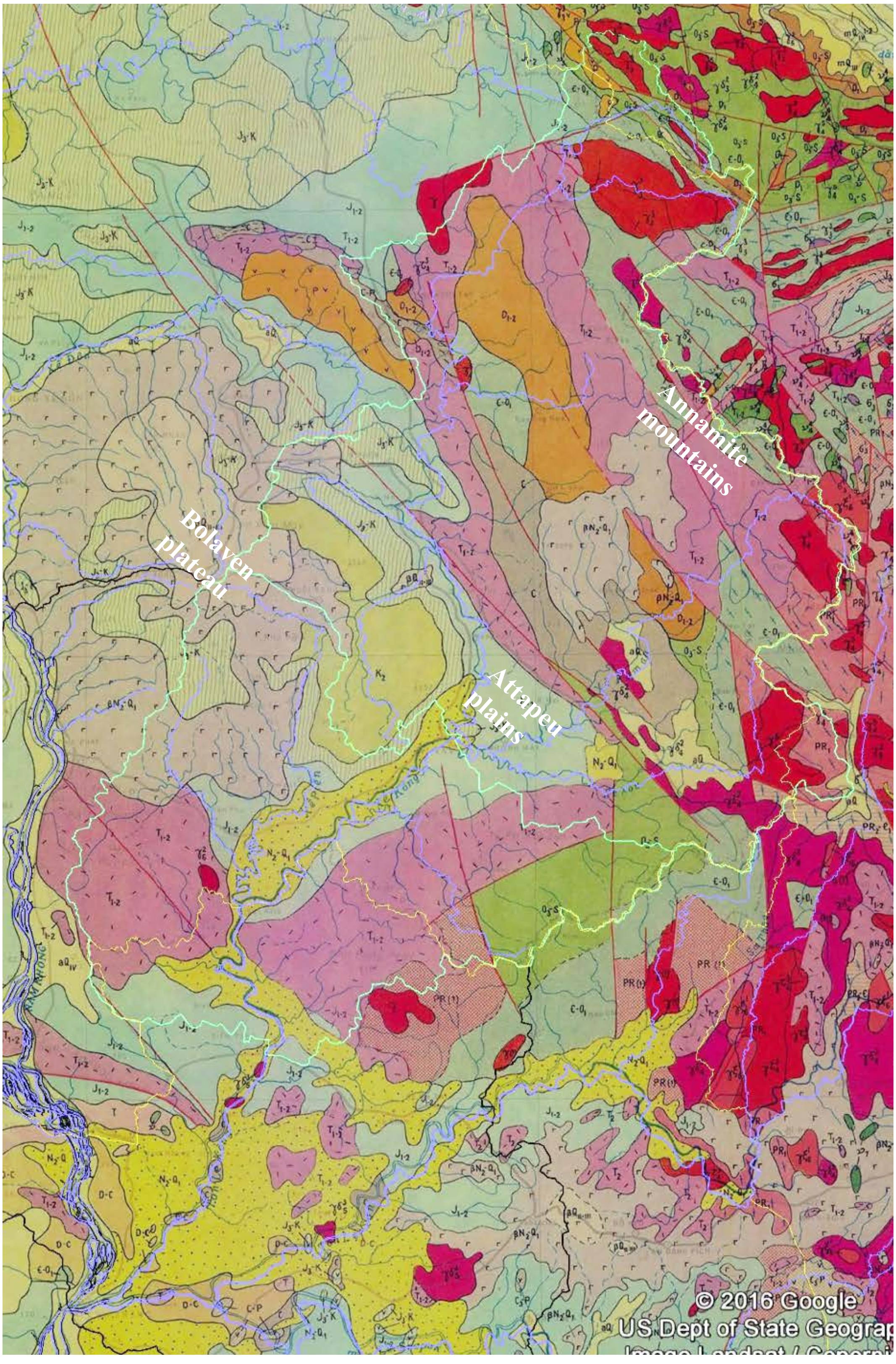

Figure 2-11. Geological map of the Xe Kong watershed. The geology is very complex. Black lines are fault lines.

Figure 2-12. Upper Xe Kong River on bed rock, steep bedrock banks and rapids with fast flowing water. (Photo courtesy of Erland D. Jensen.)

Figure 2-13. Upper Xe Kong pool between rapids and with steep bedrock banks slower flowing water. (Photo courtesy of Erland D. Jensen.)

Rapids and elevation

The mainstream Xe Kong and its tributaries on the Nam Kong and Xe Kaman have steep slopes and bedrock channels upstream of Attapeu, characterized by many rapids with deeper pools between them (Figure 2-14). The longest rapids are up to 500 m and a few have developed into small waterfalls. The lowland around Attapeu has no rapids. (There are more rapids in the highland of the Xe Kaman and Nam Kong Rivers, not included in Figure 2-14, as satellite image quality was too low to identify rapids.)

The combination of rapids, slow-flowing water in the intervening pools, and sandbars along the confluences of smaller tributaries create a complex of diverse habitats.

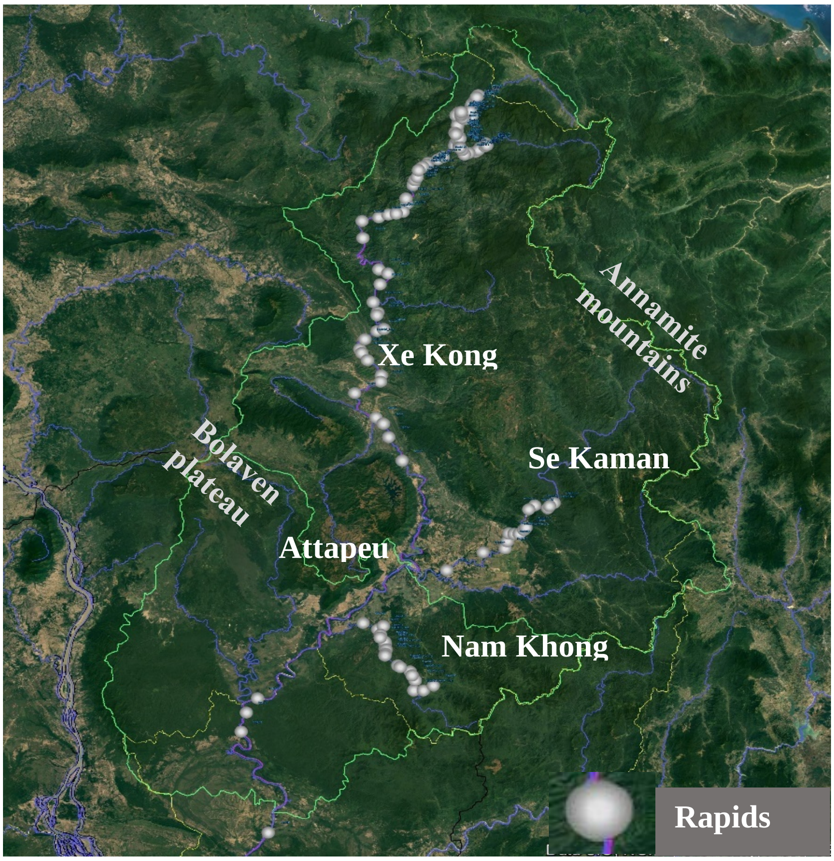

Figure 2-14. Rapids on the Xe Kong, Xe Kaman and Nam Khong rivers.

Sediment Load on the Xe Kong River

Introduction

The 3S basin of the Xe Kong, Se San, and Sre Pok covers a total area of 82,400 km^2 (ca. 10 % of the total Mekong drainage area of 795,000 km^2; see Table 2-1). As mentioned above, they drain the Ammanite Mountains, which, by virtue of their uplift history, are inferred to have relatively high sediment yields (Kondolf *et al.,* 2014). The 3S produces about 20 % of the Mekong River basin's water runoff (Wild and Loucks, 2014) and its contribution to the Mekong's sediment budget is likely over-proportional compared to its drainage area. However, there are no direct measurements of sediment transport or grain-size distribution in the 3S river system itself.

Estimates of sediment load of 3S

Kummu *et al.* (2010), Bravard *et al.* (2014), and Kondolf *et al.* (2014) presented some qualitative estimates on sediment loads from the 3S, but there is nearly no information on the origin of sediment and its movement in the 3S – despite the potential importance of such information given the multiple hydro-power schemes currently planned in the 3S, which could significantly reduce delivery of sediment to the Mekong Delta (Piman *et al.,* 2016; Wild and Loucks, 2014).

While both the total flux and grain-size distribution of sediment transport in Lower Mekong River are contested (Lu *et al*., 2014), some data on total sediment transport and grain-size for the lower Mekong near the 3S confluence are available. Koehnken (2012a) reanalyzed sediment measurements along the Mekong to derive new estimates of total sediment fluxes along the lower Mekong. She reported values of 73 Mt/yr for Pakse, 98 Mt/y for Stung Treng, downstream of the 3S confluence. Subtracting the two values, we obtain (as a residual) sediment inputs from the 3S to be approximately 25 Mt/yr (Wild and Loucks, 2014). While reasonable, like any result obtained by subtraction, they must be taken with some caution (Kondolf and Matthews, 1991). Based on these figures, sediment from the 3S would contribute up to 25% to the total sediment budget in the lower Mekong.

Some regional estimates of sediment yield from the 3S are in the range of 220-240 t/km²/yr (i.e., 18.5 to 20.2 Mt/yr, based on 82,400 km² drainage area) (Kummu *et al*., 2010) to 300 t/km²/yr (i.e., 25.2 Mt/yr) (Kondolf *et al*., 2014), see Figure 2-15.

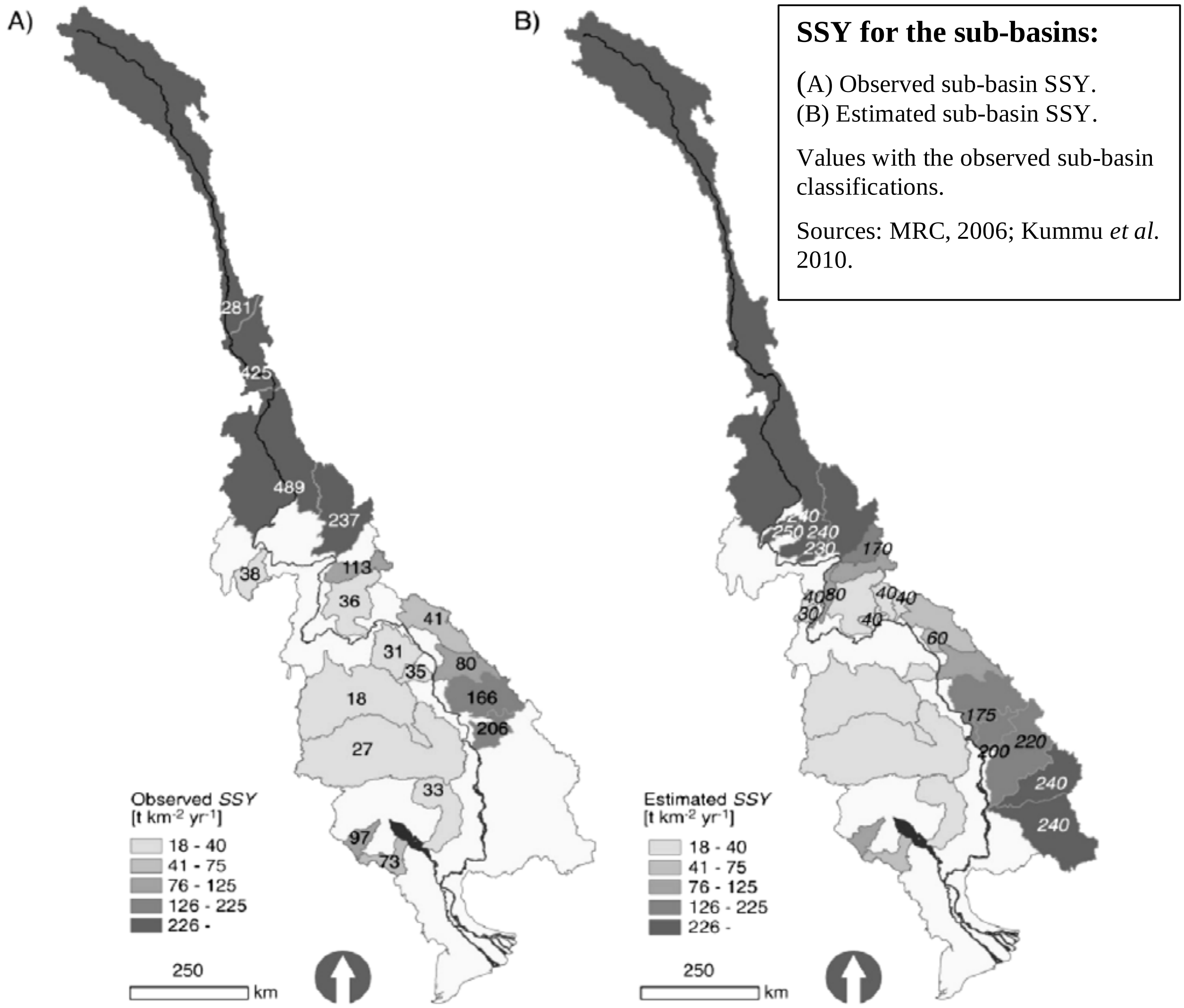

Figure 2-15. The suspended sediment yield (SSY) from the Xe Kong River basin catchment of 29,218 km² in 2006 was estimated to 220 ton/km²/year equal to a total of 6.5 million ton per year.

Grain size

While there are no data on grain sizes or fluxes of sediment from the 3S tributaries themselves, available grain size data from the mainstem Mekong can help constrain the possible loads of the 3S. Koehnken (2012a, 2012b) compiled data on sand grain-sizes (collected by national agencies) along multiple transects on the mainstem Mekong at Pakse and Stung Treng, which indicated a coarsening in the bed-material downstream of the 3S confluence (Pakse: 0.08-0.125 mm, Stung Treng: 0.125-0.25 mm) and increased medium and coarse sand components in the transported sediment (Koehnken, 2012b). While there is some uncertainty regarding the season and flows when samples were taken, additional evidence for a downstream coarsening was provided by Bravard *et al.* (2014), who sampled sandy deposits at different elevations on bed and banks during the low flow season along the lower Mekong. Sampling deposits at different elevations provided evidence of the grain-size distribution of bed material at various flow stages. Bravard collected a total of 10 samples from two sample locations downstream of Pakse, but above the 3S confluence, and a total of 6 samples from two locations downstream of the Mekong-3S confluence at Stung Treng. The mean d_{50} was 0.132 mm in the Pakse reach and 0.182 mm in the Stung Treng reach, with the difference in mean being weakly significant (p=0.07, T-test).

Hence, results by both Koehnken (2012b) and Bravard *et al.* (2014) independently indicate a coarsening of bed material between Pakse and Stung Treng. Coarsening between the sites could be explained by storage of finer sediments on intervening floodplains (Walling *et al.*, 1998), greater suspension in higher stream power reaches, or contribution of coarser sand from the 3S tributary. The Pakse - Stung Treng reach is dominated by confined bedrock channels with rare overbank flows (Carling, 2009) and potentially little floodplain storage. Stream power is elevated in some parts of the Stung Treng – Pakse reach (around Kone Falls). Stream power is the rate of energy dissipation against the bed and banks of a river or stream per unit downstream length. It is given by the equation: $\Omega = \rho * g * Q * S$, where Ω is the stream power (the energy available to transport sediment), ρ is the density of water (1000 kg/m^3), g is acceleration due to gravity (9.8 m/s^2), Q is discharge (m^3/s), and S is the channel slope. Stream power in the reaches where samples were taken (above and below the 3S confluence) is very similar (< 50 W/m^2, Bravard *et al.*, 2013). Thus, the coarsening of bed material between Pakse and Stung Treng is attributable to mixing of the sediment flux from the 3S at its confluence with the Mekong.

Results of mixing model and CASCADE sediment network model

Schmitt *et al*. (in press, a) developed a mixing model for sand-sized sediment transport in the 3S, which yielded a range of plausible values of initial grain sizes and supply from various sources in the basin that could result in the observed coarsening of mainstem Mekong grain sizes downstream of the 3S confluence. They also applied the CASCADE model for sand transport (Schmitt et al., 2016) for 7500 realizations (Figure 2-16), resulting in 7500 sets of median grain size and total sand load at the outlet. As expected, realizations that resulted in a finer sand grain size also result in a higher sediment flux due to the greater mobility of the finer sand fractions (Schmitt *et al*., in press, a).

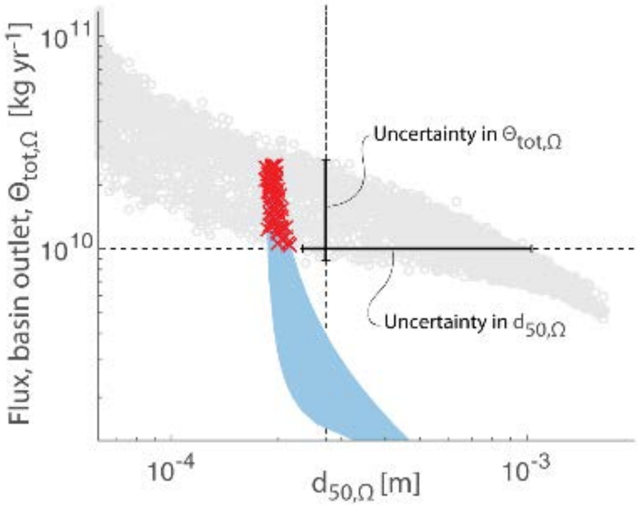

Figure 2-16. Results of the stochastic CASCADE model show a large uncertainty in median grain size (d_50) and sand flux (Θ) at the 3S-Mekong confluence (each grey dot is the result of a different model run). The blue area indicates credible values for sand flux and median grain size derived from Koehnken and Bravard. There is some overlap between model results and observations, which allows us to infer a credible range of sand flux and grain size (Schmitt *et al.,* in press, a.).

The CASCADE model runs are based in part on the sand transport capacity of different channel reaches, essentially a function of stream power (the energy available to transport sediment), which is estimated based on digital elevation data and characteristics observable on remotely sensed data, such as channel width, presence of sand bars, etc. One key result of the modeling was that sand flux from the Xe Kong River to the Mekong should be limited by extensive low-gradient (and thus low transport energy) reaches in the lower Xe Kong (Figure 2-17). While there are headwater reaches with high gradients, the low gradient reaches downstream would limit total sand transport flux through in the Xe Kong River to the mainstem Mekong. In the Sre Pok and Se San, there are sections in which transport capacity decreases abruptly and for multiple subsequent reaches, but the magnitude of decrease is lower than in the Xe Kong River. These sections of low transport constitute controls on the sand that can be conveyed downstream from the upstream parts of the respective tributaries. For example, the Xe Kong River 300 km upstream from the basin outlet cannot convey more bedload than around $1*10^{10}$ kg/yr to the outlet, and the middle Xe Kong (300 to 100 km from the outlet) cannot convey more than around $2*10^{9}$ kg/yr through a section with low transport capacity (Schmitt *et al*., in review, a) (Figure 2-18).

One might expect some accumulation of sand upstream of low-sand-transport bottlenecks, in the expectation that sand transported from steep, rapidly-eroding headwater reaches would be halted upstream of the bottlenecks. While this is a reasonable expectation, and aerial imagery provides evidence for accumulation of sediments at the Xe Kong-Xe Kaman confluence, there is no reason to expect to detect all such effects from satellite imagery alone, as sediment might be stored in deep pools (that are underwater even at low-flow conditions) or on banks.

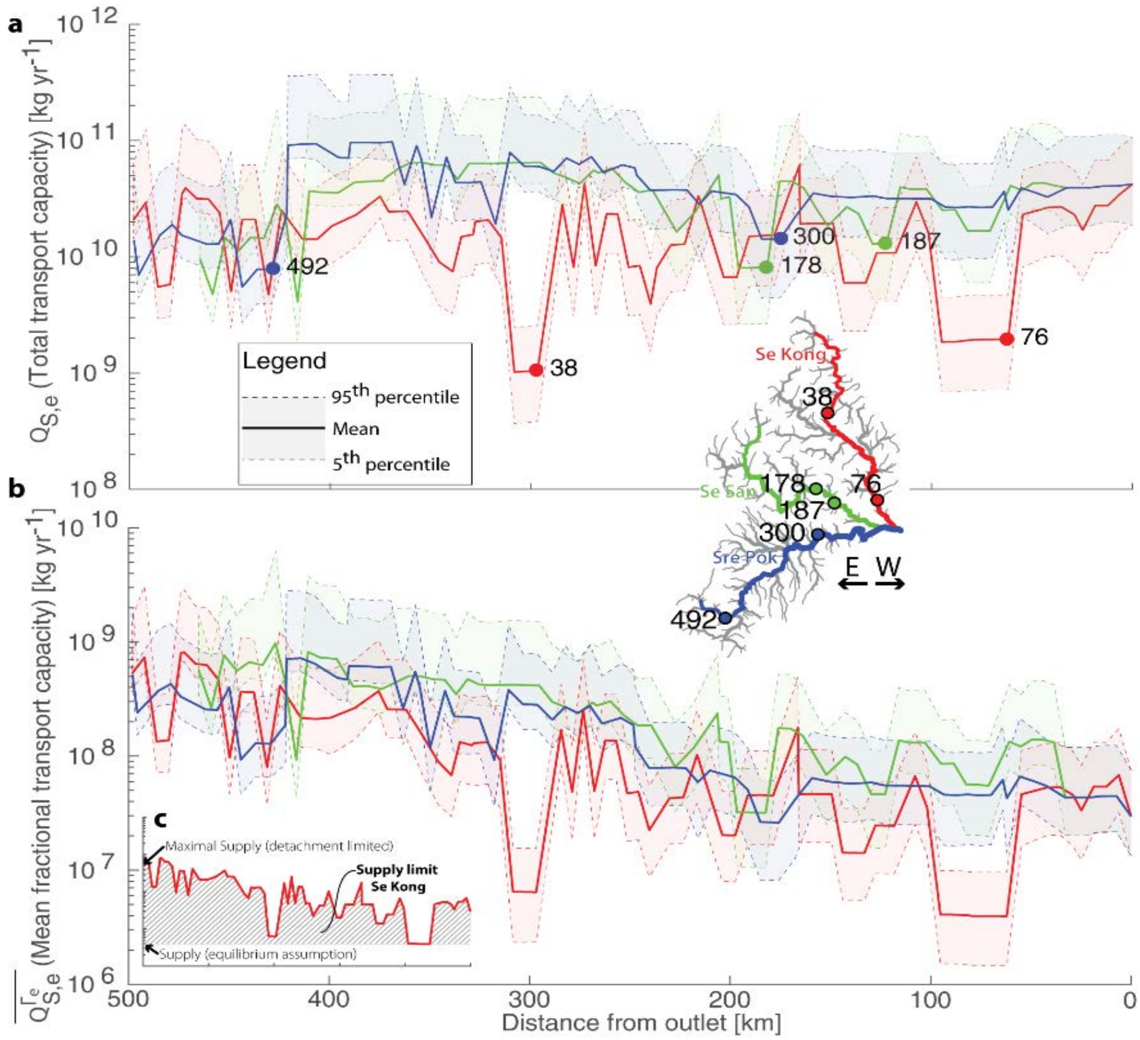

Figure 2-17. Bed-load (sand) transport capacity profiles along the Se San, Se Kong, and Sre Pok Rivers. Values are derived from 7500 stochastic runs of the CASCADE sediment transport model. Note sections of very low transport capacity in the Se Kong (marked with 76 and 38 in the top plot) – these sections effectively limit bed-load conveyance from the upper Se Kong to the Mekong River.

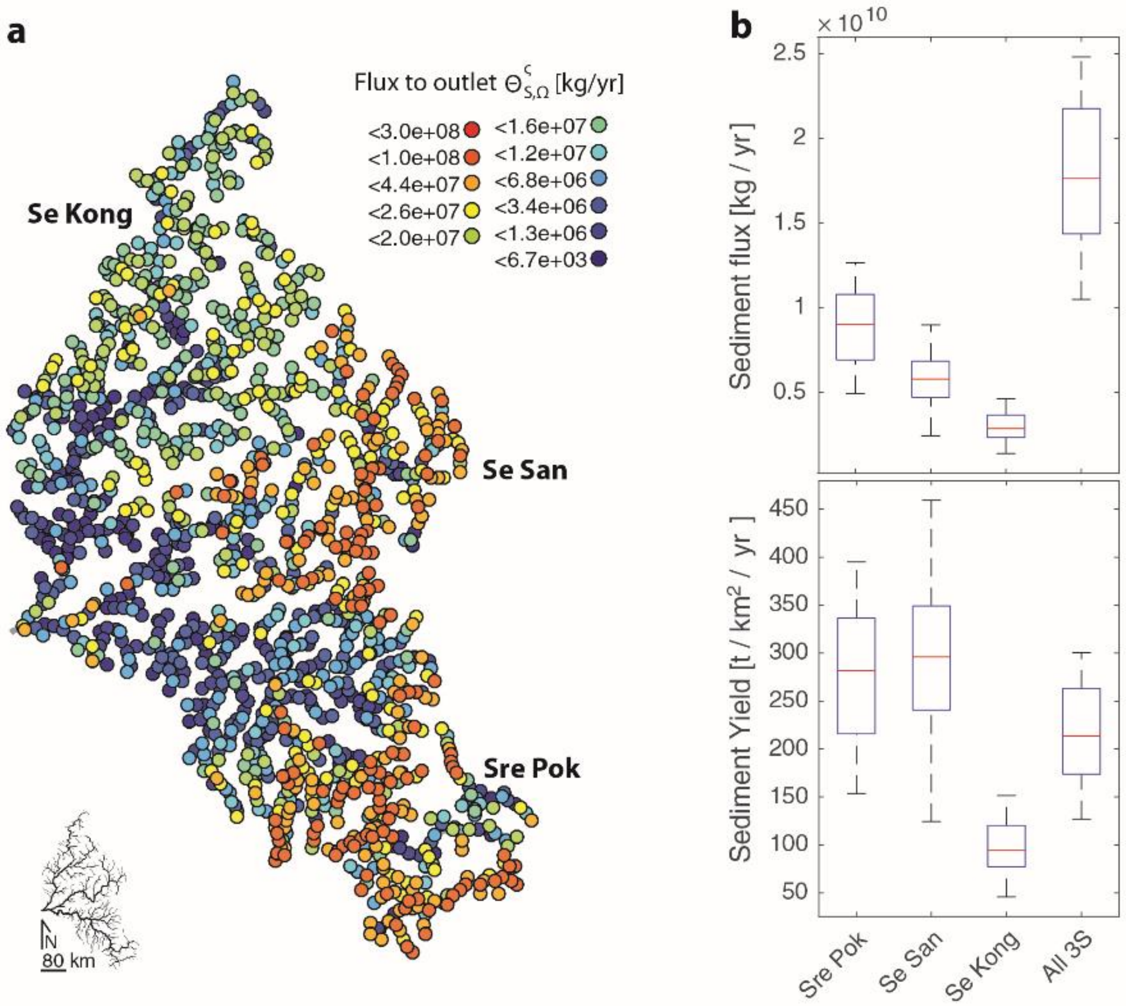

Figure 2-18. Bed-load sediment (sand) conveyance from each reach in the 3S network to the outlet. Note that conveyance is lower from upstream reaches in the Se Kong – this is because of downstream "bottlenecks" of low transport capacity. Panel b shows the resulting sand yield and total contribution of each basin. Error bars and box plots indicate variation over the stochastic model runs.

Estimated sediment (and sand) fluxes with and without planned dams

Sand is particularly important as a building material for the delta and coastal beaches. Sand is commonly transported as bedload during low flows and in suspension during higher flows (when turbulence can maintain the sand in suspension). Most dams trap all bedload (as sand is transported as bedload under the low shear stress conditions in a reservoir impoundment, most of the sand will be trapped), and a fraction of suspended load that is a function of the ratio of reservoir storage to inflowing sediment load. Modeling sand sediment trapping with CASCADE (Schmitt *et al.*, in press, b) found that dams built before the early 2000s only had a minor impact on sand connectivity in the 3S. It was only with construction of Yali dam (operational in 2002), which added 3685 GWh/yr capacity (> 10 % of the basin total) and disconnected the upper Se San River catchment (Figure 2-19C) that sand trapping significantly increased, to 15 % of the pre-1990 sand flux (reducing the sand flux from the 3S to the Mekong to around 12.6 Mt/yr). Hydropower development in the 2000-2010 period was mostly in the upper, Vietnamese catchments of Se San and Sre Pok, leading to a gradual reduction of sand flux to around 6 Mt/yt (see Figure 2-19; compare B and D, maps and box-plots), while increasing hydroelectric capacity to 11000 GWh/yr. It should be noted that some dams with major production potential (e.g., Se

San 3 and 3A) had nearly no added impact on sand connectivity, because they were constructed directly downstream of existing dams, such as Yali. Dams on the upper Sre Pok (Sre Pok 3 and 4) trap 1 and 1.3 Mt/yr, respectively (Figure 2.19D). All dams that became operational by 2017 trap 52 % of the pre-1990 sand output (6.83 Mt/yr).

However, the completion of the dam with the single largest sand trapping effect is imminent. The Lower Se San 2 (LSS2) Dam, the most downstream dam on the Se San/Sre Pok dam cascade (COD 2017, Figure 2-19F) is a large dam whose size would indicate it will trap 100% of all incoming sand. However, there is some uncertainty regarding large low-level gates, whose operation could permit fine-grained sediments and perhaps some fine sand to pass through the dam. Schmitt *et al.*, (in press, b) considered that all sediment that can be conveyed through the impoundment under full-supply level conditions to the dam would be discharged to the downstream rivers - i.e., assuming that there are bottom gates. However, we expect Lower Se San 2 Dam will reduce sand flux to the Mekong by another 80% to 1.3 MT/yr (a 91% reduction compared to pre-1990 conditions). By disconnecting all sand sources in the Se San and Sre Pok from the Mekong, Lower Se San 2 Dam will mute the 3S as source of sand for the Lower Mekong River Basin while adding 1950 GWh/yr production capacity, an increase in total production capacity of 13% compared to the previously existing dams, or 6.4 % of the total potential production capacity. Because Lower Se San 2 is already trapping most sediment, most future upstream dams in the Se San and Sre Pok catchments will have a comparably minor impact on sand fluxes (Figure 2-19, COD after 2020). Hence, the environmental performance of the Se San – Sre Pok hydropower cascades has now been determined by the construction of LSS2. The Cascade model results suggest the trapping of sand transported as bedload in the dams in the Xe Kong river is smaller than the trapping impact on the Se San and Sre Pok. In part this is because (despite the likely high sediment yield from the Xe Kong catchment), the CASCADE model results are sensitive to the low-transport capacity reaches and thus indicate a relatively smaller contribution of sand coming out of the Xe Kong (see Boxplot in Figure 2-19B) and second because most dams are planned relatively upstream.

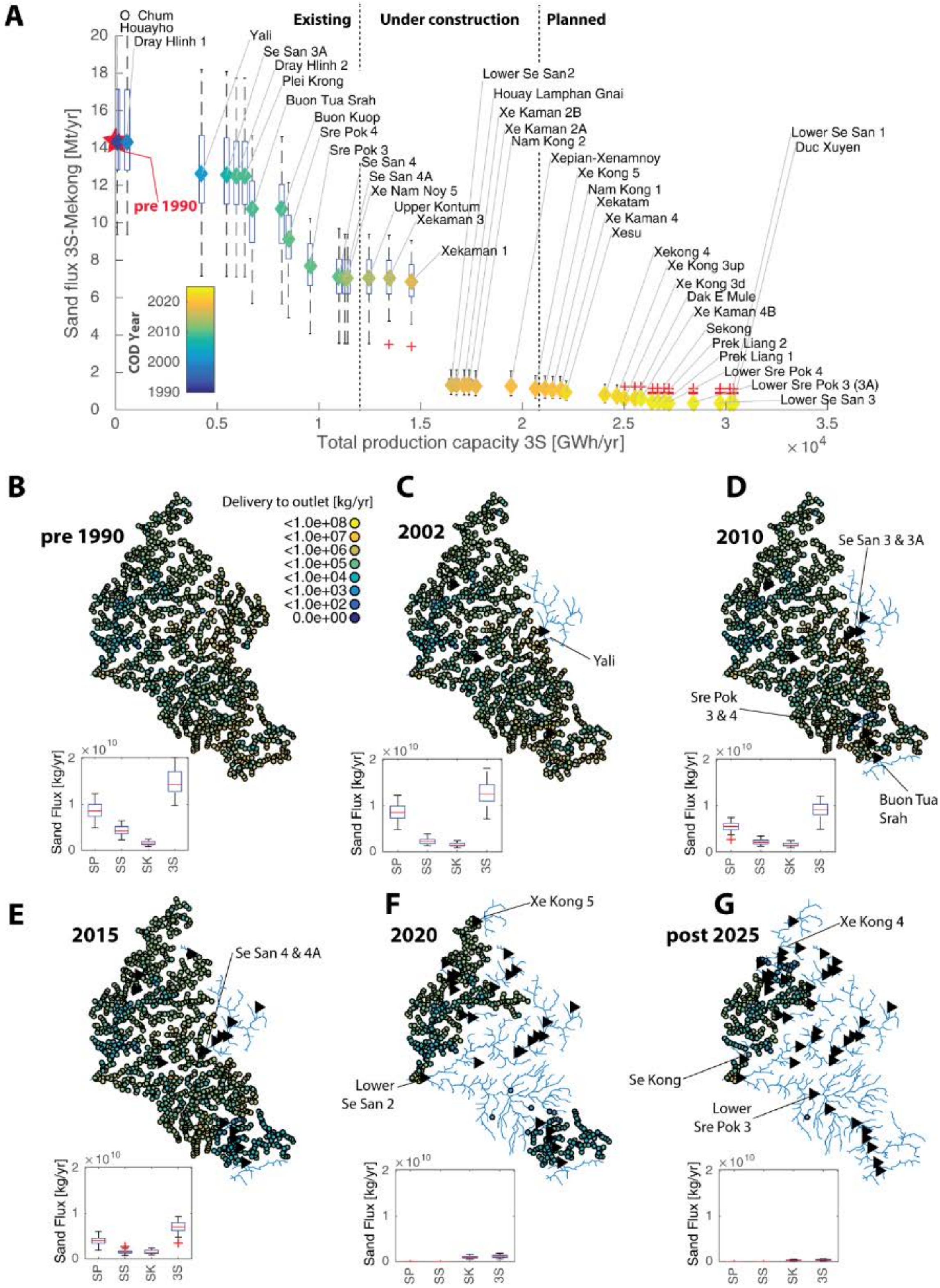

Figure 2-19. Anticipated impacts of built and planned reservoirs on magnitude and spatial distribution of sediment fluxes in the 3S. Panel A confronts the progressing expansion in hydroelectric production with the anticipated reduction in sediment flux from the 3S to the lower Mekong. Each marker indicates the construction of an additional hydropower dam over time (colors) (see Figure 2-15 for location). Panels B-G show the residual connectivity for various past and future dates. Connectivity in the pre-dam state (B) is derived from recent modelling of sand transport in the 3S[24]. Each dot symbolizes a hypothetic source of sediment and how much sediment is delivered from each source to the basin outlet (see legend in Panel B).

Estimated impact of past, current, and future dams on total load to the Mekong

Kondolf *et al*. (2014) estimated an unregulated average load of 14.3 Mt/yr at the site of Lower Se San 2. The MRC-defined "Definite Future" dams (Plei Krong, Yali, Se San 3, Se San 3A, Se San 4, Se San 4A, O Chum 2, Buon Tua Srah, Buon Kuop, Dray Hinh 2, Sre Pok 3, Sre Pok 4) were estimated to trap 4.9 Mt/y. It is now apparent that Lower Se San 2 will also be constructed, trapping an additional 7 Mt/yr, a total reduction of 12 MT/yr from the Se San and Sre Pok Rivers, which is 84% of the estimated unregulated load. Once construction of these "Definite Future" dams is completed, sediment delivery from the 3S to the mainstem Mekong will be almost entirely derived from the Xe Kong basin, thus highlighting the importance of maintaining sediment continuity in the Xe Kong river system.

Uncertainty and lack of calibration data

The different results for sand transport (modeled by CASCADE) and trapping of the total load (dominated by suspended sediment transport, as modeled by 3W) all indicate the need for basic data from the system itself, such as grain size data from points throughout the 3S catchment, field observations of sediment mobility and better DEMs or river surveys to constrain transport capacity, and ideally sediment transport measurements. To date, our efforts are based on inferences from evidence such as the grain size differences in the mainstem Mekong above and below the 3S confluence with the Mekong and differences in slope along the length of the 3S rivers – with no sediment data from the 3S rivers themselves. Given the indirect nature of the inferences we can draw now, it's not surprising that some of the indicators diverge. With a relatively modest field reconnaissance and sampling campaign, it should be possible to greatly improve our understanding of how the system works and thus our predictions of sediment transport and how it would be affected by different dam scenarios.

Thus, it is important to acknowledge the uncertainty inherent in any inferences from modeling in light of the limited data upon which the analyses are based. The nature of the river channel and its variations in gradient indicate that sand transport is likely to be affected by the low-gradient bottlenecks, but there is greater uncertainty regarding transport of the full range of sizes in the suspended load, which can include considerable sand. Regarding the merits of proposing to rethink the spatial distribution of dams in the Xe Kong, the uncertainties regarding sediment do not detract from the fact that as the last connected source of sediment (including sand sizes) to the Delta, preserving sediment continuity in the Xe Kong is of great importance to the future sustainability of the Delta. As discussed elsewhere in this report, redesigning the distribution of dams within the Xe Kong to maintain passage for migratory fish is of high ecological concern.

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3. THE XE KONG FISHERY

The mainstream of the Xe Kong is today the last major free flowing tributary to the Mekong River[13], and provides unobstructed passage for migratory fish all the way to and from the headwaters to the South China Sea, including the mainstream Mekong, the Tonle Sap Great Lake and the Vietnam Delta. As such, the Xe Kong contains a high level of fish diversity and endemism with many species spawning only in its unique habitats. While much of the rest of the 3-S Basin (the Se San and Sre Pok tributaries) are lowlands with extensive flooded forests, the Xe Kong within Lao PDR is mostly highland with steep slopes. The river therefore features many small rapids with gravels and fast flowing water interspersed with deeper pools of slower flowing water and steep bedrock banks. This creates ideal mixed habitats that provide the spawning requirements for a diverse assemblage of species.

The highlands of the Bolaven plateau and the Annamite mountains surrounding the lower plains around Attapeu are visible in Figure 3-1.

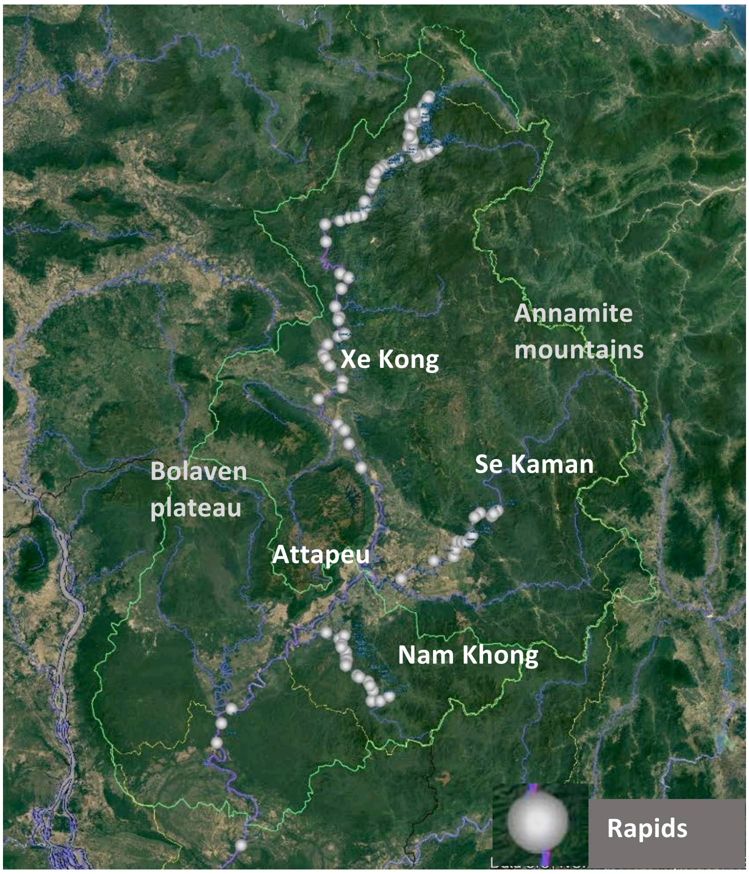


Figure 3-1. Rapids on the Xe Kong, Se Kaman and Nam Kong rivers. The longest rapids are up to 500m and a few have developed into small waterfalls. The lowland around Attapeu has no rapids.

Fish biodiversity in the Xe Kong River

There has been no ichthyological work conducted in the drainage until recently, and therefore little has been published specifically on the fish fauna of the Xe Kong drainage. Estimates of the total number of species and the number of migratory species vary somewhat. The Mekong River

[13] There is one diversion-type dam in the headwaters in Vietnam but its effect on river flows in the Lao and Cambodian sections is negligible.

Commission Secretariat (MRCS) catch data from 2003-2006 has registered 265 species in the Xe Kong River.[14] Meynell and Knight (2017) list 259 species. Others estimate 175 species in the lower reaches of the Xe Kong River, which corresponds to 22% of all Mekong fish species within an area representing only 3% of the Mekong Basin, with eighty-one of these being migratory (Cowx, 2015). Yet another estimate is presented in (Figure 3-2).

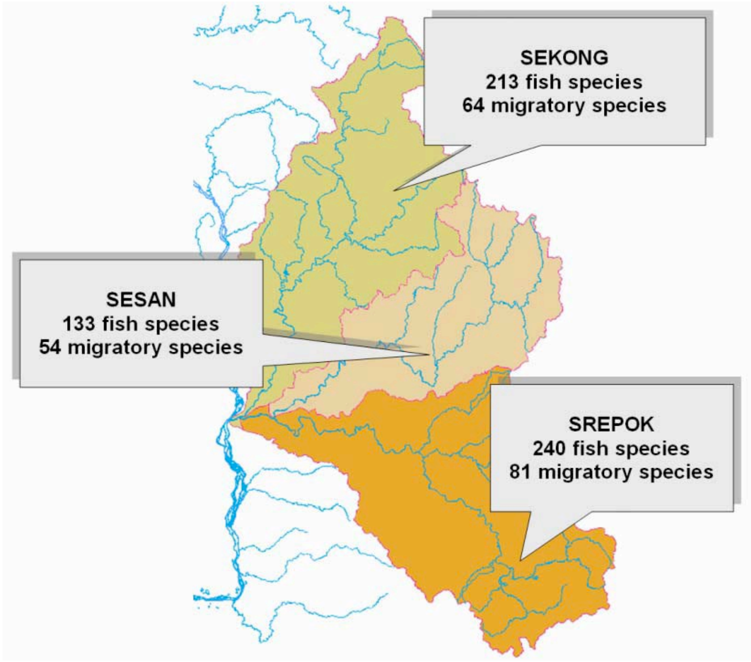


Figure 3-2. Distribution of fish species in the 3Ss rivers. (Source: Baran, *et al*., 2013).

Eleven guilds are represented in the Xe Kong River. Eighty-six species are registered as important in the MRCS migration database and 61 families are represented in the 11 guilds indicating the large diversity and uniqueness of the Xe Kong River (Table 3-1).

[14] Several studies have shown declines in the number of fish species in the '3S' (Sesan, Srepok, Sekong) (Baran and Sopheak, 2011), including populations of *Henicorhynchus siamensis & H. lobatus*, *Hypsibarbus pierrei, Hypsibarbus wetmorei, Labeo erythropterus, Scaphognathops bandanensis, Bangana behri,* and *Wallago attu.* Furthermore, there are varying estimates in loss of fishery yield from the region of between 15 and 40%, which equates to loss of up to 300,000 ton of fish per annum, but more importantly threats biodiversity, sustainable livelihoods and food security in the region (Cowx, 2015).

Table 3-1. Eleven guilds of migratory species are recorded in the Se Kong River in 61 families. R*hithron* is the upstream portion of the river that follows the crenon (the uppermost zone at the source of the river). It has relatively cool temperatures, high oxygen levels, and fast, turbulent, swift flow.

Guild No	No	Guild Description
F1	11	Rithron resident
F2	2	Main channel resident (long distant white)
F3	12	Main channel spawner (short distance white)
F4	6	Floodplain spawner (grey)
F5	8	Eurytopic (generalist)
F6	9	Floodplain resident (black fish)
F7	4	Estuarine resident
F8	1	Anadromous
F9	1	Catadromous
F10	3	Marine visitor
F11	4	Non-native
Total	61	Families

Figure 3-2 also provides an estimate of 64 migratory species in the Xe Kong. Others place the estimate at closer to one hundred (Warren, 2016). Some of these migratory fish species are the most economically important fish for many riverside communities. The estimates of endemic species also vary. By one estimate, fifteen species are found exclusively in the Xe Kong; meaning they are found in no other Mekong tributary and nowhere else in the world. By another estimate, twenty-five species (14%) have been observed in no other drainage and are potentially endemic to the Xe Kong (Kottelat, 2011).[15] The number of endangered species also vary. By one estimate, it is home to 14 endangered fish species, including the critically endangered species *Aaptosyax grypus* (giant salmon carp), *Catlocarpio siamensis* (giant carp), and *Pangasianodon gigas* (giant catfish). Meynell and Knight (2017) list nine endangered species and two critically endangered species in the lower sub-basins (see Figure 3-3).[16]

The *more-or-less sedentary* species mostly live in swamps, lakes or marshland habitats for most of their lives. Typically, they are found on the Bolaven Plateau but are also encountered in lowland habitats along the lower Xe Kong in Cambodia. They sometimes move into flooded areas during the monsoon season for spawning and feeding or both. They are migratory to some extent, but very few, if any of them, are long distance migratory. This group of fish will be less impacted by the planned hydropower projects, and in some cases may even proliferate in water impoundment. Some of these species are carnivorous (*Channa* spp. - snakeheads, *Anabas testudineus* – climbing perch, and *Clarias* spp. – walking catfish.) and can deplete populations of other non-carnivorous fish species in these reservoirs.

[15] According to Meynell and Knight (2017), the confluence of the Xe Kong with the Xe Kaman has an estimated 10 endemics, and the confluence of the Xe Kong with the Xe Pian has nine endemics. The Bolevan sub-basins have eight. The Xe Kaman has four endemic species, while the Xe Xou and Nam Khong have two endemic fish species.

[16] Annex 3.1 provides the full Meynell and Knight report with maps and details.

Some "*short distance migratory or semi-sedentary*" fish species undertake recognizable short distance migrations between seasonally flooded environments and the Xe Kong mainstream / tributary river channels. Others are confined to specific areas or seasonal habitats. These species are of less concern with respect to prospective hydropower projects.

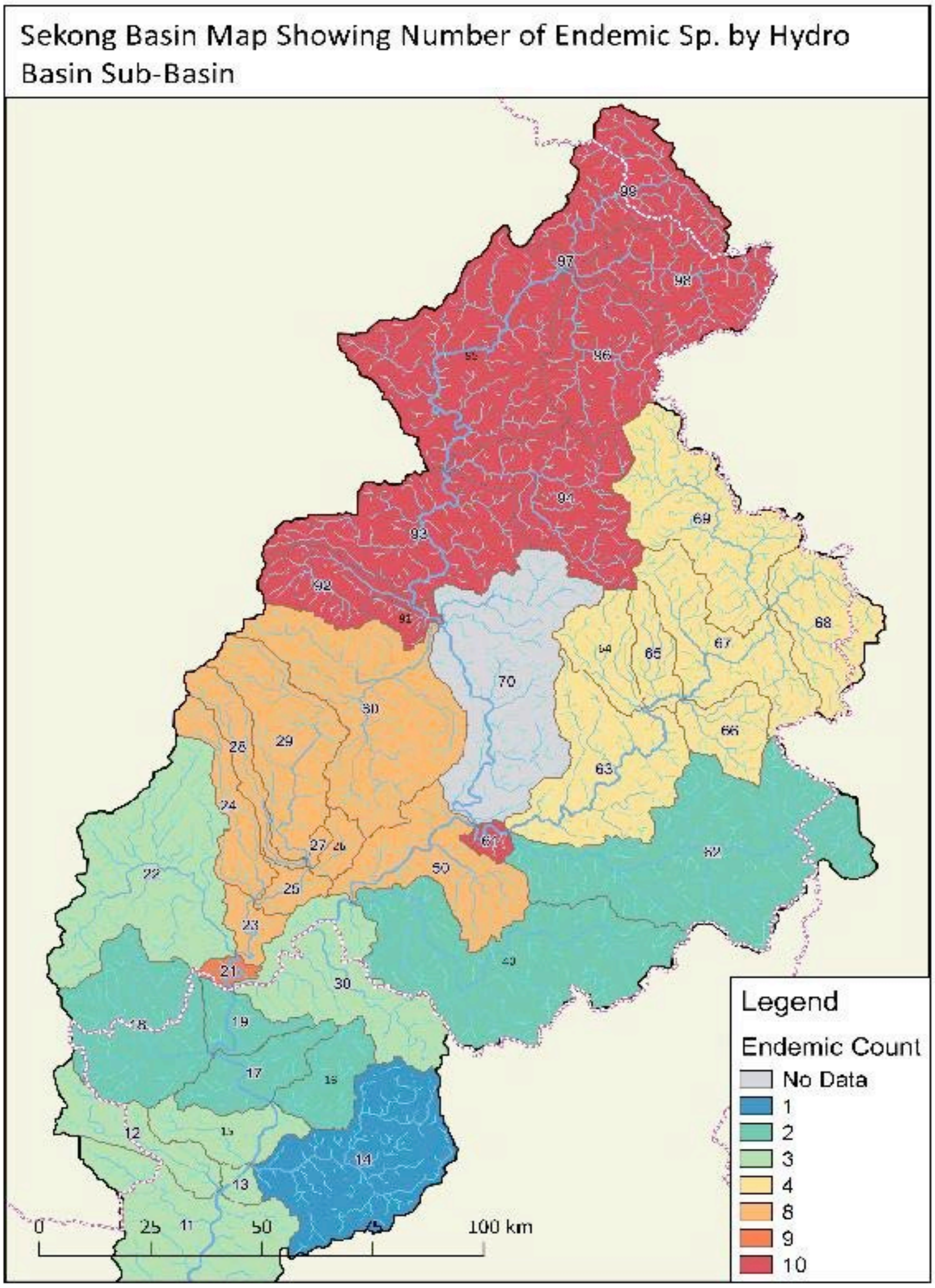


Figure 3-3. Distribution of estimated numbers of Endemic species in Se Kong sub basins. (Source: Meynell and Knight, 2017:22).

The "*highly migratory*" species usually spend most of their life-cycle in the Mekong and Xe Kong mainstreams. Many of these species are true rheophiles (require flowing water for critical life-cycle events) and will not tolerate static water conditions, or at least will only tolerate them during part of their life-cycle. They often undertake long distance migrations, sometimes in astounding volume over certain periods. (Warren *et al.*, 2005; Warren *et al.*, 1998). Some species may move out into seasonally inundated terrestrial habitats for feeding and for spawning or both. Some highly migratory species are short-lived and can complete their life-cycle within one calendar year. These can survive high levels of fishing pressure in undisturbed environments (e.g., *Henicorhynchus* spp. or Pba soi) and will survive in-situ perturbations to their environment to a certain degree.

The long-lived, native, late-maturing, large migratory fish species are potentially at far greater risk from hydropower development than the smaller short-lived, early maturing fish species, and many are of high economic and social importance for both commercial and subsistence consumption. The lower sections of the Xe Kong mainstream are populated by probably over 100 species which are either long distance (100's of kilometers) or medium range distance (less than 10 kilometers) migratory species.

See Annexes 3.2-3.6 for further information on hydrology and fisheries analysis.

Fish migrations in the Xe Kong Basin

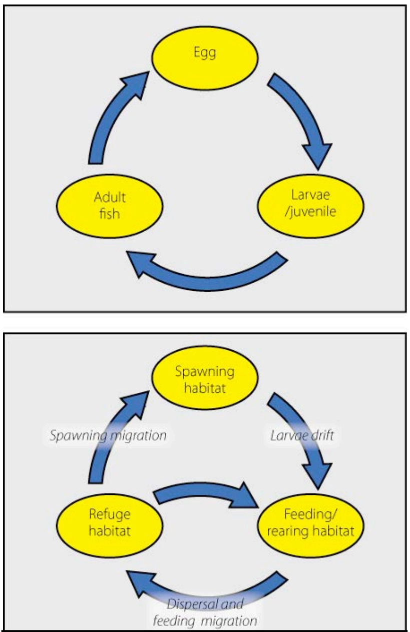


Figure 3-4. Simplified schematic representation of the life-cycles of Mekong Basin fish species. (Source: Poulsen et al., 2002. Courtesy of the MRC Fisheries Programme).

Many of the fish species found in the Xe Kong basin exhibit complex life cycles that involve migration between different areas of the mainstream and this tributary, particularly upstream migration to spawning areas. According to Poulsen *et al.* (2002) at least one third of Mekong fish species need to migrate between downstream floodplains where they feed and upstream tributaries where they breed.

A migration is an integral part of the life-cycle for fish that cannot use just one habitat for all their functions: rearing, refuge and spawning. These migrations take place on an annual basis. Figure 3-4 (left) illustrates two generalized patterns of the life-cycle of Mekong fish species.

Each migratory event is essential for the overall stability and maintenance of healthy fish stocks, ecosystem integrity, and the livelihoods of the people that depend on them. Migrations may take place laterally between flooded areas and mainstream channels, or longitudinally up and down river systems. Some migrations may involve a movement of only a few meters, whilst others may involve vast distances covering hundreds or even thousands of kilometers.

It is important to remember that the migration of fish is not confined to adult life-cycle stages. Many Mekong species spawn at, or close to, the water surface (broadcast spawners), whereby eggs are immediately fertilized by male fish after releasing sperm. Following the fusion of reproductive products, the eggs drift passively downstream with the current. For tropical Mekong species, the hatching of eggs usually takes between about 72 to 96 hours, or perhaps slightly longer, or sometimes less depending on environmental conditions such as water temperature.

The general understanding of migration patterns in the Mekong system is that there are three main groupings (see Figure 3-5): 1) the Lower Migration System (LMS, from the Delta up to Khone Falls), 2) the Middle Migration System (MMS, from Khone Falls up to Vientiane) and 3) the Upper Migration System (UPS, from Vientiane up to China) (Poulsen *et al.,* 2002).

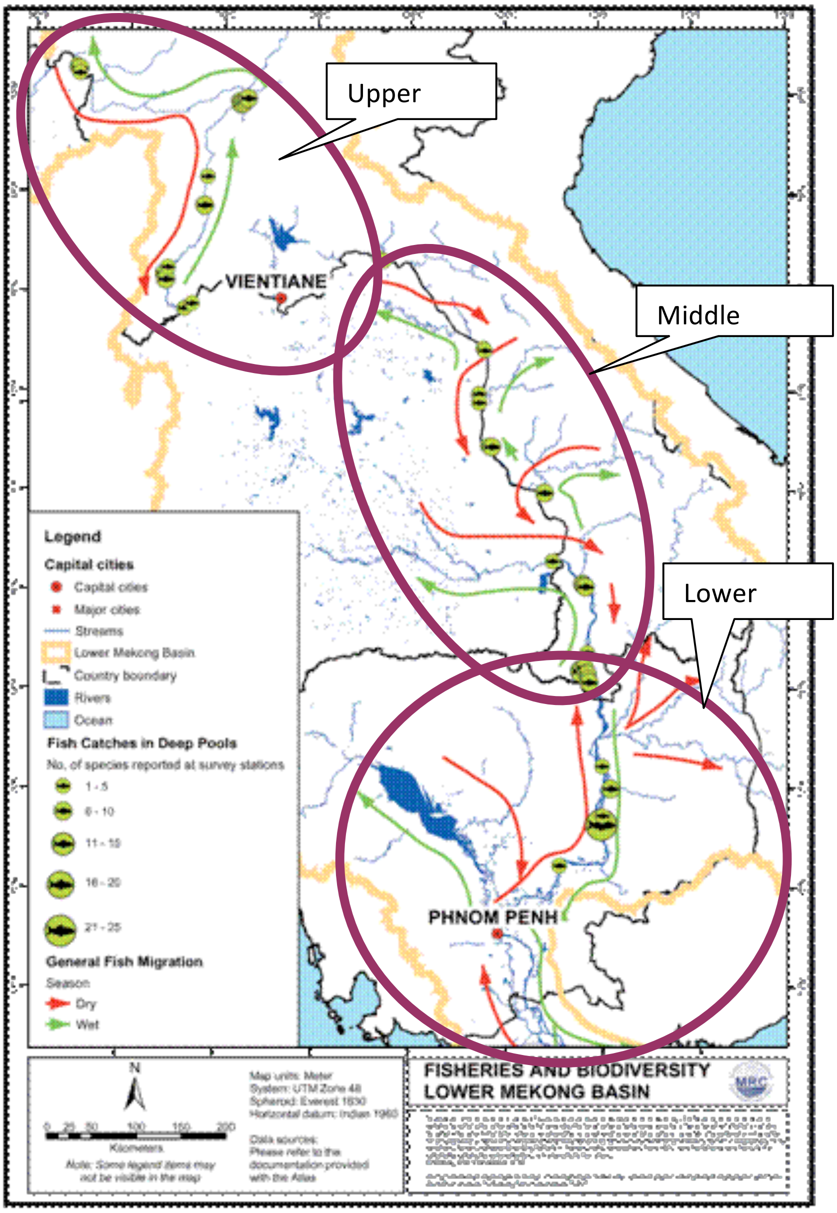


Figure 3-5. Three maps showing the LMS, MMS and UMS migratory system of the Lower Mekong Basin (Source: Poulsen et al., 2002a).

The main migration corridor is the Mekong mainstream, and the area between Phnom Penh and Stung Treng features the highest number of migratory species for which migration maps exist. There are relatively far fewer species migrating in the delta, but a surprisingly steady number of species migrating all along the mainstream up to Northern Laos. With 12 out of 18 species for which migration maps exist, the 3S system seems to play an important role (as important as the Tonle Sap River) for migratory species.

However, these zones are overlapping and inter-connected systems (Poulsen *et al.,* 2002). There are a number of species that migrate between these zones, and some species (possibly as many as 30 and often commercially valuable white fishes) that migrate longer distances. For example, *Pangasius krempfi*, an important commercial species, spends a part of its life at sea and in the brackish water of the Mekong Delta before returning to spawn in fresh water. This anadromous fish travels at least 720 km to the Khone Falls, and possibly further upstream (Hogan, 2007), including into the Xe Kong.

Many species spawn within the Mekong mainstream from Kratie to the Khone Falls and above, and in the 3S tributaries at the beginning of the flood season in May-June. Eggs and larvae then drift downstream with the current, especially at peak flows, flowing with the reversed flow into the floodplains to reach their feeding habitats in Cambodia and southern Vietnam (Poulsen *et al.,* 2002).

The migration patterns of Mekong and Xe Kong species are similar. The major importance of the Xe Kong water shed is as spawning habitat for many migratory species requiring flowing water and special ecological conditions. With hydropower dams already in place at the confluence of the Se San and Sre Pok, the importance of the Xe Kong as spawning ground becomes even more evident as the last free flowing major tributary.

Most migratory fish are mainstream species and various species migrate up and down all year (Figure 3-6, top set of graphs).[17] The floodplain species mainly migrate to spawning grounds during the onset of the raising stage of the river, and into deep pools for refuge during the down going stage to await the next flood season. The tributary species follow the same pattern, migrating into tributaries during the up going stage and down into deep pools during the down going stage (Figure 3-6 bottom set of graphs).

The specific migration in the Xe Kong and Se Kaman Rivers show that the number of migrating species declines the further upstream one looks (Annex 3.2). This holds for mainstream, floodplain and tributary species on the Xe Kong (Figure 3-7A). For the Xe Kaman only data for mainstream species is available (Figure 3-7B).

[17] The apparent dip in their down steam -and to some extend in their upstream- migration during high flow, is most likely because sampling is reduced during high flows; it is dangerous or not possible to catch fish.

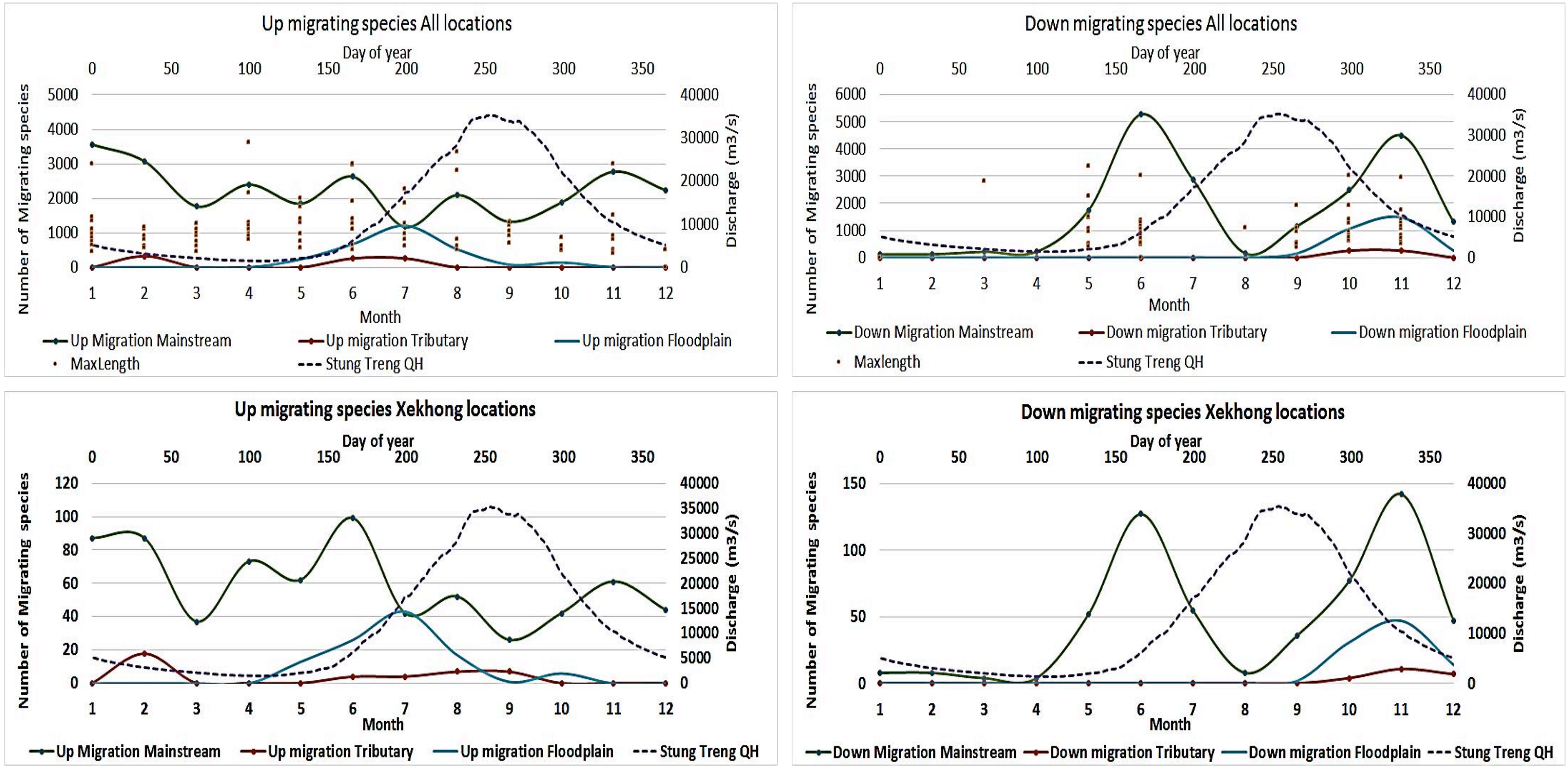
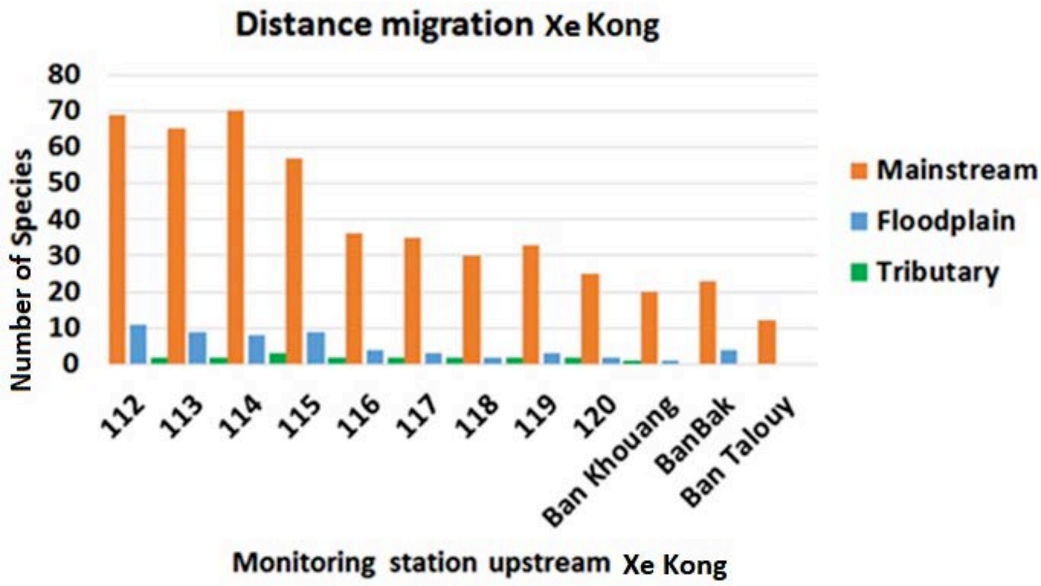


Figure 3-6. The total number of registered species at stations in the migration study, divided into their living habitats: Mainstream, Tributary and Floodplains. The migration pattern up and down of the Xe Kong is similar to the entire Mekong River (All locations).

A



B

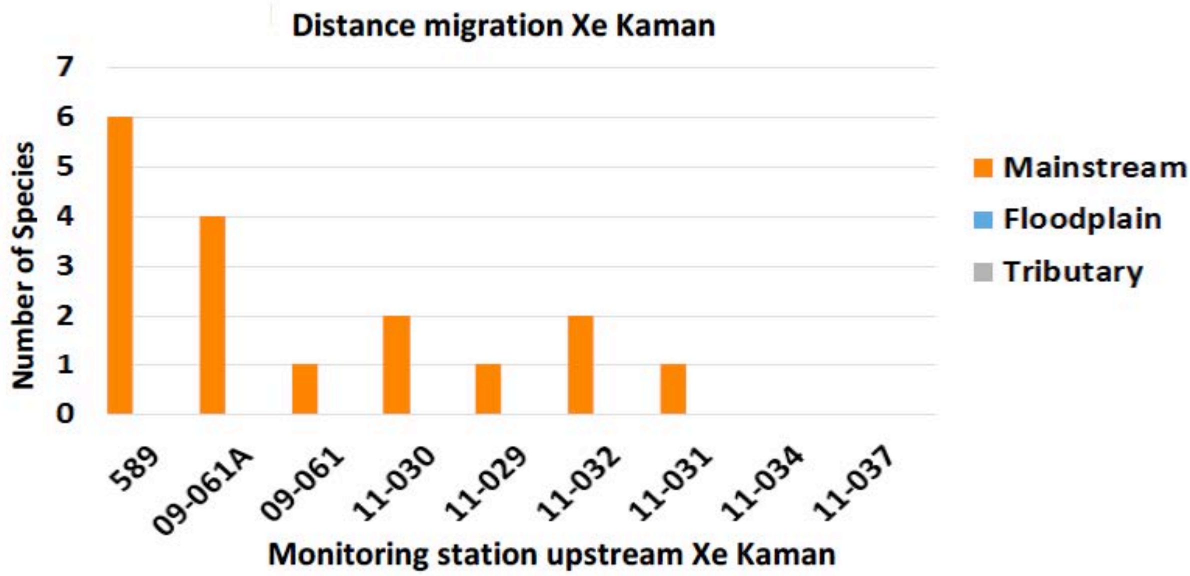


Figure 3-7 A & B: Xe Kong and Xe Kaman migration show decline in numbers of migrating species the further upstream monitoring took place, but still extended all the way to Talouy on the Xe Kong. Some of these species may come from local populations in the mainstem. The pattern is the same on the Xe Kaman. See the monitoring station locations in Figure 3-8. (Sources: MRCS Fisheries Database; Kottelat, 2009, 2011; EIA#5 (HEC, 2008) (B. Talouy) and NHI Survey, 2016 (Ban Bak and Ban Koung))

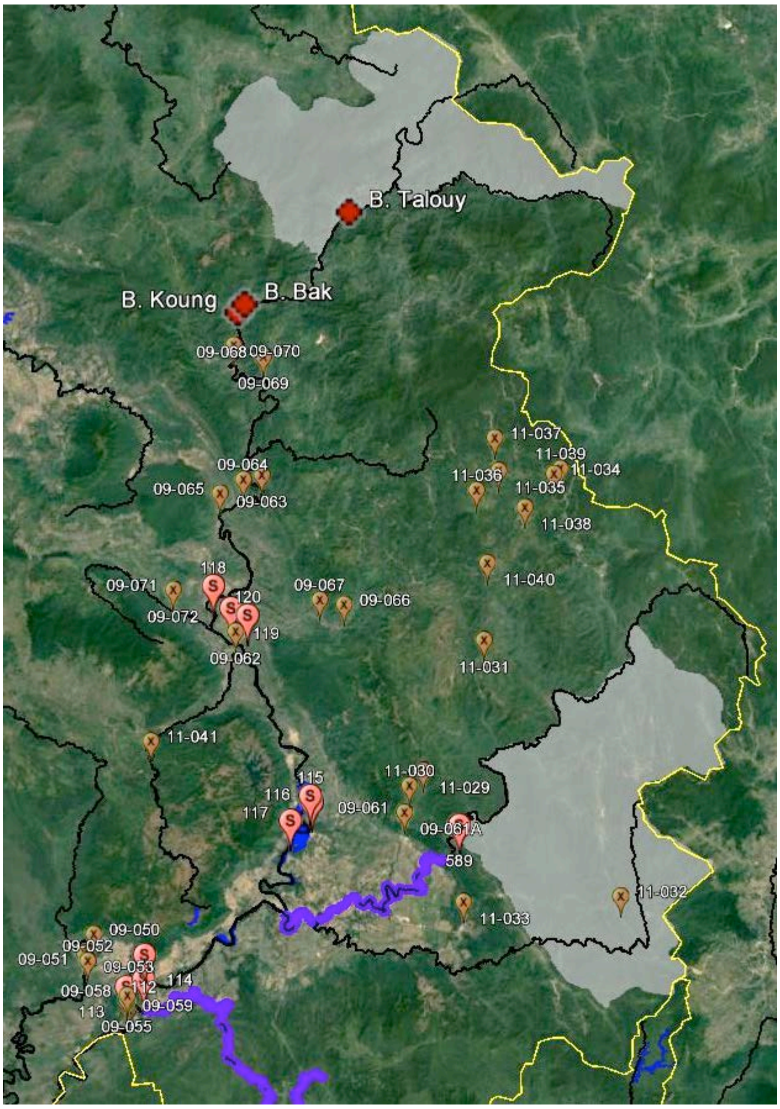


Figure 3-8. Location of monitoring stations used in the analysis in Figure 3-7 A & B (Sources: MRCS Fisheries Database; Kottelat, 2009/11; EIA#5 (HEC, 2008) (B. Talouy) and NHI Survey, 2016 (Ban Bak and Ban Koung)). Xe Kong and Xe Kaman migration show decline in numbers of migrating species the further upstream monitoring took place.

The migratory pattern is more complex than described briefly above, as catch data indicate there are local populations of small, medium and large migratory species. (Figure 3-9; see also Annex 3.3 (Catch analysis report)). The catch numbers of these particular species vary from a few up to around 1000 per catch in Cambodia and between a few and up to around 100 per catch in Thailand and Lao PDR (see Figures 3-9, 3-10 and 3-11). Lower catch numbers in months other than the peak migration season indicate that local populations exist in the LMB, MMB and UMB systems.

What is known (and surmised) about the timing of fish migrations in the Xe Kong is summarized in Annex 3.2.

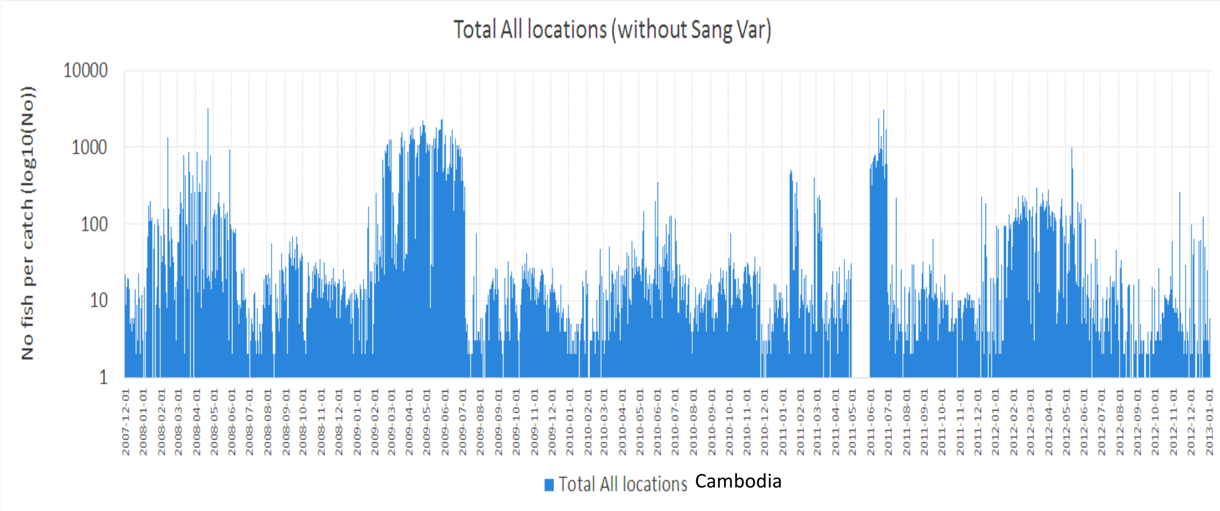


Figure 3-9. Catch numbers of 5 migratory species year 2007-2012 Cambodia (log10 scale on the x-axis to emphasize the lower catch numbers in the non-migration months (1-2 and 8-12)).

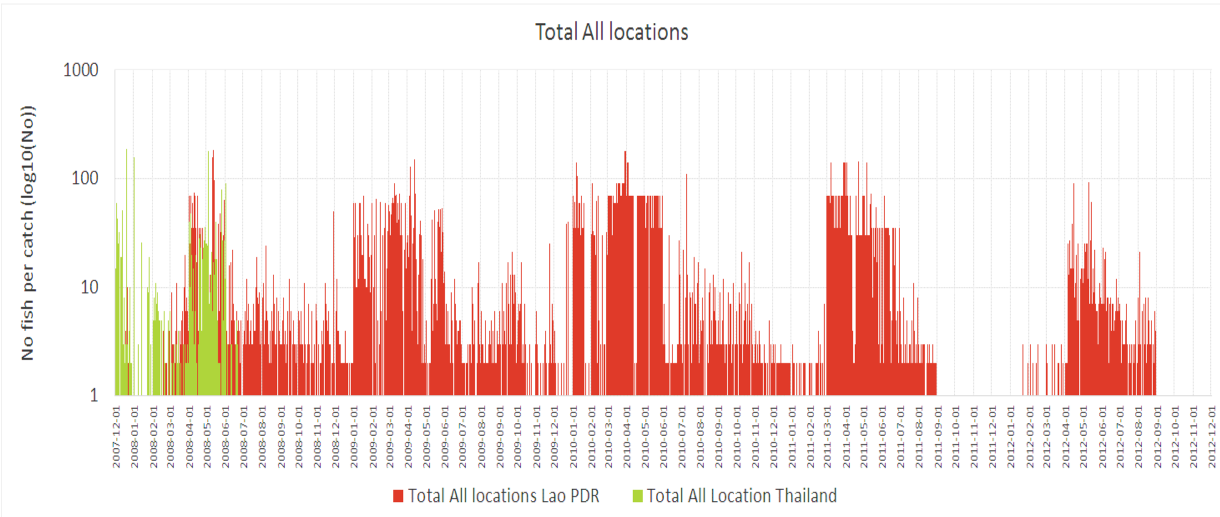


Figure 3-10. Catch numbers of 5 migratory species year 2007-2012 Lao PDR and Thailand (log10 scale on the x-axis to emphasize the lower catch numbers in the non-migration months (1-2 and 8-12).

For Figures 3-9 and 3-10: The catch numbers during the migration period (months 3-7) are 10 times higher in Cambodia than in Lao PDR and Thailand, as well as in the non-migration period months 1-2 and 8-12. Sang Var catch (See figure 3-9) is not included as it takes place near Phnom Penh and is in line with the large migrations of the Tonle Sap Lake / Vietnamese delta. 5 species from small to large are included in the data: Henichorynchus lobatus (Small), Henichorynchus siamensis (Small), Hypsibarbus malcolmi (Medium), Pangasius concophilus (Large), Probarbus jullieni (Large). Note the data gaps in 2011.

Cluster analysis

By combining data from 4 different sources (Kottelat, 2011; Kottelat, 2009; HEC, 2008; MRCS Fisheries Database), a dendrogram of the fish shows four groupings that have a similarity of 25% or more, as shown in Figure 3-11. The clusters indicate that there are local populations of otherwise long distance migratory species in the Xe Kong River basin. Local populations interbreed (see next DNA section) and are dependent on short migration routes that may be blocked by hydropower dams.

Two of these groups have clear geographic boundaries: one of the main-stem Xe Kong and one of high elevation sites in the Xe Kaman catchment.[18]

The multivariate analysis identifies four zones of fish assemblages: 1) A lowland group (L), 2) a tributary group (T), 3) the Xe Kong mainstream (X), and 4) a high elevation group (H) in the Xe Kaman.

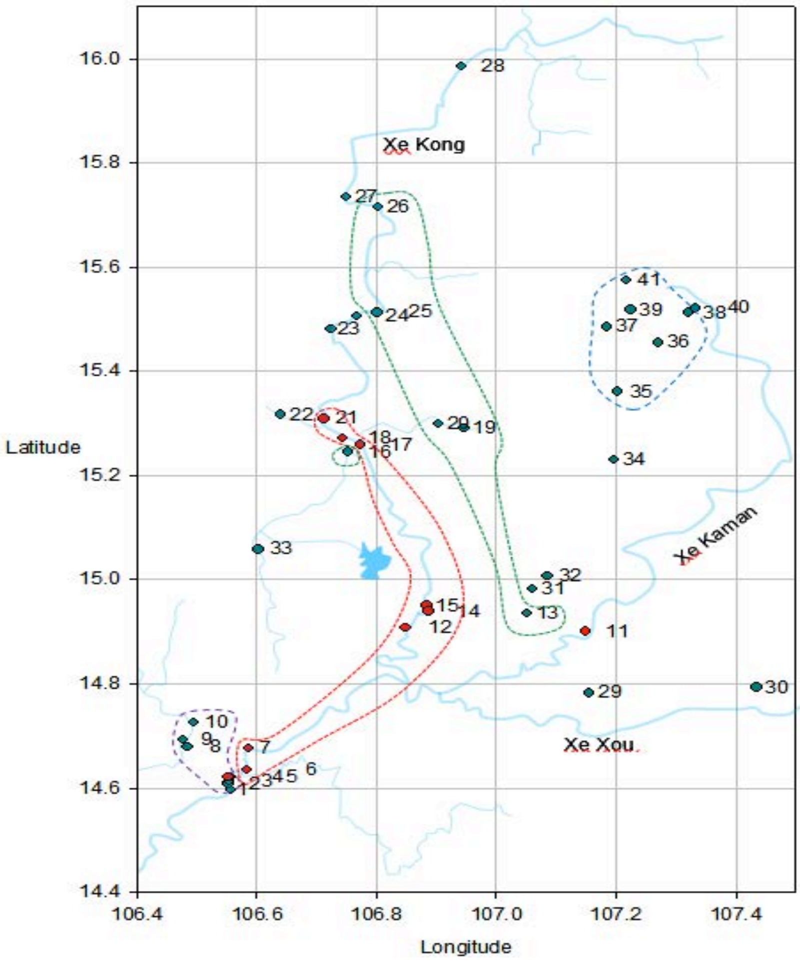


Figure 3-11. Map of the Xe Kong basin showing fish collections sites and groupings of sites from cluster analysis. MRCS sites are shown in red. Note that the groupings strongly reflect sampling methods, with MRCS sites focusing on fisher catches while the Kottelat (2009, 2011) sites focus on collection of small species.

[18] There are many sites that do not show a group. This is largely a function of the sampling, that does not use standard effort or gear between sites and in some cases, sites have only one species and therefore the analysis cannot not group them.

DNA analysis

Preliminary results of a population genetics survey of two species (Figure 3-12) indicate that local populations at Pakse (MMS) and at Attapeu (LMS) interbreed with each other, with full model probabilities of 0.93 (Figure 3-13A) and 1.00 (Figure 3-13B) (Carpenter *et al.*, 2017). These results support the findings from the catch statistics and cluster analysis that local populations exist and interbreed. Hydropower dams on the mainstream Mekong and mainstream Se Kong may block their migration routes for interbreeding, spawning and rearing, like for long distance migratory species.

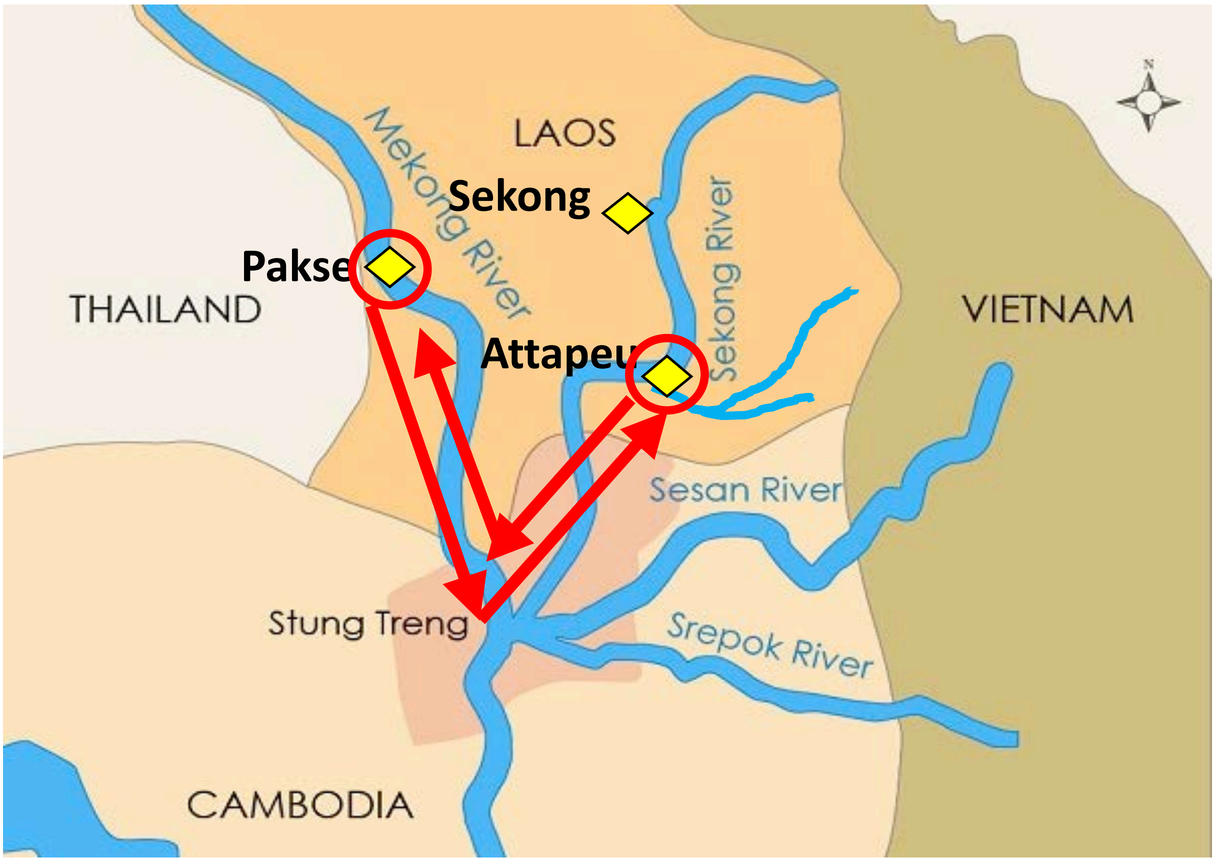


Figure 3-12. Sampling locations and preliminary results of 'Population Genetics' survey for two species, Helicophagus leptorhynchus and Hemibagrus spilopterus (Carpenter et al., 2017).

Figure 3-13. **A.** ***Helicophagus leptorhynchus.*** Full model highest probability: 0.93

B. ***Hemibagrus spilopterus.*** Full model highest probability: 1.00

Spawning

Spawning takes place in 14 different habitats in the Xe Kong River, of which the 'flowing water' is most significant as it is used by 29 species.[19] The remaining habitats supports another 21 species, see Table 3-2 for these 50 species for which data are available. River channel habitats, that may be changed by hydropower, are used for spawning by most of the large species of pangasiid catfishes and some large cyprinids such as *Cyclocheilichthys enoplos, Cirrhinus microlepis*, and *Catlocarpio siamensis*. They rely on particular hydrological conditions to distribute the offspring (eggs and/or larvae) to downstream nursery rearing habitats like the Tonle Sap. The spawning patterns show the importance of flowing waters for 29 species and diversity of ecosystems for 21 other species.

Table 3-2. Spawning habitats registered in MRCS fisheries databases for important Xe Kong fish species, including 14 different habitats and 50 species with available data.

No Species	Spawning habitat
1	Backwaters or streams and rivers
2	Flooded forest
1	Floodplains and flooded forest
29	Flowing water
1	Headwaters
1	Ponds and swamps
2	Rapids and rocky areas
3	Rapids and rocky pools
1	River Banks
4	Rivers
2	Sand and gravel
1	Small streams
1	Standing and flowing water
1	Standing waterbodies
50	Total No species

The different species utilise different aspects of the hydrograph for both upstream and downstream migration. In addition, eggs and larval life stages drift downstream to recolonise/restock the lower Cambodian floodplain and delta. The timing of these upstream and downstream migrations is variable depending on fish life cycles, but importantly, there appears to be continuous spawning in the river with peaks, during the spring (February-March) as the most important, followed by the onset of the flood (June-July) and then when the water is receding (November), see Figure 3-14. The spawning migration pattern for Xe Kong species follow the Mekong pattern (see Figure 3-6 above).

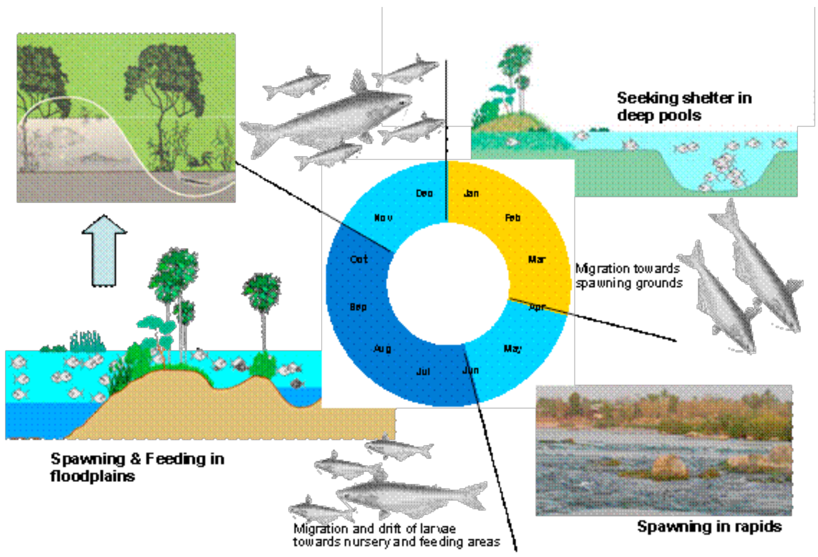


Figure 3-14. Generalized life cycle of potadromous Mekong fish (Source: Sverdrup-Jensen 2003).

[19] The 'flowing water' spawning was confirmed in the NHI '3 village' survey July 2016 where "Open broadcast spawning at the water surface during the wet season months appears to be the dominant method of reproduction, based on interviews with fishers" (NHI, 2016).

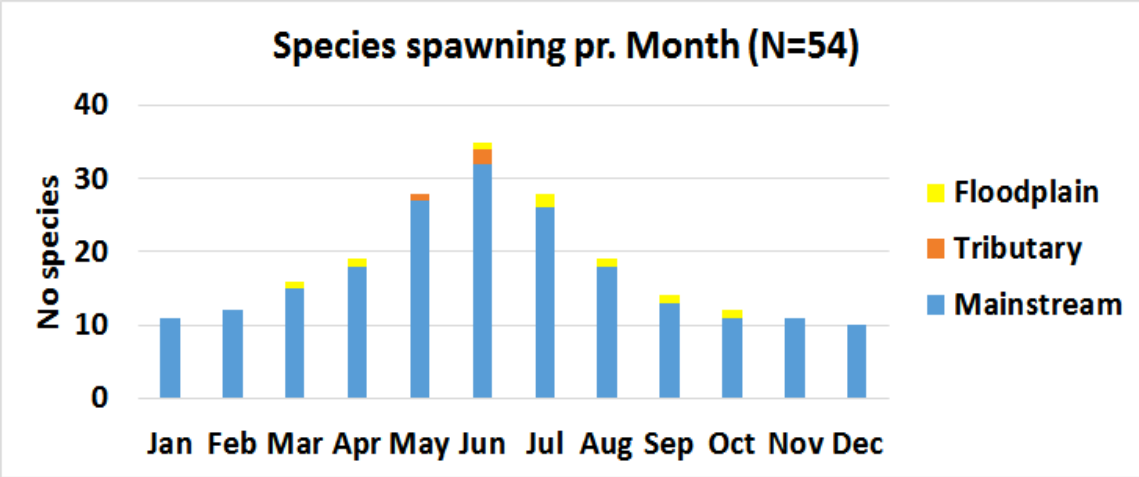


Figure 3-15. Spawning months for 54 important Mainstream, Tributary and Floodplain species of the Xe Kong River. (Source: Jensen and Phousavanh 2016).

The NHI literature survey (Jensen and Phousavanh, 2016) shows that mainstream species spawn all year but peak at the up-going stage around June. Tributary and Floodplain species spawn mainly during the wet season, see Figure 3-15 above. This is reflected by the number of species in each guild, see Figure 3-16 below.

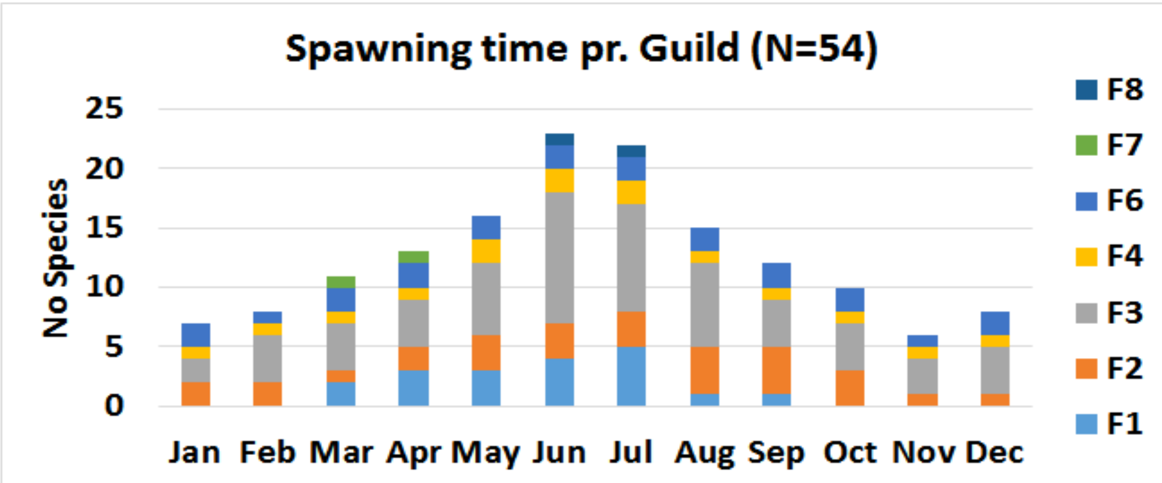


Figure 3-16. Spawning time for guilds (see Table 5-10). Migratory guilds, F2 and F3 show the same pattern of max spawning at the up-going stage as in Figure 5-10. Some species spawn over more than one month. (Source: Jensen and Phousavanh, 2016).

Spawning is triggered by rapid increase in discharge (T5), (here monitored at Stung Treng (ST)). The spawning peaks and larvae concentration peaks, follow the discharge pulses, ensuring that eggs and larvae arrive at the Tonle Sap River entrance when these pulses reverse the flow into the Tonle Sap Lake, carrying along larvae and eggs, see Figure 3-17.

During the period of major larvae drift, concentrations rapidly increase by up to 1000 times (see larvae concentrations in Figure 3-17 below) and are synchronized with the major flow pulses (yellow dots in figure 3-17). The enormous increase during these pulses may be explained by the very high fecundity that floodplain species require to ensure sufficient survival. By contrast, mainstream species do not need larvae to drift into the floodplains and therefore lower fecundity may be sufficient, see Annex 3.5 (Jensen 2016 a) and 3.6 (Jensen 2016 b).

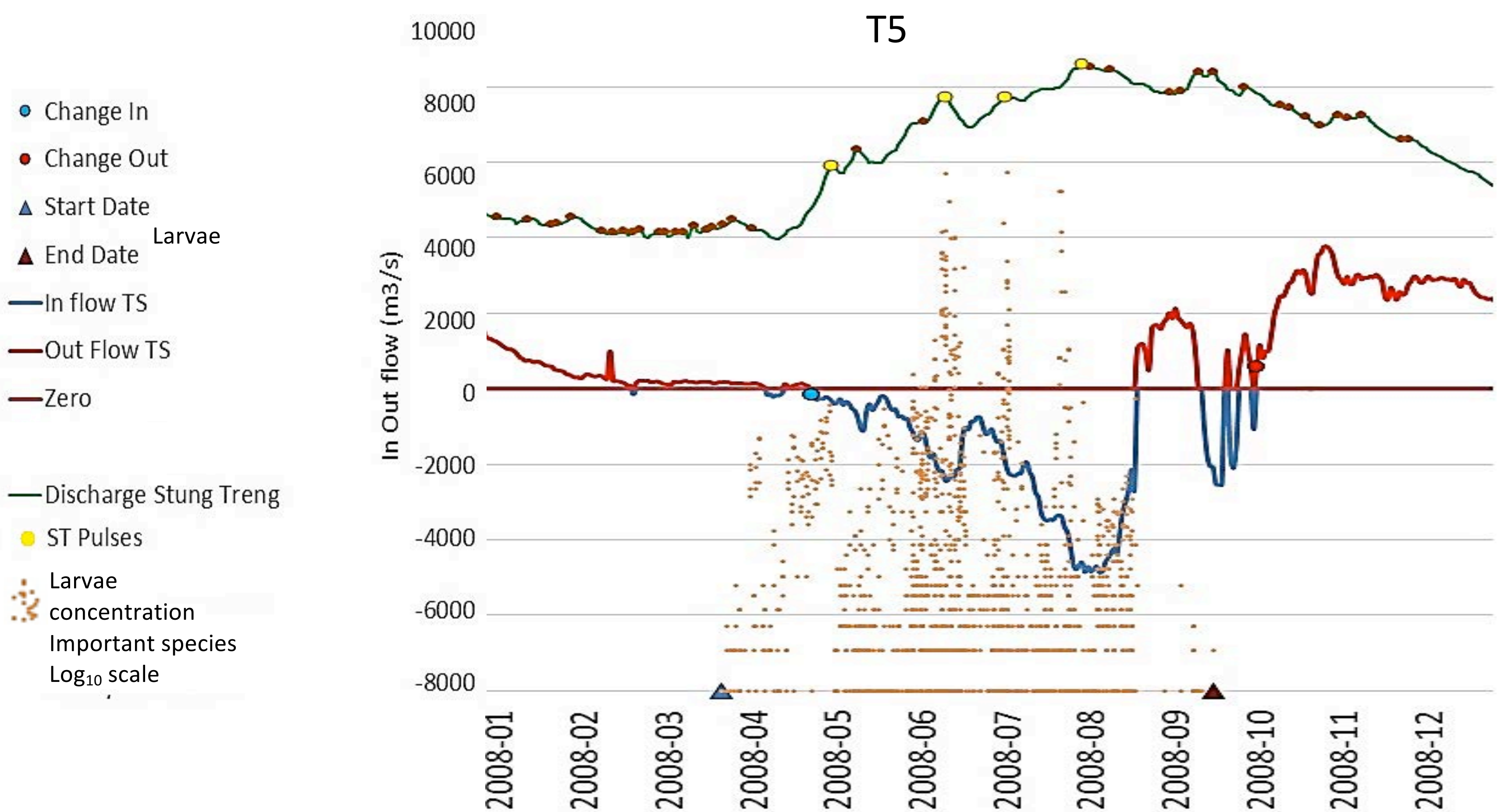


Figure 3-17. Spawning triggered by discharge pulses. ST: Stung Treng. T5: Trigger No. (Source: MRCS Hydrological data and MRCS larvae database.)

This means that upstream and downstream migration must be maintained throughout the year to avoid compromising the fisheries. To complete these migrations requires unobstructed passage upstream, as well as the capacity for adults, larvae and juveniles to migrate or drift downstream. Barriers to migration cause many fish to suffer enormous reductions in population numbers, become extirpated over their bio-geographical ranges, or in extreme cases become extinct; first economically and at a later stage, biologically degraded. The consequences of barriers to migration may not be immediately apparent, but will eventually become so. Riparian downstream communities may experience "bumper" crops in fish harvest for some years after dam construction (unless cascades of dams are built). At the same time, upstream riparian communities will experience very noticeable and immediate declines in fish catch.

Fish harvest in the Xe Kong

Almost all species within the Xe Kong - Mekong system are exploited to one degree or another, and at various stages of their life-cycle. The catch statistics for the Xe Kong River vary over a considerable range, but may be as much as 20,000 ton/year (Baran *et al.,* 2013), including both migratory and non-migratory species. Most or all fish in the Xe Kong drainage are commercially important or valuable for subsistence. The direct catch is important as a local protein source, but the larger importance of the Xe Kong River is as a spawning habitat for valuable riverine species and species that migrate to and from the Tonle Sap and Vietnamese floodplains.

Fishing activity in the Xe Kong focuses mainly on the migratory fish species and uses large fishing gears such as bag nets, gill nets, lee traps[20]. These gears can yield high catches, and are generally employed during the period of upstream migrations of many species as the water levels increase during the rainy season. There is a well-established marketing chain in the Attapeu Province. Traders supply local markets with fresh fish, but a large amount of fish, especially the big fish, are shipped to Pakse, Vientiane and other main cities in Laos and Ubon Ratachani Province in Thailand. In addition to fresh fish, the main fish products are fermented, smoked and sour fish. The processed fish products can be kept for longer time and also sold at higher prices.

However, fish species are not the only ones captured, as a diversity of other aquatic animals are found in the market including amphibians, crabs and especially snails which is particularly important in the local diet (Sjorslev, 2000). The most obvious impact of damming to these sessile animals is burial under sediment deposit in the reservoir. Impoundments of rivers reduce water velocity and allow accumulation of silt; as this settles out it can often be deep enough to cover and suffocate these animals and lead to their eradication.

[20] See **Annex 3.6** for further information about lee trap fisheries.

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4. Current State of Hydropower Development in Xe Kong Basin and Proposed New Dams on the Mainstream

Existing Hydropower Dam Development in the Xe Kong Basin

The dam development in the Xe Kong basin is presently taking place in Lao PDR. Plans in the Cambodian part are not progressing. The continued development of hydropower dams in Lao PDR can be followed on the website of the Ministry of Energy and Mines (MEM), Lao PDR (http://www.poweringprogress.org/new/). Thirty-five hydropower dams are arranged in seven categories as follows:

Category/Project Stage		# of Projects
1. Completed		4
2. Under Construction		5
3. Project Development Agreement (PDA) Stage		11
4. Feasibility Study (F.S.) Approved		5
5. Feasibility Study (F.S.) Ongoing		2
6. Feasibility Study (F.S.) Completed		2
7. Pre-Feasibility Study (Pre-F.S.)		6
	TOTAL	35

The total installed capacity from all categories is estimated to be 3,354 MW with mean energy production of 13,998 GWh/year, see Figure 4-1 and Table 4-1.[21]

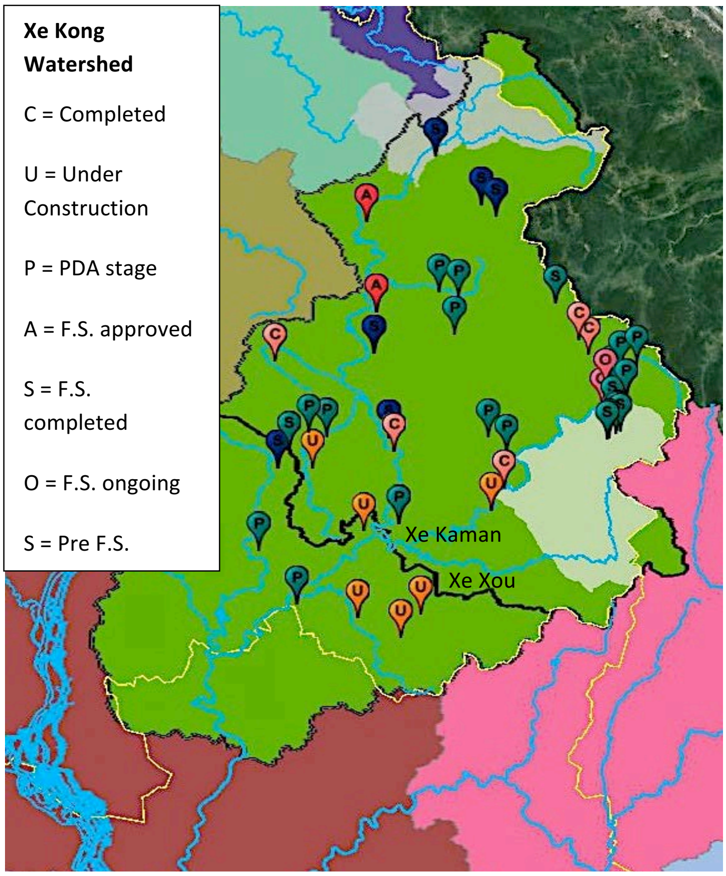

Figure 4-1. Classes of hydropower dams in the Xe Kong watershed in Lao PDR updated by Ministry of Energy and Mines (MEM) Lao PDR, June 2017. Grey areas are NPA (National Protected Areas).

[21] Data for 3 dams not available.

Table 4-1. Status of hydropower development in the Xe Kong basin in Lao PDR per June 2017 after Ministry of Energy and Mines (MEM) Lao PDR.

Project name	Status	COD	Installed capacity	Mean annual energy	Total storage FSL	Plant capacity factor**	Total project cost	Env and social cost	Substation connect	Power Destination %			
	See values below	Year	MW	GW	Million m^3		Million US$	Million US$	Station name	LAO	THA	KHM	VNM
Houayho	Completed	1999	152	450	674.00	0.338				5	95		
HouayLamphan	Completed	2015	88	480	141.00	0.623				100			
Xe Kaman 3	Redesigning*	2014	250	1000.3	_	0.457				10			90
Xe Kaman 1	Completed	2016	290	1096	4804.00	0.431				20			80
Nam Kong 2	Under construction nearly completed	2017	66	264.4	166.00	0.457				100			
Xe Kaman Sanxai	Completed	2017	32	121	9.00	0.432				20			80
Nam Kong 3	Under construction	2017	45	170.2	101.00	0.432				100			
Xepian-Xenamnoy	Under construction	2019	410	2023	1116.00	0.563				10	90		
Nam Kong 1	Under construction	2020	160	649	679.00	0.463				100			
Xe Kong Downstream A	PDA stage	Expected COD before 2025	76	334.7	95.00	0.503	147.283	5.5	Saphathong	100			
Xekatam	PDA stage	Expected COD before 2025	81	299	0.42	0.421				100			
NamAng-Tabeng	PDA stage	Expected COD before 2030	41	183.3	0.20	0.510				100			
Nam E moun	PDA stage	Expected COD before 2030	129	427.4	0.07	0.378				100			
Nam E moun Diversion Dam	PDA stage		0	0	0.87								
Xe Kaman 4	PDA stage	Expected COD before 2025	70	287.4	18.90	0.469				10			90
Xe Kong Downstream B	PDA stage	Expected COD before 2030	50	206.3	105.00	0.471	81.779	1.8	Saphathong	100			
Xepien-Houysoy	PDA stage	Expected COD before 2030	45	171.3	9.83	0.435				100			
Xepien_H.Chot	F.S completed	MOU signed with Province	21	100	_	0.544				100			
Xe Kong 3A	F.S completed	MOU	140	459	187.00	0.374	233.058	5	EVN	100			
Xe Kong 3B	F.S completed	MOU	146	418	116.00	0.327	249.107	5	EVN	100			
H.La Nge	F.S completed	MOU	60	293.75	14.30	0.559				100			
Xe Kong 5	F.S completed	MOU	330	1,613.50	3300.00	0.558	678.50	20.00	Thailand or Vietnam		100		
Xe Kaman 4A	Now Nam Bi 1-3												
Nam Bi 1	F.S approved. PDA signed in Oct. 2016	Expected COD before 2025	50	210	0.30	0.479				100			
Nam Bi 2		Expected COD before 2025	68	288.5	10.00	0.484				100			
Nam Bi 3		Expected COD before 2026	12	51.2	14.00	0.487				100			
Xe Kong 4A	F.S approved.	Expected COD before2025	175	785.1	200.00	0.512	779.08	17.5	Pakse		100		
Xe Kong 4B	F.S approved.	Expected COD before 2025	165	800.9	988.00	0.554	779.08	15.5	Xekong 4 to Pakse S/S	100	100		
Xe Kaman 2A	F.S ongoing	Expected COD before 2030	35	160	20.80	0.522				100			
Xe Kaman 2B	F.S ongoing	Expected COD before 2030	100	380.5	333.00	0.434				100			
Nam Payoun (Down Stream)	Pre F.S	Planning	0	0	_					100			
H.Makchan	Pre F.S	Planning	0	0	_					100			
Nam Krabai 1	Pre F.S	Planning	40	164	_	0.468				100			
Nam Krabai 2a	Pre F.S	Planning	9	36.45	_	0.462				100			
Nam Krabai 2b	Pre F.S	Planning	8	32.8	_	0.468				100			
Nam Krabai 3	Pre F.S	Planning	10	41.2	_	0.470				100			

COD = Commercial Operation Date

* Stop operation due to accident occurred to its penstock (broken penstock). Now redesign of new penstock line route. It will be designed in deeper underground.

** The net plant capacity factor of a power plant is the ratio of its actual output over a period of time, to its potential output if it were possible for it to operate at full nameplate capacity indefinitely.

Proposed Mainstream Hydropower Projects

Section 3 of this Master Plan describes the extraordinary value of the Xe Kong basin for the migratory fishery of the Lower Mekong River Basin—the most productive in the world-- as the last unobstructed major tributary of that entire system. As such, its spawning habitat is of unique and irreplaceable value for migratory species coming from and returning to the deep pools in the Lao reach, the mainstream Mekong, the Tonle Sap Great Lake, the Vietnam Delta, and the South China Sea. This is more the case in that the rest of the 3S basin has now been substantially compromised by the intensive upstream development of the reaches of the Se San and Sre Pok within Vietnam, and the construction of the Lower Se San 2 dam at their confluence, which blocks off the Cambodian portions of these sub-basins. To be sure, there is significant hydropower development in several of the Xe Kong tributaries, particularly the Xe Kaman and the Nam Kong. But, within Lao PDR, the mainstream and the other tributaries that are essential for spawning habitats are currently unimpeded for migratory fish.

As the last major undeveloped portion of the Mekong within Lao PDR, it is not surprising that it is of intense interest for hydropower construction, given the ambitious aspirations of the Government of Lao to exploit its hydropower potential. As of this writing, feasibility studies have been completed for seven large hydropower dams within the mainstream in Lao PDR, and four of these projects are progressing toward commissioning as early as 2025. Importantly, none have been finally approved by the Government of Lao, none are under construction, and the NHI team concludes that none of them would satisfy the criteria for approval under the Policy for Sustainably Hydropower Development, as shown in Section 5 and 6 of this Master Plan.

These seven projects are shown in Figure 4-2 and their locations, design features and status are displayed in Table 4-2.

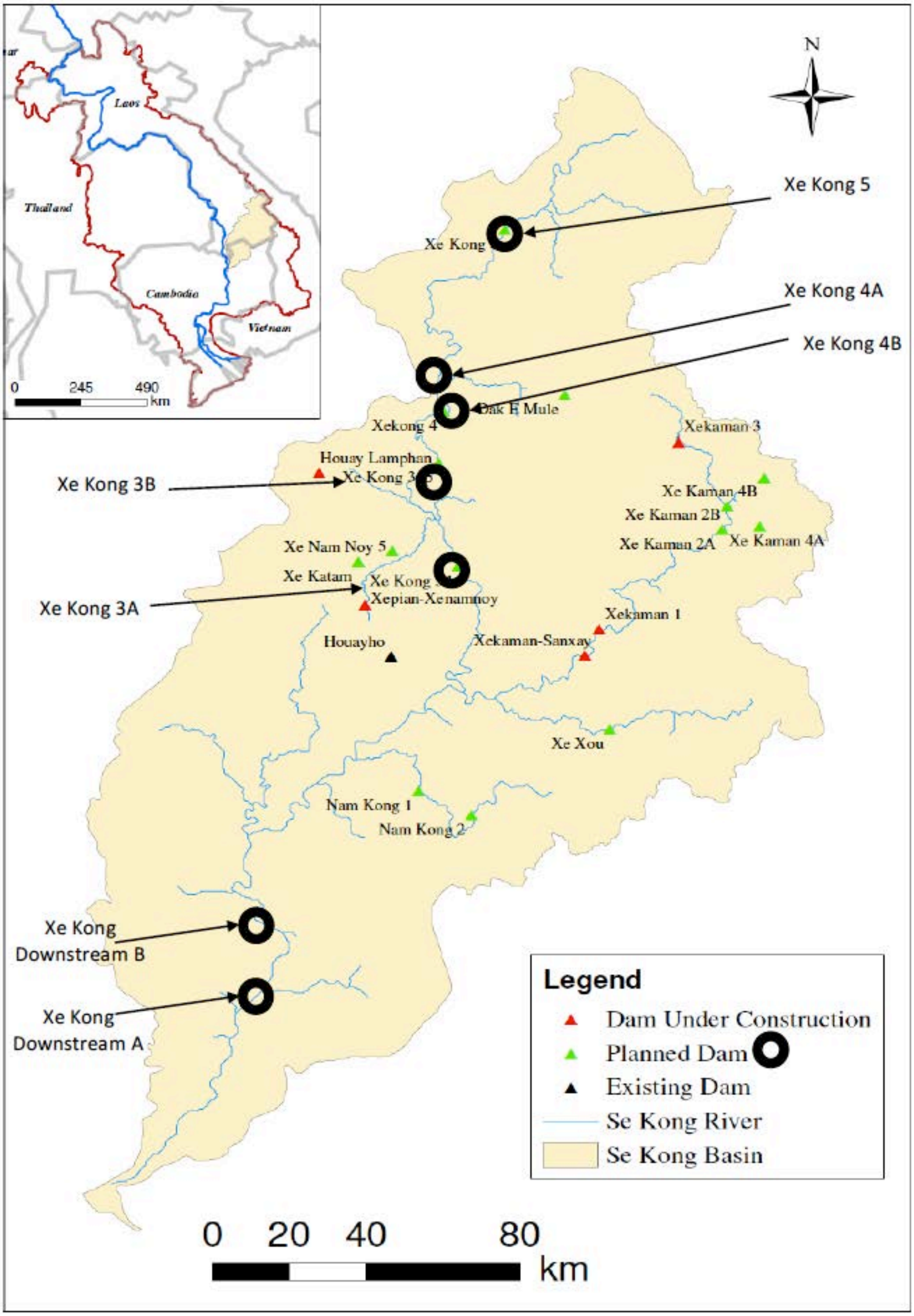

Figure 4-2. Map of location of seven hydropower dam sites on the Xe Kong mainstream that are being actively studied for feasibility under MoUs issued by the Ministry of Planning and Investment.

Table 4-2. Details for seven hydropower dam sites on the Xe Kong mainstream that are being actively studied for feasibility under MoUs issued by the MPI.

Project name	Location		Function	Status	COD	Installed capacity	Mean annual energy	Full supply level (FSL)	Minimum operating level	Max reservoir area (FSL)	Active storage volume	Total storage (FSL)	Dam Height	Maximum head	Power destination %	
	Dam site	Power house														
	Latitude Longitude	Latitude Longitude			Year	MW	GW	m	m	km^2	Million m^3	Million m^3	m	m	Laos *	Thailand ^
Xe Kong Downstream A	667305.05 1614555.54	667305.05 1614555.54	Run of the river	PDA stage	Expected COD before2025	76	334.7	95	81	25.4	22.29	95.03	8.5	7	100	
Xe Kong Downstream B	698971.93 1642734.55	698971.93 1642734.55	Run of the river	PDA stage	Expected COD before2030	50	206.3	105	97	19.03	87.23	104.52	8.5	8.3	100	
Xe Kong 3A	690926.05 1701641.69	690926.05 1701641.69	Run of the river	F.S completed	MOU	140	459	187		11.77	95.1	187.1	34.5	27	100	
Xe Kong 3B	695765.31 1672376.58	695765.31 1672376.58	Run of the river	F.S completed	MOU	146	418	116		18.35	168.4		27.8	18	100	
Xe Kong 4A	691709.63 1715836.63	691709.63 1715836.63	Run of the river	F.S approved	Expected COD before2025	175	785.1	200	180	42.6	654.9	988.3	75	50.1		100
Xe Kong 4B	688250.19 1747099.25	688250.19 1747099.25	Pondage	F.S approved	Expected COD before2025	165	800.9	297	277	22.4	633.5	1004.7	117	94		100
Xe Kong 5	709701.93 1769880.06	709701.93 1769880.06	Reservoir	F.S completed	MOU	330	1,613.50	485	480	32.8	1145	3,300	199	190.7		100

Remarks:

*EDL manages (domestic use and export)

^IPP export

Notably, most of these projects were initially proposed before the Policy was decreed by the Prime Minister. As noted in Section 1 of this Master Plan, that policy explicitly applies to all such projects. It is also important to state here the conclusion of Section 5 of this Master Plan that the adverse impacts of the projects on the migratory fishery (and on sediment discharge from the basin) increases as one moves down the basin. Thus, the lowermost dam is the most impactful, and the highest dam is probably the least impactful. The description of the projects below therefore starts with the lower most and moves up the mainstream. The information reported for each comes principally from the Ministries of Planning and Investment and the Energy and Mines. While as current as possible as of the time of this writing, the planning for these projects is quite dynamic and changes frequently.

It is also notable that, while Environmental and Social Impact Assessments have been received by MoNRE for all of the mainstream projects, as of this writing, none of these mainstream projects have a current Environmental Compliance Certificate (ECC) (see discussion in Section 12, pp 38-40) with the exception of Xe Kong 5, which has been issued a "temporary" or "interim" ECC, which presumably means that further processing by MoNRE is anticipated. The ECCs for Xe Kong Downstream A & B have expired and renewal requests are pending. None of the mainstream projects have signed Power Purchase Agreements with offtakers (customers). That probably means that the projects are not yet able to firm up the financing to build the projects. And, none of the projects have been awarded a Concession Agreement (see discussion in Section 12, pp 23-26 and 40). Therefore, none of these projects are yet ready to progress to the construction phase. As some of these projects have been pending for a decade or more, it is uncertain whether and when they actually be built.

Xe Kong Downstream A

The developer for this project and for Xe Kong Downstream B is reported to be V&H Corporation (a Lao company) that was formed by Hoang Ang Sekong Hydropower Joint Stock Company, which holds an 80% share, and a private party, Ms. Vilaykham, who holds a 20% share. The installed capacity of this project would be 76 MW, and the annual power output would be 334.7 GWh. The maximum height of this dam would be 8 m. It would be located 40 km downstream from the Town of Attapeu, and 14 km from Xanamxay, in the Xanamxay District. A Project Development Agreement was signed on 20 March 2015. It appears that further design work for the project and the search for additional investors are currently underway. The project has a contract with EDL (Électricité du Laos) for sale of electricity at 6.50usc/kwh.

A feasibility study for this project has been submitted to MEM for review (in English). Both MEM and MoNRE (in its review of environmental and social impact assessments) have expressed concerns about fish passage and sediment capture. MEM advises that it will make concession agreement contingent on design of a fishway that meets international standards.

The major concern with Xe Kong Downstream A is that it would block off the migratory fish habitat for the entire basin, from just above the Cambodia border. This would effectively destroy the migratory fishery for the Xe Kong River within Lao for a relatively small amount of power. As Section 5 of this Master Plan shows, this large impact would not be ameliorated by the construction of a fish passage facility for the upstream migrants, because the main problem is the reservoir rather than the dam. The fishway would merely introduce the adult spawners into a relatively static lake, in which they would have to navigate a long distance to reach the flowing water conditions that they need to reproduce successfully. This habitat would be greatly reduced by the inundation from the project and the barrier of the upstream projects. Even if the adult fish can find their way to the spawning reaches, the eggs and larvae would need to drift all the way back through the reservoir, and through the turbines or spillway, to reach the downstream system where they could mature into adults. The mortality is likely to be very high.

These realities seriously call into question the sustainability of this project, as it would produce massive impacts on the migratory fishery for relatively little power. Of all of the projects proposed for the mainstream, this one particularly should be replaced by alternative development options that are described in Section 7 of this Master Plan.

Xe Kong Downstream B

This project is proposed by the same developers. It is not clear whether these are considered to be alternative sites, or whether both are intended to be developed. The installed capacity of this project would be 50 MW, and it would generate 206.3 GWh/yr. It would be located upstream between Xe Kong Downstream #1 and the town of Attapeu. The feasibility study for this project has been completed.

Notably, if this project were constructed instead of Xe Kong Downstream A, the spawning habitat up to and into the Nam Kong and Xe Kaman tributaries would remain open up to the barriers created by Nam Kong #1 and Xe Kaman #1 projects, respectively. Significantly, the entire Xe Xou sub-basin would also remain open, which is both long and undeveloped at this time. But, this dam would wall off the remainder of the Xe Kong basin from just above the town of Attapeu into the headwaters and the many productive tributaries along the way, and for even less power than Xe Kong Downstream A.

Xe Kong 3A and 3B

Revised feasibility studies for these two projects have been completed but not yet approved, as of this writing. Total installed capacity would be 140 MW and 146 MW, respectively. The developer for both is the Asia Investment, Development and Construction Sale Co., Ltd (Lao Company). The consultant for the project is the East Asia Investment and Construction Consultant Joint Stock Company. The contractor for the feasibility study is Tractabel Engineering Co., in the Bangkok office. The authorities in Xe Kong province have indicated a desire to see these projects move forward.

Xe Kong 4A and 4B

Feasibility studies for both of these projects have been completed but not yet approved. The installed capacities would be 175 MW and 165 MW respectively, and the power output would be 785.1 and 800.9 GWh/yr., respectively. According to MPI, the company that holds the MoUs is the Lao World Engineering and Construction Company. However, the MEM data base states that the developer of #4 is Duangpasert Construction Company.

The Ministry of Planning and Investment (MPI) office in Xe Kong Province says that 4A is the previously studied site for which we have cited the environmental impact report in Section 5 of this Master Plan, and 4B is above that site near the town of Langkong. That official believes that the company wants to develop both sites. The MPI stated in June of 2015 that the Lao government canceled the original Xe Kong 4 project because it conflicted with plans to expand the coal mine at Chakeuy-tai. The dam was then redesigned by the Russian firm to reduce the footprint of the reservoir to accommodate the expansion of the coal mine. The entire town of Kaleum has been relocated but it is not known whether that was to accommodate this hydropower project or the expansion of the mine.

Xe Kong 5

The feasibility study for this project has been completed but not yet approved by MEM. The field work for the environmental impact assessment has been completed. The installed capacity would be 330MW, and the power output would be 1,613.5 GWh/yr. The total investment could reach $700 million, according to the Russian-Lao Intergovernmental Commission.

This project has had a complex history. The JICA Master Plan cites information from a 1984 report of the Mekong River Committee, which identified a potential project at the Xe Kong 5 dam site. The original MoU was issued to the Regional Oil Company, a Russian company, which did not pursue it. The MoU was then transferred to Inter RAO - Engineering LLC, a Russian construction company. More recently, a new pool of investors has been formed consisting of:

- A-RKSENA LLC, another Russian firm, for share 65%.
- Sino hydro for 15% investment
- EDL 15%
- Inter Rao 5% ownership and likely a contract to construct the project and sell Russian equipment.

5. Assessment of Impacts of the Proposed Mainstream Hydropower Dams and Appraisal of Their "Sustainability"

Section 4 of this Master Plan describes the current state of hydropower development in the Xe Kong Basin, including the seven hydropower dam sites on the mainstream that are being actively studied for feasibility under current Memoranda of Understanding (MoU) issued by the Ministry of Planning and Investment (MPI). The approximate locations are shown on the map in Figure 4-2, Section 4. Similarly, the pertinent details of these dams are provided in Table 4-2, Section 4. This section describes the impacts that the proposed Xe Kong dams would have on the river and the fishery.

How the Mainstream Dams Would Impair Physical Characteristics of the River

All dams and their impoundments, whether for water supply, flood control or power generation, alter the fundamental physical processes of rivers in ways that affect their biological productivity. While the list of such alterations is long, the main impacts of concern for the Xe Kong basin's fisheries are the change from a flowing-water (lotic) habitat to a still-water (lentic) lake-like habitat, alteration of the daily and seasonal flow patterns, the alteration and depletion of sediment and nutrient flows, and the barriers that the dams and reservoirs pose to both the upstream and downstream migration of fish, including their eggs and larvae. These effects are of grave concern for the mainstream of the Xe Kong tributary both in terms of individual dams and the cumulative impacts of multiple schemes. A cascade of dams on the mainstream Xe Kong within Lao PDR has the potential for the largest such impacts of any of the currently unimpaired Mekong tributaries due to exceptional value of this system for migratory fish reproduction, as documented in Section 3, and sediment and nutrient flows, as documented in Section 2.

Alteration of hydrology

Hydropower dams are non-consumptive. Except for evaporative losses, the same amount of water will flow through the mainstream Xe Kong before or after dams the construction of dams through that reach. But hydropower dams that are operated to store water for release at a later time distort the natural hydrograph on a seasonal or daily basis or both. The objective of such storage dams is to control the timing of power generation either to make it more uniform during the dry and wet seasons (seasonal storage) and/or to maximize power productions during the times of daily peak demand (daily storage).

The general understanding of the intended operations of the proposed mainstream dams on the Xe Kong is that the large reservoir at the top of the cascade, Xe Kong 5, would provide the storage for the system and the downstream dams would then use this modified flow pattern to generate power in a more or less run-or-river mode, where the daily discharge of these downstream dams would be roughly equal to the daily inflow into the reservoir. (Yet, it is notable that each of these projects has a separate developer with no obvious integration or coordination in the development or operational plans.) That means that the flow distortions that reduce the peak flows and increase the low flows will be maintained through the entire cascade and into the downstream river system. Under this assumption, and accounting for the effects of the other dams already constructed, the flow alteration at the bottom of the cascade, as the river crosses the border into Cambodia, would look like Figure 5-1 below.

Also, it is to be expected that all of these dams will be operated as peak power facilities to follow the daily load curve of the off-taker. So, each dam will maintain both seasonal and daily flow distortions. Hydropeaking would create large and rapid variations in the downstream flow patterns. These distortions would be particularly damaging to the downstream fishery.

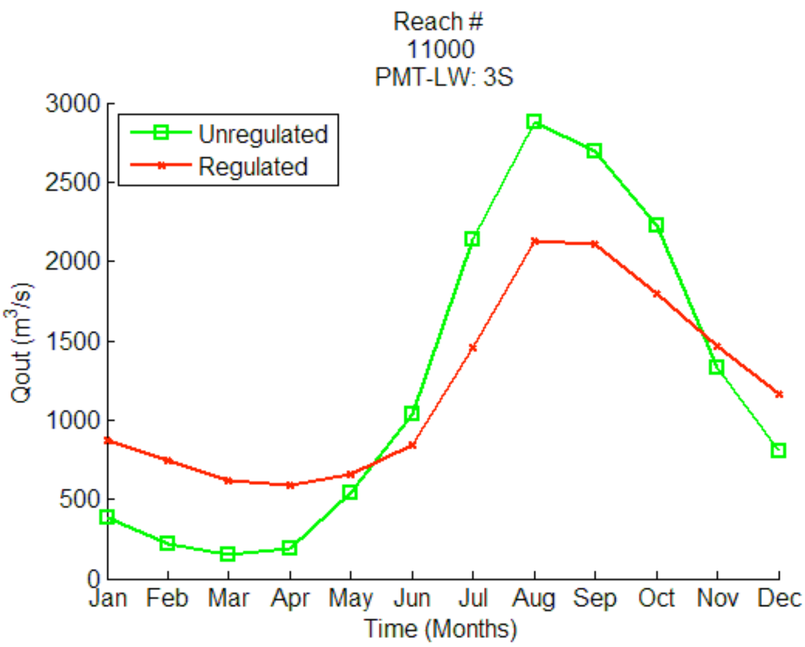

Figure 5-1. Flow alteration at the bottom of the cascade, as the river crosses the border into Cambodia.

Alteration of hydraulics and effects on the fishery

One of the most profound effects of the mainstream Xe Kong dams would be the shift from a flowing river to a series of still-water lakes with very little of the natural river remaining between the reservoirs. Fish that migrate up the Xe Kong river have a variety of spawning strategies. But most of these riverine species spawn in flowing water habitats and when these flows are altered by reservoirs, fish will either not spawn or their eggs and larvae cannot drift and die. These fish often have sticky eggs that attach to vegetation, sand and rocks and it is likely that some have eggs that drift. Under natural conditions the eggs hatch and the larval drift in the flowing water; this is an essential aspect of their life cycle which transports them to productive floodplains.

These species generally decline in abundance because of inability to complete their life cycle, to be replaced by species that are able to exploit static water conditions. The riverine species that tend to be lost are the larger, commercially important migratory species and they are often replaced by low value, smaller species or alien invasive species, typically introduced for aquaculture (e.g. carp and tilapia) that benefit most from this changing environment.

Impacts on migratory fish

Hydropower projects create barriers to fish migration due to i) the physical barrier that the dam itself presents, and ii) the hydraulic barrier posed by the impounded water which creates a static water body.

The physical barrier of a dam prevents upstream migration of fish, which may ultimately lead to the loss of fish species unable to complete their life cycles usually because they are isolated from their spawning and nursery areas. If spawning conditions are suitable below the dam the species may survive (Jackson and Marmulla, 2001; Oldani *et al.* 2007), but the combined abundance in the river downstream and the reservoir upstream is much lower.

In addition to blocking upstream migrations, dams can have major impacts on downstream migrations. For hydropower dams, mortality from passage through turbines is especially significant; turbine mortality for small and medium-sized fishes is typically 5-20% (Larinier, 2001), but mortality for large-bodied fish can be expected to be up to 100%. Designing dams for turbine passage is specifically discussed in Section 11. These factors are in addition to the imposed changes in discharge and water quality, increased predation in stilling basins below dams by predatory fish and birds, and 'gas bubble disease' if the plunge pool is deep and water recirculates producing supersaturated nitrogen.

While the barrier that dams present to the passage of fish can be mitigated to some extent (see Section 9 of this Master Plan for a discussion of such strategies, the barrier that the reservoirs present usually cannot. The static water of the reservoir prevents adult fish that may access the reservoir through fish ladders from finding the *flowing water* they need to spawn. If they do, they will find these habitats greatly reduced by the inundation of the reservoir. If they can successfully spawn, their eggs and larvae must drift back through the reservoir to find the flowing water that will carry them to the downstream habitats where they feed and grow into adults. The hydraulic barrier of the reservoir produces low water velocities that are insufficient to maintain larval drift (Pelicice *et al,*. 2015). Most will starve from lack of suitable zooplankton, be preyed upon by the reservoir fish, or sink to silty substrates and suffocate from lack of oxygen. The mortality from a single reservoir will be very high. Where the reservoirs are arrayed in a cascade, the mortality may approach 100%.

Predation in the reservoir can also cause high mortalities of juvenile fish migrating downstream (Jepsen *et al.,* 1998). The reservoir can also cause delays in upstream migration of adult fish; without a strong cue of water velocity in the reservoir some fish even pass back down over the spillway before attempting to ascend the fishpass again (Keefer *et al.,* 2004). These hydraulic impacts are particularly pertinent in the Xe Kong mainstream the shallow gradient will make the reservoirs long and wide.

Dams and reservoirs can potentially be operated to provide a velocity of flow that will keep eggs and larvae in suspension through the reservoir. Significantly, this needs to be maintained all the way to the point of discharge at the spillway or powerhouse; transporting the eggs and larvae through 99.9% of the reservoir would be insufficient to prevent mortality. This velocity also needs to be maintained during low-flow periods when the volume of water moving through the reservoir is comparatively small. Usually, operating the hydropower dam to ensure these velocities will require that the reservoir levels be reduced with a consequent reduction in hydropower production that may make them uneconomic.

These points are elaborated further in Section 8 of this Master Plan on mitigation strategies.

Some species are able to utilize the reservoir for feeding and to complete their life cycles if they have access to spawning grounds in the flowing water habitats in the reaches of the river upstream of the reservoir. The severity the impact is worse if major spawning habitats are inundated by the reservoir. Despite the perseverance of some fish species in reservoirs, the total fish productivity is greatly reduced compared to the natural river system.

The degree of impact that these dams and reservoirs would cause to migratory fish, due to both the barrier they pose to fish migration and to the inundation of riverine spawning habitats, depends on their size and, most important, their location. All of the lowest six are located right in the prime migratory fish spawning habitat of the mainstream river. These would provide an absolute barrier to fish migration.

The further downstream the dam, the more impactful it would be. Thus, Xe Kong Downstream A would be the least sustainable. The major concern is that it would block off the migratory fish habitat for the entire basin, from just above the Cambodia border. This would effectively destroy the migratory fishery for the Xe Kong River within Lao for 75 MW of installed capacity, a relatively small amount of power. Section 11 of this Master Plan provides guidance on design and operation of effective fish pass facilities to get upstream migrating fish around a dam of the height of Xe Kong #1 (approximately 8 meters), but, as noted above, the greatest hazard to survival of migratory fish would not be the dam but the reservoir. Thus, this large impact would not be ameliorated by the construction of a fish passage facility for the upstream migrants, because the main problem is the reservoir rather than the dam. The mortality is likely to be very high. These realities seriously call into question the sustainability of this project, as it would produce massive impacts on the migratory fishery for relatively little power. Of all of the projects proposed for the mainstream, this one particularly should be replaced by alternative development options that are described in Section 7 of this Master Plan.

Xe Kong Downstream B is proposed by the same developers. It is not clear whether these are considered to be alternative sites, or whether both are intended to be developed. The installed capacity of this project would be 50 MW, and it would generate 206.3 GWh/y. It would be located upstream between Xe Kong Downstream #1 and the town of Attapeu. Notably, if this project were constructed instead of Xe Kong Downstream A, the spawning habitat up to and into the Nam Kong and Xe Kaman tributaries would remain open up to the barriers created by Nam Kong #1 and Xe Kaman #1 projects, respectively. Significantly, the entire Xe Xou sub-basin would also remain open, which is both long and undeveloped at this time. But, this dam would wall off the remainder of the Xe Kong basin from just above the town of Attapeu into the headwaters and the many productive tributaries along the way, and for even less power than Xe Kong Downstream A. However, the reservoir for this project would back up water all the way to the tailrace of the Xe Kong 3A project, inundating almost all of the spawning habitat for those migratory fish that were somehow able to negotiate through the reservoir. This illustrates again that the main problem with these projects from a sustainability standpoint is the reservoirs themselves.

Xe Kong 3A, 3B, 4A and 4B would block access to many substantial tributaries that are likely to be important for migratory fish habitat. Even the uppermost dam, Xe Kong #5 is problematic. Until the NHI migratory fish experts made an epic journey to the reach of the river just below the dam site, it was not known for certain whether the site was accessible to migratory fish, due to a reputed waterfall (Tat Kalang). This is now unambiguously resolved. The reputed waterfall is just a series of rapids that drop only about 6 meters in total. The NHI team clearly ascertained that this reach is navigable by migratory fish and discovered at least 10 migratory species above the rapids in the catch of the local fishers. What is not known definitively is the abundance of and total number of migratory species that access the reaches above dam site #5 for spawning and rearing. Because the reach above the dam site all the way to the Vietnam border is essentially inaccessible by either road or river, and is devoid of fishing activity, it is not feasible to ascertain the extent of degree of fish migration above the #5 dam site. But this dam would create a large impoundment, backing water far up into the Xe Xet National Protected Area.

Given these considerations, the precautionary principle suggests that it would be prudent to investigate alternative dam sites. NHI's site suitability analyses suggest that the Houay Axam site and the Xe Lon dam site may constitute feasible alternatives that would still keep one of the headwaters tributaries unobstructed all the way to the Vietnam border. Yet, given the paucity of information regarding endemic fish species in the upper Xe Kong, there is not a sufficient basis at this time for determining which of these sites would cause the least impact on biodiversity.

There is little doubt that the lower six dams, and also likely #5, cannot satisfy the Policy on Sustainable Hydropower Development as sustainability is defined in Section 6 of this Master Plan, or, indeed, under any meaningful substantive standard. Indeed, the two environmental impact assessments that have already been prepared for two of these dams make that indisputable.

The EIA for #4 states:

- "Most of the 201 species of fish recorded in the Mekong mainstream at Khone Falls will be present in the Se Kong, and some estimates put the fish diversity at between 300 and 500 species" P. 0-8
- "In Se Kong Province almost every household is engaged in fishing activities both for subsistence and for income generation...All villages in the reservoir flooding area have robust fisheries primarily for subsistence, contributing a large part of the protein in their diet. . . . Migratory fish make up over 70% of the fish caught in the Mekong river basin." P. 0-8
- "There will be a major impact upon migratory fish species, both by blocking upstream migrations, but also by delaying migration triggers such as early flood events." P. 0-13.
- "Initial estimates put the current production of fish and OAAs at about 10,000 tons per year, of which migratory fish make up 71%. With the Se Kong 4 dam in place . . . the reduction in catch may be as much as 3,300 tons a year, with a value of USD 6.25 million." P. 0-14
- Changes in the flow regime will have a major negative impact on migratory fish species." P. 4-9

The EIA for Xe Kong #5 is equally unambiguous:

- "The fish fauna will become significantly impoverished, perhaps losing as much as 2/3 of the fish species currently found there, and all fish migration from downstream will cease." P. 0-8

If anything, the five dams proposed for the lower sites would be even more impactful. If the standard of "sustainability" is implemented in a meaningful way, these dams clearly do not qualify. It is true that the environmental impact assessments for both of these dams are currently being redone under instructions from the Ministry of Planning and Investment in granting extensions of the MoUs for the feasibility studies. Yet, it is unlikely that the results will vary substantially from the previous studies as the project sites, designs and operations have not changed appreciably.

Another indication of the unsustainable impacts of the mainstream dams comes from a widely cited paper by Ziv *et al.* (2012), which finds these to be among the most impactful dams in the Lower Mekong Basin, as shown in Table 5-1.

Table 5-1. Impact of the five most detrimental dams in the Mekong tributaries on fish productivity and biodiversity (Source Ziv et al., 2012).

Dam	Average % change in migratory fish biomass	Average no. of new endangered species
LSS2	-9.3	56
Xe Kong 3A	-2.3	9
Xe Kong 3B	-0.9	3
Xe Kong 4	-0.75	3
Nam Ou 1	-0.5	2
Nam Kong 1	-0.35	2

This output predicts that Xe Kong 4 and Xe Kong 3A and 3B would result in a loss of approximately 4% of fish production in the LMB and put 15 species on the endangered species list.[22]

The adverse impacts of the proposed dams are not confined to migratory fishery. There would also be substantial impacts on the resident fish populations and endemic species and also on the sediment regime in the basin.

Distribution and zonation of Xe Kong fish communities

Understanding the distribution of fish assemblages in the Xe Kong Basin can inform decisions on hydropower dam siting, especially by identifying the extent of upstream movement of migratory fishes and other areas of high endemism. The present analysis uses existing datasets to identify assemblages of fish with the aim of delineating zones.

Three data sets were used for cluster analysis of the species assemblage: Kottelat, 2009; Kottelat, 2011; the Xe Kong 5 EIA (HPEC & Norconsult, 2008); and the Mekong River Commission (MRC) fish catch database. Data on the presence or absence or fish species drove the analysis. More comprehensive data is available in the MRC data but is not comparable with the other data as these datasets vary widely in their sampling techniques. The MRC data is focused on commercial fishers and hence is biased to larger fish and larger streams. Kottelat (2009, 2011) directly sampled small streams, which is biased to smaller fish species, and there were *ad hoc* inspections of fishermen's catches and markets, which would include larger streams. The Xe Kong 5 EIA consultants interviewed villagers near the proposed dam site.

[22] However, these outputs, although possibly reflecting the likely impacts of the dam developments, must be treated with caution. It is unclear how the productivity of the rivers were quantified and the species diversity elucidated given few studies have taken place in the area and much of the mountainous region is uninhabited and problematic to access given the terrain and problems with unexploded ordnance.

From these data there are 1,134 records, with 238 species in 41 locations (Annex 5.1). The cluster analysis used Multi-Dimensional Scaling (MDS) to group species with similarities of stream size category (small, medium and large) and elevation, both taken from Google Earth. MDS is a means of visualizing the level of % similarity of individual species in the dataset.

Results

Figure 5-2 shows a dendrogram of the cluster analysis. There are four groupings that have a similarity of 25% or more based on the stream size category, elevation and species, which are shown in an MDS plot in Figure 5-3 laid over a map of the Xe Kong Basin in Figure 5-3. Two of these groups have clear geographic boundaries: one of the main-stem Xe Kong and one of high elevation sites in the Xe Kaman catchment. There are many sites data that do not fall into any group which is largely because sampling in different surveys had different standard effort or gear between sites. In some cases sites have only one species, so the analysis does not group them.

Discussion

The multivariate analysis identifies four zones of fish assemblages: a lowland group, a tributary group, a Xe Kong main stem group, and a high elevation group in the Xe Kaman. In addition to these groupings there are two main points from this analysis:

- There is no systematic fish data of the mainstem upstream of the MRC site near the town of Sekong, so the main stem zone may extent up to the Xe Kong 5 dam site or further.
- The tributary sites may be biased by the type of gear used for survey sampling, which was mainly for small fish, and the time of sampling, which avoided the wet season.

It is important that the influence of flow and the potential impacts of abstractions and releases of water be considered within the context of each of these main fish assemblages, by linking key species per community type to their functional ecology and flow requirements both for rearing and spawning (Cowx et al., 2004). The functional ecology and flow required for spawning (Table 5-2) shows that more than half of 50 registered species in the Xe Kong require flowing water and the remaining species 21 require a diversity of habitats that will be impacted by dams.

The relationship between the rate of flow, the rate of change of flow, the duration of high/low flow events and their seasonal timing, and their influence on spawning, recruitment and growth need to be considered when evaluating hydropower changes to flow patterns. Survival and life history are directly related to intact migration pathways, including the possibility of migration into tributaries, side channels and backwaters that are often very important for reproduction, but also serve as rearing areas for larvae and young fish.

The cluster analysis shows that local clusters of species will be impacted by the proposed mainstream dams, not only long distance migratory species.

Table 5-2. Spawning habitats registered in MRCS fisheries databases for important Xe Kong fish species, including 14 different habitats and 50 species with available data.

No Species	Spawning habitat
1	Backwaters or streams and rivers
2	Flooded forest
1	Floodplains and flooded forest
29	Flowing water
1	Headwaters
1	Ponds and swamps
2	Rapids and rocky areas
3	Rapids and rocky pools
1	River Banks
4	Rivers
2	Sand and gravel
1	Small streams
1	Standing and flowing water
1	Standing waterbodies
50	**Total No species**

Each barrier to migration has an effect on the structure of fish populations and composition of the fish community upstream of the barrier. Construction of weirs and dams or altered flow regimes that affect the ability of fish to bypass an obstruction or access backwaters and side channels, will alter the fish community dynamics and functioning. Figure 5-3 shows that existing and planned mainstream dams will create barriers and division among the four community types and thereby obstruct not only long-distance migration but also the local ecosystems dynamics. In the majority of cases, the main changes, to which all others are linked, are a loss of biodiversity and a decline in the mean size of fish in the population. These are caused by the progressive loss of species that are not tolerant to the changing environment or the loss of larger individuals and species and thereby their replacement by smaller ones.

For the Xe Kong River and its tributaries, of vital importance is the use as spawning ground for hundreds of migratory and local community's species, many requiring diversified ecosystems with free-flowing water. With the Xe Kaman already blocked by the Xe Kaman-Sanxay and Xe Kong 1 dams, the Nam Kong blocked by the Namkong 1 and 2 dams and the Xe Xou potentially being blocked by dams, the Xe Kong mainstream becomes even more important to remain unobstructed as it hosts the major long-distance migrators (see Figure 3-7 A and B in Section 3 of this Master Plan), the lowland, the mainstream, and part of the tributary community (Blue, red and green dotted areas in Figure 5-3).

For the mainstream community (red dotted area in Figure 5-3) the cascade of mainstream dams will have largest impact the further downstream a dam is placed, making Xe Kong Downstream A the most obstructive by dividing the local communities. As the migration and local communities exist all the way upstream to the proposed Xe Kong 5 dam, and perhaps further up, any mainstream dam will impact the local communities. Further, the cumulative impact of a cascade of dams may have severe consequences for spawning for local communities and for the contribution to the entire Mekong River productivity.

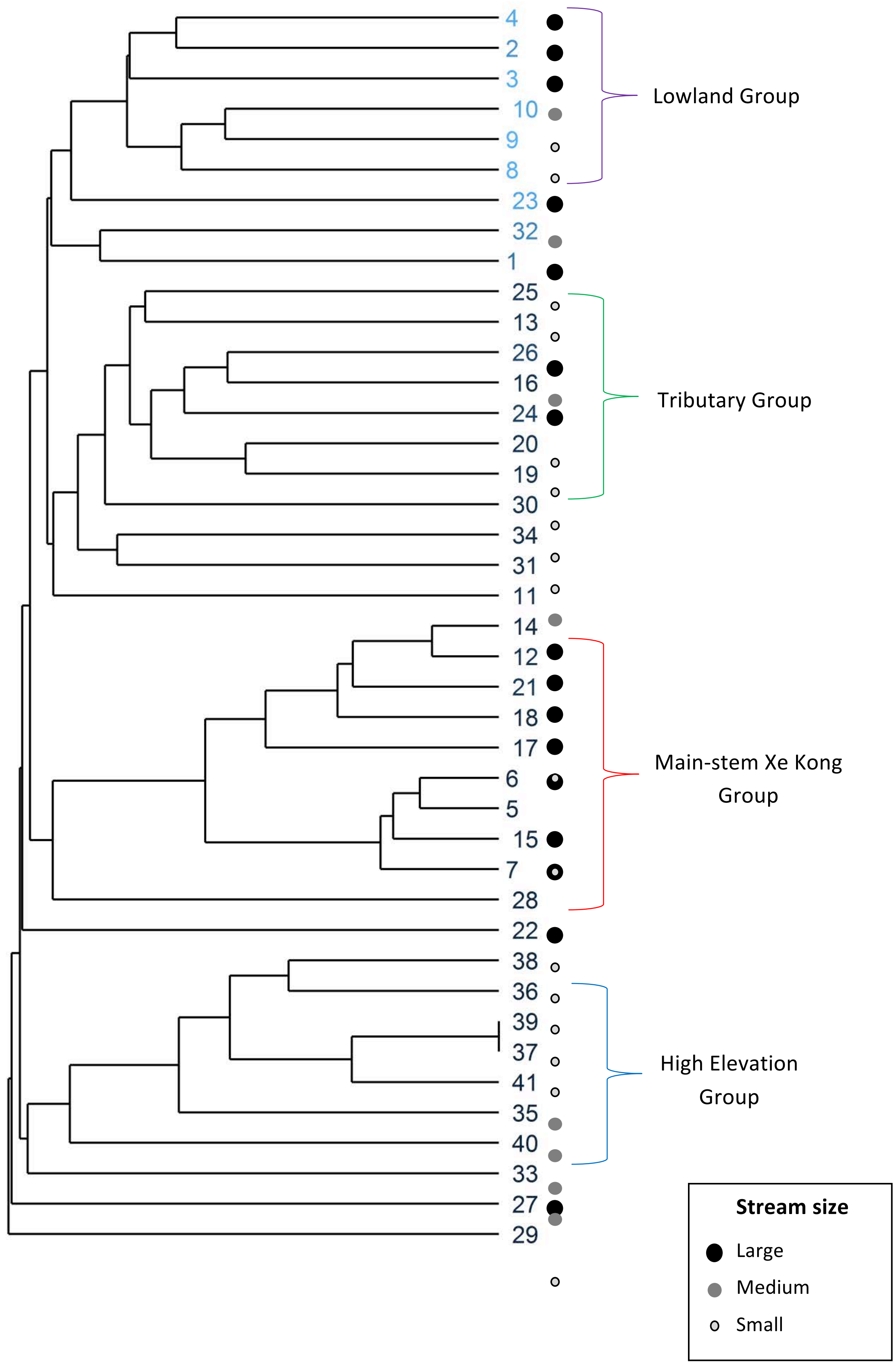

Figure 5-2. Cluster analysis of sites using presence /absence of species collected by Kotellat, 2009, 20011, Xe Kong 5 EIA (HPEC & Norconsult, 2008) and MRC fish catch database.

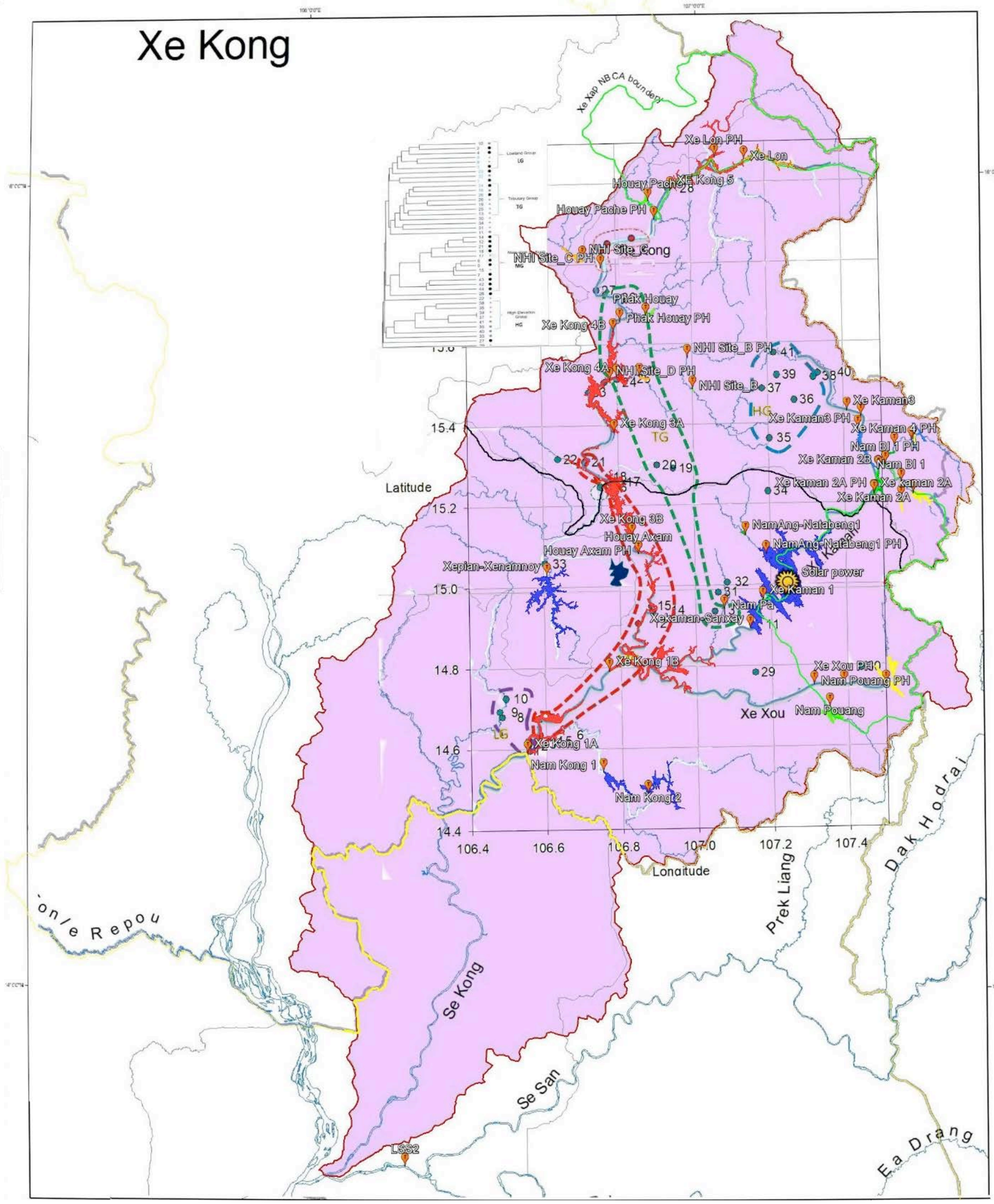

Figure 5-3. Map of the Xe Kong basin showing fish collections sites (pointed numbers) and groupings of sites (Dashed areas) from cluster analysis, overlaying a map of existing (Blue) and proposed mainstream dams (Red) that blocks, divide groups and create barriers to migration and spawning.

There are 4 groupings:

1. Red dashed areas: Main stem Xe Kong group
2. Green dashed area: Tributary group
3. Blue dashed area: High elevation group
4. Purple dashed area: Lowland group

Mortality at hydropower dams from spillways and turbines

In the Xe Kong basin, a common life cycle for riverine fish is to spawn upstream with large numbers of larvae and juveniles drifting passively downstream. Adult fish also often migrate downstream after spawning. This presents two impacts on downstream fish passage: the reservoir which, as described earlier, prevents larval drift, and passage at the turbines and over the dam's spillway. Both can cause high mortality with consequences for the recruitment[23] of fish to populations both upstream and downstream of the dam.

Fish encountering dams while moving downstream will either pass over the spillway, through specially engineered fish bypass channels, or be drawn into the turbine intakes through trash racks and then pass through the turbines themselves. Fish moving over spillways can be injured or killed if the design of the spillway does not take fish passage into account. If the flow is too strong they may not be able to avoid collisions with energy dissipating structures and flow detectors, or suffer abrasion against the spillway walls and floor if the water is too shallow.

Turbines and trash racks represent the most significant threat for downstream migrating at dams. Trash racks typically have spacing of 180-200 mm which allow all small and medium fish to pass through to the turbines but not fish larger than 900-1000mm in length (Stuart *et al.,* 2008) which would be impinged on the trash racks. Smaller fish may be impinged depending on their head width and swimming behavior as they approach the trash racks.

Fish entering the turbines are exposed to a variety of hydraulic stresses that cause injury and death. These include pressure changes (barotrauma), shear, turbulence, and strikes by the turbine blades. There is a close correlation between the length of fish and the probability of mortality caused by a blade strike; with larger fish more likely to suffer injuries (Turnpenny, 1998). In one modelled example for a Kaplan turbine in the Mekong, fish 500 mm long had a 40% chance of being hit and killed by blade strike, which rose to nearly 100% for fish that are longer than one meter (Figure 5-4) (Halls and Kshatriya, 2009). The body length of fish varies according to age and species. Therefore, older fish and those belonging to larger species are more vulnerable than young fish or fish belonging to smaller species.

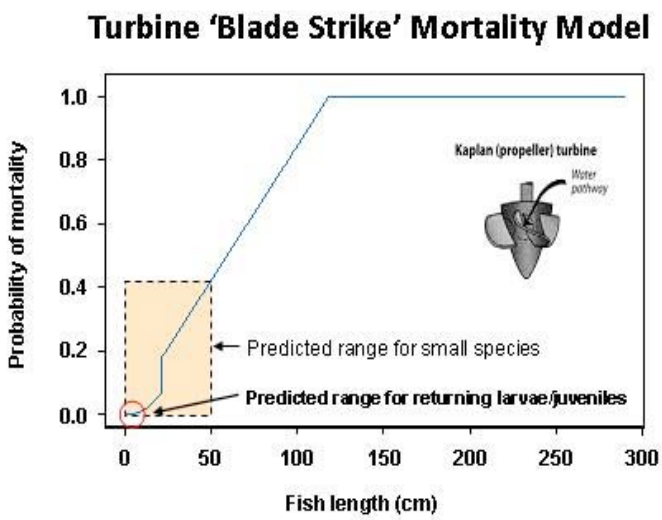

Figure 5-4. Relationship between fish length and the probability of mortality due to a blade strike Source: Adapted from Halls & Kshatriya, 2009.

Even if fish survive passage over the spillway or through the turbine, any injury suffered by the fish during the passage can reduce its chance of survival during its onward journey (Ferguson *et al,.* 2006).

[23] Survival of young.

Findings and Conclusions from Xe Kong Fishery Experts Workshop

On September 26 & 27, 2016, the National University of Lao and the Natural Heritage Institute, an International Non-Governmental Organization convened a workshop of the leading experts on the Xe Kong fishery from Lao PDR and around the world to share their knowledge, research results, and professional judgement for the purpose of providing a scientific framework for the creation of a "Sustainable Hydropower Master Plan" for the Xe Kong Basin. This group included 22 invited participants and a roughly equal number of observers, including technical and policy staff from the various Ministries and Agencies of the national and provincial governments involved in hydropower development and fisheries administration. It also included staff from the Mekong River Commission Secretariat (MRCS) and the Inland Fisheries Research and Development Institute (IFReDI) of the Royal Government of Cambodia.

The roster of Lao and foreign experts contributing to these Findings and Conclusions is presented in Annex 5.2. The Lao version of the Executive Summary of the key findings from the workshop are presented in Annex 5.3.

Key findings based on current state of knowledge

ISSUE 1: What is the relative importance of the mainstream Xe Kong River fish habitats in the context of the entire Mekong River System?

The Mekong fisheries, specifically, are characterized by a large number of species that must migrate either long or short distances to complete their life cycle and reproduce. The Mekong River system experiences large fish migrations both above and below Khone falls. Yet the greatest number of species and largest total volume of migratory biomass migrates in the 3S tributaries through the confluence with the mainstream Mekong, the Cambodian floodplains and Tonle Sap Great Lake, and the Mekong Delta (NHI, 2016a). Long-distance migratory fish that use the Xe Kong originate from the Viet Nam Delta, Tonle Sap Lake and nearby areas, from the Mekong in southern Lao and North-eastern Cambodia. Many of these migratory species require specific habitats like flowing water, rocks, vegetation etc. for spawning success. Dams restrict access to spawning and feeding habitats and impound water that submerges some of these habitats under static water.

The Xe Kong tributary is unique in being the last major tributary in the entire Mekong River System that runs unobstructed from its headwaters all the way to the South China Sea. On its way, the Xe Kong traverses the Lao reach from the Vietnam border, through Lao PDR and Cambodia, to the confluence with the Mekong mainstream, and from there through the Sambor reach, the Tonle Sap confluence, and the Vietnam Delta. The access for fish migration within the rest of the Mekong system has been compromised to a greater or lesser extent by:

- The seven Chinese hydropower dams now completed in the Lancang headwaters, which completely block access to migratory fish;
- The Thai dams for irrigation and hydropower on the Khorat Plateau which hamper fish access into and through the Mun and Chi tributaries for portions of the year;
- The 13 Vietnamese hydropower dams which have been constructed in the Sesan and Sre Pok tributaries which pose a complete barrier to fish migration;

- The Lower Sesan 2 Hydropower dam which is on schedule to be completed in 2017. It will create a barrier to fish migration in the reaches of the Sesan and Sre Pok Rivers within Cambodia in the absence of effective fish pass facilities.

- Existing or under-construction hydropower dams on the following eight northern tributaries in Lao PDR:

  - Nam Kading (Nam Theun 2 is already constructed; the Thuen-Hinboun dam is at the confluence of the Nan Theun and Nam Gnouang, which together form the Nam Kading)
  - Nam Ngiap (two dams already constructed, one under construction)
  - Nam Ngum (Nam Ngum 1, 2 and 5 are in operation; Nam Ngum 3 is being designed)
  - Nam Lik (Nam Lik 2 in operation, Nam Lik 1 under final planning)
  - Nam Khan (one dam already constructed, one under construction)
  - Nam Ou (#2, #5 and #6 already constructed, construction of 1,3,4 and 7 due to start in 2017)
  - Nam Nga (one under construction)
  - Nam Tha (one built, one under construction)

Two hydropower dams are now under construction in the mainstream of the Mekong River that will also affect fish passage. The barrier to fish passage that the Xayaburi Hydropower Project poses will be mitigated to some extent by an artificial fishpass. Notably, the Xayaburi powerhouse has a trash screen and no specific fish screen to prevent downstream migrating fish from entering the turbines. The Don Sahong Hydropower dam will block the Hou Sahong channel, which is the major migration pathway through Khone Falls. That project will afford fish passage though the Hou Xang Peuk, Hou Khone Lan, and Hou Sadam channels and reducing fishing pressure in the channels, especially by removing large fishing gear which block fish migration. How effective the Xayaburi fishpass will be is unknown. Based on experience with artificial fishpasses globally (Mallen-Cooper et al., 2015), this facility is likely to be only partially effective. Several other dams are under appraisal in Laos; including Pak Beng which is currently undergoing MRC review. These dams are all likely to block the Mekong entirely and require artificial fish passes of unknown effectiveness and efficiency.

By restricting access, these hydropower dams and their reservoirs reduce the access to habitats for migratory fish for spawning and rearing. Fisheries productivity is highly correlated with the extent of the feeding, spawning, refuge and rearing habitats. As access to these habitats is lost, the remaining accessible ones become increasingly important in sustaining fish populations and the fisheries.

In summary, the portion of the basin consisting of the Xe Kong tributary and mainstream Mekong downstream from the confluence constitutes the most productive portion of the freshwater fisheries. Because the Xe Kong is the last major tributary of the Mekong below Khone Phapheng Falls that provides free passage of fish from headwaters to the sea, this corridor constitutes a valuable and irreplaceable element of the Mekong River for migratory fish populations.

ISSUE 2: To what extent would hydropower dams on the mainstream Xe Kong impair the downstream fisheries?

Due to the seasonal variability of flows in the Xe Kong River, hydropower dams in the upper Xe Kong would likely need to store wet season inflow for release during the dry season to be economically viable (Noonan et al., 2012). The likely pattern is that the upstream dam(s) will provide the storage for the cascade and thereby dictate the downstream flow pattern.

Hydropower reservoirs in the mainstream Xe Kong basin will:

1. Permanently flood habitats of both migratory fish and non-migratory fish;
2. Cause fluctuations in daily flows and erosion of habitats and banks if they are operated for hydropeaking;
3. Diminish downstream sediment transport and trap nutrients in the reservoirs.

If these reservoirs are operated to store water seasonally, they will also cause:

4. Lower peak flows in the wet season;
5. Higher water levels in the dry season;
6. A delay in inundation of downstream floodplains at the onset of the wet season.

Depending on their severity, these hydrologic and morphological changes may impair the migration, spawning and survival of floodplain and riverine migratory species, particularly in the Cambodian portions of the system (Baird, 2007). These downstream effects of reservoir storage in the Xe Kong basin would be cumulative with those now being caused by reservoir storage in the Lancang Dams, the Vietnamese dams in the Sre Pok and Sesan, dams in the other Lao tributaries, and also with the eventual effects from other mainstream dams such as Xayaburi, Don Sahong and Pak Beng. Whether or not declines in fisheries yields and biodiversity are evident yet below the 3-S confluence, there is a limit of biological tolerance to these physical changes. Intensive dam development in the Xe Kong mainstream will contribute to the risk of exceeding these thresholds, which may result in declines in fisheries productivity and species diversity.

The probability of migratory fish passing upstream and surviving downstream passage (including drifting larvae), due to the above factors, would decline exponentially with increasing numbers of dams in the Xe Kong cascade. Even if all seven dams proposed for the Xe Kong mainstream were to be built to the MRC standard of providing safe passage for 95% of the species under all flow conditions (MRC, 2009), which represents best global practice, the cumulative effect would still be a major reduction in both biomass and species diversity.

The downstream dams in the Xe Kong cascade would have a larger negative impact on the survival of long distance migrators, and their reproductive success, than the upstream dams because the downstream dams block access to greater amounts of habitat and inundate more spawning and rearing habitat.

The proposed hydropower site for Xe Kong hydropower dam #1A would block migratory fish species for almost the entire Xe Kong basin within Lao PDR, including not only the mainstream Xe Kong, but also the Xe Kaman, Xe Xou and Nam Kong tributaries, which may also have valuable spawning habitats for migratory fish. It is appropriate to think of the #1A dam as having an impact similar to the Lower Sesan 2 Hydropower Dam in Cambodia which will also block passage to very productive spawning habitats. The #1A dam would have major negative effects on household income generation and livelihoods of the rural poor. As with the Lower Sesan 2 dam, fish passage facilities may partially mitigate the blockage of upstream passage but will not mitigate the effects of the reservoir on the drift of larvae downstream and the inundation of spawning and rearing habitats (see below).

There has been no sampling of fish species in the reaches of the river that would be impounded by the Xe Kong #5 dam. Yet, it is known that the upper reaches of the catchment have more endemic fish species. Fish species migrate upstream to reaches below the Xe Kong 5 dam site but the extent that these fish migrate upstream of the dam site is not well-documented. Therefore, we surmise that the barrier and impoundment created by Xe Kong # 5 may have larger impacts on endemic species of fish rather than on total biomass.

Avoiding ecological risks in the absence of sufficient information is a scientifically prudent strategy for sustainable hydropower development. Gathering further information is highly recommended by the workshop experts regarding fish migration above the Xe Kong #5 dam site, before a decision is made to authorize that dam. While nothing can really substitute for field work, the remoteness and difficulty of sampling the upper reaches of the catchment may require the use of second-best techniques such as stratifying the habitat using GIS and remotely sensed data and then assuming that fish diversity is related to habitat diversity. Then representative reaches could be conserved while enabling strategic hydropower development. For example, Xe Kong #5 will inundate much longer reaches of the river and will also back water up into Xe Xet National Protected Area. Given these considerations, the precautionary principle suggests that it would be prudent to investigate alternative dam sites. NHI's site suitability analyses suggest that the Houay Axam site may constitute a feasible alternative site off of the mainstream. Yet, given the paucity of information regarding endemic fish species in the upper Xe Kong, there is not a sufficient basis at this time for determining which of these sites would cause the least impact on biodiversity.

ISSUE 3: To what extent can the blockage and inundation of spawning and feeding habitat by proposed dams on the Xe Kong mainstream be mitigated by fish passage facilities, changes in dam operations, and artificial propagation (aquaculture)?

The largest factors in the reduction in fish yields and biodiversity from hydropower dams in the Xe Kong mainstream would be:

- The reduction in upstream passage;
- The mortality of adult and young fish through turbines and spillways;
- The conversion of flowing water habitats to the static waters of a reservoir;
- The alteration of downstream flows and fluctuation of flows due to varying discharges as from hydropeaking operations;
- Water quality alteration.

The blockage of fish passage can be mitigated to some extent by artificial fishways, but there are no examples of effective fish pass facilities on dams on large tropical rivers like the Xe Kong. The effectiveness of fishpass facilities to mitigate the barriers that dams pose to upstream migration depends on the discharge, the height of the dam, the proportion of river flow in the fishpass, and the migratory biomass (among other factors). The discharge threshold for effective fishpasses is generally estimated to be 10% of reservoir inflow (MRC, 2009), based on global experience. Unless fish passage is factored into the initial design and negotiations of the power purchase agreement, it is very difficult for the hydropower dam operators to allocate even 10% of the water for fish passage, since all of the available water is earmarked for power generation.

The height threshold for effective fishpasses in the Mekong system has been estimated by the MRCS at 30 meters (MRC, 2011). However, the fishpass requirements of each species will vary. With so many species traversing the Xe Kong and downstream system, it is not easy to design facilities that will be effective for all. Even if much of the biomass can be accommodated, there will be substantial biodiversity reductions.

Successful downstream fish passage is dependent upon screens to prevent large fish from entering the turbines and upon the design of the spillway, water-gate, and turbines. Mortality of large fish passing downstream through the dam can be mitigated to some extent with fish screens or behavioral barriers but this has not been done successfully at any large tropical dam (Mallen-Cooper *et al*., 2015). At present, there are no turbines that avoid mortality to Mekong fish species, although some are better than others.

Fish can suffer injuries and mortalities in turbines from: i) sudden pressure changes (barotrauma), ii) shear forces and iii) and strike from blades and other parts of the turbine. Turbines that are placed close to the tailwater surface cause high pressure changes which have very high impacts on fish with swim bladders that do not decompress easily (e.g. carps) and less impact on fish that can decompress easily (e.g. some catfish species). In theory, barotrauma can be mitigated by deep emplacement of the turbines but this has not been tested in actual applications. Gas supersaturated tailwater, with saturation levels ranging from 105% to 110%, can cause gas bubble disease in fish. Fish can die within a few hours when they are exposed to dissolved gas concentrations exceeding 140% (Chen *et al.,* 2012a).

Shear can cause high mortalities in eggs, yolk-sac larvae and moderate mortalities in other larvae and juvenile fish. Strike causes increasing impacts with fish size: small fish suffer less impact from strike and may be able to pass deep turbines with low mortality but a practical upper limit for fish size passing safely through turbines is likely to be 300 mm long; larger fish will suffer proportionately higher probability of impacts from strike.

<u>The reservoir impacts cannot be avoided or mitigated to a significant extent.</u> These are of six types:

1. The reduction in flowing water habitats for spawning
2. The inundation of rearing habitats
3. The mortality of eggs and larvae in the static waters of the reservoirs
4. Sedimentation that destroys spawning sites and habitats
5. Water quality changes, caused by seasonal stratification and consequent anoxia of lower water levels.
6. Changes in species composition and effects on the food chain.

Many migratory Mekong riverine fish species have drifting larvae[24]. Velocities in reservoirs are important for transporting the larvae. The degree of mortality of downstream drifting larvae in the reservoirs proposed for the Xe Kong mainstream may depend on two key hydraulic characteristics:

1. The change in hydraulics from flowing water to still water changes predator-prey relationships especially for those fish larvae adapted to capturing prey in flowing waters. This may also be related to reduced turbidity, which is caused by fine silts dropping out of suspension; this can make fish larvae more susceptible to predation.

2. The residence time of the water passing through the reservoir, which will affect the sustenance available in the yolk sacs of drifting larvae (among other factors).

Unless the larvae are discharged from the reservoir before their yolk sac becomes exhausted, they may not survive if suitable food resources do not exist in the reservoir. Hydropower dam cascades multiply this effect.

The hydraulics of the reservoir and the residence time can be regulated by the storage level of the reservoir and the rate of discharge from the dam. In theory, it is possible to operate the reservoir to maintain a sufficient velocity of flow to maintain hydraulics and to transport the larvae all the way to the point of discharge through the spillways and turbines before they perish from lack of nutrition, assuming that suitable food resources do not exist in the reservoir. However, these operations will affect power generation and revenues, posing a direct trade-off between fisheries maintenance and hydropower objectives.

In the Xe Kong, the vast majority of the most important commercial species migrate and spawn during the early wet season when the velocities through the reservoirs will be higher than in the dry season (NHI, 2016b). This may facilitate the drift of these larvae through a reservoir and the consequences for storage levels and power generation may not be large.

However, there are species that specifically spawn in the dry season. They typically do not rely on long distance drift for survival because they are resident fish that spawn during low flow conditions. The most critical time when larval drift through the reservoirs may be problematic is during the early wet season when a large volume of spawning takes place but the river flows are not yet high enough to provide the needed reservoir velocities.

In summary, it is the reservoirs that have the greatest impacts on migratory fish that cannot be effectively mitigated. Many Xe Kong migratory species need flowing water over various habitats to spawn. Therefore, determining the reservoir footprints of the proposed dams is necessary to assess impacts and make judgements on sustainability. Even if these reservoirs will operate more or less as run-of-river, they will need a reservoir to create the necessary hydraulic head, and this is the critical impact.

[24] Here we define larvae as the phase between hatching from the egg up to the time the fish is a juvenile. This larval phase can further be sub-divided into three stages: (i) Yolk-sac stage: after hatching the larva has a yolk sac, which is visibly attached to the anterio-ventral part of its body; (ii) Pre-larval stage: this stage begins when the eye is fully pigmented and the mouth and anus are open and the fish begins to feed on external prey; and (iii) Post-larval stage: during this stage, the urostyle completes upward flexion, the caudal, dorsal and anal fins develop, and the small fish begins to resemble a juvenile (Termvidchakorn and Hortle, 2013).

Artificial propagation of fish by means of aquaculture in the reservoir does not replace the species, productivity, or livelihoods that are lost when the natural capture fisheries is impaired by the construction of dams. Fish farming generally entails different and generally lower value species; substantial reduction in fish diversity; different capital, ownership and marketing structures; and different skills than those possessed by the natural capture fishers. The survival of a species should not depend only on aquaculture or captive stock. Under unfavorable political or economic conditions, or because of insufficient profit, aquaculture and stocking could be abandoned and the species might become extinct.

Development of aquaculture in or near a new reservoir usually benefits immigrants or relatively wealthier locals, including those who have the necessary skills and business experience rather than most of the resident fishermen, many of whom typically suffer the loss of the capture fisheries and derive no benefit from the aquaculture substitute. This usually creates large distributional equity concerns. Stock enhancement, which entails releasing alien species with high food value into the river ecosystem, can cause major transformation of the river ecosystem and may not replace the productivity.

The workshop participants emphasized that water quality effects associated with, or exacerbated by, reservoirs will be an additional factor bearing on fish survival. These include the tendency of reservoirs to stratify thermally, reduce oxygen availability, and concentrate pollutants in the inflowing water (e.g. from mining operations). Water quality degradation from gold and coal mining has significantly reduced the fisheries in the Xe Kong already. Mercury contamination from gold mining may be significant and methylation of mercury in reservoirs may render the fish dangerous to eat (Chea *et al.*, 2016). This may be a temporary impairment as the Government of Lao PDR is now seeking to control these impacts. This is in contrast to the impairments caused by hydropower dams which would be essentially permanent and definitive.

ISSUE 4: How would operation of mainstream and tributary dams in the Xe Kong basin affect the genetic makeup of populations above and below the dams?

Dams in the Xe Kong should be operated to allow maintenance of the genetic makeup of populations and provide passage of both passive and active migrants to allow genetic connectivity. Data on representative species show unique population structure in the middle reaches of the Xe Kong compared to Mekong River locations but that historical genetic connectivity still exists between the Xe Kong and Mekong rivers. Habitat fragmentation from dams that restrict gene flow between these populations will reduce the genetic diversity of populations and reduce the ability of the separate populations to adapt to changing environmental conditions. This may eventually lead to local extinctions of these populations and the resultant loss of their unique genetic diversity. Local extinctions of populations will lead to changes in the trophic structure of naturally co-occurring species with potential to cause extinctions of other co-occurring species populations, and subsequent losses in fisheries productivity and livelihoods.

Genetic connectivity of populations can occur both through passive larval dispersal and through active adult migration, both of which can be interrupted by dams and these impacts must be considered while constructing dams if healthy populations are to be maintained. Direct upstream passage of migrants can be obstructed by dam structures that do not adequately allow for a fish pass upstream. Construction of fish passes need to take into consideration the highly variable needs of the 64 known migratory fishes. Mortality during downstream passage of active migrants and larvae can occur from both reservoir and mechanical shearing effects as already stated and this will further restrict gene flow between the Xe Kong and Mekong. Dam construction should take into consideration the effects of restrictions in gene flow and if construction is to proceed, comprehensive genetic testing of populations of as many species as possible above and below proposed dams to provide for mitigation planning and restoration action (e.g. Raeymaekers *et al.,* 2009).

ISSUE 5: How would operation of existing tributary dams in the Xe Kong basin affect downstream flow patterns important for migratory fish reproduction and survival?

Any dams in the Xe Kong should be operated to discharge a flow pattern that is conducive to the requirements of migratory and resident fish, often referred to as "environmental flow requirements". The general approach is to maintain much of the natural seasonal variability of flows and temperature, especially avoiding large hourly or daily fluctuations in flow. This may require discharge attenuation and re-regulation of flows below the reservoir.

Migratory fish are present in the 56 km of river reach in the Xe Kaman tributary from Xe Kaman Sanxay Dam to the mainstream confluence. There are many species of smaller fish found there (Kottelat, 2011; Kottelat, 2009). Migratory fish are also present in the Xe Xou which has no dams at present. It joins the Xe Kaman downstream of the Sanxay Dam and before the confluence with the Xe Kong mainstream at Attapeu. This means that the Xe Xou flows unimpeded from its headwaters all the way to mouth of the Mekong at the South China Sea. However, there are not sufficient data to quantify the value of these reaches for migratory fish spawning and rearing. If this reach is determined to be important for migratory fish, consideration should be given to operating the Xe Kaman Sanxay dam to discharge an environmental flow pattern as defined above. This may necessitate operating Xe Kaman Sanxay Dam as a re-regulation reservoir or constructing a separate re-regulation weir downstream to counteract the flow distortion from the upstream cascade of dams in the Xe Kaman tributary. The best approach would be to establish environmental flow and water quality criteria that all dams would be required to meet.

Assuming that the Xe Kaman contributes 15% of the flow at the confluence with the Xe Kong, the flow distortion from hydropeaking and/or seasonal storage at Xe Kaman Sanxay may be attenuated in the floodplain areas downstream (mostly in Cambodia), although hydrodynamic modelling is needed to confirm the extent of attenuation. Hydropower operation in the Mekong basin has influenced the annual water levels as far downstream as Phnom Penh. However, the effects of daily peaking are more localized (NHI, 2016b).

Migratory fish are also present in the ~75-km river reach in the Nam Kong tributary from Nam Kong #2 Dam to the mainstream confluence. This reach of river is deep and has deep pools. It may therefore be important for migratory fish reproduction. Studies are needed to confirm this. In March 2016, the Ministry of Energy and Mines issued a concession agreement for construction of Nam Kong #1 dam in the downstream reach below Nam Kong #2. This would create a reservoir that back up almost to the #2 dam and, therefore, cuts off a substantial portion of this habitat. If this reach is determined to be important for migratory fish reproduction, consideration should be given to operating the Nam Kong #1 dam to discharge an environmental flow pattern as defined above. This may necessitate operating that dam as a re-

regulation reservoir or constructing a separate re-regulation weir downstream to counteract the flow distortion from the upstream cascade of dams in the Nam Kong tributary. The best approach would be to establish environmental flow and water quality criteria that all dams would be required to meet.

ISSUE 6: What would be the nature of the ecosystem that would result if the flowing conditions of the Xe Kong were replaced by the static conditions of reservoirs?

The hydraulic barrier of the reservoir, as described earlier, produces low water velocities that, among other impacts, may be insufficient to maintain larval drift (Pelicice et al., 2015). In a static reservoir, the larvae do not drift. In addition, they can starve from lack of suitable zooplankton, be preyed upon by larger fish, or sink to silty substrates and suffocate from lack of oxygen. The reservoir can become a favorable habitat for predators and can cause high mortalities of juvenile fish migrating downstream (Jepsen et al., 1998). The reservoir can also cause delays in upstream migration of adult fish; without a strong cue of water velocity in the reservoir some fish even pass back down over the spillway before attempting to ascend the fishpass again (Keefer et al., 2004). Migratory fish will either not spawn or the eggs will die. These hydraulic impacts are particularly pertinent in the Mekong dams which would be long, narrow impoundments because of the shallow gradient of the Lower Mekong Basin. Hence, changes in hydraulics can be devastating for migratory fish populations while hydrology (discharge) remains little changed, as in run-of-river hydropower.

With such changes, indigenous riverine species generally decline in abundance because of inability to complete their life cycle, to be replaced by more lentic species, opportunistic or exotic species which are tolerant and able to exploit static water conditions. Critically, it is usually alien invasive species, typically introduced for aquaculture and that have escaped from the culture units (e.g. carp and tilapia) that benefit most from this changing environment. The riverine species that tend to be lost are the larger, commercially important migratory species and they are often replaced by low value, smaller species or alien invasive species. Similarly, some species are able to utilize the reservoir for feeding and to complete their life cycles if they have access to spawning grounds in the flowing water habitats in the reaches of the river or tributaries upstream of the reservoir. The scale of the impact is worse if major spawning habitats are located immediately upstream of the dam and are inundated by the reservoir. A few short-distance migratory species also survive in reservoirs if there is sufficient length of flowing water habitats in the river upstream. The species that are able to exploit the reservoir and increase in abundance contribute to overall fish harvest, however the total fish productivity is likely to be reduced compared to the natural river system. Eutrophic lakes may be an exception.

Knowledge gaps most urgent to fill to provide a solid foundation for hydropower development planning in the Xe Kong Basin

Following are the major knowledge gaps identified in the workshop that need to be addressed to fully understand the impacts of development proposals on the Xe Kong and Mekong fisheries. Many of these issues will require years of effort to answer and will not be resolved before the sustainable hydropower development master plan is adopted. Instead, where practical, the Ministry of Natural Resources and Environment (MoNRE) should require that they be addressed in the environmental impact studies prepared by proponents of particular hydropower projects as a pre-condition to eligibility for a concession agreement to construct the project. Where the issues can only be addressed at the basin scale, they should fall within the mission of the Mekong River Commission.

What is the ecological value of the Xe Kong fishery that is at risk from hydropower development?

- What is the fraction of fish harvested in the Mekong basin that require the habitats of the Xe Kong within Lao for some aspect of their life-cycle? What is the best estimate of the effects on fish harvest in Cambodia and Vietnam from various scenarios for loss of spawning habitat and mortality of larvae in Xe Kong reservoirs in Lao PDR?

- What and where are the critical habitats for migratory fish spawning in the Xe Kong mainstream? (See map of rapids and hydropower sites below).

What further field work is necessary before decisions can be made on siting of hydropower facilities in the Xe Kong tributaries and upper catchments?

- There are reasonably good data to assess the extent to which the additional potential dam sites that have been identified in the Xe Kaman tributary (see Figures 5-4) would adversely affect critical habitat of local endemic fish species. Some of these data are reported by Dr. Maurice Kottelat (2011 and 2009), and in the EIA for the Xepian-Xenamnoi project (Kottelat, 2013). However, there has been no field work at all on the Houay Axam.

- Given the paucity of information regarding endemic fish species in the upper Xe Kong, surveys are urgently needed to provide a basis for determining whether the Houay Axam site is preferable to the Xe Kong #5 site for hydropower. Notably, #5 will inundate much longer reaches of the river and will also back water up into Xe Xet National Protected Area. This may constitute a sufficient basis for recommending the Houay Axam site. The field work should catalog both species and habitats with a goal of preserving representative habitats.

- The Xe Xou tributary may be of particularly high quality habitat for migratory fish. There is an urgent need to assess the value of this fishery before decisions are made on Xe Kong #1, as this dam would block access to the Xe Xou. It is also important to assess whether flow distortion from Sanxay reservoir would prevent migratory fish from accessing the Xe Xou habitat.

Fish sampling is needed in the Nam Kong below Nam Kong #1 reservoir site and Nam Kong #2 reservoir site to determine the effects of various operational policies for these reservoirs on migratory fish in the reach to the confluence. This sampling should take place over a number of years, including wet and dry seasons. While direct measurement will be most reliable, local knowledge is also needed to inform data collection.

What are the additional data requirements for making intelligent decisions on the design and operation of hydropower dams in the Xe Kong basin?

- What is the threshold of velocity of flow for hypothetical reservoirs in Xe Kong mainstream that would be necessary to avoid exceeding the residence time for survival of larvae? What would be the effects on power generation of operating the dams to maintain these flows?

- What are the thresholds of tolerance of key migratory fish species in the riverine/floodplain environment downstream of the Xe Kong within Lao to hydrologic alteration from storage dams?

- What would be the effects of various operational scenarios for Xe Kaman Sanxay on floodplain dynamics below Attapeu and in the Cambodian reach of the river, and how would these affect migratory fish reproduction and survival?

What are the critical knowledge gaps for making intelligent decisions regarding fishery impact mitigation strategies?

- What has been the global experience with artificial propagation of fish in reservoirs as a mitigation strategy for losses in the natural capture fisheries? This survey would need to account for differences in the economic and ecological value of species, the distributional equity aspects, and the hazards of stock enhancement techniques.

What advanced analytic techniques should be implemented to improve understanding of migratory fish patterns in the Xe Kong and the Mekong system below its confluence?

- To improve understanding of what migratory species access which reaches of the Xe Kong at what times and in what numbers, a number of study methods were discussed at the workshop, including genomic testing based on a sampling regime supported by USAID.

Sediment and Nutrient Capture in the Mainstream Dams[25]

Sediment are essential to maintain the complex channel and floodplain morphology that provides the diversity of habitats needed by different species and life stages of fish. Fine sediment deposited from overbank flows provide soil fertility for natural riparian forests and for floodplain agriculture. Some nutrients are carried in solution, but many nutrients essential to support the food web of the river and productivity of the nearshore coastal fisheries are associated with fine sediment (organic particles, clay, and silt). Sand and gravel bars provide essential complex habitats for many species and life stages, and the existence of these dynamic features requires a continuous supply of sediment.

For sediments and nutrients, the effects of the mainstream dams and reservoirs would be two-fold. They would both alter the natural flows patterns and deplete the quantity available downstream. In natural flow conditions, the sediments and nutrients are washed into the river by monsoon rains (with the greatest volume mobilized during the largest storm events) and are then deposited in the river banks and floodplains, which replenishes and nourishes them. But reservoirs are sinks for sediments and nutrients. When the inflowing water meets the still water of the reservoir, its velocity abruptly declines, causing sediments to drop out of suspension.

[25] Some text in this section is from a paper summarizing the results of a workshop of experts convened by the Natural Heritage Institute and the Yellow River Conservancy Commission in Zhengzhou, China, in September 2012. The authors are G. Mathias Kondolf, University of California, Berkeley, California, USAID; Yongxuan Gao, Natural Heritage Institute, San Francisco California, USA; George W. Annandale, Golder Associates, Lakewood, Colorado, USA; Gregory L. Morris, GLM Engineering COOP, San Juan, Puerto Rico, USA. The results were subsequently published in an article by Kondolf *et al.*, 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future 2(5), doi:10.1002/2013EF000184.

Reservoirs trap all the bedload (the coarse sand and gravel moved along the river bed) and a percentage of the suspended load (the sand and finer sediment carried in the water column, held aloft by turbulence). The supply of sediment to the river downstream is thereby reduced. The percentage of the suspended sediment trapped by a reservoir can be estimated as a function of the ratio of reservoir storage volume to annual volume of inflow (Brune, 1953).

By virtue of interrupting the continuity of sediment transport in rivers, dams cause sediment to accumulate upstream within reservoirs, creating four distinct problems:

First, when impoundments reduce water velocity to an extent that allows silt to deposit, the accumulating silt will bury and suffocate the sessile animals such as snails and lead to their eradication.

Second, the fine sediments (mainly silt and clay) carry the nutrients that fuel the aquatic food chain. In the Mekong, productivity of the system depends on these transported nutrients, especially in the delta area and coastal region.

The third problem is that sediment trapping by dams, particularly bed load, deprives downstream reaches of the sediments essential to maintain integrity of the river. Sediment-starved, or 'hungry', water erodes the bed and banks to regain some of its former sediment load (Kondolf, 1997). These erosive flows commonly induce incision and coarsen the bed, fundamentally altering aquatic food webs (Kondolf *et al*., 2012; Power *et al*., 1996).

The Mekong delta and the coastal area that relies on riverine sediment supply is especially vulnerable to impacts of reduced sediment supply (Vörösmarty *et al*., 2003). At present, approximately 21,000 km^2 of land in the Mekong delta is less than 2 m above sea level and 37,000 km^2 is regularly flooded (Syvitski, 2009). While sediment delivery to the Mekong delta remained relatively constant over most of the twentieth century, recent decades have seen accelerated rates of sea-level rise, more rapid subsidence due to groundwater extraction, loss of sediment to offshore waters by channelization, and in the late twentieth century, reduced sediment delivery resulting from in-channel mining of sand and gravel. Anticipated dam-induced reductions in sediment supply can only exacerbate the rate of land loss. The pre-dam sediment accumulation rate across the Mekong delta was 0.5 mm y^{-1}, while overall relative sea-level rise was 6 mm y^{-1} (Syvitski, 2009). Land erosion and subsidence combined with sea-level rise, would leave few options available to mitigate coastal retreat (Rubin, Kondolf and Carlin, 2014). The combination of sediment reduction and a 0.46 meter rise in sea level by 2100 would lead to a 50% increase in flooding, with profound consequences for coastal populations in Vietnam (Chen *et al*., 2012b; Syvitski *et al.*, 2009).

The fourth problem is that sediment will accumulate over time to the point when the reservoir loses its storage capacity and thereby impairs reservoir operation (White, 2001). The need to manage reservoir sediments to maintain reservoir storage capacity has been acknowledged by many authorities (ICOLD, 1989; Morris and Fan, 1998; Palmieri *et al*., 2003; Kawashima *et al*., 2003; Annandale 2013), but to date there are few examples of its implementation.[26]

[26] Approximately 1% of storage volume in the world's reservoir is lost each year due to sedimentation (Morris & Fan, 1998). In fact, at the global scale, reservoir storage space is being lost due to sediment accumulation faster than new storage space is being built (Annandale, 2013).

Section 9 of this Master Plan discusses design and operational techniques for mitigating the accumulation of sediments in reservoirs. However, it is notable that the effectiveness of these techniques often depends on the reservoir characteristics (see e.g. Efthymiou et al. 2017). In the case of the Xe Kong mainstream cascade, these dams are sited in relatively flat terrain which creates reservoirs that are relatively broad, long and shallow. These characteristics are not favorable for implementing economically viable reservoir sedimentation management techniques (see e.g. Annandale *et al.* 2016; Efthymiou *et al.* 2017). The exception is Xe Kong #5, which would be a narrow and deep (albeit very long) reservoir.

In sum, short reservoirs in steep terrain are more conducive to sediment management than long reservoirs in relatively flat terrain. In all cases, discharging sediment comes at the expense of power generation, making large dams less economically attractive in the short term but, by virtue of prolonging reservoir life and preventing sediment-related maintenance problems, sediment management will often be economical over the long run. These realities have important implications for sediment management in the proposed mainstream dams of the Xe Kong basin.

Section 2 of this Master Plan discusses the importance of sediment flows to maintain the morphology and ecological health of rivers such as the Xe Kong. The contribution of its sediment to maintenance of the Mekong Delta and the productivity of the Tonle Sap Great Lake warrant particular emphasis. The seven originally proposed mainstream Xe Kong dams will have a storage capacity of 5,848 $10^6 \cdot m^3$. As described in Section 2, about 8.4 Mt/yr of suspended sediment is produced in the Xe Kong, which represents roughly one third (37%) of the 22.7 Mt/yr of sediment thought to be generated in the 3S basins (i.e., Se Kong, Se San and Sre Pok). Unless designed and operated to discharge sediment, the cascade of mainstream Xe Kong dams will capture virtually all of the bed load and part of the suspended sediment that today flows out of Xe Kong into the mainstream Mekong.

To better predict the cumulative suspended sediment trapping potential of the mainstream Xe Kong dams, the SedSim model (Wild and Loucks, 2012) was used to simulate the production of daily watershed sediment loads (kg) and reservoir sediment trapping, as well as reservoir operations and channel routing. SedSim is a daily time step, deterministic sediment accounting model that has been applied in numerous Mekong studies (Wild *et al*., 2016; Wild and Loucks, 2014). Average daily reservoir water inflows (m^3/s) for a representative 24-year period from 1985-2008 used as input to the SedSim model were generated using the MRC's calibrated Soil and Water Assessment Tool (SWAT) model.

Table 5-3 below presents the following: key reservoir characteristics important for predicting sediment trapping (rows 1-5), simulated unregulated (i.e., no dams in entire Xe Kong basin) sediment inflows (row 6), regulated (i.e., 17 dams exist in Xe Kong) average annual sediment inflows and outflows (row 7-8), and average annual trapped sediment loads and associated trapping efficiencies (row 9-10). The dams are organized from upstream-most (at the top) to downstream-most (at the bottom). Importantly, trapping efficiencies shown in row 10 are computed using the Brune method as described in (Wild and Loucks, 2014; Wild and Loucks, 2012) using values from the median curve reflecting median sediment coarseness. Also, note that the reductions in sediment inflows in the regulated versus unregulated scenario (see Figure 5-1) reflects the fact that trapping takes place in upstream reservoirs (see Figure 5-5).

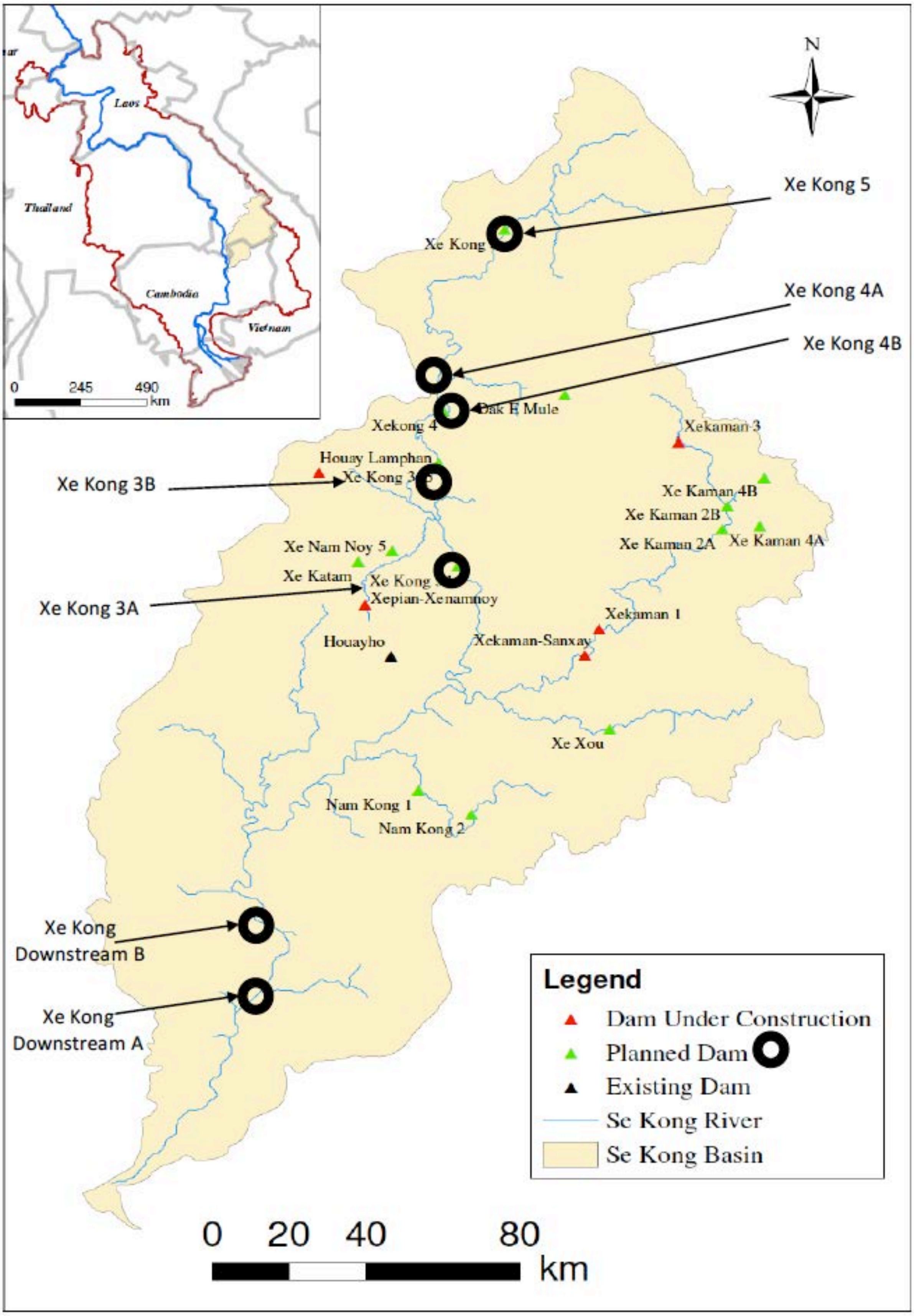

Figure 5-5. Map of location of hydropower dam sites on the Xe Kong mainstream.

As shown in Table 5-3, the capacity: inflow ratio (i.e., residence time of water) of the mainstream Xe Kong reservoirs, and therefore their trapping potential, decreases moving from upstream to downstream. Upstream dams (e.g., Xe Kong 5) have higher trapping rates, although there is relatively less suspended sediment being transported in these headwater reaches. For example, Xe Kong 5, Xe Kong 4B and Xe Kong 4A each have potential trapping efficiencies in excess of 90%. Reservoirs located in reaches farther downstream have lower trapping rates because the reservoirs are hydrologically smaller due to higher cumulative inflows.

Table 5-3. Key characteristics of the seven mainstream Xe Kong dams.

	Xe Kong 5	Xe Kong 4B	Xe Kong 4A	Xe Kong 3A	Xe Kong 3B*	Xe Kong Downstream B	Xe Kong Downstream A	Total
Total storage capacity (10^6 m^3)	3300	1005	988	187	168	105	95	5848
Mean annual inflow (m^3/s)	115	197	249	290	403	407	899	---
Capacity: inflow ratio (years)	0.911	0.162	0.126	0.02	0.013	0.008	0.003	---
Capacity: inflow ratio (days)	333	59	46	7	5	3	1	---
Assumed operation	Seasonal storage	Seasonal storage	Seasonal storage	Run-of-river	Run-of-river	Run-of-river	Run-of-river	---
Unregulated sediment inflow (10^6 tons/yr)	0.73	1.51	1.54	1.64	2.75	2.75	5.15	5.15
Regulated sediment inflow (10^6 tons/yr)	0.73	0.81	0.072	0.107	0.87	0.42	0.958	0.96
Regulated sediment outflow (10^6 tons/yr)	0.03	0.07	0.008	0.09	0.423	0.26	0.75	---
Annual trapped sediment load (10^6 tons/yr)	0.7	0.735	0.0643	0.021	0.447	0.167	0.208	2.35
Sediment trapping efficiency (%)	96	91	89	20	51	39	22	46

*Total storage estimate unavailable for Xe Kong 3B, so active storage capacity was used as an estimate of total storage capacity. Thus, sediment trapping potential is underestimated.

While Table 5-3 offers a summary of long-term reservoir sediment trapping potential, the planned mainstream Xe Kong dams will also alter the river's natural seasonal suspended sediment transport regime by trapping sediment. Figure 5-6 shows the effects that the six mainstream dams upstream of Xe Kong Downstream A would have on the natural monthly sediment regime. In other words, this displays the monthly pattern of sediment transport immediately downstream of Xe Kong Downstream B. Xe Kong Downstream A is not included in this figure because the intent is to isolate the effects of the mainstream dams.

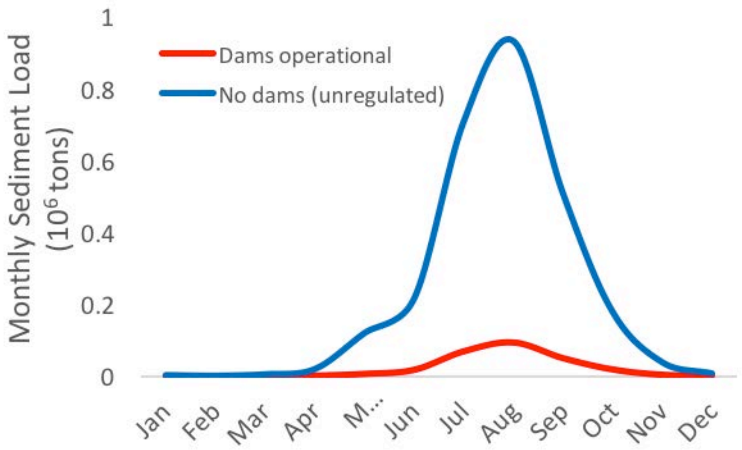

Figure 5-6. Comparison of simulated monthly average sediment load transport when the river is completely unregulated (i.e., no dams are present) versus when six mainstream Xe Kong dams (Xe Kong 5, 4A, 4B, 3A, 3B and Downstream B are operational).

The NHI Team has investigated re-designs and operations of the Xe Kong mainstream cascade that would greatly improve the discharge of sediments. These results are reported in Section 10 of this Master Plan.

One important benefit of this Master Plan for the investors, developers and government regulators alike will be to identify alternative sites, designs and operations that provide superior outcomes both environmentally and financially compared to the existing plans, and avoid expenditure of additional time, money and efforts away from dams that cannot satisfy the new government policy on sustainable hydropower.

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6. FUNCTIONAL DEFINITION OF SUSTAINABLE HYDROPOWER

As noted in Section 1 of this Master Plan, neither the January 12, 2015 Decree of the Policy of Sustainable Hydropower Development nor the implementing guidelines provide a substantive definition or standard for determining whether a project qualifies as "sustainable". Rather, these laws state outcomes or goals and procedures for achieving them. The outcomes or goals are stated in terms of avoidance, minimization, mitigation and compensation for social and environmental impacts. The pre-existing policy of "avoidance of irreversible environmental impacts such as the loss of biodiversity . . . or disruption of ecological cycles" is retained and reiterated but there is no guidance regarding the degree or thresholds of "loss" or "disruption" that would render a project unsustainable, and therefore not approvable. Since ALL hydropower projects have some adverse effect on the environment, the critical question is: how much impact is tolerable, and how much impact is too much? This is the critical question that the Decree and Guidelines do NOT answer. The policy and guidelines prescribes the roles and responsibilities of the developers and the several agencies of government in seeking and conferring approvals of applications for hydropower projects. But, they provide no mechanism for assuring that observance of these procedures will produce projects that meet the substantive standard of sustainability.

Therefore, a pre-requisite for a Master Plan for Sustainable Hydropower Development is to provide a robust and practical definition of "sustainable hydropower". We believe the best way to do that is to specify the physical attributes of a hydropower project that functionally avoids or minimizes "irreversible environmental impacts" and "loss of biodiversity". This we do by considering the measures that can counteract the types of impairments that hydropower projects cause to the physical processes of rivers, as described in Section 4 of this Master Plan, on which environmental integrity and biodiversity depend. And, we consider these measures for each of the major choices that developers and regulators make in planning hydropower projects. These are depicted in the x and y axes of Figure 6-1. Across the top, we posit the three types of impacts that need to be counteracted:

1. the barrier that dams present to migratory fish and the inundation of habitat for both migratory and resident species;

2. the capture of sediments and nutrient flows; and

3. the alteration of natural flow patterns.

The main types of choices that are implicated are with respect to siting, design and operation of the projects. In this manner, nine cells are generated that together provide the functional definition of a "sustainable hydropower project". We explicate each in Figure 6-1 and in more detail on the following pages.

Counteract impacts→→ Aspects of project ↓↓↓	Barrier to migratory fish & inundation of habitat	Trapping of sediments and nutrients	Alteration of natural flows
Siting	1. Above existing barriers to migration Avoid inundation of critical habitat for endemic native species	2. Deeper canyons in headwaters	3. Above tributaries that will modulate the flow distortion of the dam.
Design	4. Fish pass facilities, low-impact turbines, fish screens	5. Low level or radial gates for discharge	6. Low capacity factors of power plant to accommodate variable discharges; Pumped storage
Operation	7. Maintain minimum velocities through reservoirs to maintain larval drift	8. Flushing, sluicing, density current discharges	9. Run of River operations and/or re-regulation of altered flows for hydro-peaking at or below terminal dam

Figure 6-1. Diagram of depicting primary considerations for sustainable hydropower.

1. **Counteracting the barrier to migration and inundation of critical habitat in the siting choice:** The main concepts for this cell are "hydro-intensification" and designating hydropower "no-go" zones. Hydro-intensification means concentrating additional hydropower facilities in the catchments above barriers to migration. These barriers can be of two types: 1) natural barriers such as waterfalls that are too precipitous for migratory fish to navigate and 2) artificial barriers posed by existing dams and reservoirs. The natural barriers are surprisingly few. Even waterfalls as impressive as the Khone Falls on the mainstream Mekong are in fact traversed by myriad species of migratory fish. Artificial barriers are much more common in the Lao landscape. To be sure, some of these are of a scale where fish passes are feasible and may be partially effective. But, as Sections 3 and 5 of this Master Plan reveal, the more problematic barrier to successful passage of fish, particularly downstream passage of fish larvae, is the reservoir. In most respects, these pose a barrier to fish passage that cannot be practically mitigated. Therefore, additional hydropower projects above the terminal dam in a catchment will generally not be accessible to migratory fish. These reaches are therefore prime areas for siting sustainable hydropower projects.

   The logic of this principle of sustainable hydropower it that, from an ecological preservation point of view, it is worthwhile to concentrate hydropower development in portions of a river system that are already compromised to enable free-flowing conditions to be maintained in the pristine portions of a river system (Thomas, 2017).[27] In this kind

[27] Carrying this logic, its ultimate conclusion in the Mekong Basin suggests that it would be far better for the Government of Lao to further develop the reach of the mainstream Mekong from the Chinese border to Xayaburi, the now extant mainstream dam, rather than allow development on the mainstream Xe Kong, which is today free-flowing all the way from the Vietnam border to the South China Sea. That means that the Pak Beng dam, for which the Mekong River Agreement's

of a trade-off, the developed portion is sometimes referred to as a "sacrifice zone" (Thomas, 2017). One corollary of this approach is that it provides a motivation to build a first dam so that the rest of the system becomes eligible for more hydropower projects. Yet, one of the greatest virtues of hydropower development "by design", through a Master Plan of the sort illustrated by this report, is that all development will become intentional, rather than *ad hoc*. The Government of Lao will decide at the inception which watercourses to develop and which to preserve based on considerations of avoiding harm to ecological resources.

Yet, migratory fish passage is not the only siting consideration. Also, important is avoiding severe impacts on aquatic biodiversity. This is often the prime consideration for the higher reaches of the watersheds because they tend to have particularly high levels of endemic species, meaning species that are found nowhere else, (regarding the Xe Kong, see Meynell and Knight, 2017; Meynell, 2014). This is further discussed in Sections 5, 7 and 8 of this Master Plan. Since avoidance of biodiversity loss is a core feature of the policy on sustainable hydropower, it is essential that the Master Plan avoid siting of hydropower facilities that would cause extinctions of species due to inundation of their critical habitat. In the absence of definitive surveys of fish species assemblages in these upper catchments, the NHI team has devised a method for ascertaining biodiversity hotspots from the known physical characteristics of these watersheds. That method and the results are explicated in Section 8 of this Master Plan.

2. **Facilitating sediment passage in the siting of hydropower projects:** Avoiding the accumulation of sediment in reservoirs, and discharging accumulations that do occur, is facilitated by siting the dam in places where the reservoir will be deep and narrow (Kondolf *et al.,* 2014). This geometry is more conducive to sediment management than reservoirs that are wide and shallow. Deep, narrow reservoirs can be operated to maintain a velocity of flow that will minimize deposition and maximize re-suspension when the reservoir is operated to flush the sediments through the dam (Morris and Fan, 1998; Kondolf *et al.,* 2014; Thomas, 2017). This argues strongly in favor of siting hydropower facilities in the upper reaches of the watershed where the topography tends to be steeper. Demonstrably, this is the case in the Xe Kong basin. This may mean a larger number of smaller facilities because the volume of flow lower flows in the higher catchment.

3. **Siting dams that are operated for daily or seasonal storage above large tributaries that can modulate the flow distortions.** Where the discharge from the storage dam contributes a relatively small fraction of the flow (e.g., <50%) below the confluence with an unregulated tributary, the effects of the flow distortion on the downstream fishery will be significantly reduced. Houay Axam and Xe Lon are examples of projects sited in this manner.

4. **Designing hydropower dams to allow passage of migratory fish both upstream and downstream.** The design requirement for fish passes, turbines, fish screens and

Procedures for Notification, Prior Consultation and Agreement have been initiated, should be favored as a replacement for mainstream Xe Kong development from an environmental point of view. Stated another way, Pak Beng is more sustainable than the Xe Kong dams would be.

spillways to accommodate fish passage and prevent mortality are discussed at length in Section 8 of this Master Plan.

5. **Designing hydropower dams with low-level or radial gates for sediment discharge.** All of the techniques[28] for flushing accumulated sediments from reservoirs require gates to be installed in the dam for discharge of the sediments (Thomas, 2017; Kondolf *et al.,* 2014), as discussed in Section 9 of this Master Plan. Dams that do not have these features cannot be regarded as sustainable. It is usually impractical to retrofit the installation of gates when they have not been incorporated into the original design and construction (Kondolf *et al.,* 2014). While that may be possible from an engineering standpoint for concrete construction dams (but not for rock-filled dams), it is generally financially prohibitive (Thomas, 2017). However, the siting criterion for sustainability proposed by this matrix would place these dams above existing ones. This raises the serious question whether sediment discharge from an upstream dam makes sense if it will be trapped by a downstream dam that does not have the necessary low level gates. For the potential replacement hydropower dams featured in this Master Plan, that question is most pronounced in the case of the several dams that could be sited above Xe Kaman #1 which is not equipped with sediment discharge gates. Again, the question of retrofit arises, and again it is very likely infeasible to do that for this dam.

6. **Designing hydropower dams to counteract flow distortions.** Hydropower operations can cause two types of alterations of natural flow patterns. Dams that have large enough storage capacity to store an appreciable fraction of the annual inflow may be operated to alter the seasonal and inter-annual variability in river flows due to hydrologic variations (Thomas, 2017). Their operational objective is to make hydropower production more uniform throughout the year and to carry-over storage from wet to dry years. This alters migration cues (Cowx, 2014) and reduces the interaction of the river with its floodplain, both of which can reduce the productivity of the fishery.

   The resulting flow distortions can be reduced through changes in the operational policy, as discussed in paragraph 9 below, to generate power in rhythm with the seasonal changes in flow. Run-of-river operations aim to discharge water through the powerhouse at the same rate as the inflow to the reservoir, essentially just passing the variations in the hydrograph through the reservoir and into the downstream environment without substantial alteration (Thomas, 2017). This will mean that the power output will be equivalently variable from the wet to the dry season. To accommodate that variability, the powerhouse should be designed with enough turbine capacity to accommodate the high flows, to avoid losing water through the spillway except during the more extreme flood events, even though many of the turbines will become idle during the low flow season. This is called a "low capacity factor" (Thomas, 2017), meaning that the percentage of time

[28] According to Kondolf et al., 2014 (Section 6.2): "…Gates should be placed and sized with respect to the requirement to achieve the desired long-term profile. There is no standard location for the proper placement of gates, because this will depend on the situation at each dam, but in general gates should be set low enough and with sufficient hydraulic capacity to establish the desired equilibrium profile **and support the type of sediment management operation identified for long-term use.** For example, if flushing is to be performed during a low-flow period, the gates may be smaller and placed very low in the dam section, while gates for drawdown sluicing will have much greater hydraulic capacity and will probably be set at a higher level…"

that a turbine is being used is relative low. This will increase the capital cost of the hydropower dam per unit of power produced and is therefore only economically justifiable when the value of the downstream fishery is relative high. In a cascade configuration, only the lower-most dam in the cascade, which controls flows into highly productive features such as floodplains, wetlands, deltas and estuaries, may need to be operated in a run-of-river configuration. That dam and reservoir essentially takes the flow distortion out of the release patterns created by the upstream dams and reservoirs.

The second type of flow distortion caused by hydropower operations is radical changes in the daily pattern due to "hydro-peaking", that is, the operation of the dam to maximize power generation during the times of the day of highest demand in the electrical grid (Thomas, 2017). These operations can be highly destructive of the downstream fishery. There are two conventional ways to counteract that type of flow distortion. One is to construct a pumped-storage facility (Thomas, 2017), if the terrain permits. This is a smaller reservoir that is sited at a higher altitude to the main power dam. During time of low power demand, power from the main dam is used to pump water from that reservoir into the higher one (Thomas, 2017). During times of peak demand, water is released from the higher reservoir to the lower reservoir through turbines which augment the power production from the main dam (Thomas, 2017). In this way, the main dam can release a uniform flow into the downstream river channel during the daily cycle. Pumped-storage operations impose a power output penalty on the combined facility so, again, this may be most justified where the value of the downstream fishery is relatively high. Another option to counteract daily flow distortions is to construct a re-regulation weir downstream of the dam (Thomas, 2017) that can contain the surges in the discharge during peak hours and release it during the off-peak hours. Because less than one day of discharge of the dam must be contained, re-regulation reservoirs can be relatively modest in scale.

7. **Operating hydropower dams to counteract the barrier that reservoirs pose to downstream migration.** This problem is addressed in Sections 3, 5, 7, and 8 of this Master Plan. In sum, the problem is that reservoirs create static water conditions that are not conducive to the downstream passage of fish eggs and larvae as these cannot swim (Thomas, 2017; Pelicice *et al*., 2015), but must drift through the reservoir and thence through the powerhouse or spillway into the flowing water of the downstream system (Cowx, 2014), where they can mature into adults. This barrier to downstream migration can result in 100% mortality of this life stage of the species. The only way to prevent this mortality is to operate the power dam to maintain the minimum velocity of flow through the reservoir that is needed to keep the eggs and larvae in suspension all the way to the point of discharge (Mallen-Cooper, Cowx and Jensen, 2015). This is much easier to do with shorter reservoirs with a steeper geometry, the same conditions that are needed for sediment management. It is notable that the velocity of the reservoir is a function of both the rate and volume of through-flow and the storage level (Brune, 1953). During the high flow season, maintaining the velocities may be relatively easy. During the low flow period, however, it may be necessary to reduce storage levels to create the necessary velocities, which will reduce hydraulic head and therefore power generation. Whether that is necessary depends on the downstream migration behaviors of the fish species. If the migrations are largely or exclusively during the high flow period when velocities through

the reservoir are relatively high, operations may not need to be adjusted much or at all. But where species are migrating all year around, as in the Xe Kong system, operational adjustments will often be necessary.

8. **Operating hydropower dams to remove sediments.** Techniques for maintaining sediment flows through hydropower reservoirs are discussed in Section 9. Draw-down flushing will require that the reservoir be drained periodically during the low flow period (just before the monsoon season) so that the river flows are re-established to re-suspend the accumulated sediments and transport them through the low-level gates or radial in the dam (Thomas, 2017; Kondolf *et al.,* 2014). This will require hydropower operations to be suspended for a brief period. Sluicing of sediment is performed during the peak flow period by opening the radial gates to allow the high-concentration sediment waters to be released from the reservoir (Thomas, 2017; Kondolf *et al.,* 2014). This water by-passes the powerhouse and can result in a loss of power generation. However, the water released through the low-level or radial gates may be water that would otherwise be discharged over the spillway, in which event no power losses would occur. These sluicing operations should be performed annually.

9. **Operating hydropower dams to maintain a semblance of natural flows in the downstream system.** Where the value of the downstream fishery is high, such as where floodplains, wetlands, deltas and estuaries are involved, the power dam must be operated to avoid substantial distortions in both seasonal and daily flow patterns. That means operating the dam more as a run-of-river facility and less as a storage facility. This will reduce the turbine capacity factors during the times that discharges are throttled back and thereby increase the cost per unit of power produced by the dam. The logic of hydro intensification presents a need to consider the combined effects of a cascade of dams. If the objective is to maintain a near-natural flow regime into the downstream environment below the cascade, for the benefit of migratory and other species, then it is the operation of the lower-most dam that is of concern. Additional dams above the terminal dam may (almost certainly will) distort the flows in the intervening reaches (which may have implications for endemic species viability), but these distortions can be modulated or counteracted by operating the terminal dam as a re-regulation reservoir, essentially storing the inflows from the dam discharges above and releasing this water in a pattern that removes the distortion (Thomas, 2017). In the Xe Kong (and more generally), we are concerned to take the daily flow distortion out of hydropeaking facilities. That means that the terminal dam must store the daily inflows and release them in a pattern that is uniform for that day, removing the radical variation in downstream flows that would otherwise occur. As discussed in Section 10, for the Xe Kong basin, this is only an issue for the existing dams of Xe Kaman #1 (the downstream Xe Kaman Sanxay project is run-of-river), the Nam Kong #1 and potentially, the proposed Xe Kong #5 if other proposed downstream dams are found to not satisfy the Policy on Sustainable Hydropower Development. These dams may need to be re-operated to maintain environmental flows.

Where all nine of these functional targets are met, the hydropower dam should surely be considered to meet the "sustainability" criteria. Where few are met, it clearly should not. But what about the intermediate cases? Whether partial satisfaction of these targets is judged to be meet the sustainability standard, the acceptability of the facility should depend on the value of the fishery that is sought to be protected. The Xe Kong is surely a high-value fishery. Therefore, in this Master Plan, we undertake to illustrate how hydropower can be practically developed in the context of a high value fishery that will meet ALL of these targets without sacrificing power production goals or making the facilities uneconomic.

Helpful comments on the standards and criteria set forth in this Section have been provided by the Department of Environmental and Social Impact Assessment (DESIA) at the Ministry of Natural Resources and Environment. These comments suggest that sustainability criteria also be included for the construction phase of a hydropower project and for measures to maintain forest cover to prevent increased erosion and sediment accumulation in the reservoir. Notably, the same point has been made by the Department of Forest Resources Management at the Ministry of Agriculture and Forestry.

The mitigation measures suggested for the construction phase include design and operation of the river diversion canals around the dam construction site in a manner that maintains fish passage and natural river functions. DESIA also requests discussion of compensation mechanisms to offset biodiversity losses for listed species of plants and aquatic animals.

These suggestions are important and well received. They are also large issues that are beyond the scope of the work envisioned in developing a sustainable hydropower development plan. Nevertheless, the NHI Team will endeavor to give them due consideration in the final version.

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7. SUSTAINABLE SITE SUITABILITY SURVEY

Introduction

The logic and benefit of this Master Plan are to position the Government of Lao to take charge of the future of hydropower development by determining for itself the projects that will be developed, where they will be located, when they will be commissioned, how they will be designed and operated, and the service area for the electricity. It can do this by adopting a master plan for development of river basins that will then govern the types of projects for which it will solicit and accept applications for Memoranda of Understanding to conduct feasibility studies. The GoL would not itself conduct the feasibility studies in developing the master plan, just as this Master Plan for the Xe Kong does not constitute a feasibility study for the projects that it features as sustainable ones. Rather, the feasibility studies would be conducted as they are at present, by the potential developers. However, under the basin-wide master planning approach, the GoL would not just passively accept any and all proposals to conduct feasibility studies; it would itself decide which projects it want to see studied. Equally important, the GoL would decide which river reaches it wants to conserve for its natural values and place off limits for hydropower development, as determined through basin-wide programmatic environmental and social impact assessments. This is a significant reversal of the current process in which the initiative comes from investors and developers, with the Government agencies—Ministries of Energy and Mines (MEM), Planning and Investment (MPI), and Natural Resources and Environment (MoNRE)—playing a more reactive role. In Section 12 the changes in the process for planning and approving hydropower that would facilitate implementation of this Master Plan are discussed at length.

This Master Plan therefore presents a development scenario that implements the Policy on Sustainable Hydropower by identifying potential projects in the Xe Kong basin that would satisfy the criteria for sustainability proposed in Section 6. These alternatives would be given a higher priority for approval than the pending mainstream projects, which do not satisfy the criteria because they would exact an unsustainable toll on the fishery of the Lower Mekong Basin, as explained at length in Section 5. These sustainable alternative projects are displayed in Table 7-1.

Yet, the Master Plan also recognizes that "sustainability" is a matter of degree in that all dams impair natural riverine processes to a greater or lesser extent. It also recognizes that the demand for power is projected to increase over time. The Master Plan therefore presents a phased approach with the highest priority placed on potential projects that fully meet the criteria for sustainability. Notably, all of the Xe Kong mainstream projects would generate power at the dam, whereas the alternative projects in this Master Plan are diversion-style projects in which water would be diverted by barrages into penstocks or canals that would convey the water to remote powerhouses downstream located to maximize the hydraulic head. These diversion projects pose rather different impacts on downstream flow patterns and fish migration compared with projects based on simple barrier dams, as discussed below and at greater length in Section 9.

Five tiers of dam development are presented in this Master Plan. The tiers, the projects within each tier and their parameters are displayed in Table 7-1 A & B below and described in the text that follows. The location of the project sites in the five tiers are shown in Figure 7-1.

Table 7-1A. New Hydropower Sites in the Xe Kong River System: Tiers One-Four. See next page for Tier Five.

	Tier One		Tier Two			Tier Three				Tier Four	
	Solar Augmentation at Xe Kaman 1										
Project	Without transmission line enhancement	With transmission line enhancement	Xe Kaman 2A	Xe Kaman 2B	Nam Ang Tabeng	Houay Axam	Dak E Mule Downstream	Xe Lon	NHI Site B	Nam Bi 1+2+3	Xe Kaman 4
(Lat. /Long.)			15°15.01'N 107°26.33'E	15°16.52'N 107°27.00'E	15°13.46 N 107°31.57'E	16°014786N 107°044092E	15º30.80'N 106º50.84'E	15°58.83'N 107°18.84'E	15º28.80'N 106º58.94'E	15°13.46'N 107°31.57'E	15°20.83'N 107°32.15'E
Province			Attapeu	Attapeu	Sekong	Sekong	Sekong	Xekong	Attapeu	Sekong	Sekong
River	Xe Kaman	Xe Kaman	Xe Kaman	Xe Kaman	Xe Kaman	Houay Axam	Xe Kong	Xe Lon	Dak E Mule	Xe Kaman	Xe Kaman
Estimated Power (GWh/yr)	358	715	160	380.5	183	717	333	214	175	550	287
Installed capacity (MW)	200	400	35	100	41	164	76	49	40	130	70
Rated head (m)			48.6	78.8	640	566	160	190	300	423.6	459.1
Design discharge (m3/s)			155	90	20.7	64.0	49	64	11	26.0	18.4
Full supply level (m)			280	370	640	566	330	550	730	860	865
Catchment area (km^2)			1970	1740	203	799	1039	726	288	265	712
Mean annual flow (m^3/s)			77.5	68.4	10	31	44	28	12	10	29.6
Total reservoir vol (mill m^3)			20.8	333						16.5	141.5

Solar augmentation alternative

Under study per MOUs

New dam sites identified by NHI

Table 7-1B. New Hydropower Sites in the Xe Kong River System: Tier Five.

	Tier Five						
Project	**Houay Chalelu 1**	**Nam Pa**	**NHI Site C**	**NHI Site D**	**Houay Pache**	**Phak Houay**	**Nam Pouang**
(Lat. /Long.)	15°406373N 107°408824E	14°941010N 107°054225E	15º58.64’N 106º42.60’E	15º30.80’N 106º50.84’E	15º56.70’N 106º52.51’E	15º54.11’N 106º55.94’E	15º41.50’N 107º18.84’E
Province	Sekong	Sekong	Sekong	Sekong	Sekong	Sekong	Attapeu
River	Xe Kaman	Nam Pa	Xe Kong	Xe Kong	Xe Kong	Xe Kong	Xe Xou
Estimated Power (GWh/yr)	25	10	43	42	49	57	69
Installed capacity (MW)	6	2	10	9	11	13	16
Rated head (m)	20	48	134	190	172	240	145
Design discharge (m3/s)	62.8	14.3	15	9	16	14	19
Full supply level (m)	420	200	350	350	450	420	330
Catchment area (km^2)	827.2	128.9	186	110.6	186	141	298
Mean annual flow (m^3/s)	28.4	5.1	7.7	4.7	7	6	11

New dam sites identified by NHI

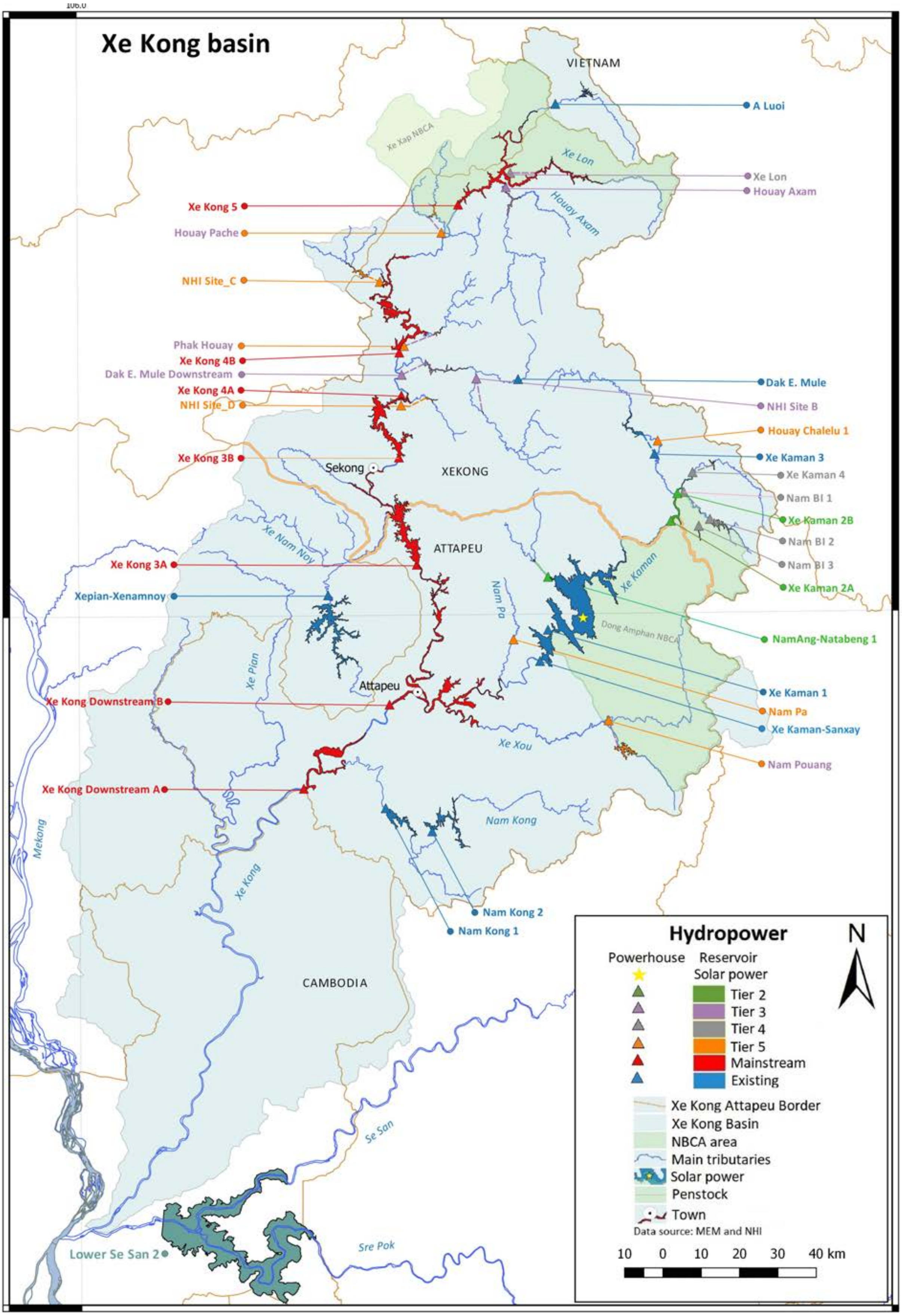

Figure 7-1. Location of projects in Tiers One-Five, including solar.

Tier One: Solar augmentation of Xe Kaman 1

Tier One involves augmentation of the largest of the existing hydropower reservoirs with a solar photovoltaic component. This concept is described in Section 11 of this Master Plan. It would create a hybrid hydro-solar facility where power generation would be wholly integrated and operated as single project. Analysis in that Section shows that the solar augmentation could add at least 358 GWh/y of power output[1] (200 MW of installed capacity) without requiring transmission capacity enhancements, and at least 715 GWh/yr of power output (400 MW of installed capacity) with enhancements that the owner and operator of the hydropower project, the Viet Lao Power Joint Stock Company, states can be accomplished without new towers. These "hybrid" facilities have the additional benefit of substantially improving the reliability of power generation compared to the hydropower dams are currently operated.

Tier Two: Replacement dams above existing barriers > 25MW

These are projects that are sited above existing barriers to migration. As of the time of this writing, all of these are already being investigated under existing MoUs. However, none have yet been approved or received a concession agreement.

The projects in Tier One and Tier Two together would fully implement the sustainability policy as defined in this Master Plan and would provide approximately 1081.5 to 1438.5 GWh/y of new power output (356 - 576 MW of capacity) (depending on transmission capacity enhancements at Xe Kaman 1 hybrid project), including the hybrid hydro-solar facility (Tables 7-1 and 7-3). This tier of potential projects should be given the highest priority and approvedl and constructed before the dams in the other tiers and, even more, the proposed mainstream dams. The best outcome for the river would be for those projects to replace the lower-most of the proposed mainstream projects for meeting the next increments of power demand because those would create the most impactful new barriers to migratory fish. Combined with Tier One, the Tier Two projects would produce more than enough power to replace the lower four mainstream projects (Xe Kong Downstream A, Downstream B, 3A and 3B). That scenario would keep open for spawning the following major tributaries: Nam Kong (up to the Nam Kong #1project), Xe Xou, 56 km of Xe Kaman, Xenamnoy, and the Houay Tayun.

Tier Three: Replacement dams that are located above the reaches accessed by migratory fish (mostly)

These are potential projects that would be sited at locations in the tributaries that experience the least fish migration because of their distance from the prime spawning reaches of the mainstream. Some of these projects are located on tributaries that form the boundary with the Xe Xap or Dong Amplian NBCAs, and would create impoundments in these boundary areas. We include these in Tier Three, however, because the existing reservoirs in the Xe Kong also have this

[1] Calculated by using SERIS 10MW floating with fixed angle to the sun to calculate the mean annual energy for 200 MW PV installed capacity.

characteristic, such as Xe Kaman 1, Xekaman Sanxay. We discern from this situation that the GoL does not consider such projects on the boundaries to violate the protected status of NBCAs.

These new projects would provide a total of 1439 GWh/y of new power output (329 MW of capacity) (Tables 7-1 and 7-3). These should receive the second highest priority for approval and construction. Combined with the Tier One and Tier Two projects, this development scenario would provide a total of 2520.5 to 2877.5 GWh/y (685 - 905 MW of capacity) (Table 7-3), almost the equivalent amount needed to replace all of the proposed mainstream dams except the highest one (Xe Kong 5). That would conserve the current level of accessibility of all of the major tributaries below the headwaters for migratory fish.

Tier Four: Replacement dams that are located within NBCAs or pose a relatively high risk to endemic species

These are projects that would be sited within, or would inundate portions of, National Biodiversity Conservation Areas (NBCAs) or that may pose a relatively higher risk to endemic resident (non-migratory) species. (For more information on endemic and endangered specieis in the Mekong Basin, please see Annex 7.1). The two NBCAs of concern are the Xe Xap in the headwaters and the Dong Amplan in the Xe Kaman sub-basin. The Xe Lon project would inundate a portion of the tributary that defines the southern boundary of the Xe Xap NBCA, and the Nam Bi cascade would create impoundments on the tributary that defines the northeastern boundary of the Dong Amplan NBCA. These were established to protect terrestrial biological resources, not aquatic ones. The only species survey in the literature is for the Xe Xap and does not even mention aquatic species (Gray *et al.,* 2012). The NHI Team therefore concludes that the dams in this tier would not violate the purpose for which these protected areas were designated. Another potential project on the Xe Xou was eliminated because it has already been cancelled by the GoL due to its location in the heart of the Dong Amplan NBCA.

As explained in Section 12, there are three management designations for forest lands in Lao PDR: 1) National Biodiversity Conservation Areas, which are designated primarily to conserve biodiversity and living resources; 2) Forest Protected Areas, which are designated to conserve the lands, waters and forest resources; and 3) Forest Production Areas, which are managed primarily for sustainable harvest of trees. Permissible activities in each of these are not well defined, but the NBCAs have the greatest protection. Even there however, "conversions" to allow hydropower development are permitted by the Council of Ministers, the Prime Minister or the National Assembly if that use is determined to provide the maximum benefits to Lao. In this determination, the degree of adverse impact on the natural resources is weighed against the potential economic benefits.[2] As hydropower development enjoys the highest priority in the national economic development plans, sites that are approved for development by the Ministry of Energy and Mines (MEM) carry a presumption of

[2] Notably, there is precedent for such exemptions in the case of the Nam Ngiep # 2 Hydropower Project.

satisfying that standard and consequently the Department of Forest Resource Management within the Ministry of Agriculture and Forestry will not objects to hydropower development within them.[3]

We also note that there is precedent for construction of hydropower projects in such protected areas, as discussed in Section 12 of the Master Plan. We put these dams in a lower priority tier, however, in acknowledgement of the designation of these areas by the Government of Lao as "protected".

The actual impact on endemic aquatic resources is another matter. To get a preliminary sense of where the areas of relatively high endemism of aquatic species are likely to be found relative to the dam sites identified in this tier, the NHI team used existing data sets on the physical characteristics of river reaches that serve as indicators of high endemism. These results are displayed below in Table 7-2. This survey of potential risk to endemic fish species suggests that some potential hydropower sites outside of the NBCAs might pose a high risk. These sites are also included in Tier Four.

However, there is no empirical basis for determining whether inundation of these relatively unique habitats would pose a threat of extinction to endemic fish species. Therefore, this Master Plan recommends that fish surveys be conducted in these reaches before decisions are made by MoNRE whether these sites should receive an Environmental Compliance Certificate. Fish surveys should be an explicit requirement in the terms of reference for the conduct of the environmental impact assessments. Specifically, these requirements should be applied to the Nam Bi cascade of projects and to the Xe Kaman 4.

Combined with the projects in Tiers One, Two and Three, Tier Four aggregates to a total of 3357.5 to 3714.5 GWh/y of new power (885 - 1105 MW of capacity) (Tables 7-1 and 7-3), enough to replace all of the proposed mainstream projects and maintain unobstructed flows all the way from the Vietnam border to the Cambodia border through two tributaries and the mainstream, of the Xe Kong. Those tributaries are the Xe Xap and the Xe Xou.

Tier Five: **Small projects for local supply**

Projects on tributaries that are less than 25 MW of installed capacity. Projects below 25MW are regarded as too small to be practical for power exports, therefore we assign them a separate tier for development. These would replace output from the mainstream dams that is intended for sale to EDL for local consumption. These aggregate to 67 MW and a total of 295 GWh/y new power (Table 7-3), which would be sufficient for likely growth in demand in the local grid that serves Sekong and Attapeu Provinces for well into the future. However, because they are small, they may also have a relatively high impact on migratory fish per unit of power produced. Therefore, these should only be invited by the Government of Lao as necessary for local development requirements.

[3] Personal communication with Mr. Oudum Sypaseuth, Acting General Director of the Department of Forest Resources Management, Ministry of Agriculture and Forestry.

Table 7-2. Indices and results for all of the current and prospective Xe Kong dams.

Dam Name	Length of river reaches	% of rare river reaches	% of high gradient reaches	% of high elevation and high gradient reaches	Protected Area	Endemic species	Number of threatened species predicted			Length class	Rarity class	gradient/ elevation class	combined score	Risk to endemic species
Sekong mainstem	**km**				**Name**	**No.**	**CR**	**EN**	**VU**					**Revised**
A Luoi	41.07	100.0	0.0	0.0		10	0	5	3	2	3	1	6	M
Xe Kong 5	71.1	86.5	14.9	13.5	Xe Sap	10	0	5	3	2	3	1	6	M
Xe Kong_US1	33.0	63.0	15.7	37.0	Xe Sap	10	0	5	3	2	2	2	8	M
Xe Kong_US2	55.4	67.7	24.1	44.3	Xe Sap	Predicted	0	0	3	2	2	2	8	M
Xe Kong_US3	56.3	86.9	35.7	13.1		Predicted	0	0	3	2	3	1	6	M
Phak Houay	201.1	29.2	17.4	0.0		10	0	5	3	3	2	1	6	M
Xe Kong 4B	15.18	0	0	0		10	0	5	3	1	1	1	1	L
Xe Kong 4A	32.66	0	0	0		10	0	5	3	2	1	1	2	L
Xe Kong 3up	92.55	6.7	2.4	0		10	0	5	3	3	1	1	3	L
Xe Kong 3d	130.3	57.9	0	0		10	1	5	6	3	2	1	6	M
Xe Kaman														
A_2	3.07	100	0	0		4	0	0	0	1	3	1	3	L
A_3	3.73	100	0	0		4	0	0	0	1	3	1	3	L
Houay Chalelu 1	1.54	100	100	100		4	0	0	0	1	3	3	9	H
Nam Bi 1+2+3	4.58	100	100	100		Predicted	0	0	1	1	3	3	9	H
Xe Kaman 4	34.89	67.8	51.7	83.9		Predicted	0	0	1	2	2	3	12	H
Xe Kaman 3	25.47	68.1	24.3	56.2		4	0	0	0	2	2	2	8	M
Xe Kaman 2B	35.13	27.2	18.2	16.4	Dong Ampham	4	0	0	1	2	2	1	4	L
Xe Kaman 2A	14.23	7.8	7.8	0	Dong Ampham	4	0	0	1	1	1	1	1	L
Xekaman 1	197.36	8.7	7.4	0.0	Dong Ampham	4	0	0	1	3	1	1	3	L
Xekaman-Sanxay	18.77	0.0	0.0	0.0		4	0	0	1	1	1	1	1	L
Tributaries													0	
A_7	11.1	68.3	0	31.7		10	0	0	3	1	2	2	4	L
Dak E Mule	51.33	54.1	25.9	71.8		Predicted	0	0	3	2	2	2	8	M
Houay Ho	52.32	39.6	0.0	60.4		8	0	0	6	2	2	2	8	M
Xepian-Xenamnoy	120.42	27.9	2.7	36.5		8	0	0	6	3	2	2	12	H
Houay Lamphan	36.61	40.8	11.6	70.8		10	0	0	3	2	2	2	8	M
Xe Katam	9.36	100	100	100		8	0	0	6	1	3	3	9	H
Xe Nam Noy 5	10.14	79.7	44.2	64.5		8	0	0	6	1	3	2	6	M
Xe Xou	138.04	3.2	0	0	Dong Ampham	2	0	0	1	3	1	1	3	L
A_5	16.4	100	49.5	30.9		4	0	0	1	1	3	2	6	M
Nam Pa	19.78	16.7	0	0		4	0	0	1	1	1	1	1	L
Nam Kong 1	45.39	0	0	0		0	1	0	3	2	1	1	2	L
Nam Kong 2	44.54	0.0	0.0	0.0		0	1	0	3	2	1	1	2	L
Nam Kong 3	111.92	1.8	1.8	0.0		0	1	0	3	3	1	1	3	L

Note correction to some of the dam site names: Xe Kong 3up is Xe Kong 3B and Xe Kong 3d is now Xe Kong 3A. Xe Kong_US1 is Xe Xet, which is not included in the Master Plan; Xe Kong_US2 is Xe Lon; and Xe Kong_US 3 is Houay Axam.

It should be emphasized that, taken in the aggregate, the first four tiers of projects would produce almost as much power as the seven large mainstream projects that are under active investigation at this time. And it is questionable whether all of those mainstream projects would ultimately prove to be feasible from both an engineering and economic standpoint. It is also doubtful that they would be preferable to the alternatives presented in this Master Plan, particularly the Tier One alternatives, on the basis of net costs and benefits, when the large natural resource costs are taken into account. This economic analysis is provided in Section 11 of this Master Plan.

Therefore, we conclude that the replacement sites should be more than ample to avoid any appreciable sacrifice of likely hydropower potential within the basin. In the unlikely event that, in the future, an official power development plan of the Government of Lao should call for more hydropower than can be produced by the replacement dams, upgrading of planned facilities, and solar augmentation of existing facilities as described in this Master Plan, the highest priority should be to replace the lowermost mainstream dams, starting at the bottom and moving up. Xe Kong Downstream should certainly be cancelled and replaced, as this dam would be the most damaging to the migratory fishery. It is the least "sustainable" dam in the entire cascade. By contrast, if some mainstream development is deemed essential, the uppermost proposed dam, Xe Kong #5, is probably the most acceptable if redesigned as described below and if it includes the mitigation measures described in Sections 8, 9 and 10.

Except for the projects in Tier One and Tier Two, the other potential replacement projects would have detectable adverse impacts on the Xe Kong fishery. Yet, these impacts would be far less than the mainstream dams currently proposed, particularly the most downstream of these dams. If the dams in Tier Three, Four or Five are authorized, they should be required to implement the mitigation measures that are described in Sections 8, 9 and 10 of this Master Plan for fish and sediment passage and for environmental flows.

In sum, to enhance the potential for fish and sediment passage in the main stem of the Xe Kong River, this Master Plan would replace the proposed mainstream hydropower dams with alternative sites on tributaries that can generate an equivalent amount of power. The tributaries of interest are those that have feasible sites either above existing dams or that are located so far up in the catchment that few migratory species would actually access them. That development scenario would leave the mainstream Xe Kong unobstructed and free-flowing all the way from the Vietnam border to the Cambodian border (and from thence, all the way to the South China Sea, if the Sambor Dam in Cambodia is not built or is redesigned to allow fish and sediment passage.

Table 7-3. Details on power output for alternative dams in Tiers One-Five.

Tier # and Description	Dam Name	GWh/y	MW
Tier One: Solar augmentation of Xe Kaman 1			
	Solar at Xe Kaman 1 without transmission enhancement	358	200
	--OR--		
	Solar at Xe Kaman 1 with transmission enhancement	715	400
	TOTAL TIER ONE	**358-715**	**200-400**
Tier Two: Replacement dams above existing barriers > 25MW			
	Xe Kaman 2A	160	35
	Xe Kaman 2B	380.5	100
	Nam Ang Tabeng	183	41
	TOTAL TIER TWO	**723.5**	**176**
	CUMULATIVE TOTAL (TIERS 1+2)	**1081.5 - 1438.5**	**356-576**
Tier Three: Replacement dams that are located above the reaches accessed by migratory fish (mostly)			
	Houay Axam	717	164
	Dak E Mule Downstream	333	76
	Xe Lon	214	49
	NHI Site B	175	40
	TOTAL TIER THREE	**1439**	**329**
	CUMULATIVE TOTAL (TIERS 1+2+3)	**2520.5 - 2877.5**	**685-905**
Tier Four: Replacement dams that are in, or would inundate portions of, NBCAs or pose high risk to endemics speces			
	Nam Bi 1+2+3 ^	550	130
	Xe Kaman 4 ^	287	70
	TOTAL TIER FOUR	**837**	**200**
	CUMULATIVE TOTAL (TIERS 1+2+3+4)	**3357.5 - 3714.5**	**885-1105**
Tier Five: Small projects for local supply			
	Houay Chalelu 1	25	6
	Nam Pa	10	2
	NHI Site C	43	10
	NHI Site D	42	9
	Houay Pache	49	11
	Phak Houay	57	13
	Nam Pouang	69	16
	TOTAL TIER FIVE	**295**	**67**
	CUMULATIVE TOTAL (TIERS 1+2+3+4+5)	**3652.5 - 4009.5**	**952-1172**
Compared to amount needed to replace all of the mainstream dams		**4617**	**1082**

Notes:

* = Calculated by using SERIS 10MW floating with fixed angle to the sun to calculate the mean annual energy for 200 MW PV installed capacity.);
^ = high risk to endemics

Methodology Used to Identify Replacement Sites

The assumptions used in the identification methodology are:

1. Topographic information from Google Earth
2. Watershed areas upstream of each hydropower site were determined using Google Earth
3. The Xe Kong River mainstream projects will not be built and therefore their reservoirs would not interfere with tailwater from the new projects.
4. The mean annual unit discharge of the tributaries is 0.05 m^3/s per km^2. Therefore, the mean annual discharge of a river at each newly identified site equals the product of the unit discharge and the catchment area upstream of the dam
5. The design discharge is 170% of the mean annual flow[4]
6. The overall efficiency of the hydropower system is 80%

The leading technical expert a MEM has questioned the appropriateness of using the estimate of 170% of annual mean flow as the methodology for determining turbine design discharge since various types of projects (run of river; small, medium, large sizes of reservoir schemes) have different reservoir storage capacity characteristics, and have different inflow patterns. This expert proposes that optimized maximum installed capacity should be used instead.

The MEM expert also proposes that a better approximation of the actually combined efficiency of a turbine and generator would be 87% (90% x 97%) instead of the 70% used in this internal review draft. NHI agrees that 87% is reasonable and that estimate was used in the final Master Plan.

Hydrology

Detailed hydrologic studies for each individual new site were not possible within the time and budget constraints of this study. Instead, the average annual flows of previously identified sites within Xe Kong basin were used, and indicated a reasonably consistent unit discharge. Table 7-4 presents the average annual flow and the unit discharge of the previously identified sites. The unit discharge equals the average discharge divided by the catchment area in square kilometers.

Based on this analysis, an average unit discharge equaling 0.05 m^3/s per km^2 is considered a reasonable estimate for identification purposes of new sites within the Xe Kong River watershed. This is considered reasonable because the Xe Kong 5 site, the most-upstream proposed site in the mainstream, has a unit discharge of 0.052 m^3/s and the unit discharge of the Xe Xou tributary is 0.061 m^3/s. Most of the new sites are located in the upstream reach of Xe Kong and Xe Xou.

[4] The design discharge of existing and planned projects varies from average annual flow to over 200% of the average annual flow, with most of the design discharges in the range of 150% to 170% of the average. This study assumes 170% of the annual average flow as the design flow for identification purposes.

Table 7-4. Average Annual Flow at Different Locations of Xe Kong Watershed.

Item	Site	Watershed Area (km^2)	Average Annual Flow (m^3/s)	Unit Average Annual Flow ($m^3/s/km^2$)
1	Xe Kong 5	2,615	137	0.052
2	Xe Kong 4	5,400	205	0.038
3	Xe Kong 3B	5,882	240	0.041
4	Xe Kong 3A	9,700	316	0.033
5	Xe Kaman 1	3,580	175	0.049
6	Xe Kaman 2A	1,970	77.5	0.039
7	Xe Kaman 2B	1,740	68.4	0.039
8	Xe Kaman 4	192	7.4	0.039
9	Xe Kaman 3	712	26.6	0.037
10	Dak E. Mule	127	16.1	0.127
11	Nam Kong 1	1,250	58.3	0.047
12	Nam Kong 2	860	45	0.052
13	Xe Nam Noy 5	60	3.6	0.060
14	Xe Katam	38	1.25	0.033
15	Houay Lamphan	140	6.5	0.046
16	Xe Xou	1,273	77.2	0.061
			Average	**0.049**

Five Tiers of Hydropower Development

Tier One: Solar augmentation at Xe Kaman 1 with or without transmission line enhancement

The Tier One scenario consists of the opportunity to augment the output of power from the Xe Kaman 1 Hydropower Project by deploying floating solar photovoltaic arrays on the reservoir, an integrating this component into the hydropower operations so they woul operated a single hybrid project (see Section 11). Under existing transmission constraints, this can be done at scales between 200-400MW in a manner that would be compatible with efficiency objectives for both components. This option is described and analyzed in detail in Section 11. This Tier One option is given the highest priority in the Master Plan because it would impose no adverse environmental or social impacts at all.

Tier Two: New dam sites above existing barriers to fish migration >25 MW

The Tier Two scenario entails intensification of power development in the Xe Kaman sub-basin (see Figure 7-1). The Xe Kaman River is the major tributary of the Xe Kong within Laos. It has already been extensively developed for hydropower. Seven hydropower projects have already been constructed or identified on the Xe Kaman River. Notably, the two lowermost projects, Xe Kaman #1 and the companion dam below it, Xe Kaman Sanxay are already constructed and pose an absolute barrier to fish migration. Fish passage facilities around Xe Kaman #1in particular are not possible. In the upper catchment, Xe Kaman 3 is already in operation (although now under repair) and three others are in the planning stage (Table 7-5).

The Tier Two scenario includes Xe Kaman 2A, Xe Kaman 2B and the Nam Ang-Tabeng 1 Project, the latter which is currently under investigation under a MOU from the Ministry of Planning and Investment, with potential to produce 41 MW. The cumulative mean annual energy output for Tier Two scenario is 723.5 GWh/y (176 MW of capacity).

Table 7-5. Salient Features of Proposed Hydropower Projects on the Xe Kaman River.

Item	Xe Kaman 2A	Xe Kaman 2B	Nam Ang Natabeng 1
Status	Planning	Planning	Planning
Province	Attapeu	Attapeu	Xekong
(Lat. /Long.)	15˚15.01'N 107˚26.33'E	15˚16.52'N 107˚27.00'E	15˚13.46'N 107˚31.57'E
River	Xe Kaman	Xe Kaman	Xe Kaman
Installed capacity (MW)	64	35	41
Annual Energy (GWh)	160	380.5	183
Rated head (m)	48.6	78.8	640
Design discharge (m^3/s)	155	90	20.7
Full supply level (masl)	280	370	640
Catchment area (km^2)	1,970	1,740	203
Average annual flow (m^3/s)	77.5	68.4	10
Total reservoir volume (mill m^3)	20.8	333	16.5

Tier Three: New Dams Sites Above the Reaches Accessed by Migratory Fish >25 MW

The Tier Three scenario includes four new dam sites – Dak E. Mule Downstream, Houay Axam, Xe Lon and NHI Site B (see Figure 7-1), which are described below. The cumulative mean annual energy output for Tier Three is 1439 GWh/y (329 MW of capacity).

Dak E Mule Downstream

This project is included because, while it would be sited below rather than above an existing project (Dak E. Mule), and it would only cut off 12 km of potentially suitable spawning habitat in that tributary. However, this is a diversion project that would also dewater another 17 km reach. This may not be problematic if this diversion dam would spill water during the peak migration period. With the tailrace of Dak E. Mule at 346 masl, the HWL of Dak E. Mule Downstream is set at 330 masl. The mean annual energy output is 333 GWh (76 MW of capacity). Other salient features of this project are presented in Table 7-6. The general arrangement of the project is shown in Figure 7-2. Figure 7-3 shows the profile of the project.

Table 7-6. Salient Features of Dak E. Mule Downstream Project.

Item	Dak E Mule Downstream
Location (Province)	Sekong
Location (Lat. /Long.)	15º 30.80'N 106º 50.84'E
River	Xe Kong
Installed capacity (MW)	76
Annual Energy (GWh)	333
Rated head (m)	160
Design discharge (m^3/s)	49
Full supply level (m)	330
Catchment Area (km^2)	1039
Average annual flow (m^3/s)	44
Headrace tunnel (km)	4.7
Penstock (km)	2.0
Dam height (m)	--

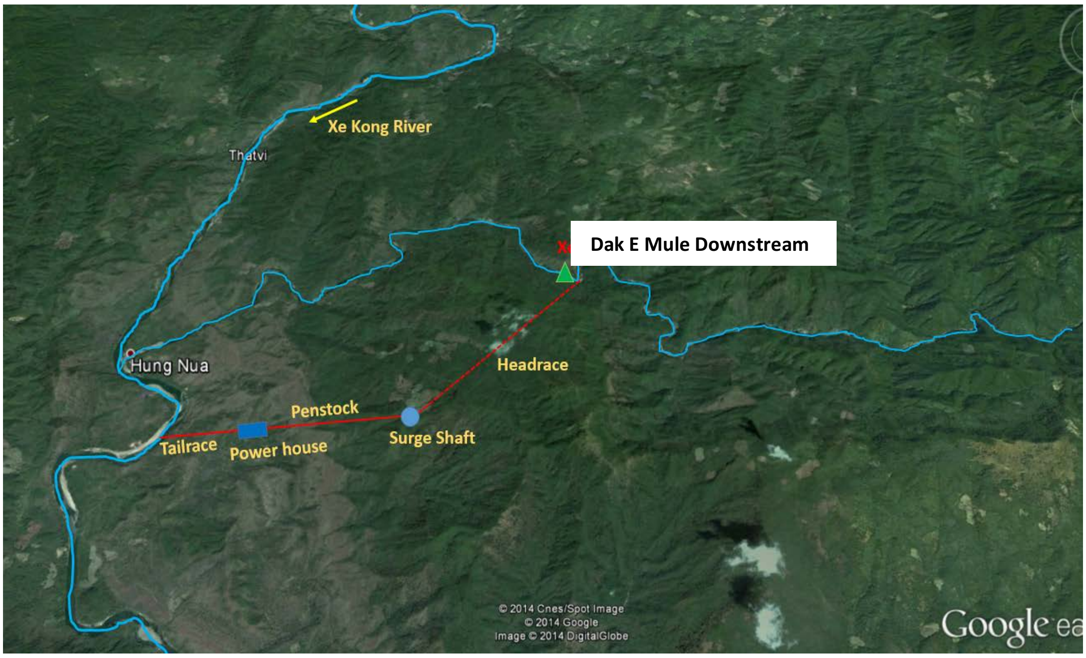

Figure 7-2. Layout of Dak E Mule Downstream Hydropower Project.

Figure 7-3. Profile of Dak E Mule Downstream Hydropower Project.

Figure 7-4 shows Dak E. Mule Downstream relative to the existing Dak E. Mule project in the vertical profile.

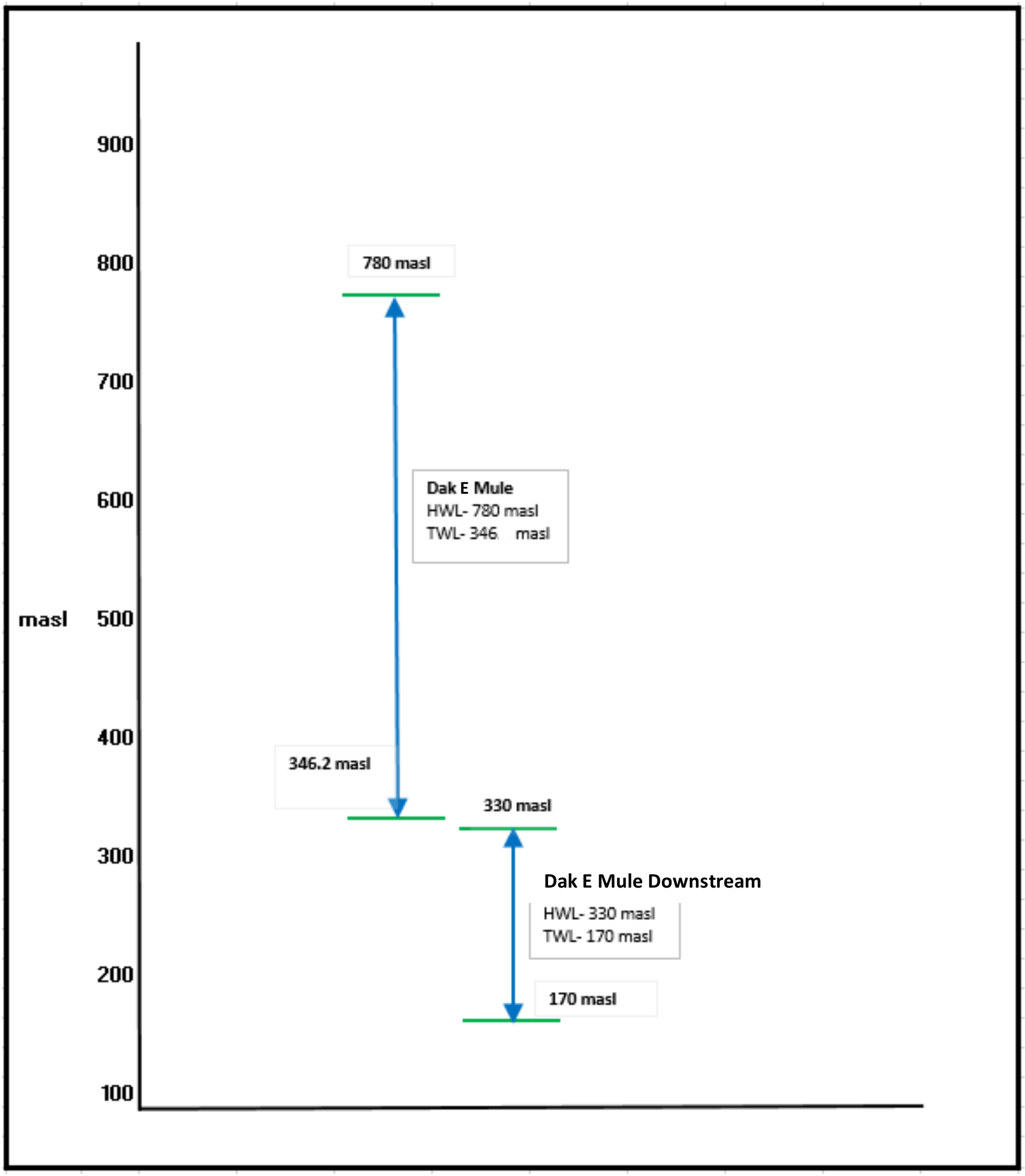

Figure 7-4. Dak E Mule and Dak E.Mule Downstream Hydropower Projects.

Houay Axam

The mean annual energy output for Houay Axam is 717 GWh (164 MW of capacity). The location of this site is depicted in Figure 7-5 and its salient features are presented in Table 7-7. Figure 7-6 shows the vertical profile and Figure 7-7 the general profile.

Figure 7-5. Location of Houay Axam Site.

Table 7-7. Salient Features of Houay Axam Project

Item	Houay Axam
Location	Sekong Province
Location (Lat/Long.)	16º014786'N 107º044092'E
River	Xe Kong
Installed capacity (MW)	164
Annual energy (GWh)	717
Rated head (m)	566
Design discharge (m^3/s)	64
Full supply level (m)	566
Catchment area (km^2)	799
Average flow (m^3/s)	31
Dam height (m)	138

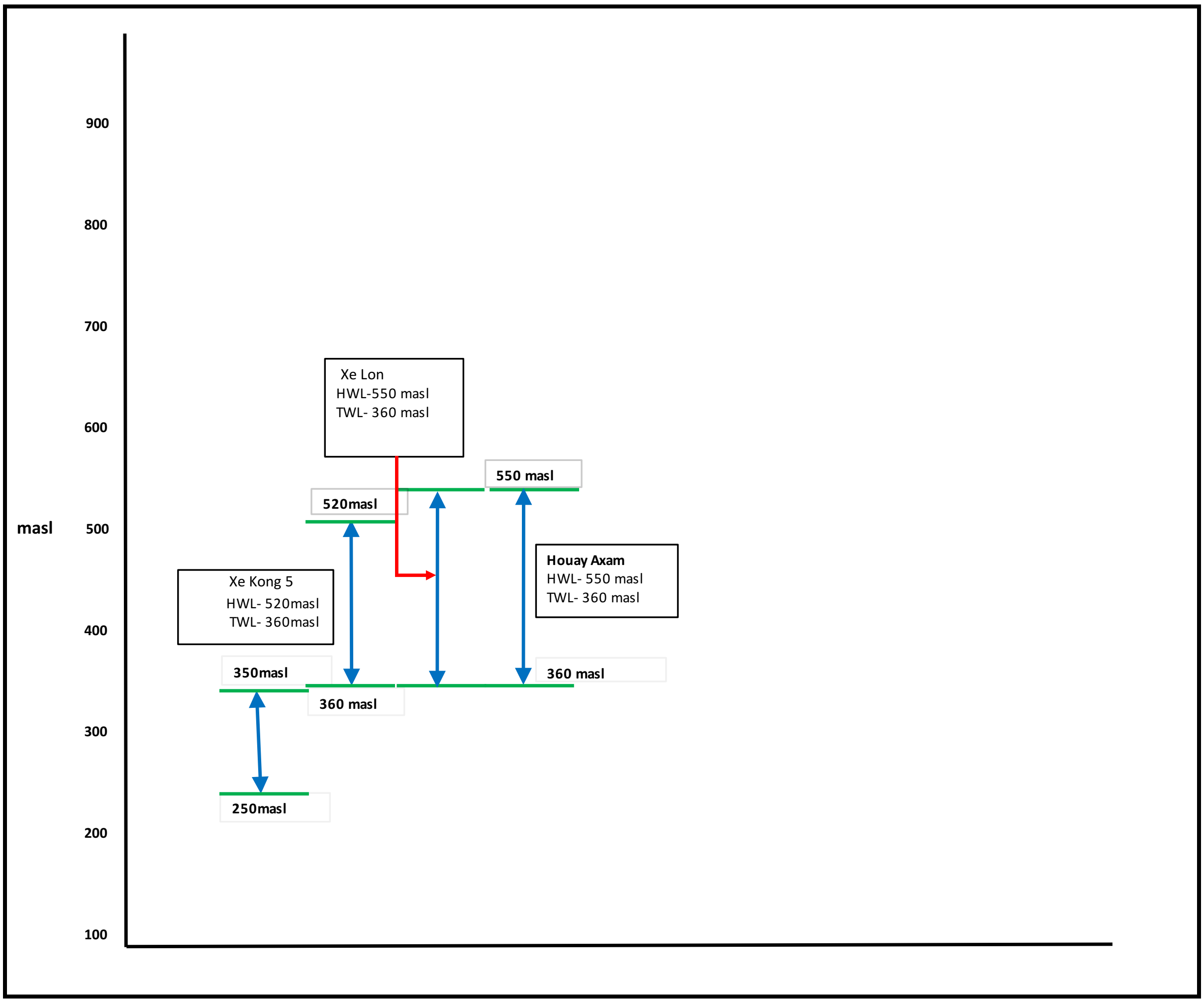

Figure 7-6. Vertical Profile of the Houay Axam, Xe Lon and Xe Kong 5 Revised Hydropower projects

Figure 7-7. Approximate Profile of Houay Axam Project.

NHI Site_B

Figure 7-8 shows the general arrangement of NHI Site_B, and Figure 7-9 provides the profile. The mean annual energy output of this project is 175 GWh (40 MW of capacity) with the design head of 300 m and design flow of 11 m^3/s. Table 7-8 presents the salient features of the site.

Figure 7-8. Layout of NHI Site_B

Figure 7-9. Profile of NHI Site_B Hydropower Project.

Table 7-8. Salient Features of NHI Site_B.

Item	NHI Site_B
Location (Province)	Attapeu
Location (Lat. /Long.)	15º28.80'N 106º58.94'E
River	Dak E Mule
Installed capacity	40
Annual energy (GWh)	175
Rated head (m)	300
Design discharge (m^3/s)	11
Full supply level (m)	730
Catchment Area (km^2)	288
Average annual flow (m^3/s)	12
Headrace tunnel (km)	5.7
Tailrace (km)	2.3
Dam height (m)	5

Xe Lon Hydropower Site

The mean annual output of Xe Lon is 214 GWh (49 MW of capacity). The location of this site is depicted in Figure 7-10 and its salient features are presented in Table 7-9. Figure 7-11 shows the vertical profile of the project.

Figure 7-10. Location of Xe Lon Site.

Table 7-9. Salient Features of Xe Lon Project.

Item	Xe Lon
Location (Province)	Sekong
Location (Lat / Long.)	15º58.83'N 107º18.84'E
River	Xe Kong
Installed capacity (MW)	49
Annual energy (GWh)	214
Rated head (m)	190
Design discharge (m^3/s)	64
Full supply level (m)	550
Dam height (m)	88
Catchment area (km^2)	726
Average flow (m^3/s)	28

Figure 7-11. Approximate Profile of Xe Lon Project.

Tier Four: New dam sites impinging on NBCAs or with potential for high risk to endemic species

The new dam sites in Tier Four are described below and displayed in Figure 7-1 above. The cumulative mean annual energy output for Tier Four is 837 GWh (200 MW of capacity).

Xe Kaman 4

The mean annual energy output for Xe Kaman 4 is 287 GWh (70 MW of capacity). For other details on Xe Kaman 4B, see Table 7-1 and Table 7-3.

Nam Bi 1, 2, 3 Cascade

The three Nam BI projects replace the formerly Xe Kaman 4A dam. They are placed on the edge of the northern side of the Dong Amphan NBCA and are planned as diversion dams. Together, their mean annual energy output is 550 GWh (130 MW of capacity) (see Tables 7-1 and 7-3).

The Nam Bi cascade of potential dams and the Xe Kaman 4 dams are included in Tier Four specifically because they are rated as a high risk to endemic species (see Table 7-2 above).

Tier Five: Small-scale hydropower sites for local consumption

The projects in Tier Five are described in Annex 7.2. If all these smaller projects (<25 MW) were built on the tributaries, they would aggregate to 67 MW of capacity and a mean annual energy output of 295 GWh (see Tables 7-1 and 7-3). These projects would only be suitable for local consumption.

Reconfiguration of Xe Kong 5 to avoid interference with potential dam sites in the head-waters tributaries

The NHI Team has identified an alternative design for Xe Kong 5 that would shorten the reservoir so that it could more efficiently flush sediments and nutrients. This also permit two additional headwaters dams to be built that are in this Master Plan. These are Houay Axam and Xe Lon. This would reduce the installed capacity of Xe Kong 5 from 330 MW to 115 MW, a 215 MW reduction, but would add 247 MW from the additional dams. But, that would defeat the objective of maintaining at least one portion of the headwaters system in a free-flowing condition all the way to the sea to accommodate long-distance migratory species. Therefore, this Master Plan does not recommend retaining Xe Kong 5 even in a reconfigured design.

References:

Gray, T.N.E., Calame, T., Hayes, B., Hurley, M.J., Nielsen, P.H., Lamxay, V., Timmins, R.J. and Thongsamouth, K. (2013), Biodiversity Surveys of Xe Sap National Protected Area Lao PDR 2012. WWF Greater Mekong, Vientiane, Lao PDR.

Kottelat, 2011. Fishes of the Xe Kong drainage in Laos, especially from the Xe Kaman.

8. DESIGNING SUSTAINABLE FISHERY MITIGATION MEASURES

This Master Plan presents a development alternative that would avoid the need to site any dams on the mainstream of the Xe Kong river to fully comply with the Policy on Sustainable Hydropower Development as defined by the principles and criteria set forth in Section 6 of this Master Plan. The dams presented in Section 7 of this Master Plan that meet the siting criteria for sustainability would be located in portions of the catchment that are relatively inaccessible to migratory fish, either because they are located above existing barriers to migratory fish (dams already in place), or because they are located so far above the prime spawning reaches that few migratory fish reach them. Those above barriers would not require fish passage facilities. For the second category of replacement dams, however, these projects will be more sustainable if they are required to include measures for fish passage both upstream and downstream. And, in the event that the Government of Lao PDR authorizes some dam construction on the mainstream, it is quite essential that these also incorporate adequate measures for fish passage to mitigate their impacts as much as possible.

This first part of this Section reviews the global experience with such fish passage measures and recommends designs and operations for successful migratory fish passage both upstream and downstream for dams that generate power at the dam site, whether they are operated as storage dams or run-of-river projects. These are the measures that should be required for any mainstream dams.

The second part of this Section provides guidance on fishery mitigation measures for diversion-style hydropower projects in which water is diverted by a barrage into a canal or penstock that conveys it by gravity flow along the gradient to a remote off-stream powerhouse located well downstream or in an adjoining watershed, that then discharges back into the river. These projects maximize the power potential from a given quantity of stream flow by maximizing the hydraulic head at the powerhouse. These facilities present a rather different set of mitigation challenges associated with screening to prevent entrainment at the point of diversion, flow alteration and depletion in the reaches below the barrage, water temperature management in that reach, and fish pass around the barrage, as well as the mitigation issues associated with passage through turbines and spillways.

Part One: Fish Passage in Large Tropical Rivers: Design Principles and Preliminary Concepts[29]

As documented in Sections 3 and 5 of this Master Plan, the Xe Kong migratory fishery is a major source of food and livelihoods and large hydropower dams on the mainstream would threaten the migrations. Despite the long history of mitigation through fish passage facilities (e.g. fishways, fish screens, turbine design) the experience in large tropical rivers has been

[29] The text for this section is adapted from a report originally prepared for the Natural Heritage Institute (NHI) under funding from USAID and the MacArthur Foundation. Subsequently, the authors developed this more detailed manuscript, drawing from ideas generated while the authors were funded by the Mekong River Commission, NHI, and the authors' respective universities. The authors are: Martin Mallen-Cooper, Fishway Consulting Services; Boyd Kynard, BKRiverfish; Lee Baumgartner, Institute for Land Water and Society, Charles Sturt University; Ian Cowz, Hull International Fisheries Institute, University of Hull; and Luiz Silva, Universidade Federal de *São João Del Rei.*

consistently poor with no examples of migratory fish populations sustained upstream of large dams.

The objectives of this Section are to describe fundamental design principles for fish passage in large tropical rivers and present preliminary concepts for fish passage mitigation measures that would improve the ability of dams on the Xe Kong mainstream and headwaters to sustain migratory fish populations, even though this would not make these dams fully sustainable.

Status of fish passage on large tropical dams

It is useful to summarize the record on fish passage facilities on large tropical dams to highlight the problems. Most of the experience has been in South America, which is reasonably well documented, with some in Africa. The record shows that fish passage in large tropical rivers has consistently performed very poorly in passing fish upstream and often failed entirely in passing fish downstream (Agostinho *et al.*, 2007).

The reasons for these failures include:

- Biology and migratory ecology are poorly understood and there has been little attempt to investigate the key knowledge gaps or:
  - document them,
  - accommodate them by choosing conservative design criteria, or
  - provide flexibility in fish passage design for future modification.
- Biomass volumes have been underestimated (only 2% passed in one case (Oldani and Baigún, 2002)).
- Size range has been underestimated (adult fish assumed to be the major group migrating upstream but smaller immature fish, with poorer swimming ability, often make up greater numbers and biomass).
- Diversity of behaviour has been underestimated (some large species use the deepest channel in the river [thalweg] and will not move to the side of the dam where fishways are located (Oldani and Baigún, 2002)).
- The need for downstream passage has been ignored.
- The entrance for fish passes has been located where the fish cannot find it.
- Insufficient water has been provided for fishways, so there is little attraction for fish to enter.
- Design criteria are often selected to reduce cost (e.g. increase gradient for pool-type fishways, or reduce the size of lock chambers or fish lift hoppers) without consideration of impacts on fish passage.
- Monitoring and adaptive management have not been provided or have not had performance standards or funds for improving the design and operation.

These poor design decisions are often a result of fishery mitigation being under-resourced. The prefeasibility studies and business cases consistently underestimate the cost of fish passage. When, as is the usual case, the detailed data on migratory behavior of diverse species is not adequate, the option of the choosing precautionary designs is rarely available because of initial capital estimates used in the business case.

Design principles to avoid these shortcomings are outlined below.

Principles of design

There are common approaches and principles in fish passage design that should be applied to the hydropower dams in the Xe Kong basin.

Principle 1. Assess site fish passage objectives in a basin-wide context of habitats, migrations, and proposed dams.

Fish passage at a site needs to be considered in a basin-wide context because migrations of fish are basin-wide. The objective of fish passage is to provide for migration past a structure to enable life cycles to be completed and for fish populations to be sustained, or impacts minimized. In this context the location of spawning, nursery, feeding and refuge habitats - and the connectivity between these - must be the consideration upon which a site-based fish passage solution is evaluated and measured. Sections 3 and 5 of this Master Plan presents the relevant considerations for the Xe Kong basin.

A basin-wide siting plan should:

i) Account for the difference in biodiversity, biomass and numbers of migratory species in various parts of the catchment;

ii) Account for the change upstream of the dam from a flowing river habitat to a stillwater lake habitat. Fish that are adapted to flowing water need access to these habitats upstream to feed and spawn.

iii) Include a model of the life cycle of each fish species, or guilds[30] of fish using available data. For the Master Plan, the NHI team used the available data to construct a "zonation model" that shows the extent of penetration of representative migratory species into the catchment. But, Section 5 also acknowledges the substantial knowledge gaps.

Strategically, developing a river system for hydropower needs to consider the degree of fragmentation of the river and the dam locations relative to the overall fish species distribution, and the modification of habitat and accessibility to key habitats to complete life cycles. Where maintaining migratory fishes is a priority, as in the Xe Kong basin, maintaining minimum lengths (e.g. 300-500 km) of flowing water between dams is essential to allow for migration upstream and larval drift downstream, as well as to complete other aspects of the life cycle. As Section 7 of this Master Plan shows, the cascade of dams planned on the mainstream would create a series of contiguous lakes, severely reducing the likelihood of maintaining these populations.

Principle 2. Integrate biology, hydrology and hydraulics

Developing fish passage solutions is a combination of three disciplines: biology, hydrology and hydraulics. The relationship between these disciplines is shown in Figure 9-1, along with some key design parameters.

In biology, it is important to know the:

[30] Guilds are groups of fish with similar characteristics; e.g. spawning in the river with drifting eggs or spawning on the floodplain with adhesive eggs.

- smallest fish that are migrating as these usually have the weakest swimming ability and this determines the maximum water velocity, turbulence and gradient of upstream fishways.
- largest fish, which determines the depth and space required in the fishway, and
- migratory biomass, which determines the size of the fishway and flow required.

Fish behavior is a key biological characteristic defining fishway design, although many aspects of migratory fish behaviour are universal (see below). Hydrological data, specifically headwater and tailwater levels, are essential in fishway design; combined with biological data, they are used to set depths, operating range and determine the length and gradient of fishways.

A critical aspect is integrating biology and hydrology to examine the migration ecology and specifically the flows in which fish are migrating. This analysis influences the:

- Location of the fishway entrance, or entrances. For example,
  - Fish migrating at high flows would need an entrance a distance away from high turbulence of the spillway, whereas fish migrating at low flows would need an entrance close to the spillway.
  - If fish are migrating in the dry season and the dam is used for hydropower, then fishway entrances would be needed at the powerhouse.
- Operational range of headwater and tailwater. For example,
  - If fish are migrating at high flows, a fishway entrance with high walls would be required, otherwise flows from the fishway are submerged by high tailwater and attraction is diffused.
  - If fish are migrating at different periods of the year when the headwater is likely to vary, then the upstream exit needs to have sufficient depth to accommodate this variation.
- Type or application of fishway design. For example,
  - If fish are migrating at high river flows then the fishway type will need to have the capacity to pass high flows so that fish are attracted to the fishway.
  - If small fish are migrating at low flows, then the fishway will need to have low velocities and turbulence at these flows.
  - If fish are migrating only in the day or night (diel) they may need to complete their ascent in one diel period; hence, fishways on a gradient would need large resting pools.
- Downstream passage requirements; for example,
  - If fish are migrating downstream in the dry season then all the flow will be through the powerhouse; hence, the turbines will need to pass fish safely or be screened to prevent fish entering.
  - The size of fish migrating downstream will determine the spacing of the screens.
  - If fish are migrating downstream at high flows then the gates and spillway need to be designed for safe passage.

All these characteristics, and many more, form a set of hydraulic criteria for fish passage design, which can be directly used to develop fish passage options (Figure 8-1). The cost-benefits of each option can then be evaluated. Note that cost is the final filter in this process after all the design parameters and initial options are developed. The final design is then driven by the economic viability of the fish passage solution and the net benefit likely to be achieved in terms of fishery production and conservation of biodiversity.

The following three principles can be considered subsets of integrating biology, hydrology and hydraulics but need to be separately identified as they are often neglected in fishway design and cause the failure of fishways and ultimately the decline of fish populations.

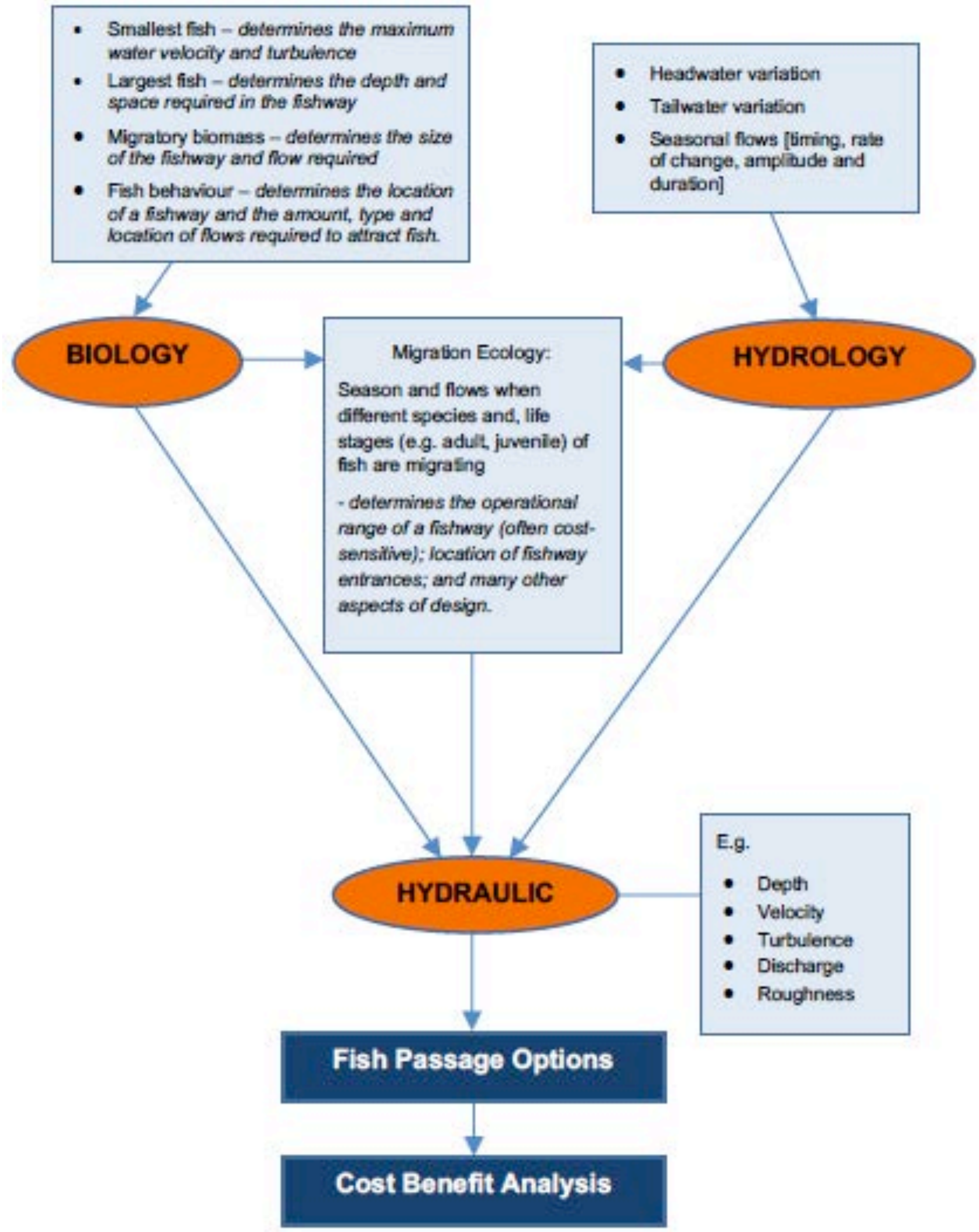

Figure 8-1. Diagram showing the interaction of three disciplines – biology, hydrology and hydraulics – in developing fish passage options. Key parameters are show in light blue boxes

Principle 3. Address upstream and downstream migration

Fish migration is cyclic, involving upstream and downstream movements or return lateral movements on and off floodplains. It is most commonly seasonal, and this applies in the Xe Kong basin where most species make return annual migrations, and there are a few species that migrate upstream to spawn as adults once and die, like salmon. Therefore, in designing fish passage measures for the Xe Kong dams, it is necessary to provide for both upstream and downstream migration. Without safe downstream passage the life cycle is not completed and the function of upstream passage facilities to maintain or rehabilitate fish populations is severely or completely defeated.

The migration pattern in the Xe Kong is for adult fish to migrate upstream to spawn, feed and return downstream, alongside immature fish (sub-adults) that are dispersing often throughout the LMB (Lower Mekong Basin). Larvae and juveniles drift downstream. Most species have sticky eggs so these don't drift and whether yolk-sac larvae drift is unknown. The relevance of this life history is that, to meet fish passage objectives, upstream passage needs to consider adult and sub-adults fish (of varying sizes) and downstream passage needs to consider returning adults, drifting larvae, and juveniles.

At the large hydropower dams planned for the Xe Kong mainstream or suggested for the headwaters, there are two components of downstream passage to consider:

i) passage through the impoundment or reservoir which can change from a flowing river that enabled larvae to drift passively downstream, to a lake where larvae stop drifting and can die from: settling out on the bottom, or lack of food or predation; and

ii) passage at the dam itself, which will potentially have four paths: turbines, spillway, fishways and sluice gates for sediment.

Principle 4. Design for fish attraction and passage

There are two components of effective fish passage:

i) attraction, which involves ensuring the hydraulic conditions (flow paths and turbulence) near the dam and powerhouse guide fish to the fishway entrance or entrances; and

ii) passage, which involves the hydraulic and physical design of the fishway itself.

A common and fundamental flaw of poor upstream fishways is locating the entrance away from attracting flows such as a powerhouse or spillway; often this is done to reduce cost by reducing design and construction complexity.

A fishway itself can have outstanding engineering and hydraulics that are suitable for all migratory fish in the river, but its effectiveness is completely dependent on fish finding the entrance. If only a very small proportion of fish locate the fishway then fish populations decline and the fishway has not fulfilled its function.

Designing for fish attraction is mostly independent of the choice of fishway design; it involves the design of the dam orientation, spillway, gates and abutments to guide fish to one or more fishways. Flows at dams are complex and physical modelling is essential (Figure 8-2). Computer modelling (Computational Fluid Dynamics) has been used to model flows for fish passage but the limitation is the outputs are fixed whereas in a physical model flows can be manipulated in real time.

Figure 8-2. Example of a physical model of a 32 m high dam and fishway in Australia that was used to determine entrance location and hydraulic conditions for the fishway. Scale is 1:20 but 1:10 is preferred.

The objective of physical modelling is to create flows that guide fish to specific locations, rather than have migratory fish attracted to numerous locations across the spillway and powerhouse. There are some universal characteristics of migratory fish behaviour that can be used in physical modelling and integrated into design principles for optimizing fish attraction:

i) Fish are attracted to flow.

Fish that are migrating upstream will be attracted to the powerhouse, particularly when it is passing the majority of flow in the dry season, and to the spillway in the wet season when it is passing flow. Generally, the proportions of fish attracted to each area are directly related to the proportion of flow through each pathway.

Fish that are migrating downstream will also follow the flow, so they can also be expected to be attracted to the powerhouse when it is passing flow and the spillway when it is passing flow.

ii) Locate the fishway entrance at the limit of migration.

Fish that are migrating upstream will swim until they reach the limit of their swimming ability, which may be a physical barrier (e.g. dam wall), high water velocities or high turbulence. The key implication for design is that the fishway entrance needs to be at that upstream limit of migration, otherwise fish will bypass the fishway. If this limit varies with different river discharge then multiple entrances or fishways are required. Importantly, the upstream limit of migration, which is determined by hydraulics, is a key feature that is manipulated in design when using physical modelling.

At some large dams a barrier weir is built downstream solely for fish passage. The weir creates a discrete upstream limit of migration that can then be specifically designed to guide fish toward fish passage facilities. The weir needs to be a sufficient height so that it is not submerged in high flows when fish are migrating.

For fish that are migrating downstream the limit of migration can be used in design to guide fish to specific locations that have downstream fishways.

iii) Avoid recirculating flows.

Migrating fish orient and swim against, or with (for downstream migrants), the direction[31] of the current[32]. At large dams, recirculation flows can occur near spillway abutments (Figure 8-3), regulating gates that have asymmetrical operating regimes (Figure 8-4), or powerhouses. Recirculating flows cause migrating fish to orient to these circular directions and swim past fishways (Quirós, 1989). These recirculating flow patterns need to be minimized and ideally flow direction should not differ by more than 90° from the stream centerline. The main method of predicting these flow patterns and minimizing them is physical modelling. Reducing recirculating flows is also a key design objective of dam engineers as it reduces the likelihood of erosion near the abutments.

iv) Ensure fishway flow is not masked by competing flows.

The fishway entrance needs to not only be at the limit of migration, as described earlier, but also have integrity of flow so that the flow is easily distinguished by fish and not masked by other flows and turbulence. This is particularly important at dams with high discharge. As for the principles and design objectives above, the main method of ensuring integrity of fishway flow is using physical modelling.

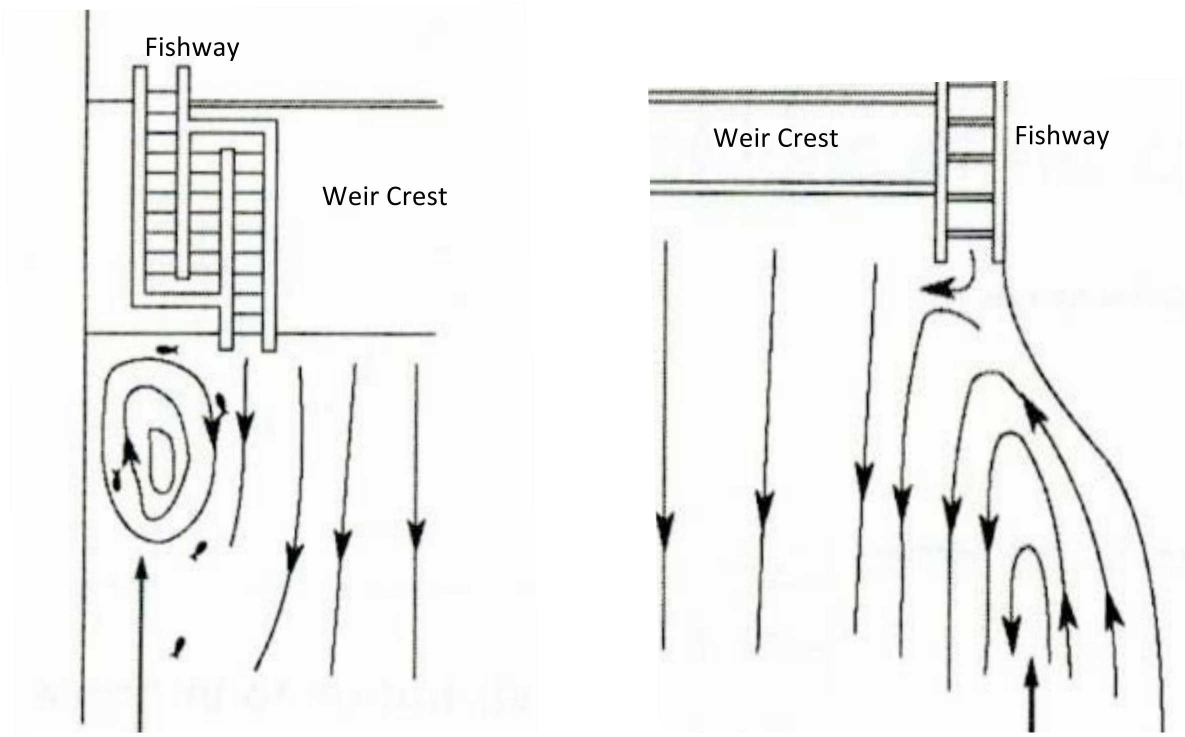

Figure 8-3. Examples of recirculation eddies that mask fishway flow and direct fish away from a fishway (Larinier, 2002).

[31] vector

[32] called rheotaxis

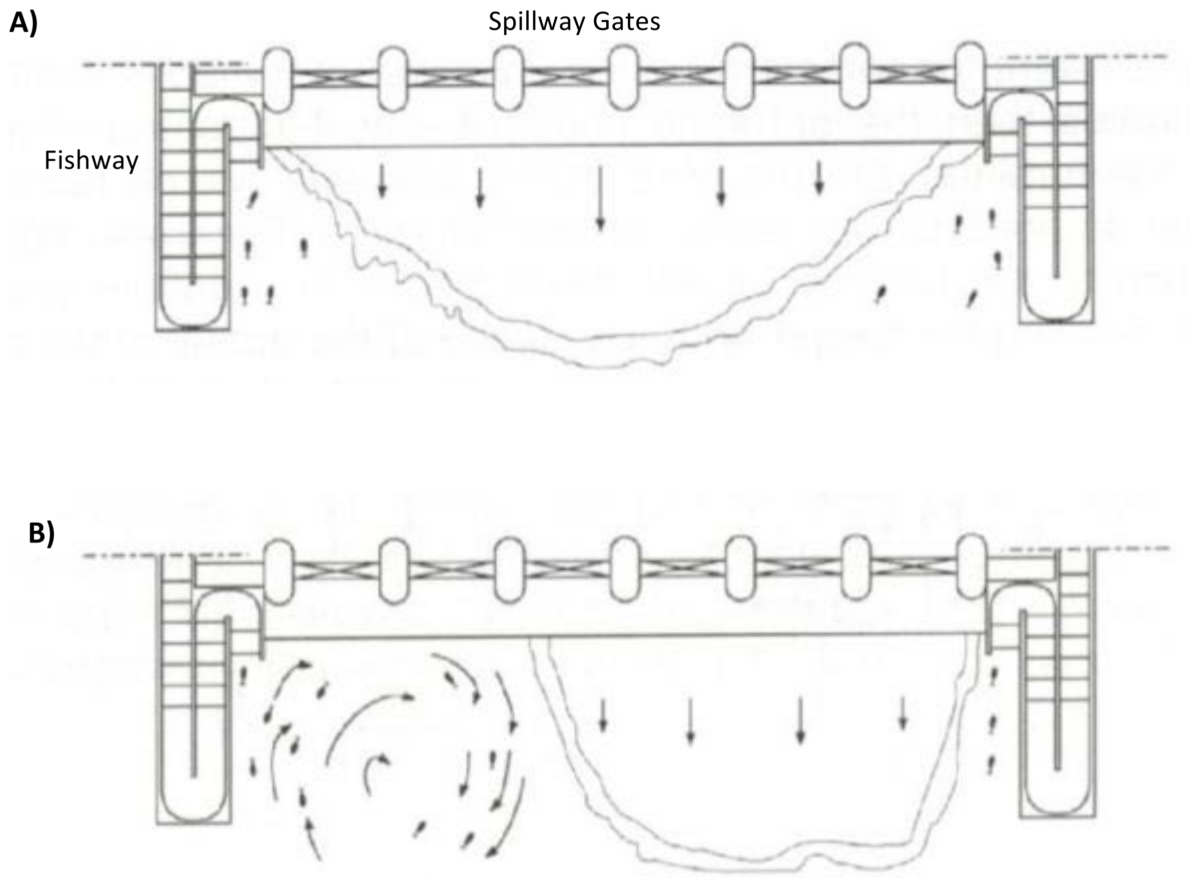

Figure 8-4. Diagram of spillway gates showing A) optimised for fish attraction, and B) a recirculation eddy caused by asymmetric gate operation. (Larinier, 2002).

Principle 5. Size the fishway to meet the biomass and flows of the river system

Fishways need to be sized to suit the river system. Small rivers such as the headwaters tributaries in the Xe Kong may be suitable for small fishways because the migrating fish are relatively small and the volume of biomass is also small. In the mainstream dams, the fishways need to be suitably sized to accommodate large fish, large biomass and high flows.

Underestimating these three characteristics in tropical rivers in South America has led to fishways passing as little as 2% of the migratory biomass of fish (Oldani and Baigún, 2002); these fishways also use less than 1% of river flow and hence there is very poor attraction for fish. Best practice is using greater than 10% of flow for fish passage. Fishways in France that have passed a high biomass of fish for temperate rivers, have passed up to 8% of turbine discharge (Larinier, 1998). For the mainstream Xe Kong, it is likely that at least 10% of total flow is required for effective attraction and passage of fish. This can be easily accommodated in the fishway at low river flows, although there is subsequent loss of hydropower production, but would be more difficult at peak flows and alternative mechanisms for attracting the fish to the fishway may be required.

Acknowledging the use of water in fishways is important in the early stages of design so that it is included in economic models and the business case.

Principle 6. Document assumptions and use adaptive management

For the proposed Xe Kong mainstream dams and the suggested replacement dams on the headwaters tributaries, we simply do not have all the specific biological data need to design fish passage measures with a high level of confidence. The method to overcome this in the fishway designs is to:

i) Produce a model of fish migration that includes the key design characteristics, such as migration flows, based on any available data including the other 3S tributaries, the same or similar species elsewhere, or anecdotal information;

ii) Document the assumptions and use this to develop a targeted monitoring program;

iii) Assess the design criteria that are based on available biological knowledge and that also have the most influence on the design, and build flexibility into the design to enable adaptive management, whereby the design can be modified in response to interpretation of the outputs of the monitoring programme.

Biology, hydrology and hydraulics

In this section, we expand on the second principle of design with specific reference to the Xe Kong River. Much has been written about fish migration in the lower Mekong Basin (e.g. Poulsen et al., 2002, 2004). Fish migration in the Mekong is often condensed and summarized by the diagram in Figure 8-5.

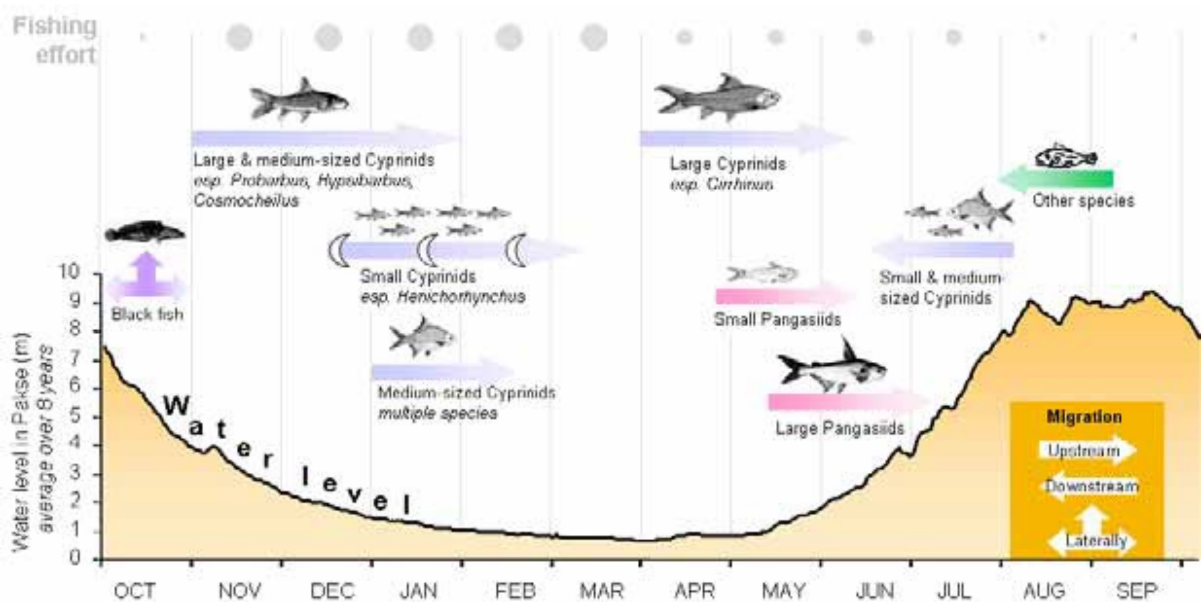

Figure 8-5. Fish migration patterns at Khone Falls, in the lower Mekong River (Baird, 2001).

As described previously, the migration pattern in the Xe Kong River and large tributaries is for adult fish to migrate upstream to spawn; larvae and juveniles drift downstream; with adults returning downstream later. Hence, upstream passage needs to provide for immature fish possibly as small as 30 mm and adult fish as large as 3000 mm. Downstream migration needs to consider the two components of:

1. passage of larvae and larger fish through the impoundment or reservoir which has changed from a flowing river to a lake; and

2. passage at the dam itself, which will have three paths: turbines, spillway and sluice gates for sediment.

The hydrology and seasonality of migration can be summarized to:

1. There is migration all year round but less towards the end of the dry season.
2. There is a peak of upstream migration as flows increase in the wet season but it is difficult to determine if this carries through the main flood season because of reduced fishing intensity.
3. There is a peak in downstream migration as flows recede in the late wet season, with this migration continuing into the early dry season.

A more detailed analysis of the seasonal migrations of key migratory species in the Xe Kong shows this pattern (Figure 8-6) (migration data are from the Mekong River Commission fish database). Figure 8-6 also shows the typical period of spillway operation. Hence, both peak upstream and downstream migration periods coincide with two conditions of dam operation, when there is:

a. only flow from the powerhouse, and

b. flow from the powerhouse and spillway.

Implications for fish passage design

For both upstream and downstream migration, at large hydropower dams, fish are attracted to both the powerhouse and spillway over a wide range of flows, tailwater levels, and hydraulic conditions (e.g. turbulence and flow patterns). For fish passage design these can be grouped into three cases:

1. Low flows and low tailwater. All fish will be attracted to flow from the powerhouse (Figure 8-7).
2. Moderate flows and tailwater level. Occurring in the early wet and late wet season. Typically, a few gates would be used on the spillway and fish would be attracted to both the powerhouse and spillway. Upstream-migrating fish will be able to migrate up relatively close to the spillway because some spillway gates will not be used, which creates areas of low velocity and turbulence on the spillway apron (Figure 8-8).
3. High flows and high tailwater level. In the peak of the wet season most gates of the spillway would be used which will pass the major flow and will be a major attraction for migrating fish. In these conditions, the spillway area will be very turbulent and the upstream limit of migration is likely to be at the end of the spillway area and abutments (Figure 8-9). Note if fish will be able to negotiate upstream passage through the spillway gates because water velocity greatly exceeds swimming ability.

Combining the biological information on migration with the hydrology and the expected hydraulic conditions in the tailwater shows that upstream fish passage facilities need to have entrances at the powerhouse and spillway. At large dams multiple fishways at different locations are common to meet these varying hydraulic conditions (Clay, 1994).

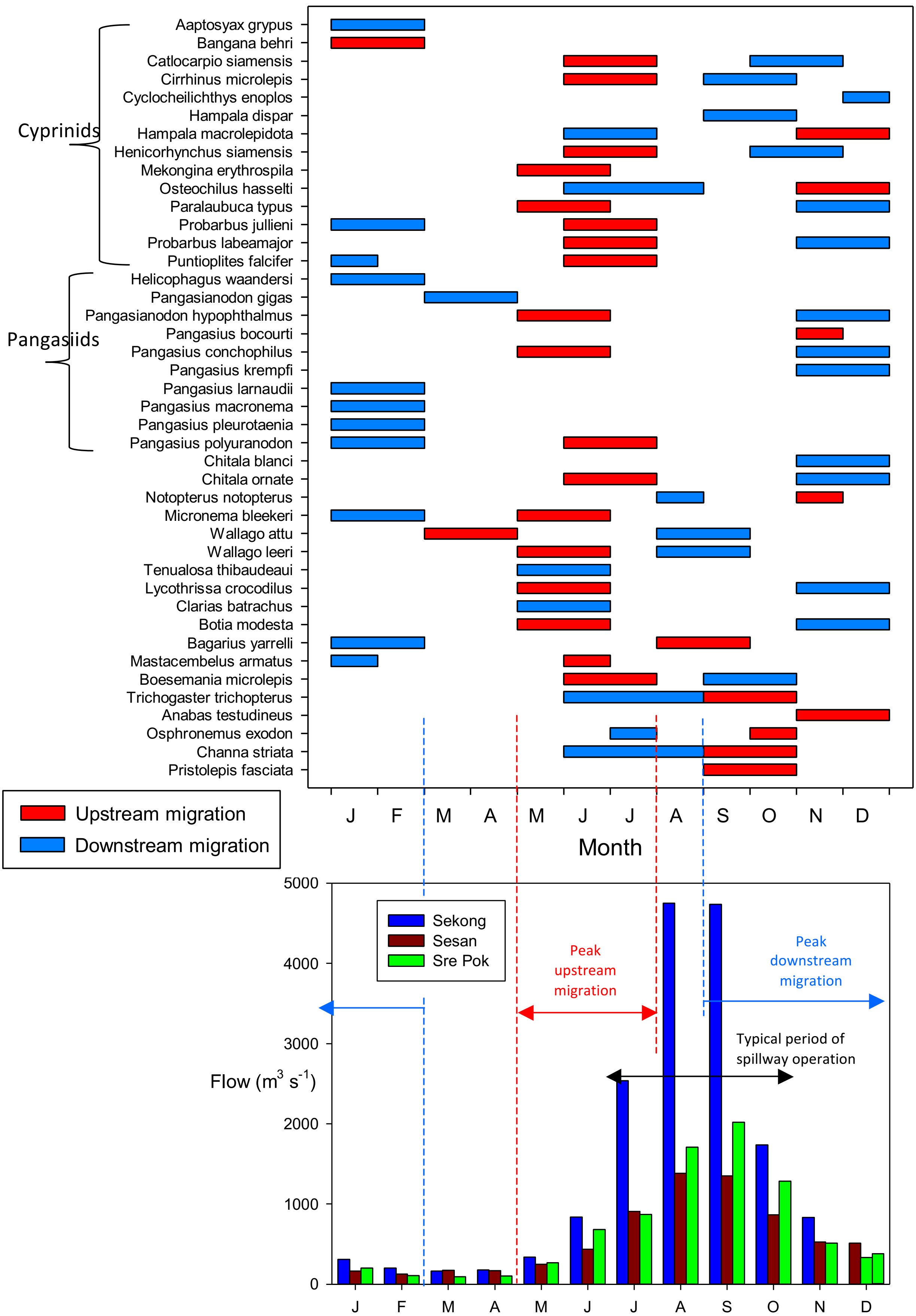

Figure 8-6. Direction and season of migration of key species in the 3S system, shown with the mean monthly flow of each river (Fish data, MRC; flow data, CNMC).

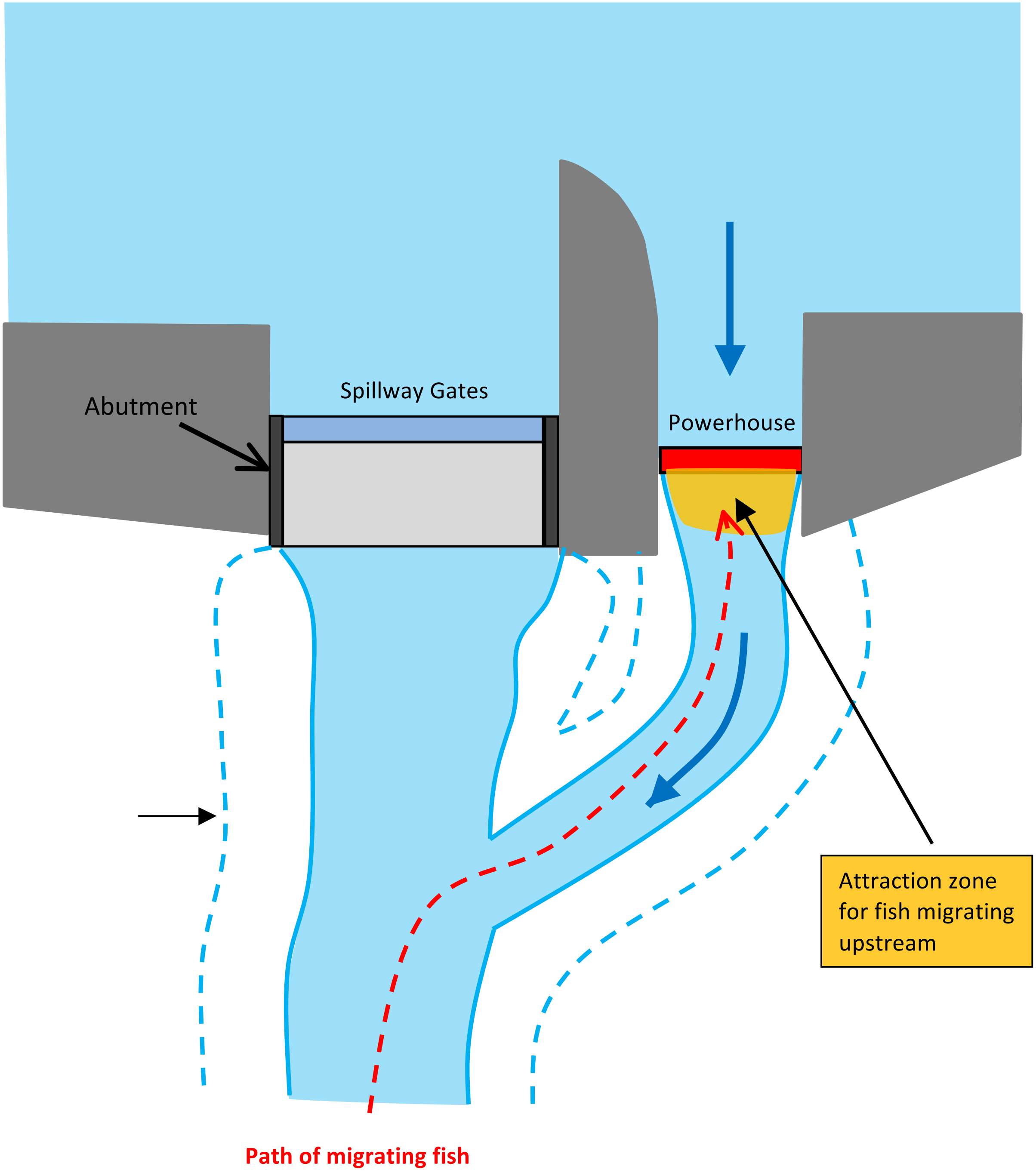

Figure 8-7. Diagram of a typical large hydropower dam passing low flows through the powerhouse and showing the attraction zone for fish migrating upstream.

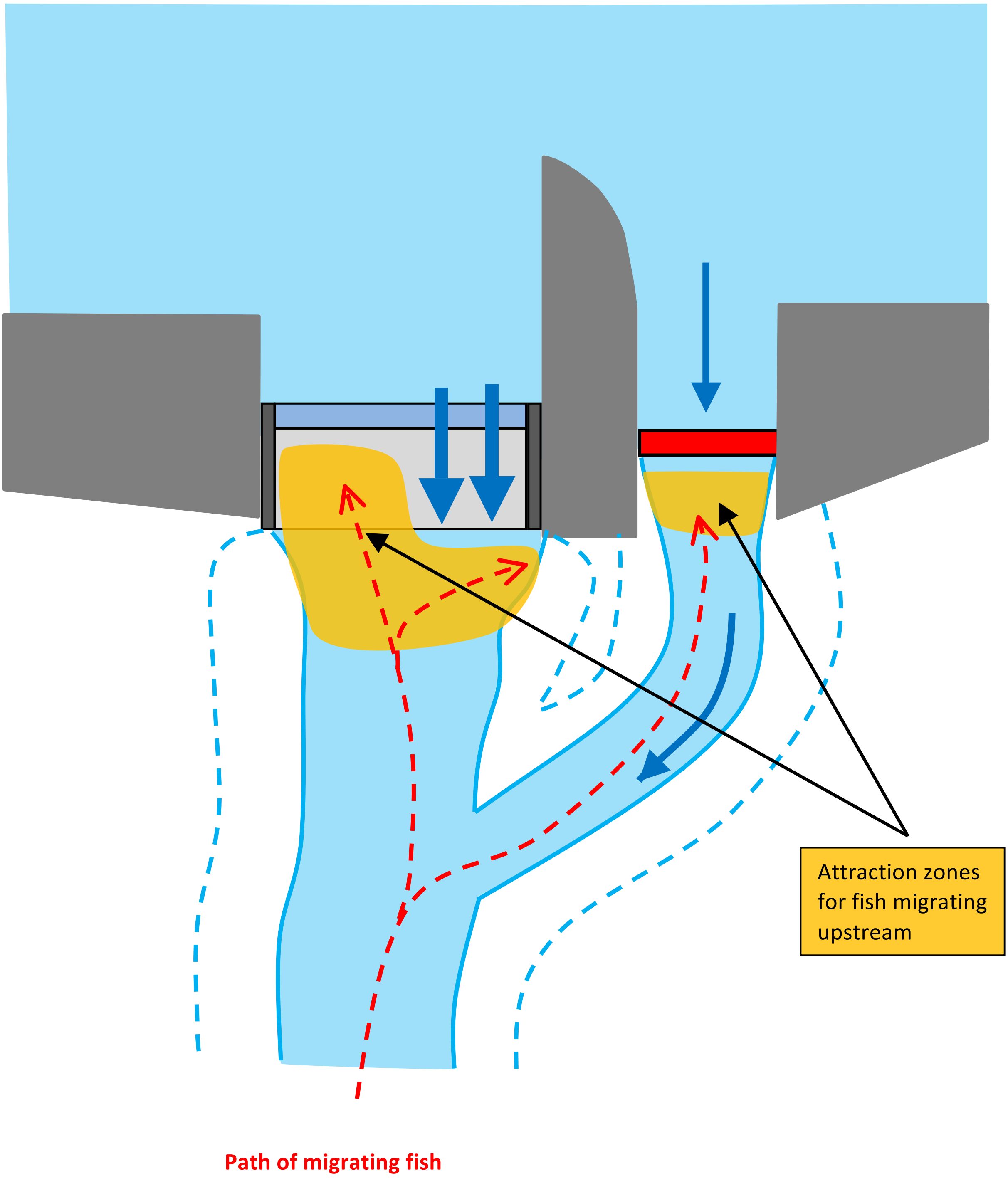

Figure 8-8. Diagram of a typical large hydropower dam passing moderate flows through the powerhouse and some of the spillway, showing the attraction zones for fish migrating upstream.

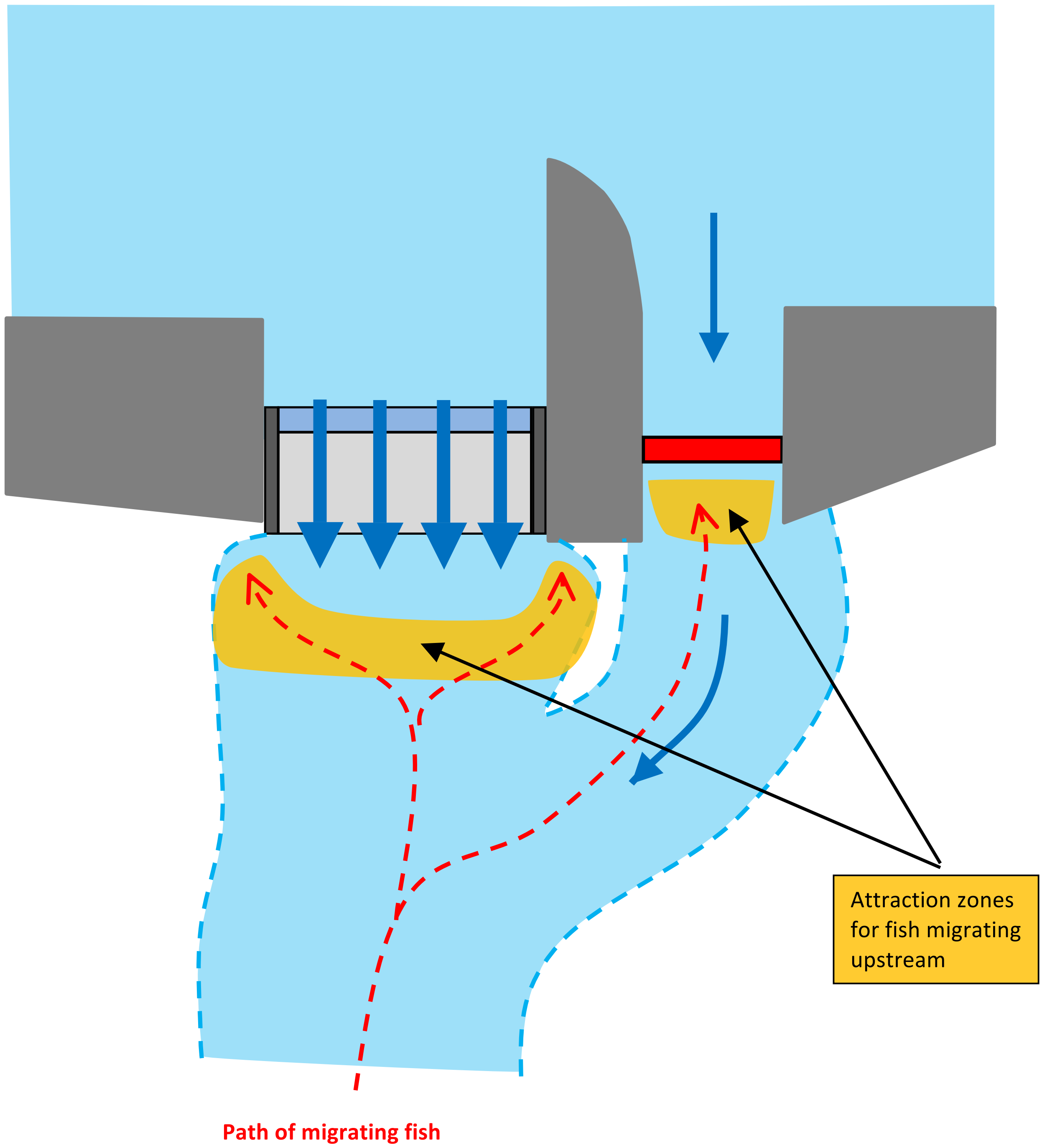

Figure 8-9. Diagram of a typical large hydropower dam passing high flows through the spillway with continued operation of the powerhouse, showing the attraction zones for fish migrating upstream.

Design philosophy

Upstream passage

Use conservative assumptions

Often fish passage designs are based on the behavior and swimming ability of specific fish and life stages (e.g. adults, juveniles). In large tropical rivers like the Xe Kong there is a wide range of species and sizes of fish that migrate, but a range of conservative assumptions can still be made that can guide fish passage design. At a high level it can be assumed that:

1. fish from 30 mm to 3000 mm are migrating upstream,
2. there is a massive biomass, and
3. there will be surface, midwater and benthic species that follow the deepest part of the channel (thalweg).

Hence, fish passage design needs to accommodate a wide range of depths and velocities, with sufficient discharge and space to attract and pass a high biomass. Considering that biomass has been grossly underestimated it is likely that a suitable design of fishway would be much larger that has been previously built. Where criteria are interpreted or estimated, conservative values need to be used to ensure the design is not undersized and to enable flexibility to refine the design after construction and monitoring. In a pool-type fishway, for example, the gradient needs to be very low to ensure water velocity and turbulence are low and can be refined if they are found to be too conservative, but if the fishway is too steep for fish it cannot be corrected.

Use river hydraulics to inform design

River hydraulics provide a real world dataset of water velocities, turbulence and gradients that fish can negotiate. Natural channels and anabranches that presently enable fish migration can, in some cases, be used as design template. For example, bypass channels are one fishpass solution that has been proposed for Mekong dams (Gätke *et al*,. 2013). A useful template for a bypass channel in the lower Mekong is the Hou Sahong channel at Khone Falls, which is the most well documented channel for fish migration in the Mekong (Baird, 2001). It is well known for providing fish migration throughout the dry and wet season. The channel has a 1:250 gradient, with some areas that are 1:100, plus a steeper section called Tad Poe, that restricts some fish migrating at low flows. These gradients are possibly conservative for fish passage but they provide initial criteria for a fishpass that confidently passes Mekong fish.

Design for attraction and passage

As discussed earlier, attracting and guiding fish to a fishway is as important as passing fish through the actual fishway. The design approach is generally to develop a configuration for the dam and then retrofit the fishway design. For any hydropower dam in the Xe Kong the design of the dam, spillway, powerhouse and abutments needs to be integrated into a cohesive design from the beginning that guides fish at all flows to various fish passages while meeting the structural and hydraulic requirements for the dam. One useful consideration is to tilt the axis of the dam and powerhouse to direct fish to the main upstream fish passage.

The proportion of total river flow passing through the fishways is critical, both to attract fish and pass a high biomass. The Hou Sahong channel again provides a real world example of suitable flows for fish passage; it passes close to 10% of flow. Interestingly, although this is a natural channel, the proportion of flow aligns with best practice for fishway design worldwide.

At hydropower dams there is a major missed opportunity in fish passage design, which is using water that spills. This flow is excess to the powerhouse and can be used for fish passage with no loss of energy production. Using this water would ensure high attraction for fish to enter the fishways.

Downstream passage

As discussed earlier there are two components to downstream fish passage at large tropical dams:

1. passage of fish, particularly drifting larvae, through the impoundment; and
2. passage at the dam itself, via turbines, spillway and the sluice gates for sediment.

Use river hydraulics to inform design

Again, river hydraulics provides a suitable template for fish passage; in this case the passage of drifting larvae through the impoundment. It is noteworthy that despite the strong seasonality of migration in the Xe Kong there is dry-season and wet-season spawning and year-round drift of fish larvae, as demonstrated by MRC data on larval drift at Stung Treng (Figure 8-10).

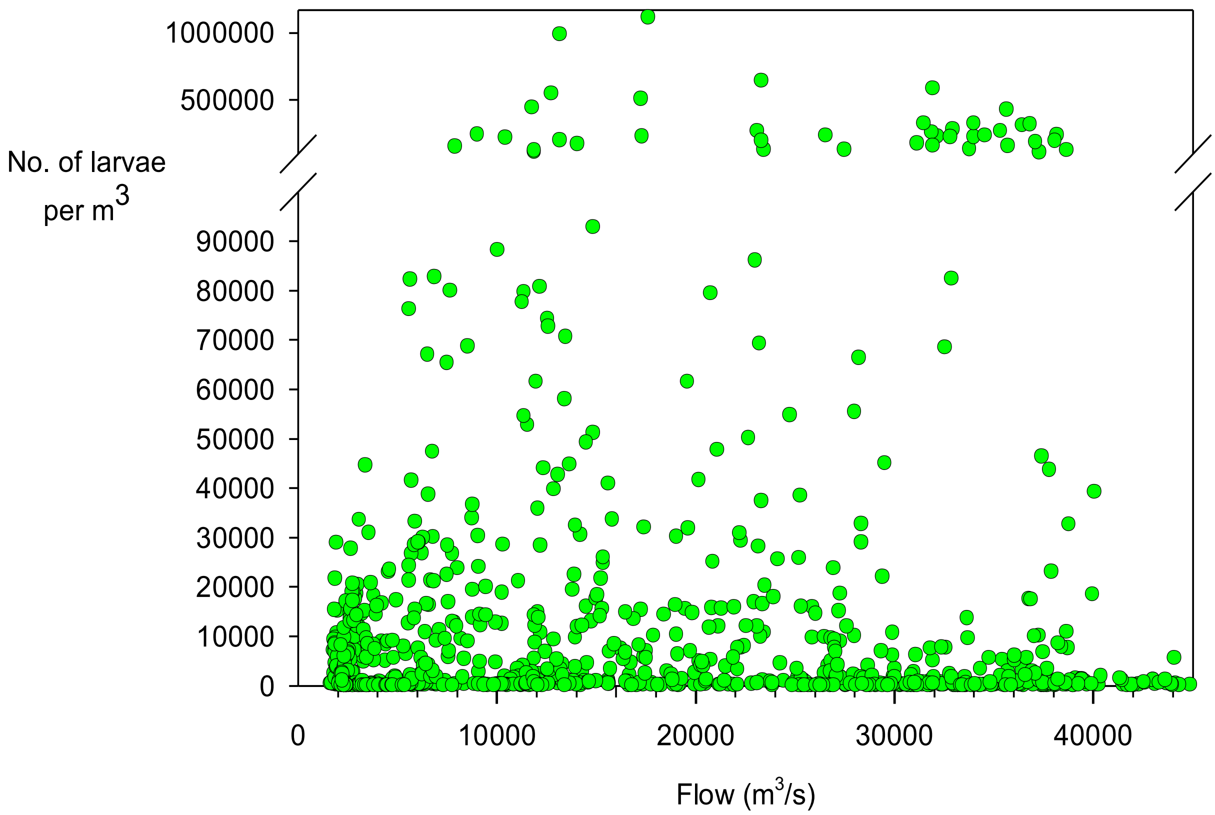

Figure 8-10. Density of drifting fish larvae in the Mekong River at Stung Treng in 2013. Intensive migration occurs in the dry season and during the start of the wet season.

Recent ADCP data for the Mekong mainstream shows how to use data on river hydraulics to inform the minimum conditions required for larval drift. Mean channel velocity is plotted against river discharge in Figure 8-11. Mean water velocity can be over 1.5 m/s, although velocities along the edges are always much lower. In the dry season the mean velocity could be as low as 0.3 m/s. To maintain larval drift in impoundments in the lower Mekong, 0.4 to 0.5 m/s is suggested as a minimum target range of velocities within the impoundment in the dry season and a middle range of 0.8-1.0 m/s is suggested for the wet season, which is likely to have fish larvae that are adapted to higher mean water velocities. These criteria directly affect dam heights and operation and need to be incorporated in the prefeasibility design and power generation models, which are integral to the business case. This same approach could be used to determine the operational requirements for the mainstream Xe Kong dams to maintain larval drift.

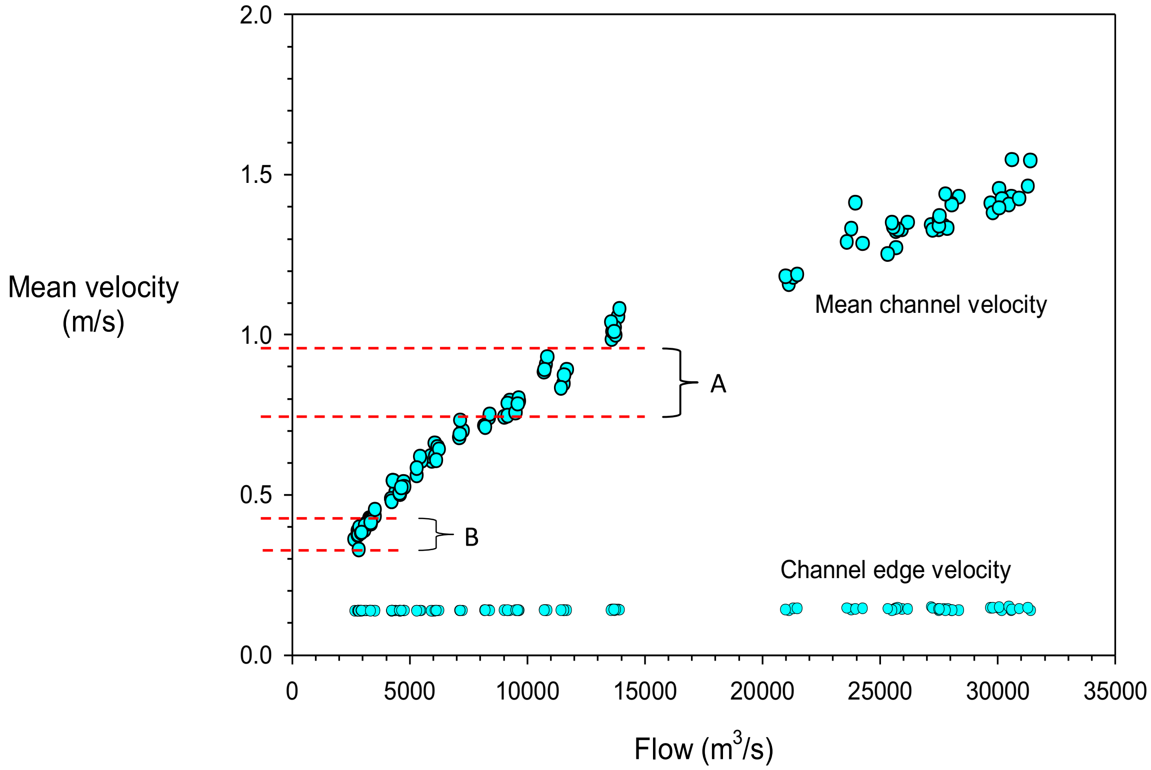

Figure 8-11. Mekong River discharge versus mean channel velocity at Kratie (from ADCP data). Red dashed lines show the range of minimum mean velocities to model for larval transport in the impoundment for the wet season (A) and dry season (B).

Use conservative assumptions

Passage at a dam itself is complex due to the range of pathways (turbines, spillway, sluice gates), and the range of fish sizes (larvae to large adult fish). Fish passing through turbines are exposed to pressure changes (barotrauma), shear stress and blade impacts. There is little specific data for tropical fish species that apply to turbine design. Using data from other species, we have summarized the latest design criteria that apply to turbines (Lee Baumgartner, Craig Boys and Luiz Silva pers. comm.) which are conservative interpretations of the available data that would provide high expected survival (e.g. 99%) of a range of fish species (Table 8-1). These criteria have yet to be incorporated in turbine design but they provide a quantitative approach to this issue for both stakeholders and turbine manufacturers. Interviews with turbine manufacturers indicate that these criteria are achievable, except for impact speed, but there would be a small loss of efficiency.

Some general trends in turbine design[33] that would improve fish passage are worth noting: large diameter, slowly rotating turbines with fewer blades reduces risks for fish and locating the turbine below tailwater (e.g. 10 m) reduces the specific risk of pressure changes (barotrauma). Most importantly, even if all the characteristics in Table 8-1 were incorporated into turbine design the risks for larger fish being injured and killed by blade strike are still very high. Hence, fish screens that enable large fish to bypass the turbines need to be an essential feature of large dams in the Mekong if sustaining migratory fish populations is an objective.

The criteria in Table 8-1 relating to barotrauma and ratio of pressure change show the sensitivity of fish to acclimation pressure; that is, the depth of acclimation before they enter the turbine. For example, if fish are acclimated to 10 m depth (200 kPa) as they approach the turbine and exit the turbine in the tailwater near the surface (100 kPa) the swim bladder will double in size and in some species (e.g. physoclists) it may rupture and cause death. Hence, there are pressure impacts that can be in addition to the turbine design. One solution is to ensure fish volitionally acclimate to surface pressure before they enter the turbine, which could be done with a sloping weir in the intake channel. A second option is to locate the turbine and draft tube deep in the tailwater, at the same relative depth as fish enter from the reservoir; therefore, fish enter and leave the turbine at the same pressure. Locating the turbine deep in the tailwater also enables the nadir of 100 kPa to be achieved.

Table 8-1. Turbine design criteria for passage of Mekong fish. These are conservative values to ensure 99% survival (including drifting eggs, larvae and adults diverse in size, shape, and swim bladder morphology).

Criteria	Value	Notes
BAROTRAUMA (pressure impacts; dependent variables)		
Pressure of nadir. (on suction side of turbine blade)	100 kPa (Atmospheric)	
Ratio of pressure change. (Acclimation/Exposure)	1.0 for 99% of paths through the turbine	
SHEAR STRESS		
Strain rate	< 100 cm s^{-1} cm^{-1} for 99% of paths through the turbine	
BLADE STRIKE (dependent variables)		
Impact speed (combination of water speed and blade speed including peripheral runner speed)	< 2 m s^{-1} (difficult to achieve and would need to be modelled with blade strike)	Depends on fish length and thickness of leading edge of blade.
Thickness of leading edge of blade	> fish length e.g. 30 cm thick for 30 cm fish	Assume large fish are screened. Possible screening for Mekong: > 500 mm fish
Number of blades	3 maximum	May depend on screening and blade strike models

[33] For further details, see page 22 below on Turbine Design.

Preliminary fish passage concepts

Upstream passage

Upstream-migrating fish are attracted to flow and at tropical hydropower dams are attracted to the powerhouse in the dry season and to both the powerhouse and spillway in the wet season. These define the locations that require fish passage.

Pool-type fishway

Large pool-type fishways for high dams have been used in North and South America (Figure 8-12). These have been successful for salmon but much less so for tropical species in South America. Pool-type fishways have predictable hydraulics and their effectiveness is largely due to selecting the appropriate design parameters rather than inherent features of this type of fishway. Often a high gradient is selected because it results in a shorter fishway and saves cost, but this creates turbulent hydraulics and results in reduced fish passage.

The hydraulics and design of this type of fishway can be readily adapted to Mekong fish species, as has been shown on a small scale recently in Laos PDR (Baumgartner *et al.*, 2012). Without specific data on the swimming ability of Mekong fish species and the size of fish when migrating, conservative design criteria would need to be selected to ensure effective fish passage. For example, a maximum water velocity of 2.4 m/s is often used for salmonid fishways, which equates to a 0.3 m difference in water level between fishway pools. However, where this design criterion has been used for non-salmonids in South America - where there is a high diversity of fish species with both immature and mature fish migrating upstream – fishways have been unsuccessful is passing all the migratory fish. In Australia, a maximum water velocity of 1.7 m/s has been used, which equates to approximately 0.15 m difference in water level between fishway pools, which has proved effective for mature and immature non-salmonids over 150 mm in length (Mallen-Cooper, 1999).

Alongside water velocity, turbulence is a primary design criterion of many types of fishways and is particularly applicable to pool-type fishways. Turbulence is the energy of water entering a pool and the pool volume available to dissipate it; it is measured in Watts per cubic metre (W/m^3). Salmonid fishways use 200 W/m^3, whereas fishways for non-salmonid fishes that are over 150 mm in length use 100 W/m^3 (Mallen-Cooper, 1999) and fishways for smaller fish use 30 or 40 W/m^3 (Mallen-Cooper pers. comm.). Initial pool-type fishways for Mekong fishes should use no higher than 100 W/m^3.

Water velocity and turbulence are combined with discharge to determine the minimum size of the fishway pools to meet hydraulic criteria. Fish size and biomass is then used to determine a suitable pool size for design. Large fishways for salmon have pools that are 9 m wide by 5 m long and in some cases these have been undersized for large salmon runs (Clay, 1994). For lower Mekong sites, which will have a very high migratory fish biomass, preliminary design criteria are 50 m wide by 10 m long pools on a 1:67 gradient (0.15 m head loss between pools). These are cost-sensitive criteria in fishway design but underestimating these criteria to reduce cost has caused many large tropical fishways to fail.

As mentioned earlier, in tropical dams there is the opportunity to use water that is surplus to the powerhouse; that is, water that would normally be directed to the spillway. The fishway could have two channels, one for low flows (e.g. 12 m^3/s) and one for high flows (e.g. 120 m^3/s) that are both controlled by a regulating gate and engage only when there is water surplus to the powerhouse.

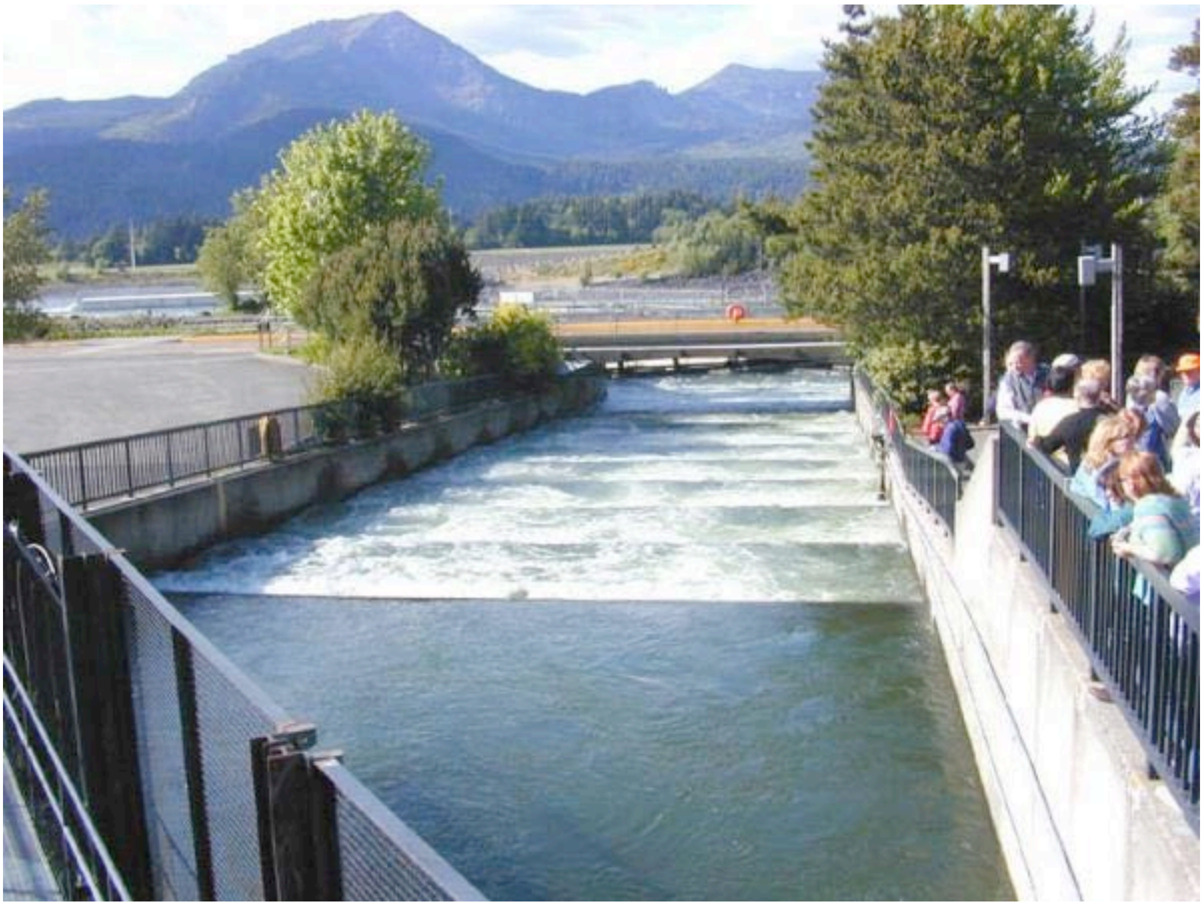

Figure 8-12. Example of large pool-type fishway on the 27 m high Bonneville Dam, Columbia River, USA. A suitable fishway for the lower Mekong, which would have a high migratory biomass, would be five times wider.

Downstream passage

Concept

Downstream passage through dams and reservoirs would be provided by:

i) Managing water velocity through the impoundment,

ii) Design of the turbines,

iii) Design and operation of the spillway gates,

iv) Design of the sluice gates, and

v) Design of the spillway and apron.

Managing water velocity through the impoundment

As discussed earlier a key aspect of downstream passage is drifting larvae. Managing water velocity through the impoundment is a major component of maintaining larval passage. Operation of the Xe Kong mainstream dams to achieve this objective is discussed in Section 9 of this Master Plan.

Reducing Fish Mortality through Improved Spillway Design

Passage through undershot gates, such as radial gates, can injure and kill fish when they are partly open. Hence, these gates need to either be fully open or shut. This operation can restrict spillway operation to coarse increments of flow. Hydrological and hydraulic modelling should examine gate usage. If fine control of flow is required then an overshot gate should be included which can be operated at variable discharges. Overshot gates can also be incorporated within radial gates.

A spillway can be designed to pass fish safely. The designs should include relatively laminar flow over a smooth spillway, with no sudden deceleration, or sudden transitions. Generally, this result in a "ski-jump" shape spillway with a long apron and no endsill or dissipators. The smoothness of the concrete needs to be specified and sometimes it needs to be coated with a smooth epoxy to ensure fish are not injured. Turbine design criteria for pressure and shear also apply. The spillway gates need to operate in "overshot" mode as undershot gates create extreme pressure and shear. At higher flows the whole radial gate would be opened fully.

Reducing Fish Mortality through Improved Design and Operation of the Sluice Gates

The sluice gates for sediment will release sediment and flow from close to the bottom of the dam. As flow was released into the tailwater on the downstream side of the dam there would be high pressure changes similar to turbines that would injure and kill fish.

A potentially innovative solution is to release the flow into a large decompression chamber and pipe that would provide slow decompression. The option would need computer and possibly physical modelling but in theory could mitigate impacts from rapid decompression of fish. A major knowledge gap is the time required for decompression, which is likely to be longer for fish with closed swim bladders that need to regulate gas exchange through membranes.

Reducing Fish Mortality through Improved Turbine Design

Turbine mortality

There are three elements of turbine mortality to consider:

i) blade strike (including grinding between the blades and runner housing),
ii) pressure impacts (barotrauma), and
iii) shear.

Blade strike

Blade strike can be estimated by a blade strike model, first developed by von Raben (1957) and widely accepted with minor variations. There are two components of the model: i) probability of strike and ii) "Mutilation Ratio" (MR) which refers to the proportion of fish that are struck by a blade and suffer a mortal injury. The final blade strike mortality value is a product of these two variables. The first component is based on physics and hence has not varied much from von Raben. MR however, is much less exact although it has also not varied much. MR stems from von Raben who observed that predicted strikes appeared to be higher than observed mortality from which he concluded that some fish were struck and survived; he considered the ratio of predicted strike to actual mortality was 0.43. It should be noted that von

Raben (1957) made his observations at low-head installations (4 m) with slowly-rotating turbines (68rpm) and no methodology for collecting fish data was described. Hence, it is possible that the turbines had less impact than installations at higher heads.

Validation of MR in-situ has not been done and remains a significant assumption. Much field work has been done on turbine mortality of salmon juveniles (smolts), which are less than 110mm, but it is not possible to clearly separate blade strike from barotrauma or shear. Turnpenny (1998) provides some quantitative basis for MR but acknowledges the limitations. He used freshly-killed fish in a laboratory setup with a moving blade travelling at 5-7 m/s. Kaplan and bulb turbines with 10-30 m head, similar to main-stem Mekong dams although the blades are travelling much faster. Turnpenny acknowledges that 20 m/s would occur near the blade edge even in low-head turbines (<10m) but it was not possible in the laboratory setup to get such high velocities, so he concluded his results apply to near-centre (hub) strikes. For the low velocities tested, he concluded that 47% of fish > 200g – or a MR ratio of 0.47 - that were hit by a blade exhibited visible injury, while lower MRs of .37 and 0.012 were recorded for fish 20-200g and <20g. Assessment of mortality from injuries was done over 48 hours although delayed mortality over longer periods has been observed (Ferguson et al., 2006) which would further increase this ratio. MR was refined by Turnpenny et al. (2000) with an equation based on length with larger fish have a higher MR, and this has been used widely (Deng *et al*,. 2007; Ferguson *et al.,* 2008; Halls and Kshatriya, 2009).

In summary, blade strike probability would appear accurate assuming fish are passive particles, while blade strike mortality which is a product of strike probability and MR, would appear much less certain for medium and large fish. It is also not possible to separate blade strike from other causes of mortality in situ, and calculate the contribution of blade strike.

Barotrauma

Barotrauma arises from pressure changes and specifically decompression of fish as they pass through the intake, turbine and draft tube. If decompression occurs – that is, any pressure experienced by the fish is less than the acclimation pressure - then expansion of the gas bladder (swim bladder) occurs. Typically, injuries result if more than 40% expansion occurs.

Shear

The impacts of shear on fish in turbines is less well-known. The shear environmental of the spillway and tailwater, and the impacts on fish, is also largely unknown; these represent major knowledge gaps. Values for mortality due to shear were provided and reviewed by experts (Drs Baumgartner, Boys, Mallen-Cooper); however, in the absence of field data on shear profiles in turbines or spillways, these represent opinion.

Combined mortality of turbines

Any reported mortality of fish passing through turbines in situ is a combined mortality of blade, strike, shear and barotrauma, because it is not possible to conclusively attribute the injuries to any specific cause. These combined mortalities in Kaplan and bulb turbines at dams up to 35 head - which are typical main-stem lower Mekong dams - include ranges of 5-20% (Larinier, 2008), 2 to 25% (Pracheil et al., 2016), and 0-40% (Hadderingh and Bakker, 1998) which comprised 0% for small fish (4.5 to 12.2 cm), 20-25% for medium-sized fish (28-47cm) and up to 40% for eels over 65 cm. Radiotracking studies on individual medium-sized fish support these data with 22% mortality (Bell and Kynard, 1985).

Improved turbine design

Mortality of fish passing through turbines can potentially be reduced by improved turbine design and/or by preventing fish from entering the turbines. There are two main methods to exclude fish from turbines: i) fish screens that divert fish to bypass systems, and ii) surface collectors with large nets that direct fish to a barge, which they are trapped and collected for transport downstream either by barge or truck. These systems can be effective for small (e.g. 10cm) to large fish, but are not practical for eggs, larvae and very small fish, which would then pass through the turbines where they would be susceptible to injury and death from shear and pressure changes. Surface collectors and nets are only practical in relatively low discharge rivers and would not be practical in the main stem of the Mekong River. Both fish screens or diversion nets need to be continuously maintained and cleaned to be practical.

Considering that large fish have very high mortality in turbines, or on trash racks, some method of diverting large fish around turbines in the Mekong River would be required if preserving populations of these fish is a priority. Fish screens with a bypass at the turbine intake would appear to have the greatest potential to meet this requirement. Table 8-1 outlines some preliminary criteria for the design of turbines for Mekong fish species. These are conservative criteria with the objective of 99% survival. However, due to the lack of data on Mekong fish and turbine passage, field assessment would be required.

Turbine location and design can influence the extent that fish can pass safely. The turbines should be located approximately 10m below tailwater to minimize barotrauma. This should be combined with a pressure acclimation weir in the intake channel which ensures fish volitionally acclimate to surface pressure, which also minimizes barotrauma.

Turbines that are placed deep below the tailwater greatly reduce highly damaging negative pressures; this has the added benefit of reducing cavitation, but increases capital cost through extra excavation. The impacts of pressure on fish relate to the change in pressure so that fish that are adjusted (i.e. acclimated) to surface pressure before entering the intake have a greater probability of survival; hence, a submerged weir in the intake channel that forces fish to the surface would enhance turbine survival.

Bulb turbines have the lowest mortality, followed by horizontal axis Kaplan turbines and then the vertical axis Kaplan turbines (Hadderingh and Bakker, 1998). Francis turbines and impulse turbines (Pelton) have the lowest survival ratios (Larinier, 2008).

A low number of blades and a low rotation speed reduces impacts on fish. Grinding of fish can occur in the gap between the blades and the housing, so Voith-Siemens reduced the gap in the Kaplan turbine (called a Minimum Gap Runner or MGR) although none are yet fully operational. However, this represents a minor variation of a Kaplan turbine. A radically different design is the Alden-Voith turbine (Figure 8-13). The Alden turbine has been under development by the US Department of Energy and the Electric Power Research Institute (EPRI) since 2009 (EPRI, 2011). The key design features of the Alden turbine that reduces risks for fish are: i) three blades (the minimum possible) in a corkscrew shape that has a decreasing radius, ii) thick leading edges to minimize blade strike, ii) slow rotation, and iv) unlike any other turbine design, the blades are part of the housing so the whole housing rotates which means there is no friction or grinding of the blades against the housing wall. These fundamental physical characteristics ensure it will have a lower impact on fish than equivalent Kaplan turbines with multiple blades that are not integrated into the housing and faster rotation.

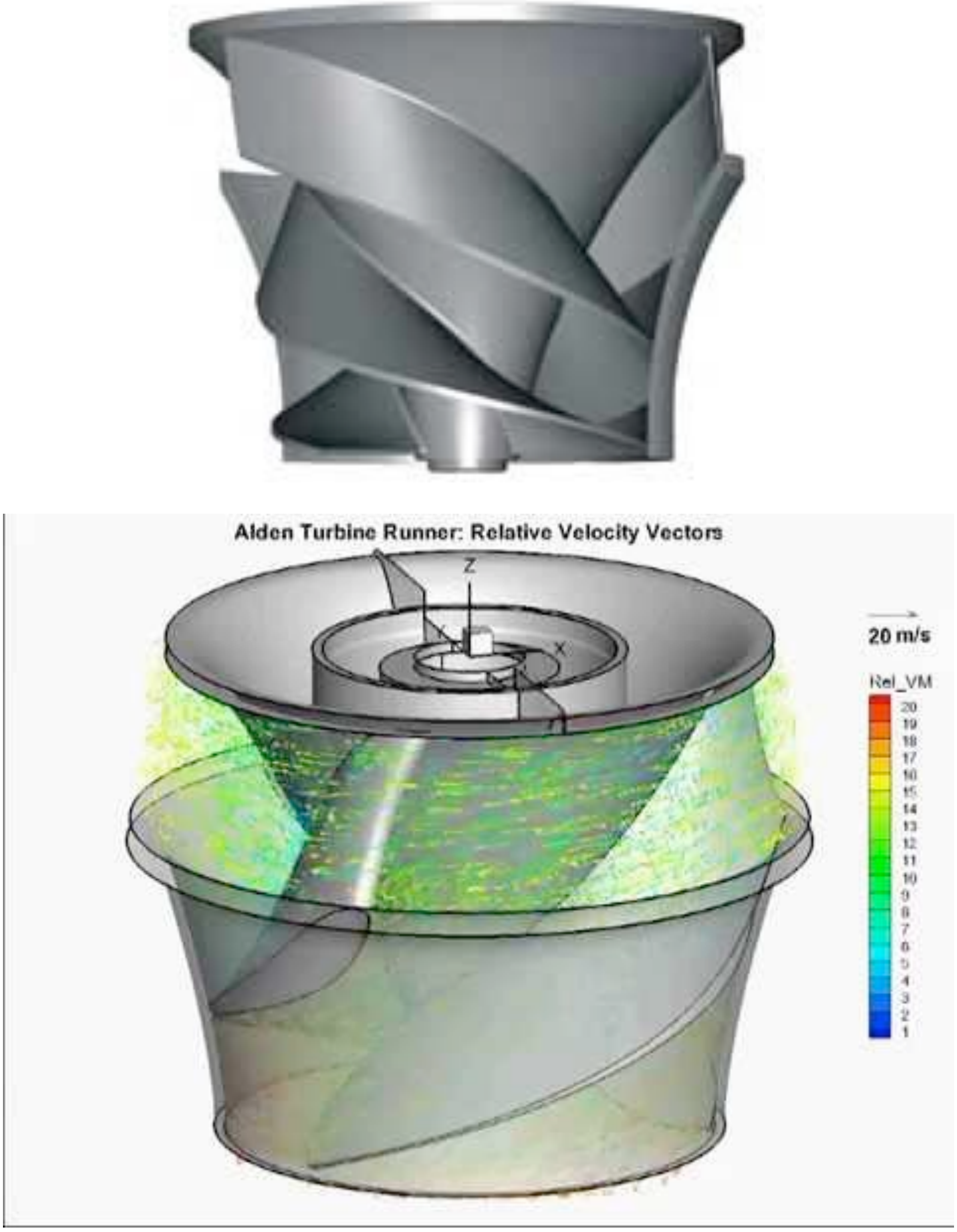

Figure 8-13. Diagrams of Alden turbine, considered to have the least impact on fish. Source: Perkins et al., 2013.

Blade stride models, theoretical analysis and some lab testing show significantly higher survival of large fish with the Alden machine. The design has been tested in 1:3.25 scale prototype and engineering investigations are complete. Numerous fish have been tested in the scale prototype with positive results. Over a range of species of interest to US applications, survival for juvenile fish are predicted to be as high as 98% (compared to less than 85% for Kaplan and Francis turbines) – though these results were for North American species[34] and mainly fish less than 200mm; and yet to be demonstrated at commercial scale. Pressure and shear were not directly measured in these tests and may not be directly transferable to 1:1 scale. Despite the experimental limitations, the results indicate high levels of fish survival and give cause for optimism.

Turbine reviews

NHI sent the turbine design criteria listed in Table 8-1 above to turbine manufacturers and they were asked to assess the feasibility of achieving the design and performance criteria. Three turbine manufacturers (Alstom (GE), Andritz, and Voith) were interviewed[35]. These companies reported that meeting the criteria was indeed feasible. However, a custom design would be required and detailed computer modelling would be needed to fully assess their performance. The responding manufacturers also stated that turbines that optimise fish passage may have a 4-7% loss in efficiency, but this is uncertain until the detailed design phase.

It is possible that blade strike can be greatly mitigated for fish < 300 mm in length using thicker blades. It may even be possible to pass fish safely up to 750 mm in length but there could be significant reductions in turbine efficiency (e.g. >10%). Finally, the companies stated that shear is difficult to evaluate without detailed modelling and design work. As a design trend, the more that blade strike is reduced, the more that shear stress is generated. Computer modelling would be needed to evaluate these aspects together.

In 2015, the MRC reviewed the state of knowledge on the effectiveness and economics of so-called fish friendly turbines[36] (Nielsen, Brown and Deng, 2015), as an alternative to conventional Kaplan turbines that are the indicated choice for the head and discharge conditions for Mekong mainstream hydro projects.[37] Several such designs have been proposed including the Alden turbine, and the Voith MGR designs. The MRC review suggests that the Voith MGR design might be achievable at full scale with comparable costs and efficiencies. Further, the MRC review proposes that a fish-friendly turbine (e.g., an Alden turbine) be installed on a hydro project in the LMB as a pilot demonstration. This would both allow research to be carried out and raise the profile of this approach to improving survival rates for downstream fish passage, perhaps at a carefully selected Mekong River tributary. This would be an important step in the eventual development and production of Alden turbines of a size suitable for the mainstream Mekong River plants. However, prior to such an application, fish passage testing, including the effects of barotrauma, needs to be carried out at a suitable prototype site.

Barotrauma study

The impact of pressure changes on fish (barotrauma) relates not only to the turbine design itself but also to the location of the turbine relative to the tailwater, and the conditions that fish

[34] The species modelled include Alewife, Coho Salmon, White Sturgeon, Smallmouth Bass and Rainbow Trout.

[35] The two largest Chinese companies, Harbin and Donfang were also contacted but did not respond.

[36] Low impact turbines have no precise definition, but compared to conventional Kaplan turbines, have larger rotating diameter Slower rotational speed Reductions in the number of turbine blades Reductions in gaps between moving and fixed parts Thicker leading edges on blades, vanes and gates.

[37] A review reveals that 10 of 11 designs for LMB hydro projects would use Kaplan turbines.

experience prior to entering the turbine. (i.e. acclimation). Locating the turbine deeper has potential to mitigate barotrauma so NHI commissioned a CFD (Computational Fluid Dynamics) study to assess the value of deep turbines, which is described in the next paragraphs.

The initial acclimation pressure of the fish as they approach the turbine greatly influence barotrauma; if fish are acclimated to surface pressure they are at less risk of injury. Hence, the intake channel would have a shallow section (which may require a submerged rock weir) that ensures that fish swimming along the bottom, swim to the surface; thus, acclimating them to surface pressure and enhancing turbine survival.

Barotrauma injuries in fish are caused by changes in pressure either from sub-atmospheric pressures in the turbine or by a net decrease in pressure, both of which cause the swim bladder to expand causing injuries and mortalities in fish (Figure 8-14, Figure 8-15, Figure 8-16). To assess the extent that pressure changes could be mitigated by increasing the depth of turbines, pressure profiles of a Kaplan turbine were assessed by Franz Jacobsen of Engys, using computer modelling (CFD) (Figure 8-17).

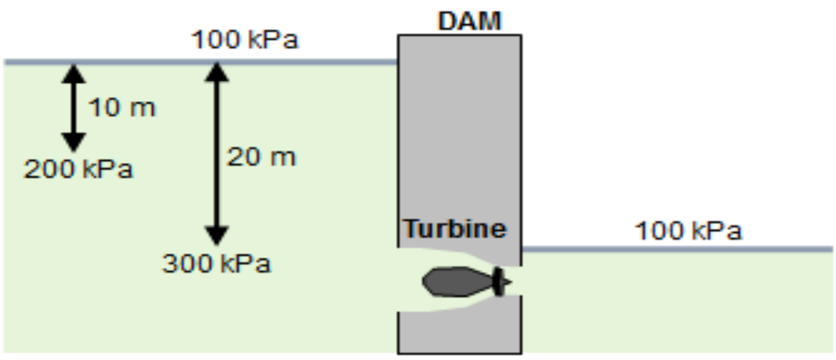

Figure 8-14. Schematic of pressure changes (barotrauma) experienced by fish at a typical 20 m high hydropower dam.

Figure 8-15. Example of barotrauma at a hydropower dam, showing the swim bladder protruding from the mouth (Photograph courtesy of Luiz Silva).

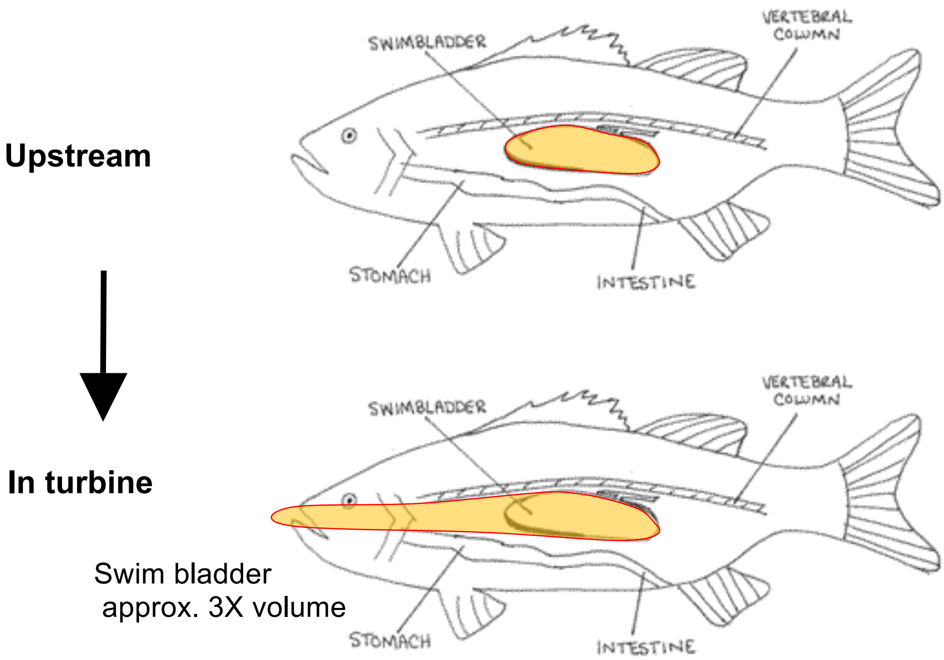

Figure 8-16. Example of barotrauma at a typical 20m high hydropower dam. Upstream of the dam the swim (or gas) bladder is normal size but as the fish passes through a turbine it typically experiences very low (sub-atmospheric) pressure which expands the swim bladder up to three times.

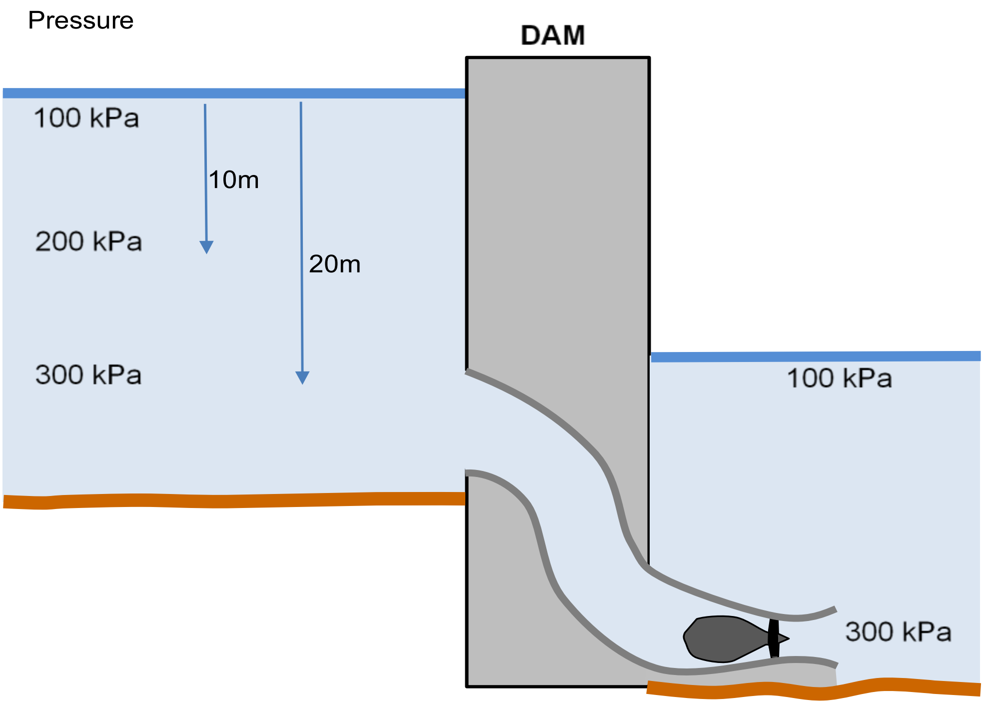

Figure 8-17. Concept of deep turbine, showing the pressures that fish would potentially experience. Note that fish passing through the turbine potentially do not experience a lower pressure than upstream, and hence do not have decompression or barotrauma.

Methods

The numerical software used to undertake the Kaplan turbine study is called HELYX, developed by ENGYS. HELYX is based on OpenFOAM, which is produced by OpenCFD Ltd. HELYX includes opens-source utilities and solvers that can simulate complex fluid flows involving chemical reactions, turbulence and heat transfer.

The computational domain consists of an unstructured grid mesh. The mesh has been refined in the areas of interest such as around the turbine and the concentration of grid points is reduced in areas of less interest. The mesh is comprised of 360 000 cells (Figure 8-18). The dimensionless value of y+ indicates the required resolution of the grid spacing in the boundary laminar layer.

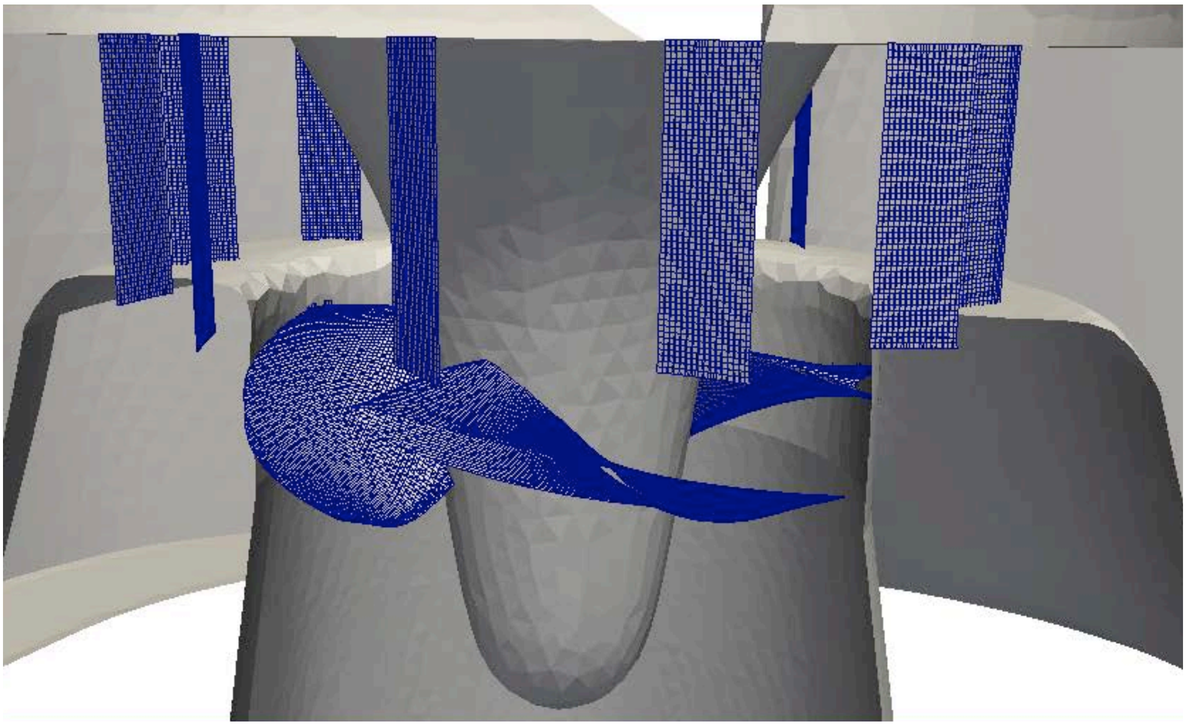

Figure 8-18. Sample of CFD mesh used to model pressure in a Kaplan turbine.

The type of solver used for the simulation comprises of a steady state flow regime, where the fluid is assumed to be incompressible. A fully turbulent solution is obtained using the k-omega SST turbulence model. Finally, the rotating components of the model such as the turbine runner is simulated using the MRF (Multiple Reference Frame) methodology.

The example modelled was with the turbine runner 20 m below the tailwater and with the dam having a total head of 20 m.

Results

The study showed that deep turbines, such as Kaplans, can theoretically greatly reduce – possibly even eliminate - pressure impacts (barotrauma) on fish. Figure 8-19 shows that there are no sub-atmospheric pressures in the turbines, which cause injuries in fish. The model run used a turbine 20m below tailwater, which met the criteria to eliminate sub-atmospheric pressures – a major cause of barotrauma.

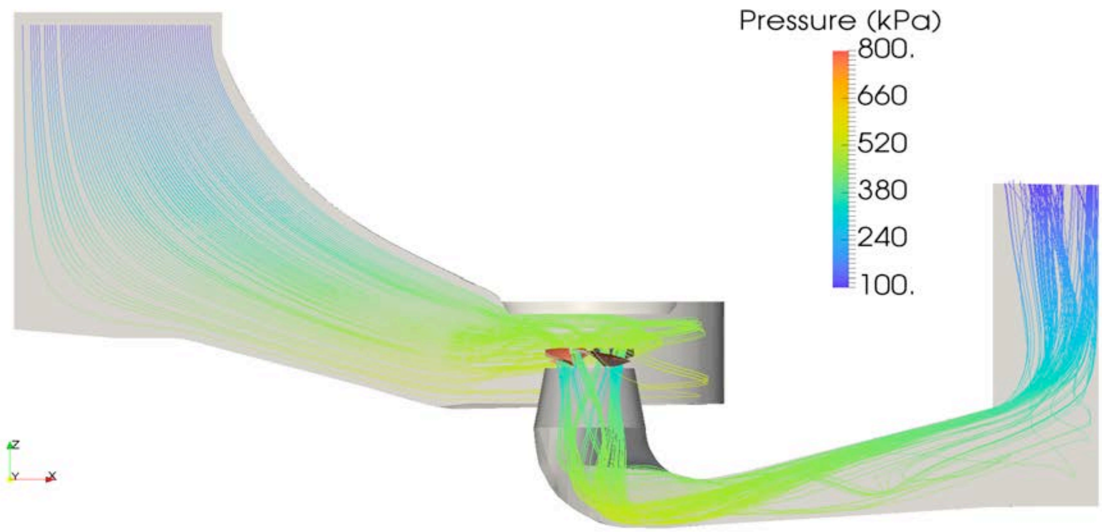

Figure 8-19. Cross-section of 3D CFD model showing pressure in a deep Kaplan turbine. Note that there are no blue lines near the turbine, indicating that there are no sub-atmospheric pressures, which cause injuries in fish.

Figure 8-20 shows a summary of 100 paths through a deep Kaplan turbine. The figure shows that, not only is no path is sub-atmospheric in the turbine, fish entering and leaving the turbine start and finish at atmospheric pressure, with no net change. The results are preliminary but show high potential for mitigation of barotrauma.

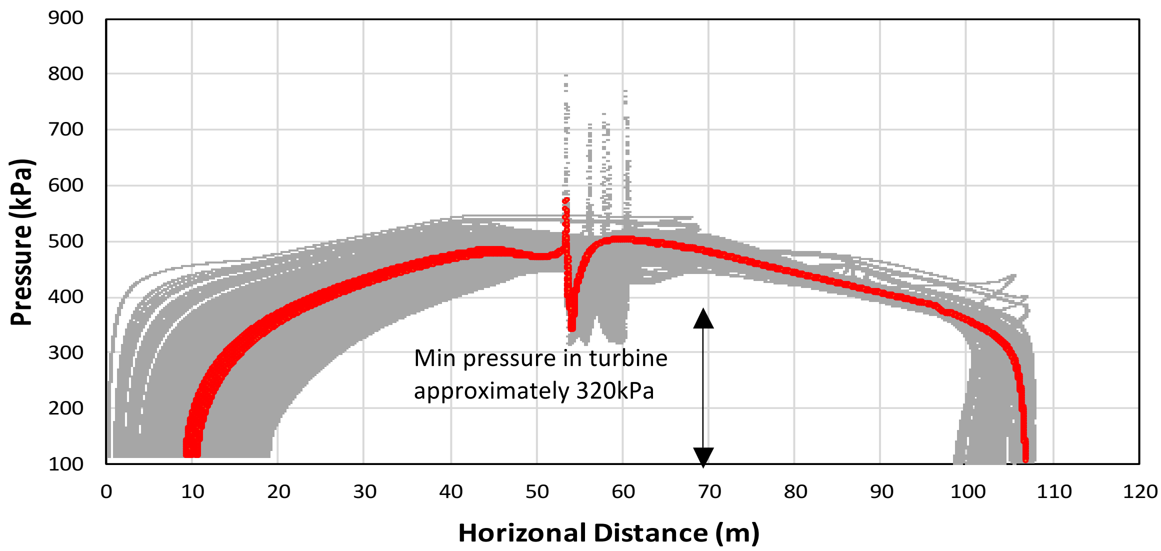

Figure 8-20. Summary of 100 paths through a deep Kaplan turbine, with the median path in red. The figure shows that no path is sub-atmospheric (<100kPa) in the turbine, while fish entering and leaving the turbine start and finish at atmospheric pressure, with no net change.

Summary

- Computer modelling suggest that pressure impacts can be greatly reduced, and possibly eliminated, by deep turbines.
- Blade strike can very likely be eliminated for fish up to 0.3m in length; hence, fish screens are required for larger fish.
- Shear requires detailed modelling and design work, before an assessment can be made.

Text Box 8-1. Fish passage requirements for hydropower in the lower Mekong.

- Upstream fish passage is required at the powerhouse and spillway for varying flows; hence multiple fishways and multiple entrances would be required.
- To attract fish into fishpasses and pass the high biomass, > 10% of flow is required.
- Upstream fish passage facilities need to accommodate the locations where the fish congregate due to attraction flows, which include:
  - the draft tubes of the power house;
  - each side of the power house;
  - the spillway apron at low discharge;
  - each side of the spillway near each abutment at high discharges.
- Downstream migration includes larvae that require flowing water in the reservoir to maintain drift:
  - From ADCP data it is likely that a mean channel water velocity of 0.4 to 0.5 m s^{-1} is required in the dry and early wet season and 0.8 to 1.0 m s^{-1} may be required in the wet season. We have assumed an absolute minimum of 0.3 m s^{-1} for initial modelling.
- Maintaining survival of fish approaching the turbines is required, either through turbine design and/or screens to divert fish.

Part Two: Compensation for Loss of Natural Capture Fishery Due to Hydropower Development with Fish Farming in Reservoirs

Dam construction has been seen as a regional catalyst for aquaculture[38] development in the Mekong Basin (Friend and Blake, 2009, cited by Pukinskis and Geheb, 2012). There has been a considerable increase in aquacultural production in the Mekong Delta over recent decades, but much of this production is for export (Friend and Blake, 2009; ICEM, 2010; Mainuddin *et al.,* 2011). By 2008, aquaculture ventures throughout the Mekong Basin had increased considerably, but heavily concentrated in the Mekong Delta area, and estimated to amount to some two million tons by weight. As such, this represented a comparative figure of 78% of wild fisheries consumption.

Can the combined production from the man-made lake or reservoir plus any aquaculture production compensate the fishery production from the original riverine system? This is difficult to assess because very few examples exist world-wide where data have been consistently recorded. Data on aquaculture production for the Mekong region are generally poorly reported. Adding to the confusion surrounding this subject is the fact that every riverine (lotic) and reservoir (lacustrine) system is unique in one or many different respects, and productivity is usually governed by a host of endogenous and exogenous factors. Riverine fish productivity (in terms of kg / ha / yr) is difficult to measure in general, especially in large tropical rivers with significant populations of migratory fish moving upstream, downstream and sometimes laterally into tributaries on a seasonal basis. That is to say, that the productivity of any one river stretch changes over time depending on the migratory patterns of fish species.

[38] Here, aquaculture is defined as "an enclosed, controlled system where artificially bred aquatic animals are raised, or a place where wild aquatic animals are entrapped, held in captivity and provided with either their total or partial dietary requirements in various forms".

Estimating the productivity of a lake, reservoir, canal, culture pond or back-swamp is much simpler, but at best, only crude estimates can be made.

Compensating for the loss of riverine fisheries following dam construction by creating man-made fisheries can be difficult to achieve. The larger the river, and the lower the reservoir is on the riverine system, the more difficult it becomes for reservoir fisheries to compensate for the loss of riverine fisheries (Jackson and Marmulla, 2000). The practicalities of establishing reservoir fisheries to compensate for the loss of riverine fisheries are greater in shallower reservoirs in tropical regions. But, intensive aquaculture in pens or cages can help to boost fish production considerably within the reservoir environment.

Two of the most important methods used for farming fish in man-made lakes and reservoirs are the floating cage system and the raising of fish in wooden or metal pens. The density per unit volume of the farmed fish is vital for health, survival and growth. Fish that feed high up in the water column are generally easier to farm than bottom-dwelling (demersal) species because the former can occupy the whole cage whereas bottom dwelling fish are sometimes subject to overcrowding, cannibalism and prone to stress-related diseases. It is essential for farmers to have a good knowledge of the nutritional requirements of the species being cultivated. Some fish species can be fed trash fish - *Channa* spp. (snakeheads) and *Clarias* spp. (Clarid catfishes). Many species will grow on commercially produced pelleted feeds – *Oreochromis* spp. (Tilapias) and many species of the Cyprinidae family, and yet some filter-feeding fish don't require any feed at all in the juvenile stages of life such as *Hypophthalmichthys molitrix* and *H. nobilis* – Chinese silver and Bighead carp respectively, and grow well in waters where zoo- and phytoplankton populations thrive (green water).

The main problems associated with cage culture are seasonal poor water quality, fouling of netting material, floods and high winds, physical damage to cages over time, predatory birds, disease, occasional theft and physical obstruction to boat traffic (Beveridge and Stewart, 1998, cited by FAO Fisheries and Aquaculture Department).

In some cases, aquaculture production can greatly exceed the productivity of the original riverine system, but usually only when the production from aquaculture is fueled and driven by external inputs (feed and supplements). In other cases, aquaculture and reservoir fisheries can compensate for lost riverine fisheries production initially, but this is rarely a sustainable and stable situation. For a newly formed reservoir created for hydropower or irrigation or both, much depends on how the terrestrial landscape is treated prior to inundation and what type of terrestrial landscape existed before they were submerged. In almost all cases where lakes or reservoirs have been man-made, aquatic productivity, including fish production, will decline considerably over time. As this situation advances, the intensification of aquacultural operations can help to offset losses to the overall productivity of the system, providing external inputs are supplied.

This comes at a price, however. Rural people cannot harvest aquaculture fisheries 'for free' (Pukinskis and Geheb, 2012). The benefits of enhancement do not accrue to those formerly dependent on wild or capture[39] fisheries, and their access to land, water and feed resources may

[39] Capture fisheries are defined as the purposeful exploitation of wild aquatic animals that live out their entire life-cycle in uncontrolled habitats and environments without external dietary inputs.

be jeopardized by enhancements" (Baran *et al*., 2009). Inland capture fisheries are not necessarily viewed as economically important and therefore not worth monitoring. Many rural communities often lack any type of real political power and have not, or dare not, have a "voice" concerning control of inland fisheries. Often local stakeholders or sectors that do not want the true value of the resource known for personal or political reasons can be a major problem. Official statistics are often based on guess work and estimates, and not even based on actual "real" data.

In addition, the ecological impacts of large-scale aquaculture intensification need to be factored into any cost-benefit analysis of such a strategy. The construction of dams usually leads to a reduction in overall fish species diversity and also biodiversity overall.

The case of the Nam Ngum reservoir in the Lao PDR

The 155MW Nam Ngum 1 hydropower scheme, built on the Ngum River, was constructed in three stages beginning in 1968. Commercial Operation Date (COD) began in 1971. After the closure of the dam in 1971, a fishery quite quickly established itself and was composed of almost entirely riverine species that were trapped above the dam. About 70 species formed the main fishery. Some could complete their entire life-cycle within the waters of the large storage reservoir (about 350 to 460 km^2 surface area depending on season). Other riverine species were able to adapt to the reservoir conditions and grew fast and large in the early stages of the fishery, but had a requirement to return to the large inflowing streams to spawn under riverine conditions. Fishery yield reached its peak in the early 1980s at around 1,500 tons per annum. It then suffered a gradual decline over the next two decades and had stabilized at around 350 Tonnes per annum by the late 1990s. Following the construction of the Nam Ngum 2 dam during the decade from year 2000 to 2010, which effectively blocked off access to riverine conditions upstream of the Nam Ngum 1 reservoir tail-waters, fishery yield declined even further (Warren, 1997).

Warren (1997) conducted village surveys around the perimeter of the reservoir including sites where the free-flowing Ngum River entered the tail waters of the Nam Ngum 1 reservoir. Under wet season conditions the area known as Keng Noi Fish Sanctuary resembled the free-flowing Ngum River and was a place where many fish species came to breed.

Interviews with elderly people around the Keng Noi Fish Sanctuary area revealed the conditions prior to the construction of the Nam Ngum 1 dam in the very late 1960s and very early 1970s. People described waves of fish migrations entering from the Mekong River and travelling way up into the more mountainous areas around the site of the current Nam Ngum 3 dam. Perhaps over 100 species were reportedly targeted during their migrations and their abundance was high. Many of the species caught prior to the construction of the Nam Ngum 1 dam are no longer caught now throughout the Keng Noi Fish Sanctuary area (Warren, 1997).

Aquaculture began to establish itself in the reservoir around the middle 1990s. This followed the intensive training of five selected individuals from villages around the reservoir at the Asian Institute of Technology (AIT). Pen and cage culture developed rapidly over a three-year period. However, pens and cages were placed in sheltered areas away from waves and winds that were also the places that acted as nursery sites for wild fish. Water quality problems soon became apparent due to the waste produced by the aquaculture operations. This, together with the natural deterioration of pen and cage structural materials and fish disease led to lack of interest in continuation of the ventures. By the middle of about year 2000 decade, most operations had been abandoned.

As this case study shows, reservoir fisheries and aquaculture can be established to offset "lost" riverine/wild catch production to some extent, but this is not easy to achieve and not always sustainable. To assume that reservoir fisheries alone, or in conjunction with intensified aquaculture in cages or pens can offset "lost" riverine fisheries is not necessarily correct, and each situation has to be taken on a case by case basis.

Part Three: Mitigation Measures for Diversion-Style Hydropower Projects

Introduction

As discussed in Section 7, the proposed alternative hydropower projects for the Xe Kong basin rely on dams (Table 7-1) which would divert water from tributaries to powerhouses sited at much lower elevations similarly to the scheme shown in Figure 8-21. Two of the Tier 2 projects and one of the Tier 3 projects (whose main parameters are shown in Table 8-2) are considered to be within the zone where a relatively high biomass of migratory fish might access the tributaries, so these projects should be fully appraised for assessment and mitigation of fisheries impacts during the EIA process. These projects would discharge near the Xe Kong mainstream.

Table 8-2. Diversion dam projects which should be prioritised for fisheries mitigation assessment.

Parameter	Houay-Axam	Dak E Mule	Xe Lon
Discharge (m^3/s) - Min	0.6	1.4	0.5
Discharge (m^3/s) - Max	312.6	374.0	297.5
Discharge (m^3/s) - Mean	31.2	44.2	28.0
Discharge (m^3/s) - Median (50% flow)	11.9	20.3	10.4
Design Discharge (m^3/s) (T 7-1)*	64	49	64
Catchment Area (km^2)	**799**	**1039**	**726**
Reservoir Area (km^2)	3.18	4.48	6.55
Dewatered tributary length (km)	5.8	11.7	14.5

Notes: * needs to be checked as design discharge is more likely to be close to median flow.
** 96.4 km of Nam Pouang downstream will be impacted.

This section focuses on issues which require particular attention for diversion dam projects on tributaries, as shown in Table 8-3, with mitigation measures discussed in each sub-section below. These can only be covered in general terms to provide a guide for data collection and more detailed appraisal, and for estimating the likely costs of mitigation measures, which are needed for evaluating project viability.

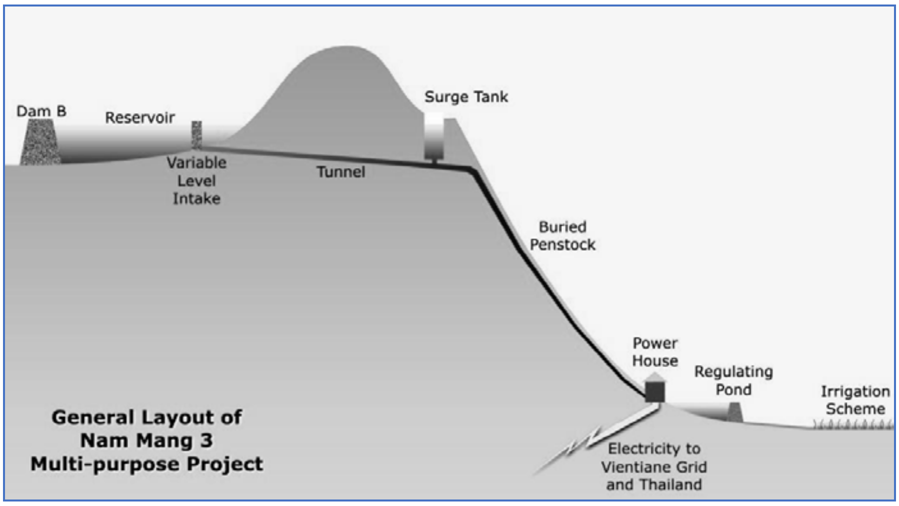

Figure 8-21. A cross-section of a typical diversion scheme, Nam Mang 3 Hydropower Project. Source: Electricité du Laos (EDL) (20050 as cited in Kouangpalath (2016).

Table 8-3. Diversion dams: some likely impacts and mitigation measures.

Impact	Possible Mitigation Measures
Depletion of flow in a watercourse downstream of a diversion dam.	E-flows.
Excess water or variations in the flow of water in the receiving watercourse.	Re-regulating pondages.
Disruption of fish migration in the tributary.	Screening and passage over the dam to the tributary.
Disruption of upstream fish migration in Xe Kong.	Screening and/or barriers, and guidance.
Water quality impacts downstream.	Biomass clearance pre-construction, multi-level off-takes, re-regulating pondages, and aeration.

Technical approaches for mitigating impacts on upstream and downstream fish passage at the mainstream dams (addressed above in this report) are similar in concept to those discussed for the tributary dams, so are not covered in detail here.

As well as fisheries, other general impacts of hydropower projects require assessment for the diversion dams and the associated roads, tunnels and transmission lines, which cause direct and secondary impacts on forests and other land uses, and exacerbate erosion of sediment to watercourses. Some impacts may be more severe for diversion projects compared with mainstream projects and need to be accounted for. Minimization of all of these impacts requires careful design and construction. Secondary impacts are likely to be ongoing and long-term if there is no control on use of access roads. Tributary reservoirs will draw in fishers and their families, and will provide a route for boats to access their watersheds, facilitating increased exploitation of timber and NTFPs. These impacts all need to be evaluated in comparing the relative sustainability of alternative dam projects.

Depletion of flow in a watercourse downstream of a diversion dam

Overview

Depletion of flow causes impacts on aquatic biota, including algae which are an important food source for fish and for people in the dry season, as well as other aquatic animals (OAAs), which also feed fish and many of which are exploited directly by people. Some fish may be permanent residents of steep tributaries, while others are likely to migrate into the tributaries to feed on algae and perhaps to breed, but more information is needed to document such migration patterns in the Xe Kong tributaries. Fish downstream of a diversion dam (whether migratory or resident) are directly affected by reduced habitat area and volume of water, and by increased temperature and poor water quality. Assuming that excess water will be available downstream of a diversion dam during the wet season, the main impacts will be caused by lack of water during the dry season, which not only affects aquatic biota including fish, but other animals, riparian plants, and of course any people utilizing the river water. These impacts may be exacerbated by lack of dilution for any human wastes.

Setting environmental flows (E-flows) for diversion dams

There are many approaches to setting E-flows, but in general, release of E-flows to rivers and streams should seek to maintain a proportion of the volume of pre-dam flows, with retention of some of the natural flow characteristics and parameters (timing, magnitude, frequency, duration, variability etc.), as well as maintaining water quality within acceptable parameters.

Ideally E-flows would be set from modelling based on scientific data on hydrology, hydraulics, water quality and the functioning of the various components of the ecosystem, including fish (Arthington, 2015; King *et al*., 2015).

While the need for E-flows has been discussed for many years, legislative frameworks and field application are relatively novel, so in most countries very few existing dam projects provide E-flows, and where E-flows have been prescribed they are rarely based on sound scientific data; often only a minimum flow level is set based on rather simple criteria, such as providing some potable water to downstream users.

The vast majority of LMB dams, including several diversion dams, do not have prescribed E-flows, so lack of water and/or unpredictable and extreme flow variations have caused problems for the environment and water users downstream of many dam projects. The general lack of E-flow requirements at existing Mekong basin dam projects is a consequence of many projects being built prior to development of EIA laws and regulations and the lack of any specific legal frameworks for E-Flows. In Lao PDR, after several years of consultation and development, the new <u>Water and Water Resources Law</u> was approved in mid-2017. The law requires (Article 30) minimum flow_determinations to be made for all watercourses to meet the basic needs of people who rely upon them and the sustainability of the ecosystems in affected areas. So, any E-flows proposed for Xe Kong tributaries would need to be consistent with the minimum flow determinations which will be made by MoNRE under the Act. There is at present no other specific mandate under which MoNRE can require any particular amount or pattern of E-flows, but E-flows could be negotiated under the EIA process, as was the case with some recent projects, including the Don Sahong project and the Nam Ngiep project, or if the project's owners or funders have their own environmental requirements.

As shown in Table 8-4 below, three diversion dams in Lao PDR have prescribed minimum E-flows of 0.2 - 6 m^3/s, but there are no scientific supporting data to justify the values, nor are there any monitoring data to evaluate the effects, so while these E-flows have set precedents, they provide no scientific justification for setting any particular value(s). For another five Mekong basin diversion dam projects for which information is available, E-flows have apparently not been required, including for three projects in the Xe Kong basin: Houay Ho, Xepian-Xenamnoy and A Luoi (in Viet Nam) (Table 8-4).

Table 8-4. Environmental flows at diversion dam projects in Lao PDR.

Project	Dammed River	Receiving Waterbody	Pre-dam flow	Environmental Flow	Capacity (MW)	Commercial operation	References
Nam Theun 2	Nam Theun	Xe Bang Fai	Mean 238 (min.-max. 4.4-6,134) m^3/s	Minimum flows of 2 m^3/s to Theun River, and 0.2 m^3/s to Nam Kathang, a small stream which was cut off by a re-regulating dam	1075	2010	Descloux et al. (2014)
Nam Theun-Hinboun	Nam Theun	Nam Hai to Hinboun	Mean 460 m^3/s	Initially a minimum flow of 2 m^3/s, later increased to 5 m^3/s.	210	1998	ADB (2002)
Nam Song	Nam Song	Via a canal and small stream to Nam Ngum Reservoir	Mean 65 (min.-max. 2-210) m^3/s	Initially a minimum flow of 2 m^3/s; increased to 6 m^3/s in 2000	6	2008-11	ADB (1997) & Schouten (2001-unpublished) & MRC database
Nam Leuk	Nam Leuk and Nam Poun	Nam Xan then to Nam Ngum Reservoir	Mean 16.4 m^3/s, 0.1-77 m^3/s mean monthly min. to max.	No E-flow. Flow of 0.06-0.14 m^3/s estimated as leakage only. Nam Kan enters 800 m downstream of the dam.	60	2000	ADB (1996), ADB (2004)
Nam Mang 3	Nam Mang	Nam Nyam then to Nam Ngum Reservoir	Est. mean 3 m^3/s based on catchment area.	No E-flow.	40	2004	Kouangpalath (2016), MRC database
Houay Ho	Houay Ho River	Small tributary of Xe Kong River	Mean 9.5 m^3/s	No E-flow.	152.1	2000	https://en.wikipedia.org/wiki/Houay_Ho_Dam
Xepian - Xe Nam Noi	Xe Pian, Xe Nam Noi & Houay Makchan	Xe Kong	Mean 24.3 m^3/s	No E-flow.	410	2018	MRC database
A Luoi (Viet Nam)	Xe Kong (A Sap in VN)	Diverts water out of the upper Xe Kong into the Huong Dien Reservoir on the Bo R., which runs to the Co Bi R., which runs to the east in Viet Nam	No data	No E-flow.	170	2012	https://www.power-technology.com/projects/luoihydropower/

As interim advice solely for the purpose of costing projects, E-flows could be set as the maximum of:

(a) 20% of the lowest mean monthly baseline dry season flow in each month; (in some other regions 10% has been recommended, but given the high biodiversity in Lao PDR and high seasonal variability, and to avoid severe effects during the dry season, a higher minimum is warranted), or:

(b) a fixed minimum flow rate of 2 m^3/s in each month, which is hypothesized to be a likely minimum flow to support any significant quantity of resident aquatic biota, including algae in the dry season, and to support a minimum level of fish migration; setting a minimum also avoids the very low flows which would result from setting a percentage value during the dry season.

It should be noted that sub-tributaries which enter a short distance below a diversion dam will mitigate the impact of flow diversion, so sub-tributary flows also need to be understood and accounted for in E-flow assessment. Some level of flow mitigation may also result from leakage from the reservoir, which should be taken into account.

Data collection for setting E-flows

If a diversion project proceeds to feasibility and EIA studies, these should include collection of scientific baseline data which is adequate to determine whether E-flows are required and what values should be set for the main flow parameters.

Hydrological data collection should include full delineation of sub-catchments of a tributary for simulation of inflows and collection of daily discharge data in the tributary over at least one year to support simulation of long-term flows which will better describe variability of the tributary and sub-tributaries.

Other data on fish and fisheries should be collected hierarchically, beginning several years before construction begins to generate adequate data to cover natural variability. Such data should include:

1. LEK (local ecological knowledge): interviews by recall of fishers, traders and households on catches, species, migration patterns and long-term variation. LEK provides a good coverage on many aspects of fisheries which is very useful for interim decisions and for developing monitoring programs.
2. Fisheries monitoring: fishers and households fill daily logbooks of catch and consumption; such data provide good information on the size and value of catches and the migration patterns of the main taxa, but may be unrepresentative of actual abundance patterns of fish, as fishers target or neglect certain periods and species, varying their gears and effort.
3. Standardized sampling: fisheries-independent data are collected by setting standard gears in the same manner at regular times in various locations; the data are likely to represent underlying changes in the fish fauna, but are usually more costly to collect than LEK or fisheries data, and provide less spatial coverage.
4. Supporting data: hydrology, habitat, water quality, other aquatic fauna and others.

The E-flows should also take into account how to provide water of suitable quality for fish (see discussion below).

Note that E-flows are also needed downstream of all projects (1) during construction, filling and commissioning periods, and (2) during any peaking operations, where a minimum flow needs to be provided during off-peak times and the rate and of increase and decline in flows needs to regulated, as is planned at Nam Ngiep 1 (ERM, 2014).

Excess water or variations in the flow of water in the receiving watercourse

High flows or fluctuations caused by hydro-peaking may directly impact people and their activities, as well as aquatic biota; high flows may cause increased flooding of adjacent rice fields and houses, and erosion of banks (e.g. (Kouangpalath *et al.,* 2016). Compared with other LMB diversion dams for hydropower, such impacts are likely to be of less significance for the proposed Xe Kong diversion projects, because most would discharge to the mainstream Xe Kong River, introducing water that would have entered the Xe Kong mainstream further upstream via the dammed and diverted tributaries. However, if the diversion projects discharge peaking flows there could be significant surge effects in the Xe Kong, particularly if several projects discharge peaking flows simultaneously. Re-regulating ponds (See Figure 8-21) for each project's discharge would mitigate these impacts, so should be considered and costed if hydrological modelling indicates that excess flow impacts could be significant. Re-regulating ponds need to be adequate to retain peaking flows and release them as a minimum E-flow during off-peak periods; the minimum flow in this case would need to take into account the overall effect on Xe Kong mainstream flows. Re-regulating ponds also provide for some improvement in water quality of the discharged flows as discussed below.

Disruption of fish migration in the tributary

Overview

As a diversion dam will inevitably cause a large reduction in flow in a tributary river, it is highly likely that any upstream fish migration will be greatly reduced or eliminated, regardless of provision of E-flows or other mitigation. If there are significant spawning migrations upstream past the dam site (as shown by monitoring), a judgement first needs to be made on whether it is likely that such migrations can be maintained, taking into account:

- the effect of depleted flows on upstream migration and the need to divert larval and juvenile fish and returning adults away from off-takes and guided downstream via the depleted flow of the tributary (see below);
- the height of each dam,
- water quality impacts, and
- increased fishing pressure on fish migrating upstream and downstream in a tributary where the flow is depleted and it is more accessible post-damming.

While technically feasible to mitigate any impacts, the costs may be much higher than any likely benefits, indicating a need for careful appraisal during feasibility studies.

Diverting fish away from intakes

Fish which are migrating downstream through a tributary reservoir are likely to move with the main flow of water and enter the intake of the hydropower plant. Such intakes are usually screened to prevent organic debris from entering, so if mitigation of the impact on fish is attempted, those screens should also be designed to divert fish away from the intake to a channel or other structure or system which would provide safe passage downstream via the diverted tributary. A paired screen for a small hydropower plant is shown in Figure 8-22.

Screens must be carefully designed to meet criteria for fish passage; these could be based upon Environment Agency (2005) or other guidelines, and include the following considerations:

- flow should be at least 2% of the generating flow, and in the case of the diversion dams it would also be necessary to meet a minimum E-flow as discussed above;
- the diversion should cover the full water column at the intake;
- the mesh size or bar spacing must be small enough to exclude fish down to a chosen size; generally it would not be practical in Mekong tributaries to exclude fish less than 5-10 cm in length, because of the large quantities of debris and algae which would clog fine screens rapidly;
- smaller fish will pass through the turbines which should ideally be designed as 'fish-friendly' as possible, but it is likely that given the high head, Pelton or Francis turbines will be required, and these will cause very high mortality of any fish passing through them;
- screens should <u>not</u> be built at right angles or an acute angle to the intake flow, rather at a shallow angle which reduces the flow velocity to prevent fish becoming impinged, and which guides fish towards the downstream end and into a bypass channel; screen angle depends upon fish swimming speeds so needs to be calculated case-by-case, but is typically about 15^{o} to the flow;
- a screen must not be so long that fish tire, impact the screen and are injured; the maximum screen length depends upon maximum sustainable swimming speed (MSSS) (Environment Agency, 2005); and
- provision must be made for periodic cleaning, which may require that screens are removed and flushed; alternatively screens may rotate or have airburst systems which periodically flush material off them.

As fish will require adequate water to migrate through the tributary river, downstream passage must be integrated with E-flow releases of good-quality water. The options for downstream passage at any tributary dam site include:

- spillway passage, which may not be an option because of dam height and limited flow at most times, which would lead to fish being injured;
- a constructed fish passage channel, which will be longer and proportionally more expensive at higher dams;
- an Archimedes screw, which can provide safe transport downstream, while generating power via a small turbine at the dam site; and
- trapping and physical transport of fish downstream.

Figure 8-22. Fish screen at Iffezheim Dam, Rhine River. The screens direct fish into a vertical slot fish pass (centre), away from the turbine draft tubes. Photo: Marmulla (2001).

Behavioural barriers are an alternative or supplement to physical barriers (screens) at intakes; these could include some combination of sound, air bubbles, strobe lights and electrical fields which fish avoid, such as noise, lights, air bubbles or electric currents, to repel them from intakes (Figure 8-23). Behavioural barriers are less likely to be affected by clogging and damage from suspended materials than screens.

As the powerhouse intakes must include a screening system for debris, the most cost-effective approach would be to design the seeing system to also screen and divert fish, as mentioned above. Behavioural barriers could be utilized as a supplement if screening is found to be inadequate.

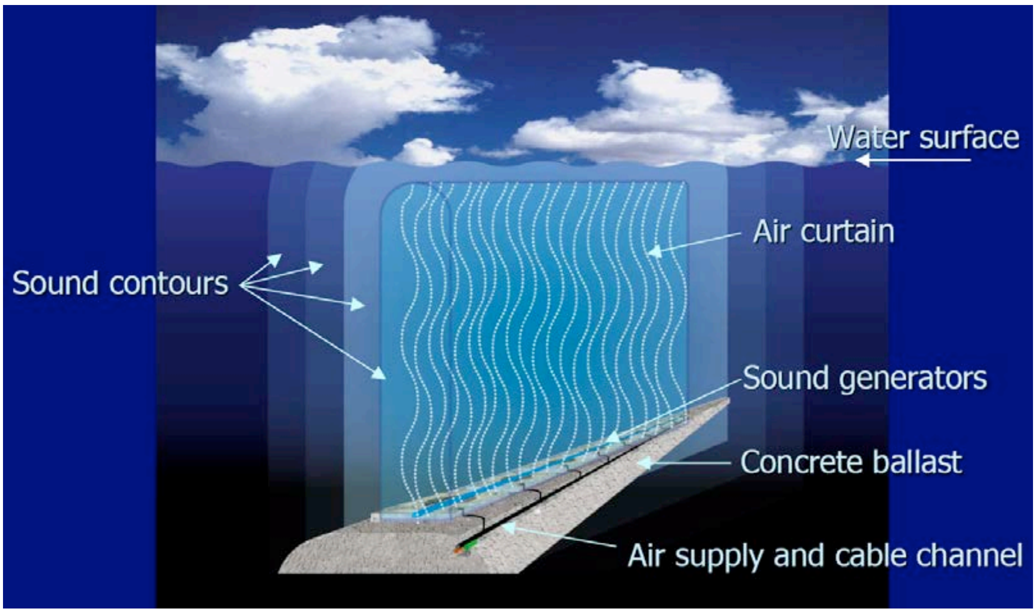

Figure 8-23. A behavioural barrier combining sound and an air curtain to repel fish. Diagram from (O'Keeffe and Turnpenny, 2005). The bioacoustics fish fence (BAFF™) is produced by Fish Guidance Systems UK.

Disruption of fish migration in the Xe Kong

The tailrace from the turbines of a diversion dam project (Figure 8-21) may attract and provide a trap for fish which are migrating up the Xe Kong Mainstream.

Fish could be prevented from entering the tailrace by physical barriers (screens) or behavioural barriers, or some combination as discussed above. Screening of outlets is likely to be simpler than screening inlets, as there will be little or no debris, and screens could be built at an acute angle to the flow (as fish migrating upstream cannot impinge on them).

Another (or supplementary) approach would be to build a low dam at the tailrace inflow to the Xe Kong mainstream to provide a hydraulic jump to hinder fish entry and to guide fish so they migrate upstream past the tailrace confluence; alternatively, standard top-down water-gates will prevent fish entry to the tail race channel. The dam and/or water gates could form part of the design of a re-regulating pond which should ideally be built downstream of any diversion dam. The details of such measures should be covered in EIA assessments for each tributary project.

Water quality impacts downstream

Overview

For some years after construction, hydropower dams in the LMB discharge 'bad water' which contains elevated concentrations of hydrogen sulphide, methane, ammonia, reduced iron and manganese, and low concentrations of dissolved oxygen, and in some cases methylated mercury (e.g. see ADB, 2004; Chanudet *et al.*, 2016a; IRN, 2008; Koizumi, 2006). Bad water is generated by decomposition of drowned terrestrial vegetation and dissolution of elements from sediments under anaerobic conditions, a process that is exacerbated by seasonal stratification of reservoirs. Blue-green algae (cyanobacteria) often dominate in stratified reservoirs, and add an additional element to the water quality problems evident downstream. Bad water has been a common problem during the early years of operation at many hydropower sites in the LMB, and can persist for many years, depending upon nutrient levels, the amount of residual biomass, the rate of supply of biomass into the reservoir, depth of the reservoir and turnover time. The effects on people and aquatic biota downstream can be very severe, preventing any beneficial uses of the water, including provision of E-flows for fish. Hence measures to ensure good water quality must be considered as part of E-flow provisions.

Mitigation of water quality impacts

For E-flows to be effective as a mitigation measure, bad water cannot be discharged untreated, so measures to mitigate this problem must be included in project design. Such measures include (1) pre-construction biomass clearing and burning on the reservoir footprint, (2) multi-level off-takes or other measures to select clean surface water for discharge, (3) aeration of discharges and/or retention of discharges in regulating ponds or a stilling basin downstream of the dam wall to allow time for oxygen absorption and for precipitation or air-dispersion of the main pollutants. These three measures have all been applied at some new LMB reservoirs (e.g. Chanudet *et a*l., 2016b; Descloux *et al.*, 2014). To limit the problem at source, catchment management aims to reduce nutrient and biomass inputs to a reservoir, while destratification of a reservoir can also limit the problem developing. Destratification is common at water supply reservoirs elsewhere, as the cost is justified by the relatively high value of clean potable water. In the Mekong basin one response to mitigate the unavailability of drinkable river water downstream of hydropower dams has been to provide groundwater wells, rather than fixing the problem of bad water directly.

Modelling is required prior to plant construction to ensure that turbinated discharges meet Lao PDR water quality standards for protection of aquatic life, which should be validated by pre- to post-construction monitoring (e.g. Chanudet *et al*., 2016b).

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9. SUSTAINABLE DESIGN AND OPERATIONS FOR SEDIMENT DISCHARGE

Section 2 of this Master Plan describes the essential role of sediment flows to maintain the ecological health of the river system, the morphology of the river channel, the availability of nutrients to fuel the aquatic food chain, and the integrity of the Mekong delta. In this Section, we present the general principles for designing and operating hydropower dams to discharge sediment that should be applied to all of the future dams in the Xe Kong basin that trap sediments that would otherwise flow into the Cambodia reach and the mainstream Mekong. However, many of the new dams that are included in the Master Plan as satisfying the sustainability criteria would be located in the upper reaches of the Xekaman sub-tributary, which already has two dams in the lower reaches. The largest of these dams, Xe Kaman 1, has no outlet for discharging sediment, and impounds a reservoir that is wide and shallow. All of the bedload sediments and much of the suspended sediments and nutrients that are discharged from upstream dams will be largely trapped in this reservoir. This raises a genuine question whether it would be worthwhile to design and operate the upstream dams in the Xe Kaman River for sediment passage. The benefits of doing so would likely not be worth the cost.

Additionally, it is important to notice that all of the new dams in the Tiers in Section 7 are designed as diversion-style projects. The barrages in these projects would also trap sediments and nutrients, just like storage dams. But they would need to discharge water continuously to the downstream channel to avoid unacceptable damage to the fishery. If these discharges were through low level gates, that might also serve to keep sediments from accumulating. Also, most of these dams are located in the upper catchment where sediment loads may not be particularly high. However, this Section also describes design and operational requirements for the Houay Axam dam alternative that would maximize its sediment discharge capabilities.

The most important application the principles and measures described in this Section would be for any mainstream dams that the Government of Lao might authorize. This Master Plan does not include these dams because they are considered to be more or less "unsustainable" under the proposed standards and criteria. If these dams are not cancelled, at least they should be considered to be a lower priority than the tiers of the more sustainable dams described in Section 7, with the priority descending from top of the cascade to the bottom. NHI previously submitted a detailed report on sediment management techniques for these mainstream dams which showed how these principles and measures for managing sediment could be applied to the uppermost four of the seven mainstream dams to vastly improve their sediment discharge. This analysis points in the direction of substantial redesign of two of these four dams. It is essential that similar dam designs and operations be implemented also in any dams sited lower in the mainstream as it is not worthwhile to discharge sediment from upper dams that will then be trapped in lower dams. The content of the previous memo is retained in this report as Annex 9.1.

Sustainable Reservoir Sediment Management for Siting, Design and Operation of Hydropower Dams[40]

Introduction

As described in Section 2 of this Master Plan, by virtue of interrupting the continuity of sediment transport in rivers, dams cause sediment to accumulate upstream within reservoirs, thereby impairing reservoir operation and decreasing storage, and depriving downstream reaches of the sediments that are essential to maintain the integrity of the river. We can think of the sediments accumulating in reservoirs as “resources out of place”. While they are a problem in the reservoir, these same sediments would be beneficial downstream to maintain the river channel and ecosystem.

Although many dams can be designed and operated to pass sediment, either through the dam or around the reservoir, this is rarely done, and there are many missed opportunities to make reservoirs more sustainable. Sediment management is more easily done on small run-of-the-river dams, but has also been successfully done on some medium-sized and even large dams (Morris and Fan, 1998). With many hydropower projects planned in developing countries, it is timely to draw upon these experiences to inform planning and design of new dams, and to establish policies and design standards for reservoir sediment management, both to preserve reservoir capacity and to minimize impacts of sediment starvation downstream. At the 5th International Yellow River Forum in September 2012, reservoir sediment management experts from abroad joined Chinese experts for two fruitful days of presentations and discussion to exchange collective experience in sustainably managing sediment in reservoirs and addressing problems of downstream sediment starvation. This [section] summarizes key principles drawn from insights shared at the workshop and compilation of experience from building and operating sediment management projects in Asia, Europe, Africa, North and South America, as reported by Kondolf et al., 2014.

For descriptions and explanations of various sediment management techniques to preserve reservoir capacity, see Morris and Fan (1998), Wang and Hu (2009), Annandale (2011), Sumi et al. (2012), Annandale et al. (2016) and Efthymiou et al. (2017). Sediment management classifications of Morris and Fan (1998) and Kantoush, Sumi and Takemon (2011) distinguish among three broad categories: 1) approaches to minimize the amount of sediment arriving to reservoirs from upstream, 2) methods to route sediment through or around the reservoir, and 3) methods to remove sediments accumulated in the reservoir to regain capacity. Annandale et al. (2016) expanded this classification by adding adaptive management approaches as a fourth category (Figure 9-1).

[40] This text is from a paper summarizing the results of a workshop of experts convened by the Natural Heritage Institute and the Yellow River Conservancy Commission in Zhengzhou, China, in September 2012. The authors are G. Mathias Kondolf, University of California, Berkeley, California, USAID; Yongxuan Gao, Natural Heritage Institute, San Francisco California, USA; George W. Annandale, Golder Associates, Lakewood, Colorado, USA; Gregory L. Morris, GLM Engineering COOP, San Juan, Puerto Rico, USA. The results were subsequently published in an article by Kondolf *et al*., 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents. Earth's Future 2(5), doi:10.1002/2013EF000184.

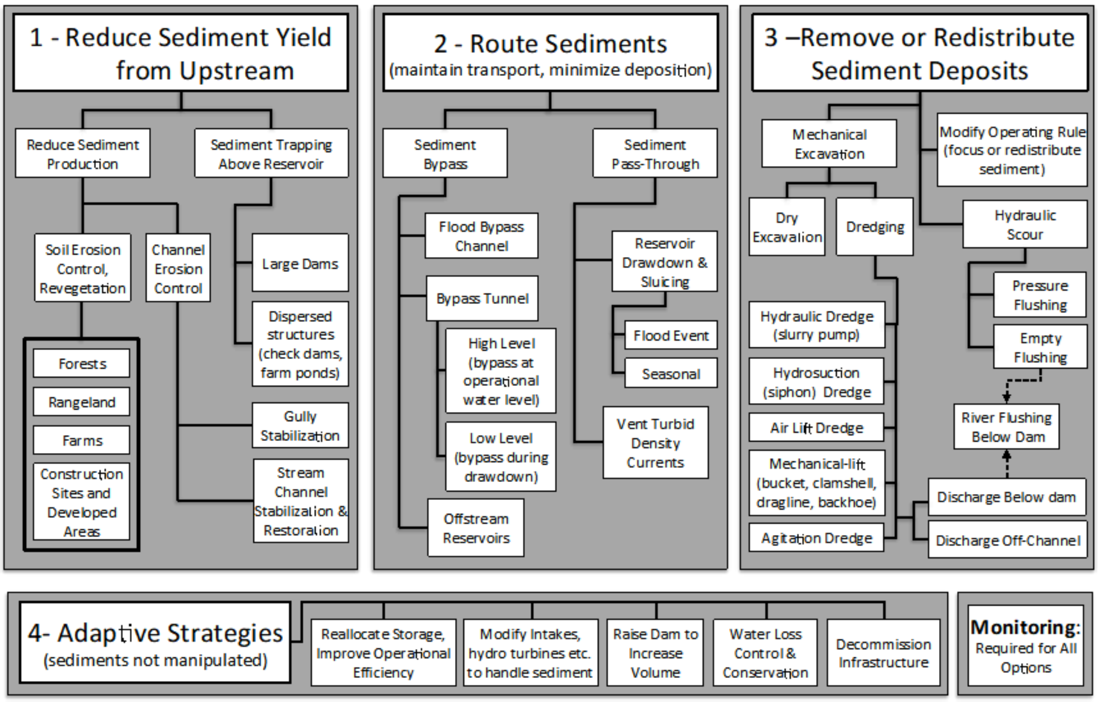

Figure 9-1. Classification of Strategies for Sediment Management.

Techniques for reducing sediment capture in reservoirs

Where possible, it is best to operate the reservoir so that sediment capture is minimized. For instance, the majority of the sediment load enters the reservoir during the peak inflow period when the velocity of the water into the reservoir is at its highest. By operating the reservoir with a high-water velocity during this time, the suspended sediments (as distinguished from the bedload sediments) may be sluiced right through the reservoir and not settle out. This may mean allowing a considerable fraction of the discharge from the dam to by-pass the turbines. However, when sediment does drop out of suspension in the reservoir, several challenges are created.

Much of the sediment, especially the coarser grains such as sands, will drop out of suspension at the point where the inflow meets the still water of the reservoir. That means that the sediments accumulate at the upper extreme of the reservoir, which may be many tens of kilometers from the points of discharge at the dam itself (the spillway and powerhouse). It is therefore obvious that it is easier to discharge accumulated sediment through short reservoirs than through long ones.

Absent mechanical methods of collecting and transporting accumulated sediment, which tend to be prohibitively expensive, the most effective technique for removing the sediment involves drawing down the reservoir such that the river flows continuously through the reservoir, re-suspending the sediments, and discharging them through large, low level gates in the dam designed for this purpose. The problem is that during the sediment flushing operations, the powerhouse will be offline. Thus, there is a direct trade-off between sediment management and power generation. This “drawdown flushing” technique will work best in reservoirs with steep channel slopes that also have a deep and confined channel and steep sides. And, it will be most successful if it is employed relatively frequently.

Flushing a reservoir can pose substantial hazards to the downstream fishery. During the routine operations of the dam, unnaturally clear water ("sediment starved" water) is discharged. The fish that occupy the immediate downstream reach will be those that can adjust to this condition. Then, during flushing operations, unnaturally turbid water is discharged into that same environment, without any transition. This can be devastating to the fish thus affected. For this reason, flushing operations often use two levels of gates in the dam. The lower gate is for discharging the highly sediment-laden layers, while the upper gates discharges clear water to dilute the sediment concentration (see example of "environmentally friendly flushing" in Kondolf *et al*., 2014).

In sum, short reservoirs in steep terrain are most readily flushed, long reservoirs in relatively flat terrain are very difficult to flush. In all cases, discharging sediment comes at the expense of power generation, making large dams less economically attractive in the short term but, by virtue of prolonging reservoir life and preventing sediment-related maintenance problems, sediment management will often be economical over the long run. These realities have important implications for sediment management in the proposed mainstream dams of the Xe Kong basin.

General Principles

While there is no one-size-fits-all solution for sediment management that is applicable in every (or even most) cases, there are some general principles that are broadly applicable, and which can guide project planning towards more sustainable designs, as summarized from Kondolf et al. 2014.

All dam proposals should address sedimentation

Sediment trapping by dams creates problems for dam operation, reduces dam and reservoir lifetime, and causes downstream sediment starvation. We recommend that sedimentation be explicitly addressed in planning and design documents for all proposed dams, including quantification of upstream sediment yield to the reservoir, and with projections of reservoir sedimentation rates into the future for the conventional design approach as well as management based on more sustainable principles. Rivers vary widely in their sediment loads, and the load carried by the river should be explicitly acknowledged in planning documents. Planning and design documents should indicate how reservoir sedimentation will be managed in the long term to ensure sustainable development.

Plan over sufficiently large spatial and temporal scales

In planning dams, a spatial scale much larger than the reservoir and its immediate environs should be adopted. The upstream river basin should be analyzed for its sediment production, with respect to additional dams, and other changes. Downstream impacts to the river sediment balance should be an integral part of the analysis of proposed dams, and extending downstream far enough to incorporate the limit of impacts, including the coastal zone where appropriate. Likewise, reservoir sustainability and downstream impacts should be analyzed over a sufficiently long temporal scale (300 years or more) to capture long-term impacts.

Adopt a life-cycle management approach to design and operation

For purposes of dam design and operation we recommend adoption of a life-cycle management approach in lieu of a design life approach. Planning and economic studies for reservoirs are commonly based on a design life of only 50 years (Morris and Fan, 1998), which effectively makes it difficult to manage sedimentation problems during and after that period. A 50-year design life is the economic norm, because all costs and benefits are usually calculated to represent present values. The costs are then compared to the benefits using a market-based discount rate. Because any benefits farther than 50 years in the future, when reduced to a present value, are extremely low, additional capital costs to manage sedimentation well into future generations are not "economically justified". This means, for example, that most dams do not have facilities to manage sediment both during a traditional design life and well beyond. To the extent that sedimentation has been considered, it has most commonly been addressed by provision of a sediment storage pool within the reservoir's dead storage, commonly designed to accommodate 100 years-worth of sedimentation (Morris and Fan, 1998). However, with adequate maintenance and management of sedimentation, the usable life of a reservoir can be extended for a much longer period. Through adopting a life-cycle management approach, the implementation of reservoir sedimentation management approaches, combined with regular operation and maintenance and refurbishment activities, aims at using the dam and reservoir in perpetuity (Palmieri *et al.,* 2003; Annandale, 2013; Annandale *et al.,* 2016).

Understand the dual nature of reservoir storage space

In reservoirs that are (by design) allowed to fill with sediment, reservoir capacity is in such cases classified as an *exhaustible resource*. Alternatively, in reservoirs managed to prevent or minimize storage loss from sedimentation, reservoir capacity can be viewed as a *renewable resource* (Annandale, 2013). This fact means that the nature of reservoir storage space depends on a developer's decision to either implement reservoir sedimentation management approaches or not. A decision not to implement reservoir sedimentation management approaches means that reservoir storage space, once lost to sedimentation, is no longer available for use by future generations. In such a case it is consciously, by choice, classified as an exhaustible resource.

However, if reservoir sedimentation management is incorporated as an integral part of hydropower development to preserve or minimize loss of reservoir storage to sedimentation, the reservoir storage space can be viewed as a renewable resource. The decision as to whether reservoir sedimentation management should be implemented or not, i.e. whether the reservoir is viewed as an exhaustible or a renewable resource, has significant implications for the economic analysis of dam and reservoir projects (Annandale, 2013). Thus, sustainable development of dams and their reservoirs requires close attention to either preventing sediment deposition or removing deposited sediment from reservoirs.

Distinguish between behavior of fine and coarse sediment

Both suspended and bed load sediment are important to river systems. Reservoirs trap different grain sizes with different efficiencies. It is important to understand downstream sediment impacts and to plan for them. The impacts of fine and coarse sediment are quite distinct, and should be considered separately.

Guidelines for Siting, Design and Operation

Drawing upon decades of collective experience in a wide range of environments, a set of specific guidelines can be listed for siting and developing designs and operating regimes of reservoirs, which collectively can reduce their sediment impact which, in effect, operationalize the general principles (Kondolf *et al*., 2014).

Siting

Decisions about siting reservoirs largely determine future reservoir performance. Sediment problems can be minimized by giving preference to river channels with lower sediment loads (e.g., in less erodible areas, and perhaps higher in the catchment) and to sites where sediment passing is more feasible (e.g., steep gorges instead of low-gradient reaches). For a given level of hydroelectric generation within a river basin, it may be possible to minimize impacts by concentrating dams in a smaller number of rivers (preferably with naturally low sediment yields), allowing other rivers to flow freely, contributing sediment and supporting habitat.

Dams in series

Dams in a series should be operated in concert to achieve management of sediment transport along the river system. Poor design and conflicts between upstream and downstream dams will result if dams are operated independently. Therefore, when a series of dams are developed along any river, particular attention should be given to establishing the appropriate coordination and data sharing among the parties, including both the historical and real-time monitoring data required to determine the efficiency of the operation and to identify means to improve the operation and pass sediment.

Gates and equilibrium profile

The long-term equilibrium profile should be calculated in advance for every project. Gates should be placed and sized with respect to the requirement to achieve the desired long-term profile. There is no standard location for the proper placement of gates, because this will depend on the situation at each dam, but, in general, gates should be set low enough and with sufficient hydraulic capacity to establish the desired equilibrium profile and support the type of sediment management operation identified for long-term use. For example, if flushing is to be performed during a low-flow period, the gates may be smaller and placed very low in the dam section, while gates for drawdown sluicing will have much greater hydraulic capacity and will probably be set at a higher level. In many cases, an array of large radial gates at the bottom of the dam may be the best option. Their high initial capital costs are likely to be offset by the longer economic lifetime of the reservoir.

Installing and planning for gates and outlet tunnels

Although the need for a new outlet tunnel or new gates may not be manifest until some future point when sedimentation has advanced to the point that a new operational rule is required, such future needs should be anticipated during initial design and the dam designed to accommodate such future requirements. It is preferable to install the needed gates at the outset for the integrity of the dam and so that they are more likely to be operated when needed to pass sediment.

Intake location

The location and configuration of intakes should take into consideration the long-term equilibrium sediment profile and the ability to naturally scour sediment away from the area of the intake to sustain water deliveries despite sedimentation.

Retrofitting existing dams

Retrofit is best accomplished in concrete dams rather than compacted earthen dams. In theory, it is always possible to retrofit a concrete dam with additional low level outlets for sediment flushing, as was done three times for Sanmenxia reservoir to facilitate sediment passage. However, retrofitting is much more expensive than incorporating such outlets in the initial design and construction, and will often prove to be prohibitively expensive. Furthermore, it may impair the stability of the dam. Where retrofit of low level gates is not practical, an alternative retrofit approach is to construct tunnels around the dam for sediment discharge.

Frequency of flushing

Flushing or other sediment removal techniques will be more effective and less impactful on the downstream environment if implemented frequently (e.g., annually) rather than at longer intervals, and if followed by clear water releases to remove deposited sediment from the bed.

Regional integration of power grids

Operational flexibility to flush sediment while minimizing impacts on power system costs or reliability is easier to achieve in larger grid systems where the fraction of power generated by the reservoir relative to the total mix of generators is relatively modest. Therefore, regional integration of power grids may enable improved sediment management operations.

Sediment data

The availability of long-term, accurate hydrologic and sediment data is essential for the purpose of design and for analyzing impacts. However, analysis cannot be any better than the data on which they are based. Therefore, data collection efforts should be emphasized, as well as data-sharing.

Conclusions

As sediment is trapped behind dams, it can impair reservoir functions and ultimately reduce or eliminate storage capacity, threatening hydropower generation and the health of the ecosystem downstream. Good dam sites are limited, and can be considered a non-renewable resource. If a conscious design decision is made to allow a reservoir to fill with sediment, reservoir storage capacity should be viewed as an exhaustible resource, and, consequently, reservoir storage capacity should be valued more highly than it is presently in dam planning. Today many dams are planned and built without any consideration of sedimentation, or at best, the reservoir is designed to store anticipated sediment loads for 50-100 years before its functions are impaired. Yet in many cases, dams can be designed to pass much of their sediment load. Measures to reduce sediment trapping by a dam and facilitate sediment passage through or around dams must be an integral part of any hydropower planning and development (Kondolf *et al.*, 2014).

Choices in the siting, design, and operation of dams determine their ability to pass sediment. Siting decisions are irreversible, and to retrofit dams after they are built with sediment passage facilities such as discharge gates is costly and often impossible. Thus, plans for dams not yet built should be revisited to consider a full range of sediment passage options. For existing dams, an assessment of options to improve sediment management is recommended.

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10. Sustainable Operations for Hydropower Dams in the Xe Kong Basin

The existing hydropower dams in the Xe Kong basin, particularly Xe Kaman 1/Xe Kaman Sanxay and Nam Kong 1 (now under construction) block off spawning habitats in the reaches above them. They can also have a deleterious effect on the downstream fishery (for both migratory and resident fishes) if they distort the flow pattern in a manner that makes that habitat inaccessible or unusable, or disrupts the migratory cues. Even those "sustainable" dams featured in this "Master Plan" in the headwater tributaries (Houay Axam and Xe Lon) will have some effect on downstream flow patterns. And, certainly, the proposed mainstream dams, especially Xe Kong 5, if designed and operated as storage dams, would have such impacts. The most serious concern if these dams are operated as hydro-peaking facilities is that they will discharge radically fluctuating flows during the day, alternatively dewatering the downstream channel, and then releasing a surge flow. If they store water seasonally (as Xe Kaman 1 does) the concern is they will reduce the peak flows that inundate the floodplains and then inundate the riffles, spawning gravels and vegetation in the river channel that the migratory fish need for spawning. Some distortions are probably inevitable. The critical issues (1) how much distortion will occur at what times and through what reaches, and (2) what are the thresholds of tolerance of flow distortion for the migratory species.

This Section of the Master Plan assesses the flow alteration to be expected from the existing dams, specifically from Xe Kaman 1/Xe Kaman Sanxay and Nam Kong 1. In effect, Xe Kaman Sanxay and Nam Kong 1 may need to be re-operated somewhat as re-regulation dams to counteract the flow distortions caused by the upstream dams.

For the potential new dams, there are three development and operational scenarios, but only two scenarios pertinent to flow distortion in the mainstream Xe Kong. Xe Kong 5 as a storage project would preclude Xe Lon and Houay Axam because it would inundate those project sites. Conversely, Xe Lon and Houay Axam would preclude Xe Kong 5 as a storage project, but not as a diversion-style project. So, there are three scenarios: 1) Xe Lon and Houay Axam as diversion projects—no seasonal storage but operated as hydropeakers that would refill on a daily basis. There would be Xe Kong 5 project. 2) Xe Kong 5 only, operated for seasonal uniformity of power generation to the extent possible and also operated as hydropeaker. 3) All three projects as diversion style projects with no seasonal storage but operated as hydropeakers. But, Xe Kong 5 operations only would be pertinent to downstream flow patterns because Xe lon and Houay Axam return flows are upstream of Xe Kong 5 reservoir. So, this is the same scenario as #2 for estimating flow distortion in the mainstream.

The flow distortion from the potential headwaters dam would be much larger from the proposed Xe Kong 5 project, if it were designed and operated as a storage dam, than from the smaller Xe Lon and Houay Axam projects, which are not storage projects. These distortions would gradually attenuate as with distance downstream such that the effect of the Xe Lon or Houay Axam projects would probably not affect migratory fish habitat in the reaches most frequented. Xe Kong 5, by contrast, would set the flow pattern through the downstream reaches where the other mainstream dams are proposed and would make them more practical to operate. Thus, it would not only substantially change the flow regime, but potentially result in the rest of the mainstream river within Lao PDR becoming a series of lakes.

However, these projects are mutually exclusive. If Xe Kong 5 were constructed as proposed, it would inundate the Xe Lon and Houay Axam sites, and if the latter were constructed, they would interfere with the Xe Kong 5 storage reservoir. If, on the other hand, Xe Kong 5 were redesigned as a diversion project, as described in Annex 9.1 for improved sediment discharge, all three sites could be developed. In that event, the flow distortion potential of Xe Kong 5 would be only with respect the daily rather than seasonal flow patterns and would make the rest of the dams in the downstream cascade less attractive. The daily flow distortion might be quite significant in the spawning habitat reach, however.

To determine whether these dam operations need to be modified to assure flow conditions that enable the migratory fish to access and use the prime spawning and rearing habitats and that protect the resident fishery, environmental flow prescriptions should be developed for the reaches below these dams to the extent necessary. The desired pattern will resemble the natural flow regime in terms of timing, duration and magnitude of high and low flows as closely as possible. This additional analysis should be a central part of the environmental and social impact assessment for these projects.

In assessing operational alternatives that will maintain the natural flood regime of the river, provincial officials have asked the Natural Heritage Institute (NHI) to consider how the flood events can be controlled to prevent property damage and loss of life from extreme events. The towns of Sekong and Attapeu, as well as the smaller villages downstream from the Xe Kaman confluence, may be at risk in the event of extreme flood events. Notably, the reservoirs already in place on the Xe Kaman and Nam Kong can provide adequate flood protection on those tributaries. Therefore, it is just the mainstream that is of concern. The mainstream dams, if built, can be operated to provide flood control benefits. The Xe Lon and Houay Axam projects, if built instead of Xe Kong 5, are diversion-style projects that will not have substantial flood retention capacity. Therefore, the better strategy for flood protection is land-use controls that aim to keep the vulnerable people away from the river, rather than the conventional approach of aiming to keep the river away from the people. That is also a much better strategy from the standpoint of maintaining the interaction of the river with its floodplain, which will maintain its biological productivity.

Of the seven mainstream Xe Kong dams, the simulation modeling described below assumes that only Xe Kong 5 is large enough to be operated as a seasonal storage facility that can be operated to even out the seasonal hydrologic variability as much as possible. The six downstream dams would then operate essentially as run of river, re-turbining the flow pattern that emerges from Xe Kong 5 while maintaining maximum storage levels throughout the year to maximize head and therefore energy production. Elsewhere in the Xe Kong basin, Nam Kong 1 and Xe Kaman 1 are assumed to be operated as seasonal storage facilities in the simulation model.

The reservoir operating policy of Xe Kaman 1 is currently unknown, as is the reservoir's sub-daily peaking operation regime. We assume that Xe Kaman 1 is operated to maximize annual energy production, as well as following the shape of the EVN energy demand curve. Data available to develop a reasonable representation of the operating policy for Xe Kaman 1 reservoir include inflow hydrology, elevation-volume curve, installed capacity (290 MW), total storage capacity (4804 $10^6 \cdot m^3$), intended operating range (218-230 masl), and the EVN hourly energy demand curve.

The reservoir's total storage capacity is 4,804 $10^6 \cdot m^3$, while the average daily inflow is approximately 146 m^3/s. Thus, the reservoir's ratio of storage capacity volume to annual volumetric inflow (i.e., capacity:inflow ratio) is 4804000000/ (146*86400*365.25) =1.04 years. In other words, Xe Kaman 1 is capable of storing more than a full year of average daily inflows. The reservoir's large storage (relative to inflow) provides the capacity to release, on average, a flow rate every day that is equivalent to the mean annual inflow. Hence, the operating policy developed below assumes the reservoir has a year-round target of releasing 146 m^3/s (less evaporation and other water losses) for 24 hours per day, thus ensuring low-variance daily energy output throughout the year. This policy is not an exact representation of the actual operational strategy being implemented at Xe Kaman 1, which began operation in 2016. Rather, this policy is designed to serve as a reasonable representation of reservoir operations at Xe Kaman 1 for purposes of evaluating downstream ecosystem impacts, given an assumed objective of maintaining consistent power output throughout the year. This representative policy results in a simulated mean monthly reservoir water level fluctuation as shown in Figure 10-1. This policy results in average annual energy production of 1,087 GWh/yr, which is similar to the 1,096 GWh/yr listed in the MEM Xe Kong hydropower database. Figure 10-2 shows the average outflow rate at Xe Kaman 1 for the reservoir operating policy (i.e., reservoir water level trajectory) shown in Figure 10-1. Figure 10-3 shows the policy's daily reservoir water level trajectory during a representative hydrologic year.

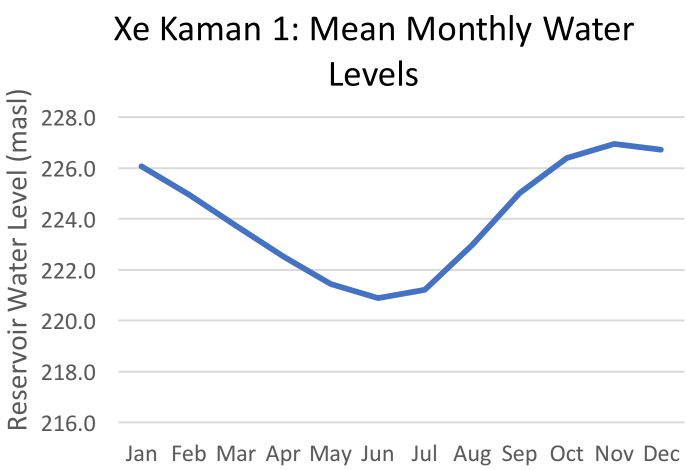

Figure 10-1. Xe Kaman 1 mean monthly reservoir water surface elevation (masl) for the seasonal variation energy maximizing policy discussed above.

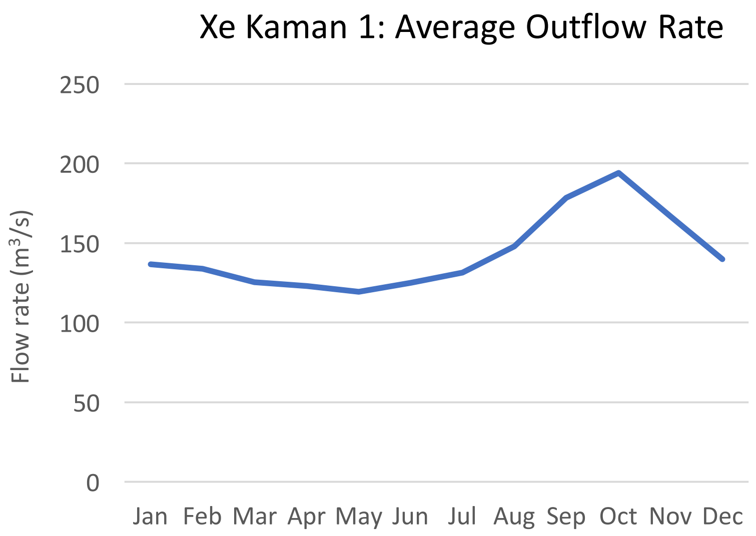

Figure 10-2. Mean monthly outflow rate from Xe Kaman 1 dam if the reservoir is operated for purposes of seasonal storage, as described in Figure 10-1.

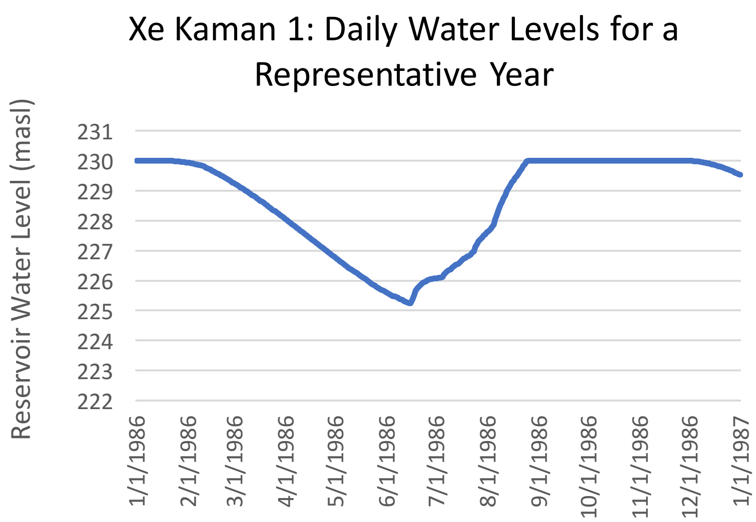

Figure 10-3. Xe Kaman 1 daily reservoir water surface elevation (masl) during a representative year of operation, for the seasonal variation energy maximizing policy discussed in Figure 10-1.

The Xe Kaman 1 policy of seasonally varying water levels results in significant alteration of the river's natural flow regime. The SedSim daily time step simulation model (Wild and Loucks 2012; Wild and Loucks 2014; Wild and Loucks 2015a; Wild and Loucks 2015b; Wild et al. 2016) was used to simulate the Xe Kong River and tributaries in both its unregulated and regulated states, assessing at five locations (denoted by numbered gray circles) the alteration of the river's natural hydrologic regime that has resulted from the operation of upstream reservoirs (Figure 10-4).

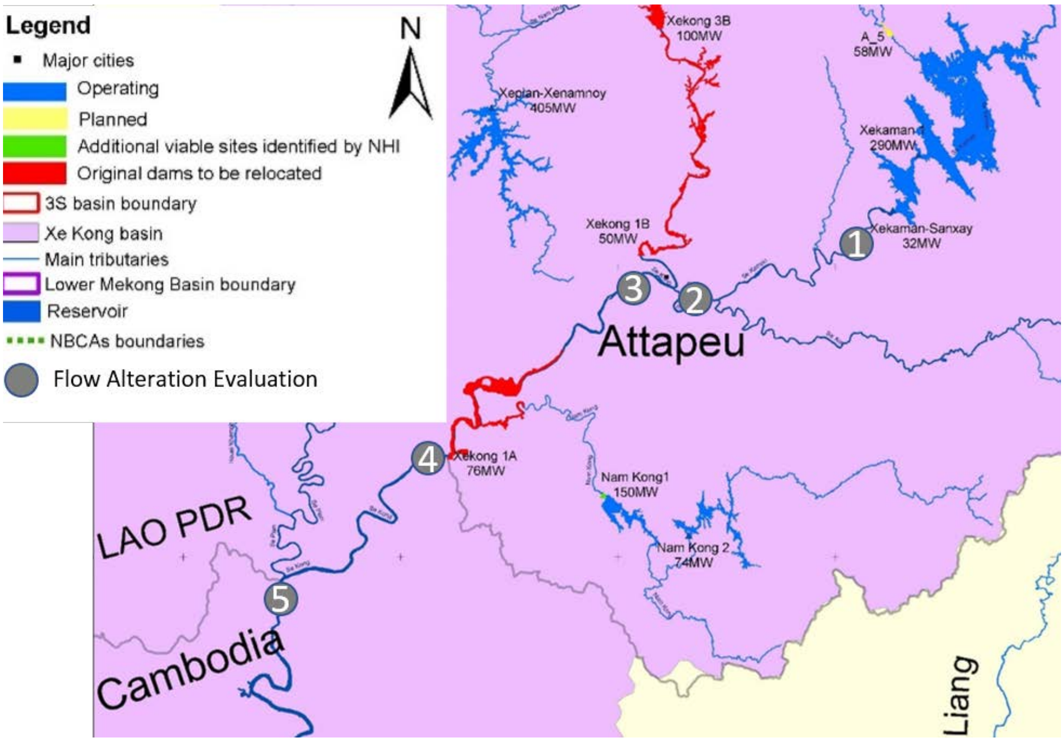

Figure 10-4. Map of a small section of the Xe Kong basin, marking with gray circular symbols the five locations at which the simulated distortion of the river's natural hydrologic and sediment flow patterns is evaluated below.

The simulated hydrologic alteration at location 1, shown below in Figure 10-5, is primarily the result of seasonal storage operations at Xe Kaman 1, which dampens all of the hydrologic variation induced by existing and planned dams upstream. (Note that location 1 was selected because it is thought to be important for migratory fish species as well as for endemics). Xe Kaman 1 has the capacity to store an entire year of inflow during an average hydrologic year. As a result, during an average hydrologic year Xe Kaman 1 has the capacity to release the rated powerhouse flow for 24 hours per day for nearly the entire year. For the reservoir operating policy in Figure 10-1, this results in a relatively constant reservoir release rate (i.e., flat red line in Figure 10-5). (Note that the Xe Kaman-Sanxay reservoir is not large enough to significantly distort the river's natural hydrologic and sediment regimes below Xe Kaman 1).

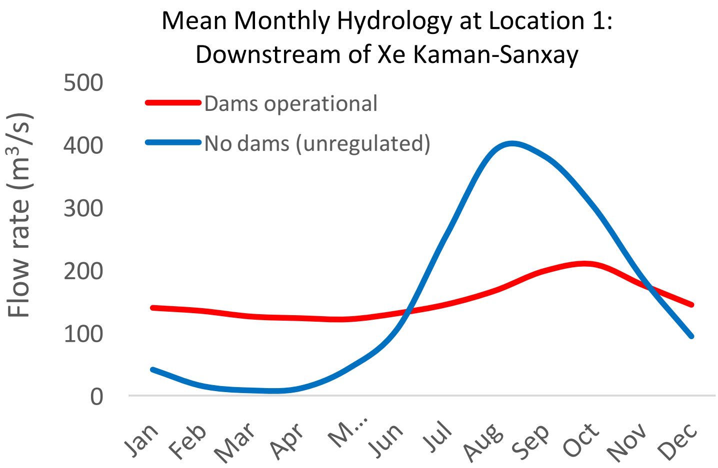

Figure 10-5. Alteration to the mean monthly hydrologic regime at Location 1 in Figure 10-4 (immediately downstream of Xe Kaman-Sanxay dam). The change in the hydrograph represents the impact of assumed operating rules to satisfy energy demand.

The hydrologic alteration at location 2 in Figure 10-4, shown in Figure 10-6, is also primarily the result of generating power at Xe Kaman 1, though the effect appears slightly dampened at this location due to the confluence of an additional, currently undeveloped tributary, Xe Xou.

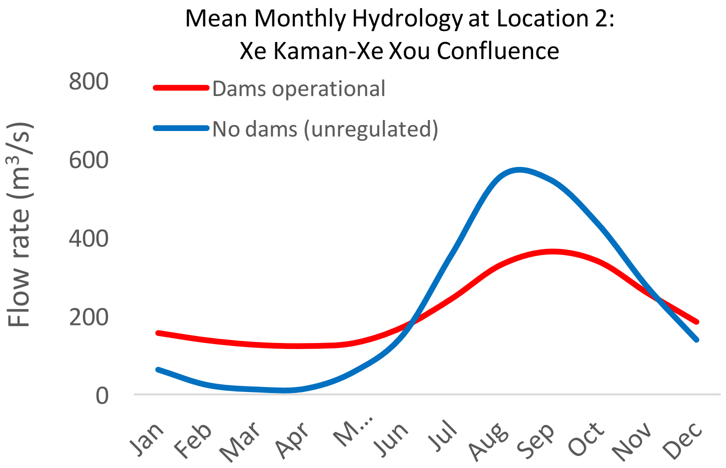

Figure 10-6. Alteration to the mean monthly hydrologic regime at Location 2 in Figure 10-4 (at the confluence of the Xe Kaman and Xe Xou tributaries).

Location 3 (in Figure 10-4) was selected because it is also thought to represent an important habitat for both migratory fish species and endemic fish species. Compared to location 2, this represents inflow from the Xe Kong mainstream, considering the six planned mainstream dams upstream of this location. Thus, the hydrologic alternation at this site, shown in Figure 10-7, is less significant compared to location 2 (Figure 10-6).

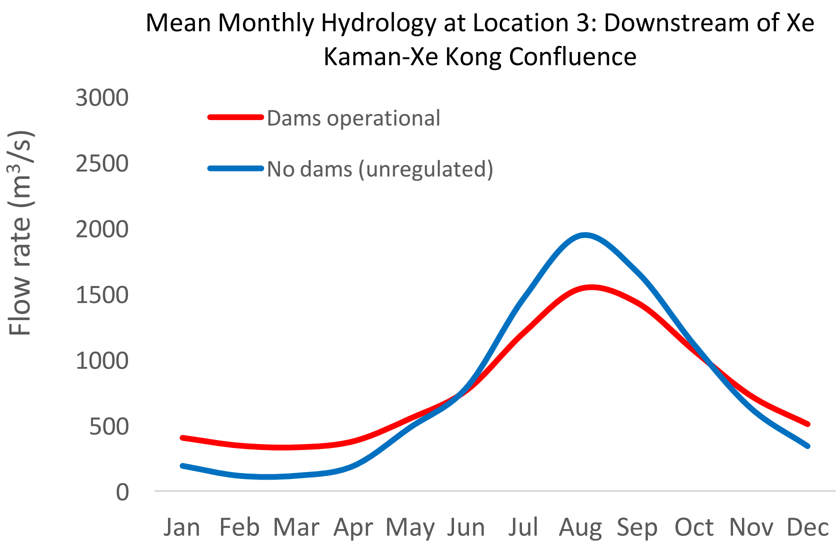

Figure 10-7. Alteration to the mean monthly hydrologic regime at Location 3 in Figure 10-4.

Location 4 (in Figure 10-4) was selected because it represents the first point at which the Xe Kong river reaches the Lao-Cambodia border. The hydrologic alteration at location 4, shown in Figure 10-8, is the result of upstream operation of all 24 existing and planned Xe Kong dams, and includes inflow from the Nam Kong tributary. These simulated results assume that Nam Kong 1 is operated as a seasonal storage reservoir.

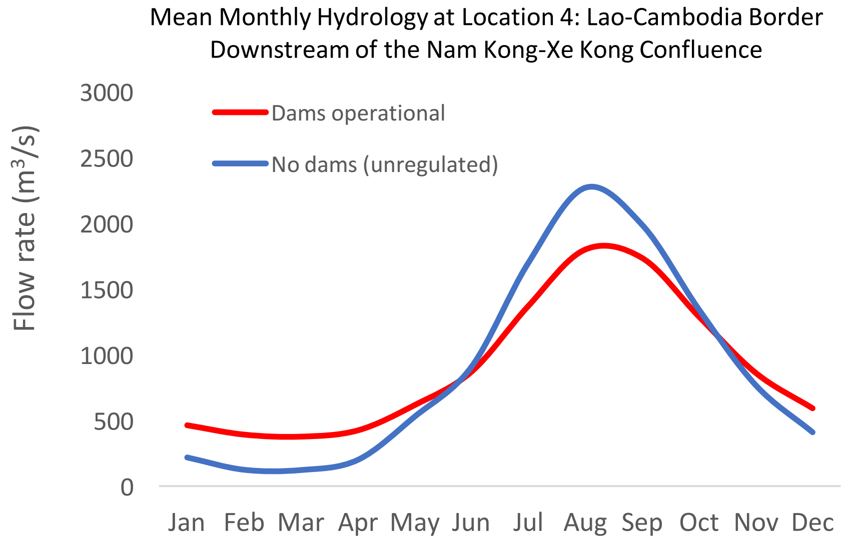

Figure 10-8. Alteration to the mean monthly hydrologic regime at Location 4 in Figure 10-4 (at the Lao-Cambodia border).

As shown in Figure 10-9, Location 5 (in Figure 10-4) was selected because it represents flow alteration at the Lao-Cambodia border with somewhat less hydrologic alteration than appears at Location 5, due to natural inflows from the Xepian-Houay Khampo tributary.

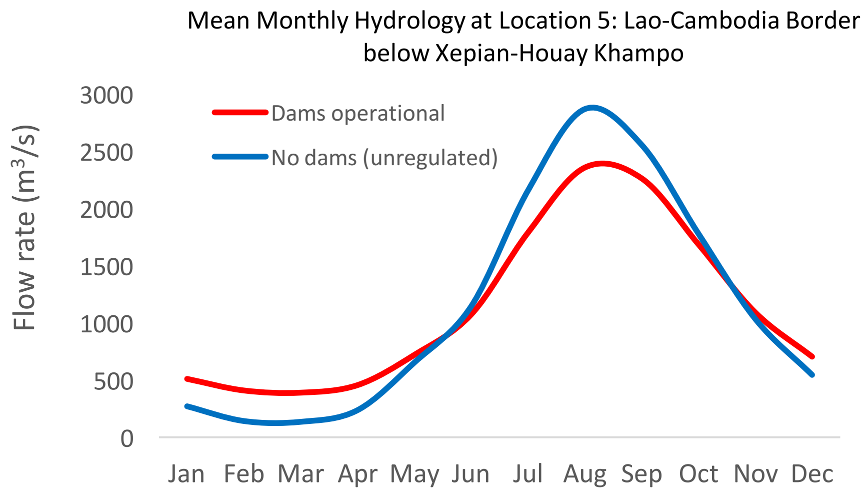

Figure 10-9. Alteration to the mean monthly hydrologic regime at Location 5 in Figure 10-4 (at the Lao-Cambodia border).

While Figures 10-5 to 10-9 capture the mean trend in the reservoir-induced seasonal redistribution of water flows, it is also important to evaluate daily changes in the river's natural hydrograph. Figures 10-10 to 10-14 show a representative year (2002) of daily flows for the five system locations of interest (in Figure 10-4). The hydrologic spates shown in the unregulated hydrographs in Figures 10-10 to 10-14 during the transition from the dry season to the wet season, which is known to serve multiple eco-hydrological purposes (e.g., triggering fish migration, inundating floodplain habitats, and transporting sediment), are significantly reduced in magnitude and variability in Figure 10-10 and Figure 10-11 as a result of operation of the Xe

Kaman 1 reservoir. The effect of seasonal operation of the large seasonal storage reservoirs Xe Kaman 1, Xe Kong 5 and Nam Kong 1 is significantly dampened by the time it reaches the Lao-Cambodia border (Figure 10-13 and Figure 10-14).

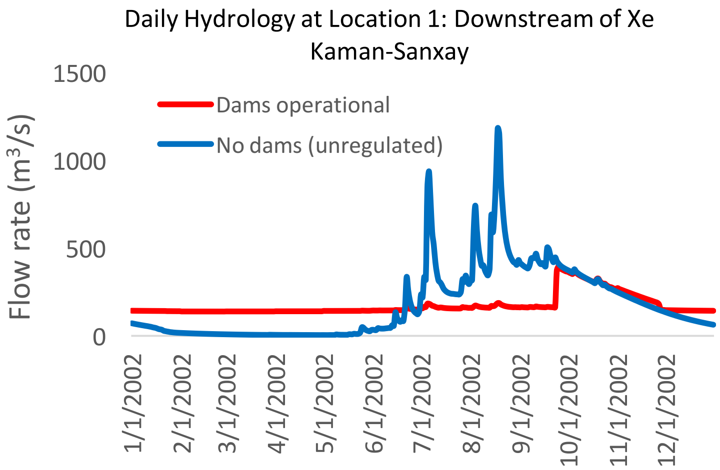

Figure 10-10. Alteration to the daily hydrograph during a representative year (2002) at Location 3 in Figure 10-4 (immediately downstream of Xe Kaman-Sanxay dam).

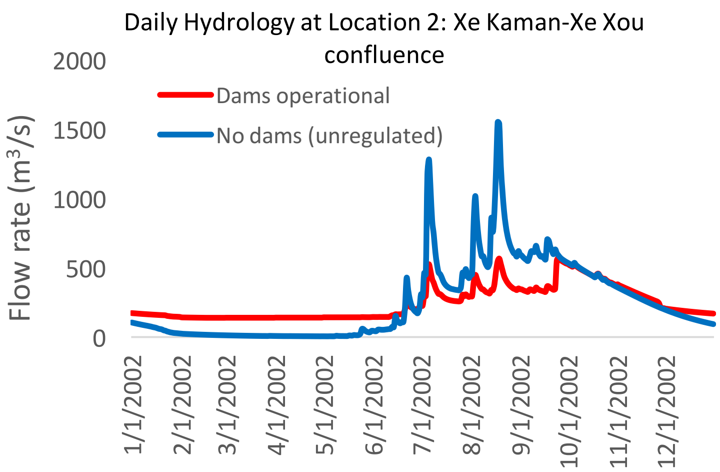

Figure 10-11. Alteration to the daily hydrograph during a representative year (2002) at Location 2 in Figure 10-4 (at the Xe Kaman-Xe Xou confluence).

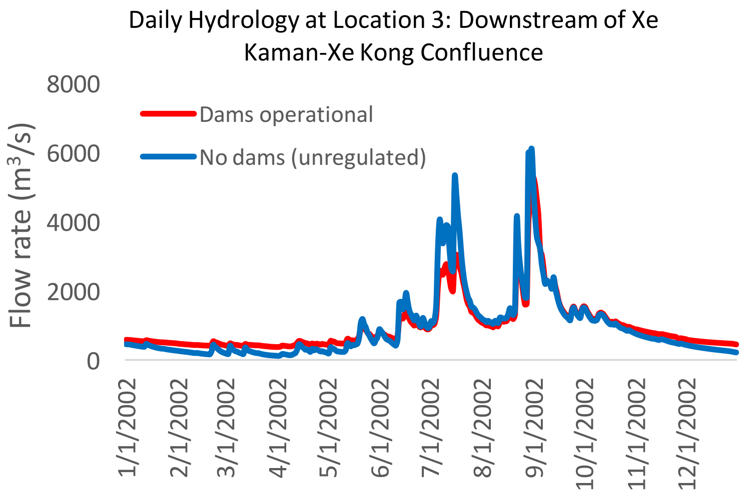

Figure 10-12. Alteration to the daily hydrograph during a representative year (2002) at Location 3 in Figure 10-4 (downstream of the Xe Kaman-Xe Kong confluence).

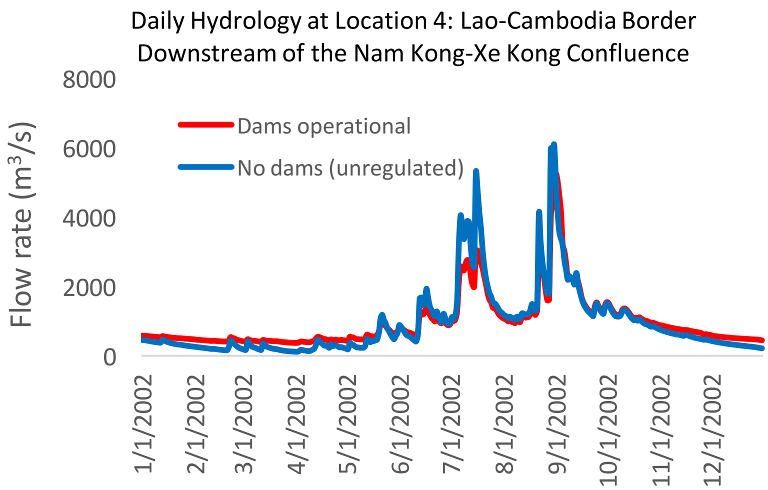

Figure 10-13. Alteration to the daily hydrograph during a representative year (2002) at Location 4 in Figure 10-4 (at the Lao-Cambodia border downstream of the Nam Kong-Xe Kong confluence).

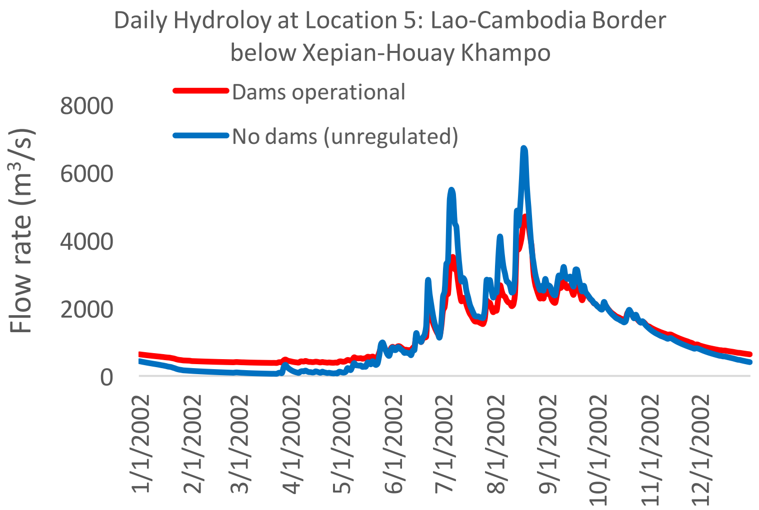

Figure 10-14. Alteration to the daily hydrograph during a representative year (2002) at Location 5 in Figure 10-4 (at the Lao-Cambodia below the confluence of the Xe Kong with the Xepian-Houay Khampo).

While Figures 10-5 to 10-14 capture the general trend in the reservoir-induced seasonal and daily redistribution of water flows, hydropower peaking operations, which are highlighted in this section's remaining figures, also have the potential to dramatically distort the river's natural hydrologic regime on a sub-daily (e.g., hourly) basis. The Xe Kaman 1 powerhouse has two Francis turbines, each with a rated flow of about 172 m^3/s. Figure 10-15 shows the number of hours the Xe Kaman 1 dam could theoretically operate at its rated powerhouse flow rate (344 m^3/s) throughout the year without deviating from the reservoir water level trajectory shown in Figure 10-1. The reservoir has the potential to maintain significant long-term firm energy output through seasonal reservoir variation, while also maintaining enough storage to release flow at 344 m^3/s for 8-14 hour per day on average. (Releases at design flow for longer durations of time are possible in the wet season due to higher inflows, while lower duration releases are possible in the dry season.)

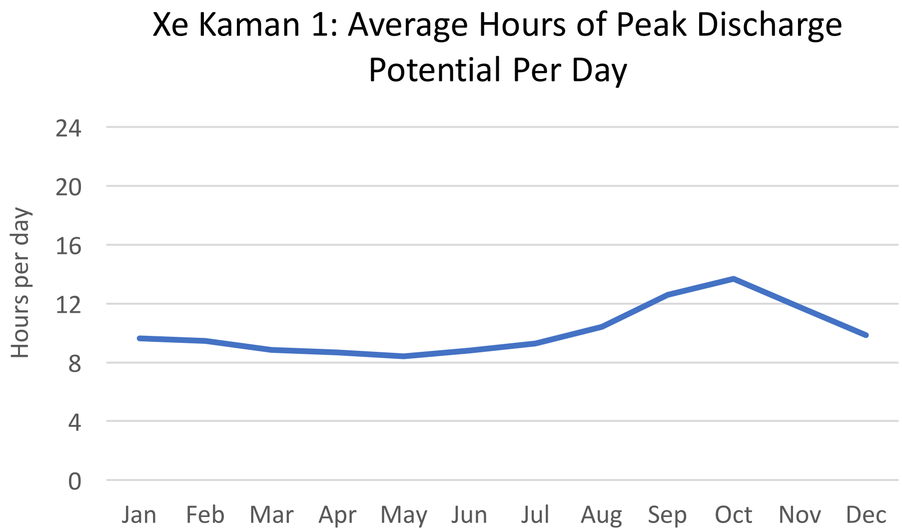

Figure 10-15. Mean monthly number of hours the Xe Kaman 1 reservoir could operate at rated flow (344 m3/s) without any long-term deviation from the seasonal storage operation trajectory shown in Figure 10-1 and Figure 10-3.

If water was indeed released from Xe Kaman 1 for 8-14 hours per day at design flow, Figure 10-16 shows (by plotting reservoir releases on an hourly basis throughout the year) that this would result in severe distortion of the river's natural flow regime. Figure 10-16 plots hourly inflows (blue line) in natural, unregulated conditions in 2002; as well as reservoir releases associated with those inflows, both with peaking operations (gray line) and without peaking operations. (Both the gray-colored and red-colored policies assume seasonal storage operations, but make different assumptions with respect to peaking). In the dry season, when peaking operations are implemented (gray line in Figure 10-16), periods of unnaturally high discharge are punctuated by periods of very low or zero discharge. In the wet season, the same rapid variation (i.e., ramping) in flow rates exists, though flows are consistently lower than the river's natural flows. The peaking conditions depicted in Figure 10-16 have been demonstrated to be ecologically problematic in numerous river basins globally (Belvheimer et al., 2015).

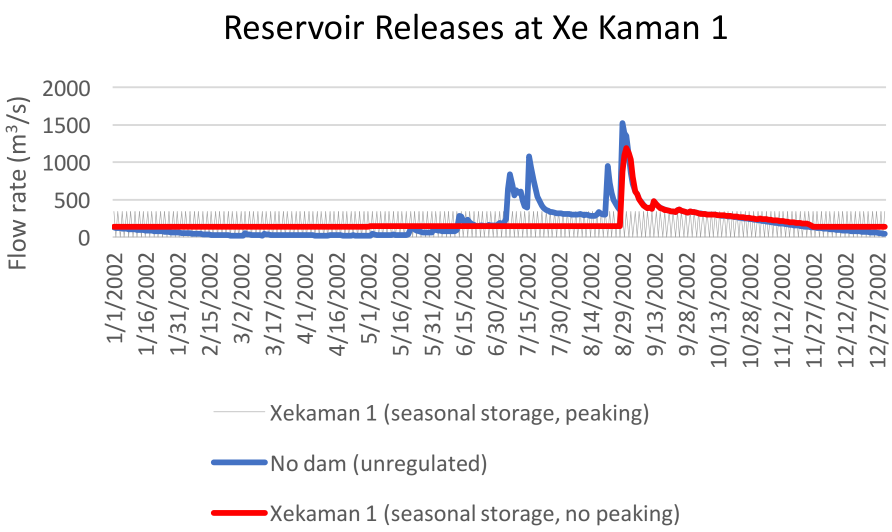

Figure 10-16. Simulated flow rate downstream of Xe Kaman 1 in natural conditions (i.e., no dam), and with and without hydro peaking taking place in the context of seasonal storage operations.

To further elucidate the hourly impacts of various forms of reservoir operation on the river's natural hydrology, Figure 10-17 isolates the simulated flows from Figure 10-16 for one particular successive dry season day (1/1/2002) at the Xe Kaman 1 reservoir. The reservoir operating policies reflected in Figure 10-17 are identical to those from Figure 10-16, except the x-axis of the figure extends over a much shorter (i.e., daily rather than annual) time scale, and an additional peaking policy is added (discussed below). Both simulated natural inflows and simulated reservoir releases are shown. (Importantly, note that the SedSim simulation model used to generate reservoir inflows operates on a daily basis. Thus, the hourly inflows in Figure 10-17 are interpolated. As the temporal scale of the x-axis in Figure 10-17 is only a few days, these interpolated hourly values appear nearly constant because there was very little difference in inflow from 1/1/2002 to 1/2/2002).

Figure 10-17 explores two peaking scenarios (whereas Figure 10-16 only explored one): (1) one turbine remains operational at all times, including during off-peak hours, to ensure the preservation of environmental flows downstream; and (2) release during off-peak hours is 0 m^3/s. In scenario 1, one turbine would operate at its minimum permissible flow rate so as to preserve water for release during peak hours. Data regarding the turbine's minimum flow rate are not currently available. Using data from existing turbines at operational dams as a proxy, scenario 1 assumes (as a lower threshold for purposes of demonstration) that this minimum flow rate is 70% of turbine rated flow, or about 120 m^3/s. (Note that operating at significantly lower than rated flow (i.e., 70%) would significantly reduce turbine efficiency). Scenario 1 enables full peaking to take place (i.e., both turbines operating at a combined design flow 344 m^3/s) for only 3 hours during the simulated day in Figure 10-16. Conversely, Scenario 2 enables full peaking for 10 hours. While the Scenario 2 policy may be beneficial from the standpoint of feeding the EVN energy demand curve, it clearly poses a potential threat to downstream ecological habitats. Conversely, Scenario 1 would significantly limit peaking duration potential, but would beneficially enable releases downstream that are more consistent with natural dry season flows.

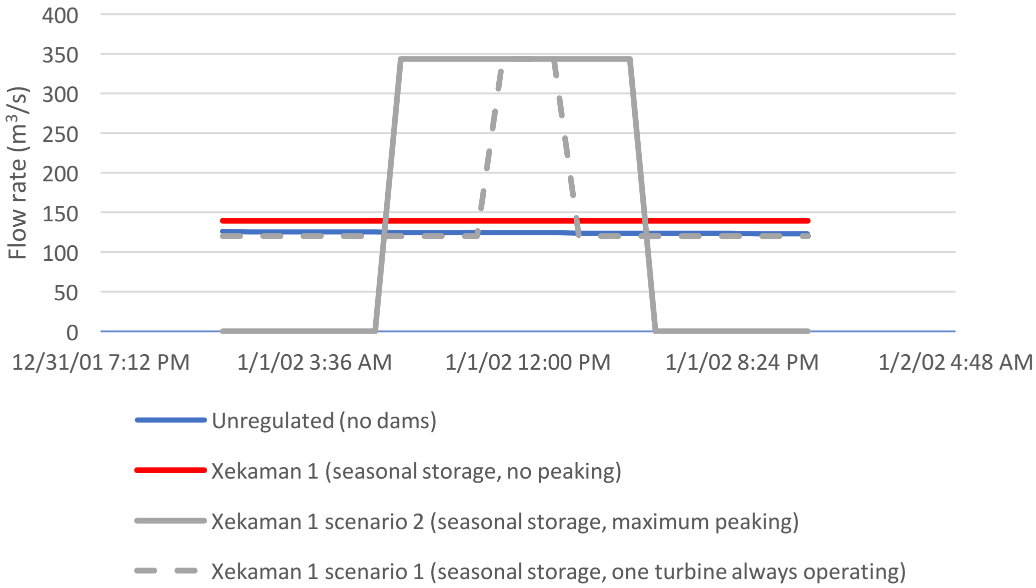

Figure 10-17. Simulated flow rate downstream of Xe Kaman 1 in natural conditions (i.e., no dam) during a 24-hour period on 1/1/2002 (blue line), and simulated hourly reservoir release with (red line) and without (gray lines) hydro peaking taking place in the context of seasonal storage operations. Two policies are shown in gray to demonstrate that different durations and magnitudes of flow releases during peaking hours are possible, depending upon the magnitude of flow being released during off-peak hours.

Conclusion

This section began by evaluating the potential for planned mainstream Xe Kong dams (and existing Xe Kong tributary dams) to alter the Xe Kong basin's natural hydrologic patterns, which are important for maintaining the suitability of conditions for fish migration and spawning, and sediment transport. Simulation results demonstrate that the potential for hydrologic alteration at monthly, daily and sub-daily (e.g., hourly) time scales is not particularly dramatic. (Importantly, the same is not true of sediment transport, which is addressed in a previous Section of this report). This occurs because, of the seven mainstream Xe Kong dams, only Xe Kong 5 (the basin's largest planned dam) is large enough to be operated as a seasonal storage facility. However, Xe Kong 5 does not store a significant fraction of the basin's flow given its location in a headwater reach, hydrologic alteration by this large dam is limited.

Hydrologic alteration from the simulated Xe Kong dams is likely to be dampened by the time the flows reach the Lao-Cambodia border. However, while effects far downstream (e.g., at the Lao-Cambodia border) may be limited, there are still critical spawning and migratory habitats within Lao in the Xe Kong basin that could be affected by local hydropower operations at seasonal, daily and sub-daily time scales. Indeed, a key result from this section is that large Xe Kong storage reservoirs that are positioned such that they control large quantities of water, and are near important ecological areas, have the potential to create strong seasonal, daily and sub-daily (e.g., hourly) alteration of the natural hydrologic conditions that are important for maintaining the suitability of conditions for fish migration and spawning, and sediment transport. As one example, discussion focused largely on the operational Xe Kaman 1 dam. At Xe Kaman 1, peaking is especially potentially ecologically problematic locally, resulting in ramping up and down of reservoir releases and corresponding impacts to local habitats. To reduce this impact would require first establishing clear ecological flow targets, and ultimately might require reduced peaking operations.

Future work should include an assessment of the tolerance thresholds for hydrologic alteration of the downstream fisheries. Operational protocols should be developed for those dams that would avoid exceeding those thresholds and assure flow conditions that enable the migratory fish to access and use the prime spawning and rearing habitats and that protect the resident fishery. On this basis, environmental flow prescriptions need to be developed for the reaches below these dams to the extent necessary. The analysis that must be conducted to determine operational parameters is often referred to as "environmental flow requirements". The desired pattern will resemble the natural flow regime in terms of timing, duration and magnitude of high and low flows as closely as possible.

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