**VOLUME 2**
**Sambor Dam Alternatives**

# SAMBOR HYDROPOWER DAM ALTERNATIVES ASSESSMENT

## FINAL REPORT

**[INCLUDES COMPARISON OF <u>DAM</u> AND "<u>NO-DAM</u>" ALTERNATIVES]**

**A component of**
***Hydropower Development Alternatives for the Mekong Basin: Maintaining the Flows that Nourish Life***

*Submitted to*
Royal Government of Cambodia

*Submitted by*
Natural Heritage Institute, San Francisco, California

**December 2017**

Photos by Gregory A. Thomas, NHI

# Sambor Hydropower Dam Alternatives Assessment

Final Report


## Principal Authors:

Mr Gregory Thomas, Project Director

Dr George Annandale, Engineering and Sediment Management

Dr Isabel Beasley, Dolphin Biology and Conservation

Dr Monika Bieri, Solar Energy Research Institute of Singapore (SERIS)

Mr John Irving, Power and Energy Engineer

Mr Erland Jensen, Informatics

Dr Martin Mallen-Cooper, Freshwater Fish Ecology and Fish Passage

Dr Peter Meier, Hydropower Economics

Dr Thomas Reindl, SERIS

Mr Gerry Ryan, Dolphin Biology and Conservation

Dr Thomas Wild, Hydrology and Systems Analysis

Dr Yanqin Zhan, SERIS

Dr Lu Zhao, SERIS

## With Contributions from:

Prof Lee Baumgartner, Freshwater Fish Ecology

Prof Ian Cowx, Fish Ecology and Fisheries Resource Management

Dr Ashley Halls, Fish Population Modelling

Dr Mathias Kondolf, Fluvial Geomorphology

Dr Daniel Peter Loucks, Hydrology and Environmental Engineering

Ms Jessica Peyla Nagtalon, Project Coordinator

Dr Wayne Robinson, Wildlife Ecology, Statistics

Dr Zan Rubin, Fluvial Geomorphology



## Supported with Funding from:

The United States Agency for International Development

The MacArthur Foundation

The Margaret A. Cargill Foundation

# ACKNOWLEDGEMENTS

This report documents the findings and conclusions of five years of work by the Natural Heritage Institute (NHI), and its team of technical experts with the Royal Government of Cambodia (RGC), under an official agreement with the the Ministry of Mines and Energy (MME) (Memorandum of Understanding signed on October 20, 2014), and in consultation with the Ministry of Water Resources and Meteorology (MOWRAM), the Ministry of Environment (MoE), the Ministry of Industry and Handicrafts (MIH), and the Inland Fisheries Research and Development Institute (IFREDI) of the Ministry of Agriculture and Forestry. NHI is grateful for the leadership of the Minister of the MME and his commitment to this project, which strives to illuminate power development options for the RGC that will maintain the rich and irreplaceable biodiversity of the Mekong River and the benefits it provides to the citizens of Cambodia and the greater Mekong Region. NHI also wishes to acknowledge all the team members and the government partners for their peerless expertise and unflagging dedication. Many others provided inspiration, insight and peer review of the results of this project. The Mekong River Commission and other organizations in the Mekong Basin also generously provided access to data and/or outputs from their complementary projects.

Gregory A. Thomas, the Executive Director of the Natural Heritage Institute led this project. The project is indebted to Jessica Peyla Nagtalon of NHI for her attention to detail in editing and formatting of this report; to Ly Nguyen Degai for administration of the project; and to Fe Hernandez for project financial management.

Finally, none of this would have been possible if not for the generous support of the American people through the United States Agency for International Development (USAID), and by the MacArthur Foundation and the Margaret A. Cargill Foundation. The contents of this report are the responsibility of NHI under Cooperative Agreement No. AID-486-A-11_00002 and do not necessarily reflect the views of USAID, the United States Government or the other funders.

USAID FROM THE AMERICAN PEOPLE

MacArthur Foundation

# Table of Contents – Volume 2

## List of Figures – Volume 2

## List of Tables – Volume 2

## List of Text Boxes – Volume 2

## List of Acronyms and Abbreviations

| | |
|---|---|
| 3S | 3S System (Se San, Srepok and Sekong Rivers) |
| AC | Alternative Current |
| ACSR/AC | Aluminum Conductor Aluminum Clad Steel Reinforcement |
| ACSR | Aluminum Conductor Steel Reinforcement |
| ADB | Asian Development Bank |
| ADCP | Acoustic Doppler Current Profiler |
| Alt-6 | Sambor Alternative 6 with the dam in the anabranch |
| Alt-7 | Refers generically to all of the Sambor alternatives with the dam in the main channel |
| Alt_7-A | Sambor Alternative 7 (dam in the main channel) with maximum upstream and standard downstream mitigation |
| Alt_7-B | Sambor Alternative 7 (dam in the main channel) with maximum upstream and standard downstream mitigation + low-impact (fish friendly) turbines |
| Alt_7-C | Sambor Alternative 7 (dam in the main channel) with maximum upstream and standard downstream mitigation + screens |
| Alt_7-D | Sambor Alternative 7 (dam in the main channel) with maximum upstream and maximum downstream mitigation (screens and low-impact, fish friendly turbines) |
| AWS | Automatic Weather Stations |
| BDP | The MRC Assessment of Basin-wide Development Scenarios |
| b | Billion (USD) |
| BTU | British Thermal Unit |
| CBA | Cost-Benefit Analysis |
| CCGT | Combined Cycle Gas Turbine |
| CDF | Cumulative Distribution Function |
| CFD (FEA) | Computational Fluid Dynamic (CFD) analysis, subset of Finite Element Analysis (FEA) |
| cm | Centimeters |
| CSP | China Southern Power (Grid Company) |
| CSP FS | China Southern Power Feasibility Study (for Sambor) |
| Cumec | cubic meters per second |
| DC | Direct Current |
| EdC/EDC | Electricite Du Cambodge (Electricity of Cambodia) |
| EDL | Electricity of Laos |
| EGAT | Electricity and Gas Authority of Thailand |
| EOCK | Economic opportunity cost of capital |
| EPBC Act | The Environmental Protection and Biodiversity Conservation Act 1999 |
| EPRI | Electric Power Research Institute (of the US) |
| ERR | Economic Rate of Return |
| EU | European Union |
| EVN | Electricity of Vietnam |
| FACTS | Flexible Alternating Current Transmission System |
| fob | free on board |
| FOREX | Foreign exchange |
| FS | Feasibility Study |
| FSRU | Floating Storage and Regasification Unit (LNG) |

| | |
|---|---|
| FTCC | Floating Tracking Cooling Concentrator |
| GDP | Gross Domestic Product |
| GHG | Green House Gas (Emissions) |
| Gms | grams |
| GMS5 | satellites |
| GOES9 | satellites |
| GWh | Gigawatt hours |
| HDPE | High-density polyethylene |
| HHV | Higher Heating Value (of a thermal fuel) |
| HPLS2Co | Hydro Power Lower Sesan 2 Company, Ltd. |
| HSRS | Hydrosuction Sediment Removal System |
| HVAC | High Voltage Alternating Current (power transmission) |
| HVDC | High Voltage Direct Current (power transmission) |
| ICOLD | International Commission on Large Dams |
| IDC | Interest During Construction |
| IEEE | Institute of Electrical and Electronics Engineers |
| IFC | International Finance Corporation |
| IFI | International Financial Institution (e.g. World Bank, ADB) |
| INDC | Intended Nationally Determined Contribution |
| IP 65 or 67 | International Protection Marking |
| IPP | Independent Power Producer |
| IPCC | Intergovernmental Panel on Climate Change |
| IRR | Internal Rate of Return |
| ISO | International Standards Organization |
| JCC | Japan Crude Cocktail (weighted average of crude imports to Japan) |
| JICA | Japan International Cooperation Agency |
| JMA | Japan Meteorological Agency |
| JNCC | Joint Nature Conservation Committee |
| K | Kelvin |
| k | Kilo |
| kg | kilograms |
| km | kilometers |
| kV | kilo Volt |
| Kw | Kilo watt |
| KWh | Kilo Watt hours |
| LCoE | Levelised Cost of Electricity |
| LHV | Lower Heating Value (of a thermal fuel) |
| LLW | Lowest Low Water (level) |
| LMB | Lower Mekong Basin |
| LMS | Lower Mekong System |
| LNG | Liquefied Natural Gas |
| LNG-CCGT | LNG fueled Combined Cycle Gas Turbine |
| LSS2 | Lower Se San 2 (hydropower project) |
| LTCR | Long Term Capacity Ratio |
| LV/MV | Lower Voltage/Medium Voltage |

| | |
|---|---|
| $m^3$ | Cubic meters |
| $Mm^3$ | Million cubic meter |
| $m\ s^{-1}$ | meters per second |
| MAFF | Ministry of Agriculture, Forestry and Fisheries (of Cambodia) |
| Masl | Meters above sea level (Ha Tien tide gauge if not otherwise noted) |
| MBC | Mekong Basin Commission |
| MBTF | Mean time between failures |
| MDS | Mekong Delta Study |
| Meteonorm | Meteonorm is a unique combination of reliable data sources and sophisticated calculations tools. |
| MIGA | Multilateral Investment Guarantee Agency |
| MGR | Minimum Gap Runner (turbine design) |
| mmBTU | million British Thermal Units |
| MME | Ministry of Mines and Energy |
| MMHSEA | Strategic Environmental Assessment of Mekong Mainstream Hydropower |
| MMS | Middle Mekong System |
| mm/yr | millimetres per year |
| MOEA | Multi-Objective Evolutionary optimization Algorithm |
| MONRE | Ministry of Natural Resources and Environment (Vietnam) |
| MoU | Memorandum of Understanding |
| MoWRaM | Ministry of Water Resources and Meteorology |
| MRC | Mekong River Commission |
| MRCS | Mekong River Commission Secretariat |
| MSY | Maximum Sustainable Yield (of a fishery) |
| Mt/yr | Million tons per year |
| MTSAT-1R | satellites |
| MUV | Manufactured Unit Value (index published by World Bank) |
| MVA | Mega Volt Ampere |
| MW | Mega Watts |
| MWac | MW alternating current |
| MWh | Mega Watt hours |
| MWp | Mega Watt peak |
| NASA | National Aeronautics and Space Administration |
| NGO | Non-Governmental Organisation |
| NHI | Natural Heritage Institute |
| NMFS | National Marine Fisheries Service (Western Pacific States) |
| NPP | North Phnom Penh |
| NPV | Net Present Value |
| NREM | Natural Resources and Environmental Management Research and Training Centre (of Mah Fah Luang University, Thailand) |
| NT2 | Nam Theun 2 Hydropower Project (in Lao PDR) |
| OAAs | Other Aquatic Animals |
| ODC | Open Development Cambodia |
| O&M | Operation and Management (cost of a power station) |
| PBR | Potential Biological Removal |

| | |
|---|---|
| PDP | Power Development Plan (of Vietnam) |
| PDP7 | 7th Power Development Plan (Vietnam) |
| PECC1 | Power Engineering Consulting Joint Stock Company 1 (of Vietnam) |
| PDR | People's Democratic Republic (of Laos) |
| PNNL | Pacific Northwest National Laboratory |
| PPA | Power Purchase Agreement |
| PPP | Public-Private Partnership |
| PR | Performance Ratio |
| PRG | Partial Risk Guarantee (of the World Bank) |
| PSS or PSS/E | Power Transmission System Planning Software |
| PV | Present Value |
| Solar PV | Photovoltaic |
| PVNEB | Present Value of Net Economic Benefit |
| RESCON | Reservoir Conservation Model |
| R&R | Resettlement and Relocation (of persons at a reservoir) |
| RGC | Royal Government of Cambodia |
| SBR | Sediment Balance Ratio |
| SERIS | Solar Energy Research Institute of Singapore |
| Solar GIS | Accurate and efficient solar energy assessment software |
| SPV | Special Purpose Vehicle (company established for implementing a project) |
| SVC | Social Value of Carbon |
| TVA | Tennessee Valley Authority |
| UMS | Upper Mekong System |
| UNFCCC | United Nations Framework Convention in Climate Change |
| US | United States |
| $US | United States Dollar |
| USAID | United States Agency for International Development |
| USc | US cent |
| USGS | United States Geological Survey |
| $USm | Million US dollars |
| UV | Ultra Violet |
| VND | Vietnamese Dong |
| VRE | Variable Renewable Energy (solar PV, wind) |
| W | Watt |
| WCD | World Commission on Dams |
| $W/m^{-3}$ | Watts per cubic metre |
| $y^{-1}$ | Per year |

# 1 PROCEDURAL HISTORY OF THE PROJECT

## Description of the Basin-Wide Program and How the Sambor Alternatives Assessment Fits Within It

This report presents the final results of an assessment of alternatives to a Sambor hydropower project as originally proposed by the China Southern Power Grid Company (CSP) for construction in the reach of the mainstream Mekong River near the village of Sambor in the Kingdom of Cambodia.[1] The Interim Report presented an analysis of the best-performing alternative out of ten options that were assessed in terms of meeting the set of environmental performance criteria that were established at the inception of the project to maintain the natural processes of the Mekong River that support its exceptional ecological productivity and diversity. This Final Report on the Assessment of Sambor Dam Alternatives includes a comparative assessment of a "no-dam" alternative that would have *no* adverse impacts on the Mekong fishery at all. It is comprised of a hybrid hydropower/solar photovoltaic facility at the Lower Se San 2 dam site. This final report will be presented to the Royal Government of Cambodia (RGC) by the end of the year, 2017.

A feasibility study for a Sambor Hydropower Project was first presented to the Royal Government of Cambodia by CSP in 1994. As originally conceived, this would be the largest hydropower dam, and the furthest downstream, among all existing and proposed dams in the Lower Mekong Basin[2] (LMB), including the cascade of large dams now completed in the headwaters within Yunnan Province in China, known as the Lancang River, and the Xayaburi and Don Sahong dams in the Lao portion of the basin. As proposed by CSP in 2008, the dam would be 33m high from the storage to the tailwater levels and an astonishing 18km wide, with a rated head of 23m and rated capacity of 2600 MW. It would create a reservoir some 82km long, backing water up to the town of Stung Treng at the confluence of the 3S (Se San, Srepok and Sekong Rivers) basin, with a surface area of 620 km$^2$ surface area. At this scale, it would be roughly twice the capacity of the largest dam now under construction in the LMB, the Xayaburi project on the mainstream Mekong within Lao PDR.

As described at length in this report, the Sambor reach of the Mekong is the corridor that experiences the largest annual migration of fish biomass on the planet. Consequently, a large-scale dam and impoundment at this site would obstruct this migration, which is vital for the completion of the life cycles of the migratory fish that characterize the most productive freshwater fishery in the world. It would also capture most of the sediments and nutrients that maintain and replenish the morphology of the Mekong Delta and nourish the food web for the fishery.

The objective of this study is to identify and assess the feasibility of alternative sites, designs and operations of a hydropower project in the Sambor reach that could achieve the power development goals of the Royal Government of Cambodia while minimizing the adverse impacts on the natural processes that sustain this highly productive river system. This work is a component of a Mekong basin-wide program conducted by a team of international experts under the leadership of the Natural Heritage Institute (NHI), and working directly with the national governments and

[1] Sambor has long appeared as one of the locations for a hydro project on the Mekong mainstream, and in previous years the site has been proposed for the development of as much as 3,300 MW, and most recently for a development of 2,600 MW as proposed in the *Feasibility Study Report of Sambor Hydropower Station*, China Southern Power Grid Co. (CSP) & Guangxi Electric Power Industry Investigation Design and Research Institute, October 2008.

[2] Comprised of the Lao PDR, Thailand, Cambodia and Vietnam portions of the basin.

hydropower developers, with the objective of transforming the course of development of the basin in a more sustainable direction. This work is a once and only opportunity to secure a durable future for one of the most important natural systems on the planet.

## Relationship to Royal Government of Cambodia—Content and Purpose of MoU

The Sambor Alternatives Assessment has been conducted under an official agreement with the RGC in the form of a Memorandum of Understanding executed by the Minister of Mines and Energy on October 20, 2014. This created a unique relationship as the first and only time that the RGC has entered into such an MoU with an international non-governmental organization (see description of NHI below). Under the terms of the MoU, NHI was charged to "formulate the specific siting design and operational alternatives that appear to be most promising for improved sediment, nutrient and fish passage at Sambor Hydropower Dam". The MoU also charged NHI to assess the feasibility of a "No-Dam" alternative. A modification of the MoU on December 22, 2016 extends the timeline to December 31, 2017 and "authorizes NHI to assess the technical and economic feasibility of such solar power alternatives as may be comparable or superior to all of the Sambor Hydropower Dam alternatives with respect to power output, cost, reliability, avoidance of financial risks, and environmental performance". NHI is instructed to compare the dam and "no-dam" alternatives and report the results to the Minister of Mines and Energy by the end of the extension period. The comparative results are reported in this **Final Sambor Hydropower Dam Alternatives Assessment.**

## Description of NHI and the Project Team

The Natural Heritage Institute (NHI: www.n-h-i.org) is an international non-governmental organization, founded in 1989, with its headquarters in the United States of America. NHI's 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 transbasin systems.

To satisfy the need for a high-level of specialized, technical expertise for the Sambor Alternatives Assessment, NHI assembled an international team of distinguished experts with a remarkable depth of experience covering the full range of disciplines needed. The main partner for the solar power alternative is the Solar Energy Research Institute of Singapore, which is a technical research facility of the National University of Singapore. Technical inputs were also provided by the Cambodian Ministry of Mines and Energy, Ministry of Environment, Ministry of Water Resources and Meteorology, Inland Fisheries Research and Development Institute, Tonle Sap Authority, Cambodia National Mekong Committee, Mekong River Commission as a "cooperating agency", the World Fish Center, and many other centers of expertise both within and beyond the basin. The NHI team of experts working on the project are listed in Appendix 1.

As charged by the MoU, the NHI team investigated some 10 alternatives for siting, designing and operating a hydropower dam in the Sambor reach of the mainstream Mekong River. In this report, we describe the best performing options from the standpoint of the environmental objectives that were established for the assessment. Before explicating these alternatives, it is important to interject that NHI is not a proponent of these or any hydropower schemes, although the findings from the assessments lead to a conclusion that the solar augmentation of existing hydropower at Lower Se San 2 provides far better results for the environmental performance objectives that were established for this comparative assessment. As noted, NHI is an environmental conservation organization whose mission is to build the knowledge base for meeting river basin infrastructure objectives of national governments and the private sector in ways that maintain the natural functions of the developed river systems. For the RGC, NHI's goal is simply to assure that the full range of options are illuminated before irreversible decisions are made that would impair the world's most productive freshwater fishery.

# 2 Biophysical Setting

## Hydrology

The Mekong River is typical of tropical rivers in that its flow is seasonal, with a monsoon-driven high flow period from July to October that produces 75% of the annual flow (Piman *et al*., 2013). Only about 7% of the annual flow comes from glacial melt, the rest from rainfall. The flood regime makes the seasonal flow patterns highly variable. The differential between the high flows and the low flow is around a factor of 20 (Gupta *et al*., 2002; Adamson *et al*., 2009), making the Mekong among the most variable large systems in the world. During the peak of the monsoon, the river causes the runoff to spread out over the landscape to inundate an area equivalent to the area of Ireland. It is the dynamic interaction of the river with its landscape that supplies the nutrients that makes the river so exceptionally productive (e.g. Baran *et al*., 2015; MRC, 2005).

The reason for this is easy to see from the vertical profile of the river (Figure 2-1) as it traverses its course from the headwaters in the Tibetan plateau, through the six basin countries, to its discharge in the South China Sea.

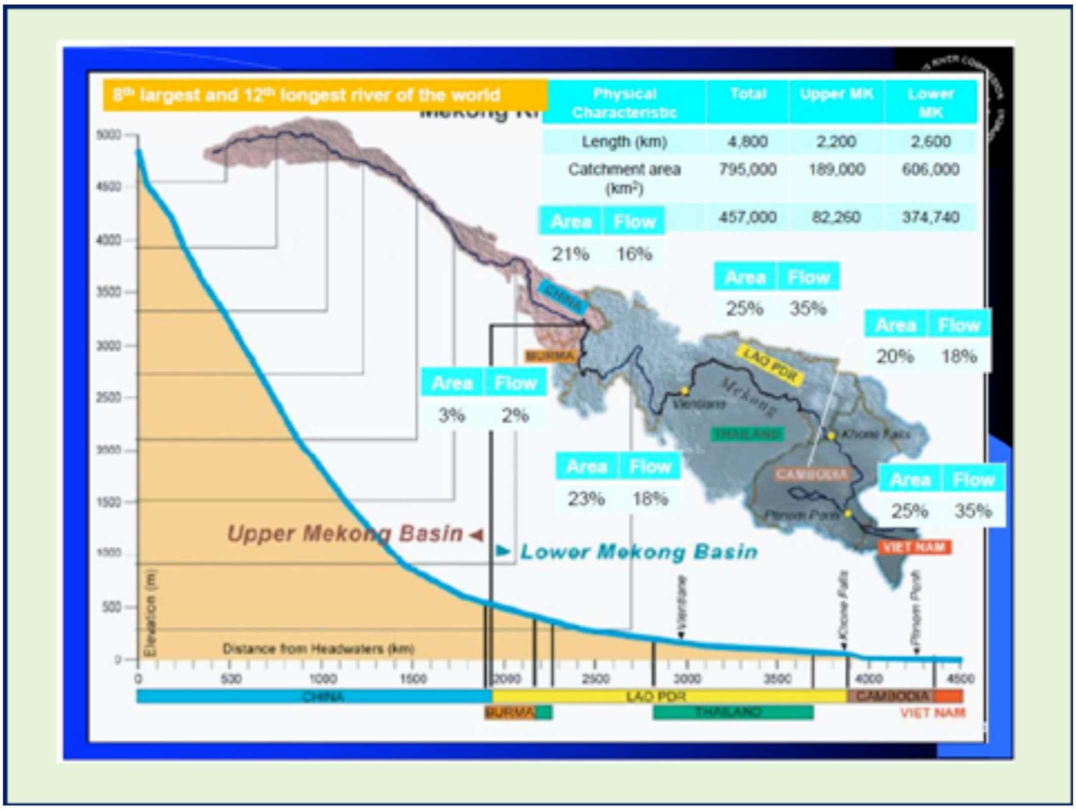



*Figure 2-1. Longitudinal profile of the Mekong River. Adapted from MRC, 2005.*

Eighty-five percent of the vertical descent occurs in the Lancang headwaters on China. By the time the river reaches Laos, its gradient is much lower for the 60% of its remaining journey to the South China Sea. The Sambor site is broad and flat, meaning that a large -scale dam would have to be very wide to create an impoundment with sufficient hydraulic head to generate sufficient power, and that impoundment would be very wide and long. Such is the situation with the original Sambor Dam proposal, as we shall see.

The hydrology experienced at the Sambor site is most accurately characterized by daily flow data from the Stung Treng gauging station above the site (Table 2-1). The flows at Stung Treng for the period between 1910 and 2016 are depicted in Figure 2-2 and Figure 2-3, demonstrating that there is significant inter- and intra-annual variability in the hydrologic record at Stung Treng.

*Table 2-1. Gauging stations.*

| Station Name | ID | Latitude | Longitude |
|---|---|---|---|
| Stung Treng | 014501 | 13.522047N | 105.933548W |

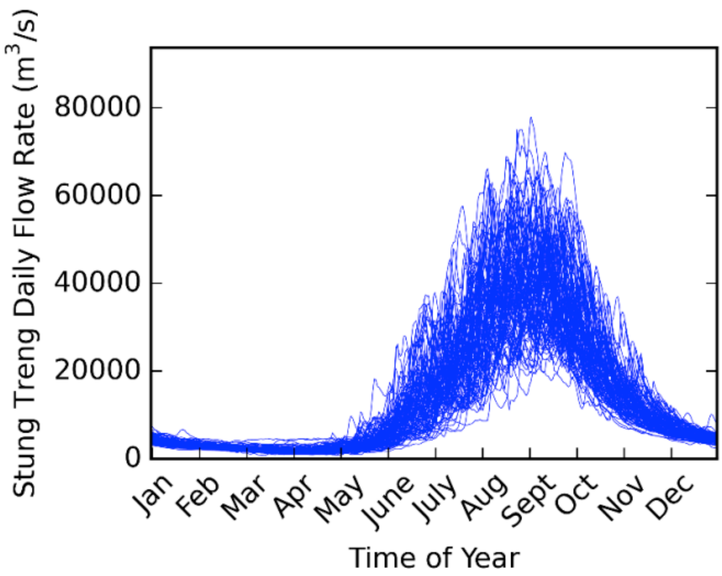



*Figure 2-2. Hydrograph for the Mekong River at Stung Treng (gauge station 014501) for the historical hydrologic record from 1910-2016. Each year from the historical record is plotted as a different line.*

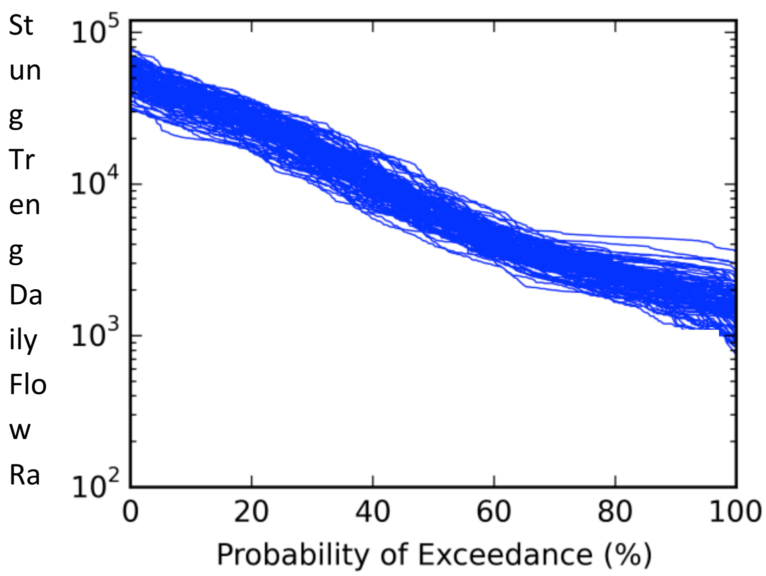



*Figure 2-3. Annual flow duration curves for the Mekong River at Stung Treng (gauge station 014501). Each year from the historical record is again plotted as a different line, with daily flow values on the y-axis on a logarithmic scale, and exceedance probability plotted on the x-axis. Both figures serve to demonstrate that there is significant inter- and intra-annual variability in the hydrologic record at the site.*

## Flood Frequency Analysis

Daily flow data from Stung Treng gauging station between 1924 and 2002 were used to conduct a flood frequency analysis (Figure 2-4). The flood frequency analysis results are shown Table 2-2. Multiple alternative flood frequency estimation methods were applied to estimate the magnitude of flood events for different return periods. These include the Extreme-Value Type 3 (EV3), Log-Pearson Type 3 (LP3(moment)), Weibull and three parameter Log-Normal (3P(MLH)). The 1:1,000-year flood was used to design the spillway (see Chapter 6).

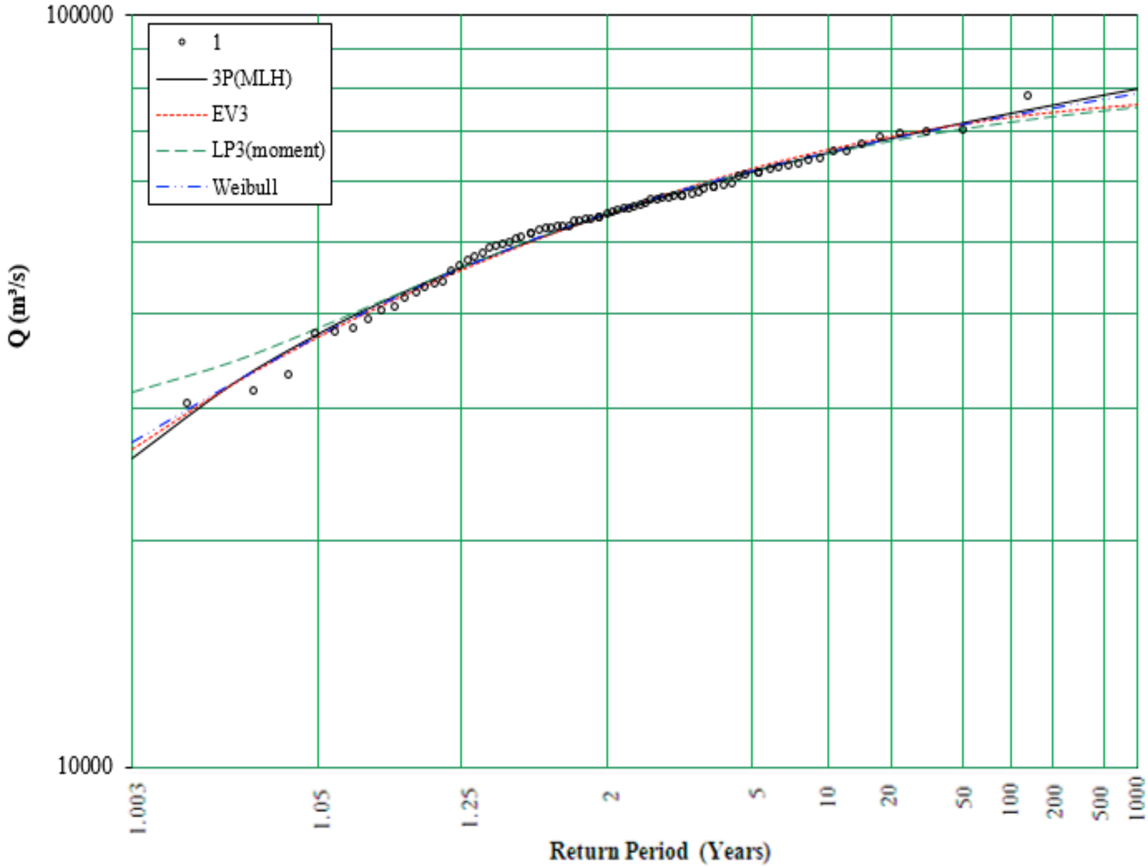



*Figure 2-4. Flood frequency analysis result for data from Stung Treng 014501. The 1:10,000-year flood was used to design the spillway. Multiple alternative flood frequency estimation techniques are shown.*

*Table 2-2. Design discharges determined using data at Stung Treng gauging station 014501.*

| Flood Frequency | Discharge (m3/s) | Comment |
|---|---|---|
| 100-year | 73,448 | |
| 1,000-year | 78,550 | |
| 10,000-year | 88,300 | Not determined by Frequency analysis in this study. Adopted from CSP (2008) |

## Discharge and Water Level

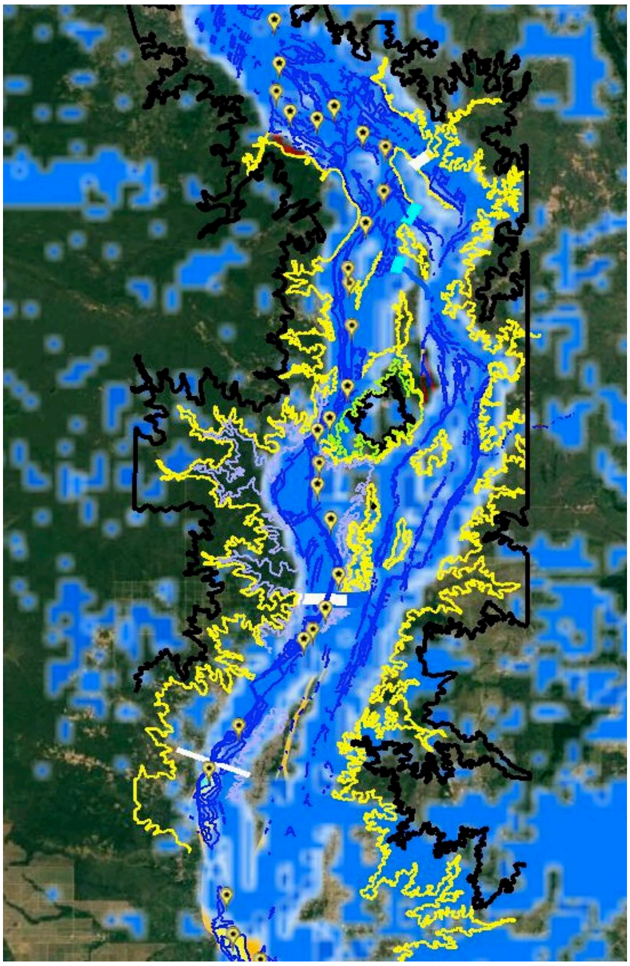


*Figure 2-5. Maximum extent of flooding during 2005-2008, derived from RADARSAT images.*

The annual water cycles followed the long-term average from 1924-2008 where a new cycle emerged. The dry season water level increased and the wet season water level decreased compared to the long-term average. The rising and falling limbs of the seasonal hydrograph were also delayed on average by 9 and 16 days (Figure 2-6). The new cycle was due to the constructed hydropower dams on the Lancang River in the Mekong headwaters reach in China.

The second-largest of those dams, Xiaowan, started filling in December 2008 and was commissioned in 2010 and the largest, the Nouzhadu dam, started filling in 2011 and was commissioned in 2015. Together all the hydropower dams on the Lancang River have a total storage around 45 $km^3$ of water. The altered cycle emerged as the result of filling and operation of these dams. This was especially visible in year 2014 (see Figure 2-6).

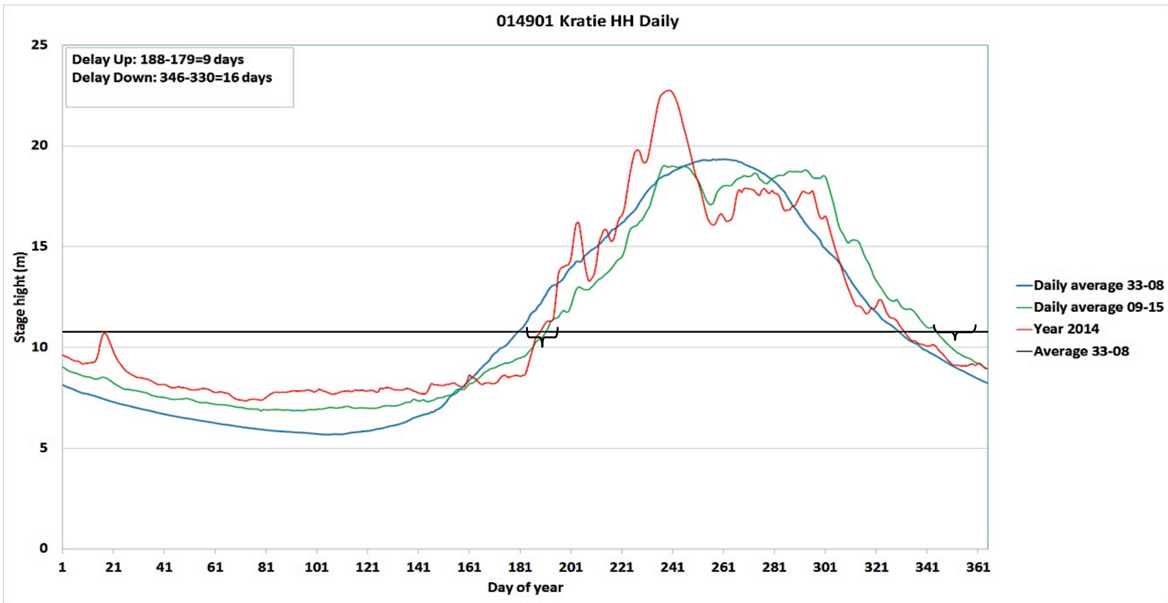



*Figure 2-6. Plot of mean daily stage for the Mekong River at Kratie (gauge 014901), period of record 1933-2015. 2014 hydrograph shown in red. Averages for each day of the calendar year from 1933-2008 shown in blue, from 2009-2015 shown in green. Black line indicates annual average stage defining the ascending start and descending end of the flooding season for reference. Black brackets show the delays of ascending and descending stages (start and end of the flood season) of 9 and 16 days.*

The differences in water level before and after 2009 are not related to differences in precipitation during the 2009-14 period (Figure 2-7). However, in 2011 and 2014, the monsoon started late and ended early (Figure 2-8). These unusually short monsoon seasons may have been related to climate changes.

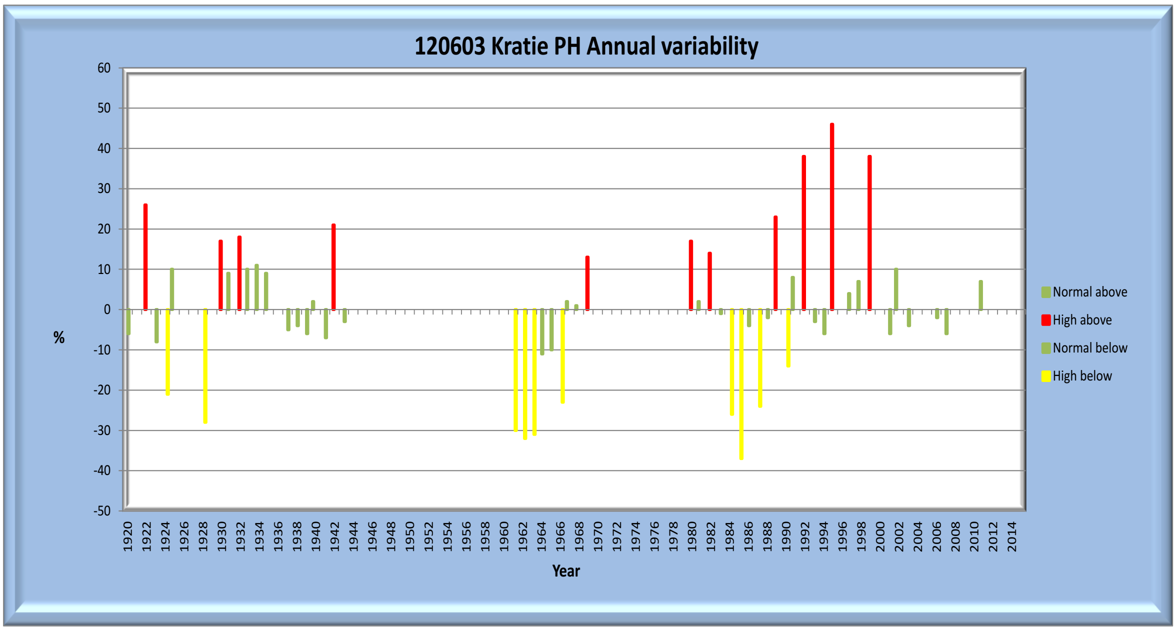



*Figure 2-7. Departures in annual precipitation (in %) from the long-term annual average at Kratie for the period of record 1920-2014.*

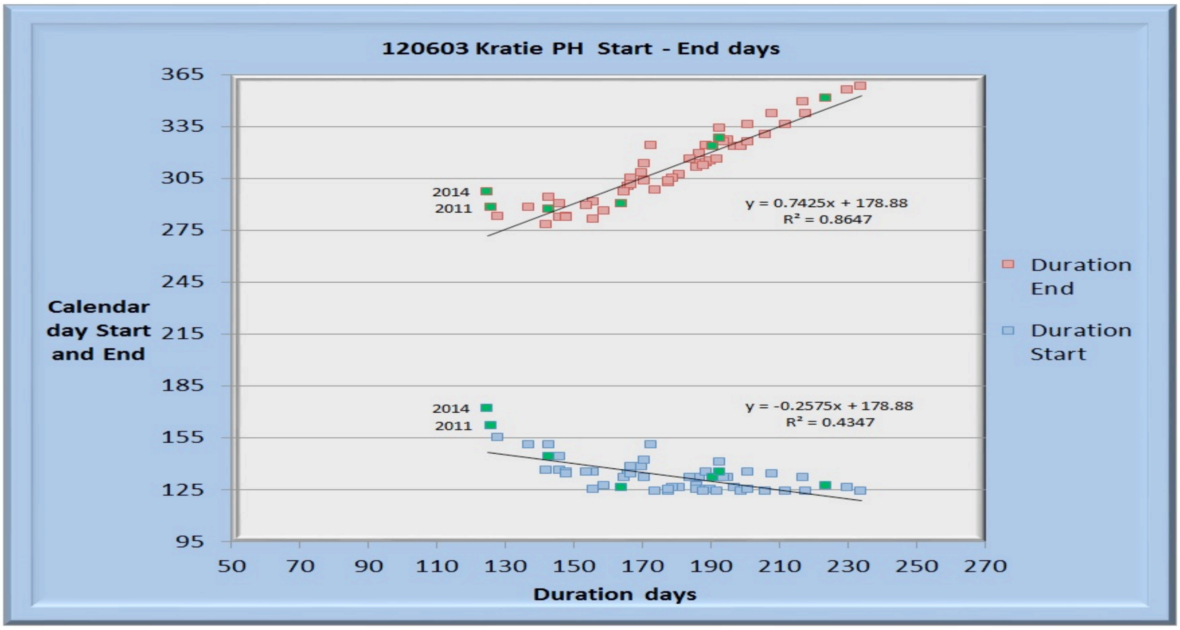



*Figure 2-8. Start and end calendar day and duration of the monsoon. The 2011 and 2014 monsoon started late and ended early and therefore lasted only a short period.*

## Sediment Load Passing Sambor Reach

The Mekong River has historically carried a large sediment load, of which about half is derived from the upper 20% of the basin in China (Walling, 2008). To understand the sediment load, it is helpful to distinguish among suspended load, which is transported in the water column, held aloft by turbulence, and bedload, larger particles that move by rolling, sliding, and bouncing along the bed. In the Mekong River, the suspended load in the upstream reaches consists of medium to fine sand and silt, while in the lower reaches it consists of fine sand and silt, and, principally, clay in the delta. In the vicinity of Kratie, close to the Sambor Dam site, the suspended load consists primarily of medium and fine silt (with some coarse silt and clay), and the bedload consists primarily of coarse to fine sand. Recent measurements indicated that the bedload can range from 3% to 15% of the total sediment load in the Mekong River (Koehnken, 2014).

Daily flow data from Stung Treng gauging station between 1992 and 2002 and sediment rating curves (suspended sediment concentration vs flow) developed from sediment sampling data at Stung Treng (Figure 2-9) and Kratie (Figure 2-10) over the period 2011 to 2013 (Walling, 2008) were used to estimate the sediment load passing the Sambor site under current conditions, which already reflect the impact of the Lancang Cascade in China. The estimated suspended sediment loads using the two respective rating curves are shown in Table 2-3. Based on this analysis the current sediment load passing through the Sambor site is about 92 million tons per year.

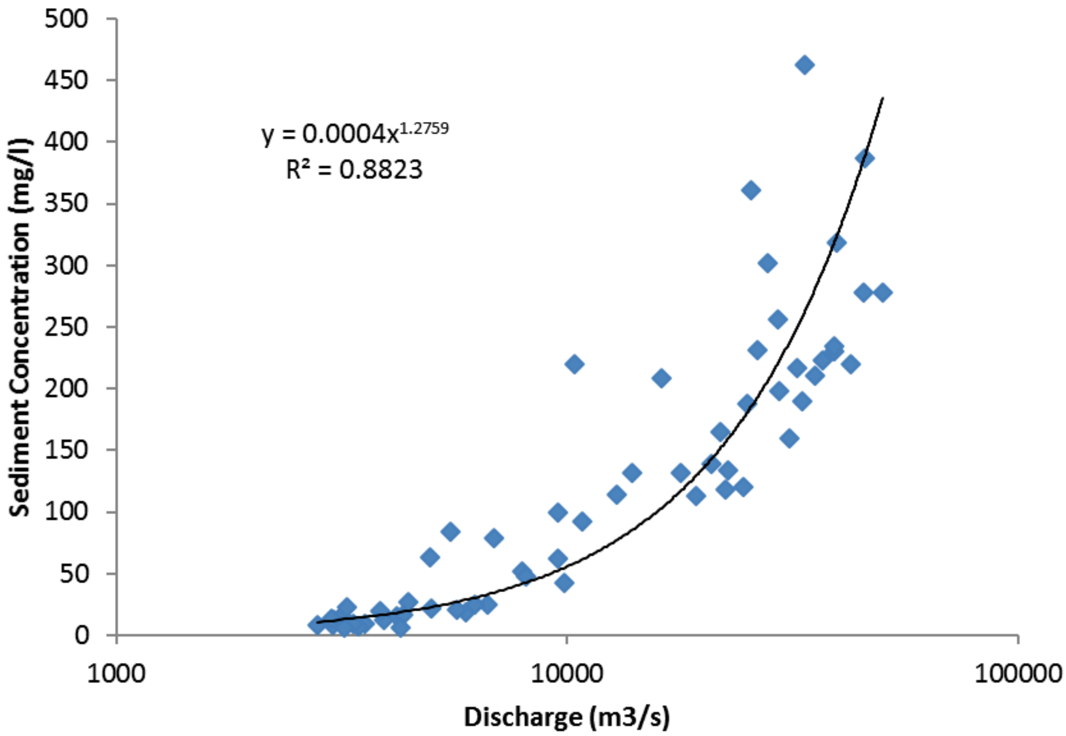



*Figure 2-9. Sediment rating curve at Strung Treng (gauge 14501). Developed from data by Koehnken, 2014.*

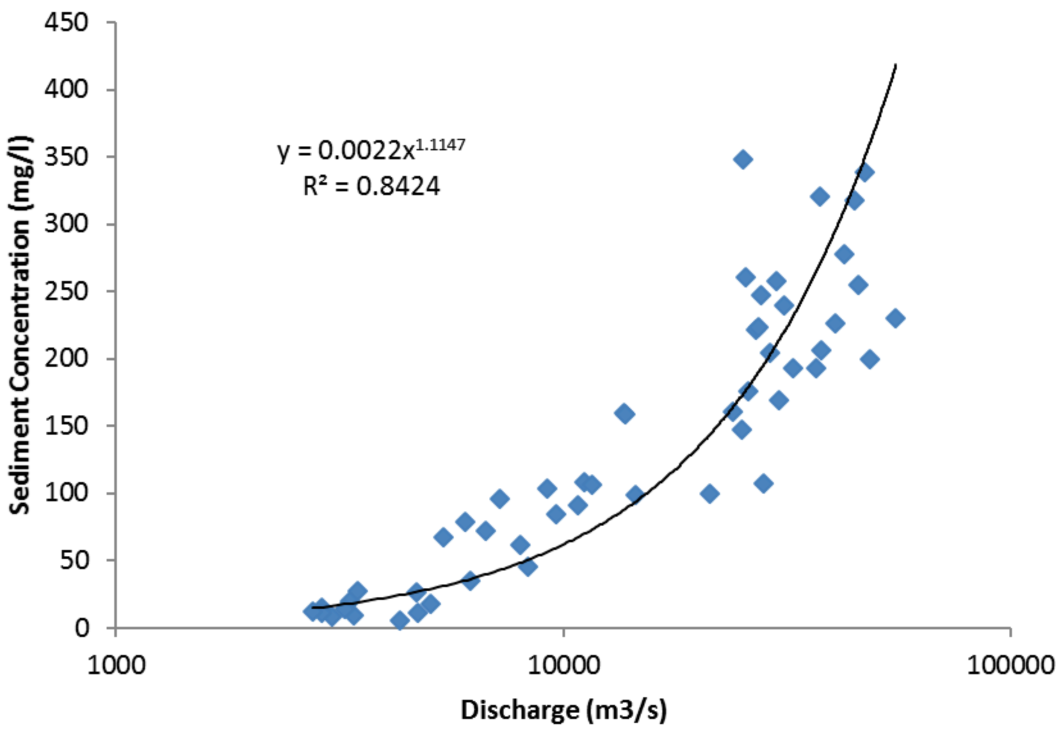



*Figure 2-10. Sediment rating curve at Kratie (gauge 14901). Developed from data by Koehnken, 2014.*

*Table 2-3. Sediment load estimate at Sambor using sediment rating curves at Stung Treng and Kratie.*

| | | |
|---|---|---|
| Stung Treng | | |
| Minimum | 260 | t/day |
| Maximum | 3,653,817 | t/day |
| Average | 249,104 | t/day |
| Kratie | | |
| Minimum | 466 | t/day |
| Maximum | 3,328,718 | t/day |
| Average | 251,839 | t/day |
| | | |
| Average Annual Sediment Load | | |
| Stung Treng | 90,922,951 | t/year |
| Kratie | 91,921,179 | t/year |

The sediments passing Stung Treng and Kratie is divided into suspended sediments (SS), Bedload (BL) and Bed material (BM). Bed material and bedload will be trapped in a hydropower reservoir (but some can be flushed occasionally), while suspended load may pass the dam if the reservoir velocity is high enough. The suspended load in the Mekong River around Stung Treng and Kratie is composed of fine silt and clay, while bedload and bed material have larger grainsizes.

## Geology

Around the potential locations for a Sambor hydropower dam the bedrocks consist of Triassic/Jurassic sandstones, Triassic sandstone, old alluvium, recent alluvium and diorite/gabbro. Rocks were sampled by NHI and MME geological department to assess the geological setting. All samples were of hard fine sandstone or quartzite with strong cohesiveness. The sandstone grain size is generally <=1 mm. Bedrock is visible in the channel overlaid by recent alluvium at tributary confluences or where local conditions allow sand to accumulate. This is the case for both the Sambor Alt_6 (dam in the anabranch) and Sambor Alt_7 (dam in the main channel).

Geological maps show fault lines not far from the mainstream Mekong River and more fault lines may be covered or invisible. No earthquakes with values >= 1 on the Richter scale have been recorded around the Sambor Alt_7 site during the last 103 years, according to the United States Geological Survey's (USGS) Earthquake Catalogue (see Figure 2-11). However, a seismological survey should be included in a full feasibility study to determine the final location of a dam.

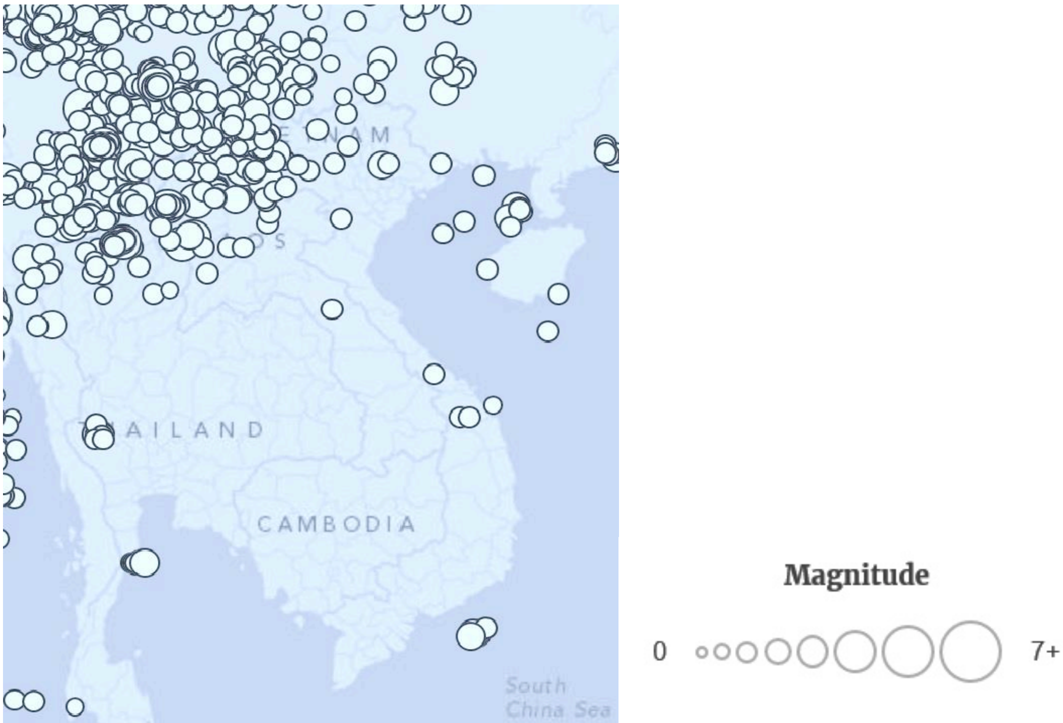



*Figure 2-11. Earthquake (Richter magnitude >1) epicentres from 1912 to 2015 in Indochina. Larger circles indicate greater magnitude. No earthquakes were registered in Cambodia during that period according to USGS Earthquake Catalogue:* http://earthquake.usgs.gov/earthquakes/search/

## Bathymetry

The Mekong River from Sambor to Stung Treng has multiple subparallel channels ("anabranches") with bedrock beds and alluvial banks. The bathymetry of the main channel is characterized by deep pools connected via a deep channel, flanked by a shallow, flat bedrock bed (Figure 2-12 and Figure 2-13). The deep pools are typically about 40m deep, but vary between 13m to 71m in depth (MRC, 1996). The anabranches lack deep pools. At confluences of tributaries and anabranches, small sand deposits occur, but are often short-lived as they are typically eroded by the mainstream.

The bathymetry has an important influence on sediment discharge, as the bedload primarily ends up in the inner channel and there is transported downstream. During the dry season, the deep pools fill with sediments and debris, but during the wet season, high flows scour clean the inner channel and pools.

The deep inner channel is the primarily path for up and downstream fish migration and is especially important for large species.

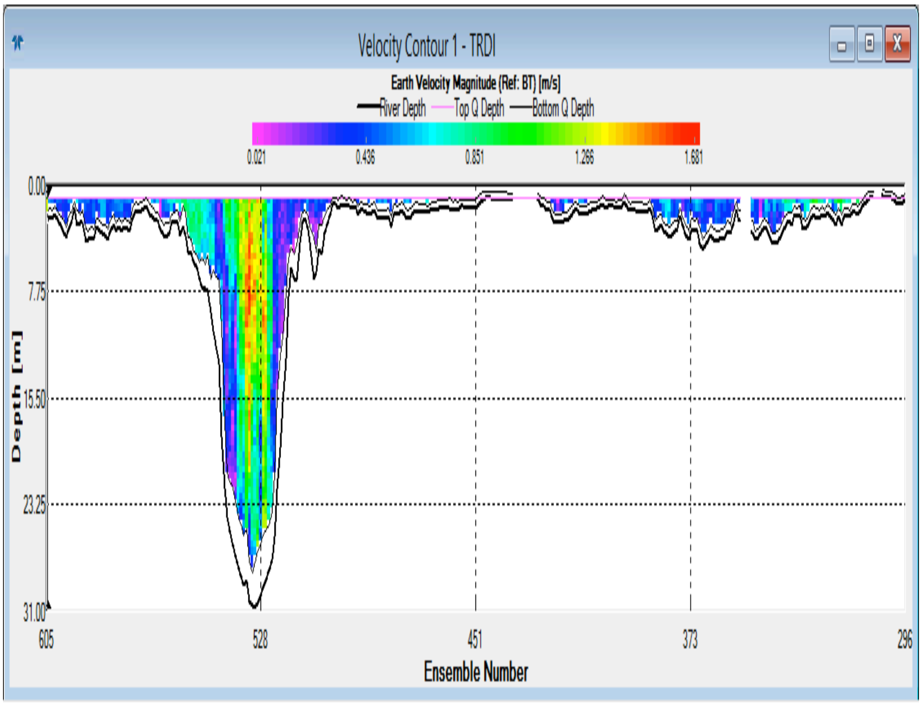



*Figure 2-12. ADCP cross section of the mainstream Mekong River 10 km upstream of Sambor Alt_7 traversing a deep pool. Data collected June 2015 by NHI and Cambodian Hydrological team. The velocity is significantly higher in the deep pools than on the adjacent shallow bedrock around.*

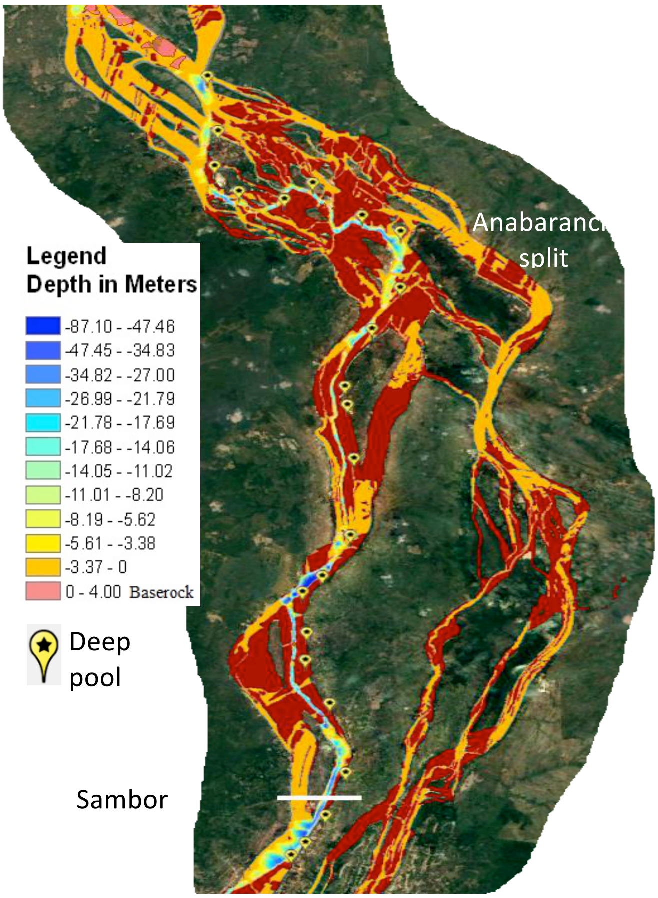



*Figure 2-13. The area around Sambor Alt_7 and upstream to the anabranch split shows the deep pools in the main channel and the location of the bedrock.*

## Land and Topography

At the Sambor site, the land areas around the Mekong mainstream and anabranches is relatively flat, as indicated by the 40-meter contour line as shown in Figure 2-14.

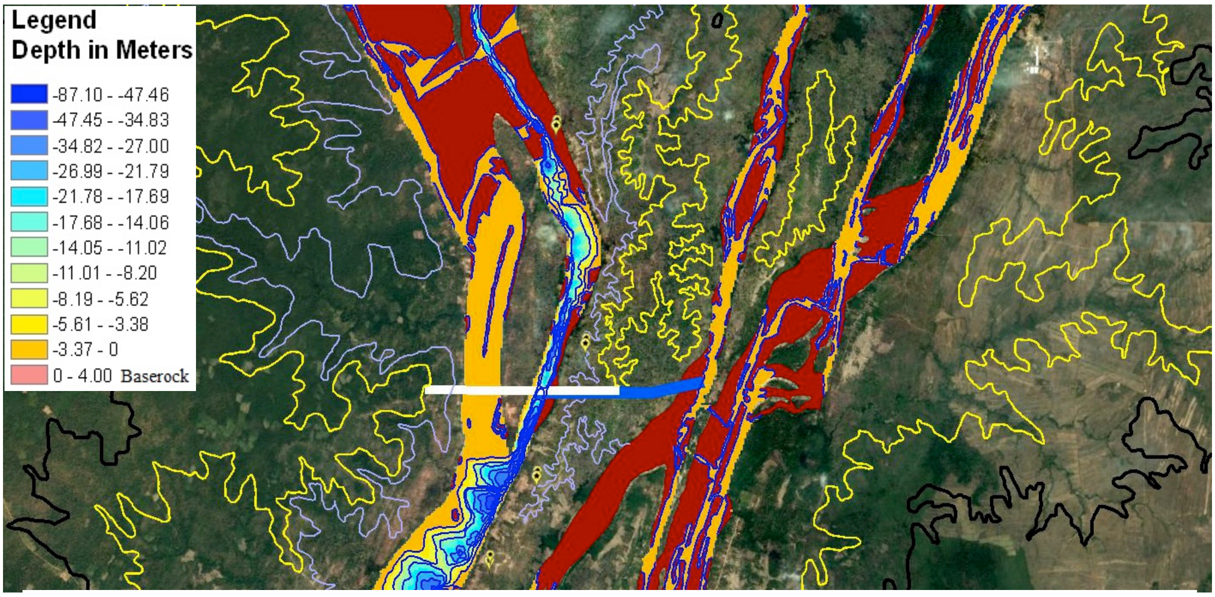



*Figure 2-14. Bathymetry and contour lines around Sambor Alt_7. White line: proposed dam. Blue line: Fish migration channel. Red Patches: Baserock.*

*35m 40m 50m contour lines (Ha Tien zero)*

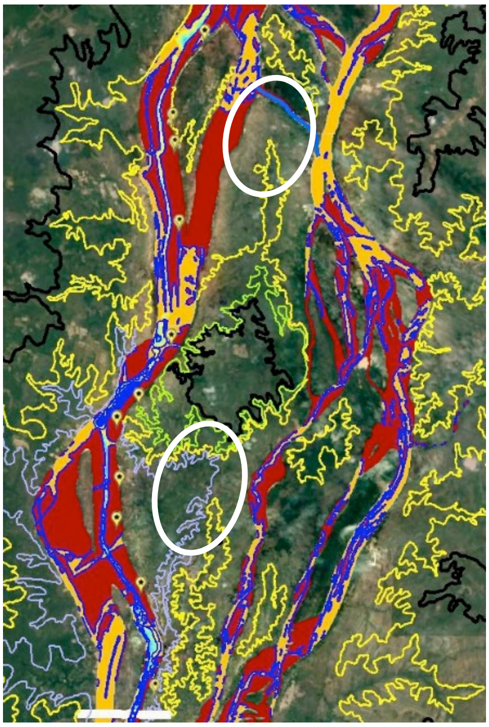


*Figure 2-15. Areas between mainstream and anabranch with elevations between 35m and 40m above Ha Tien zero encircled.*

## Suitability of the Sambor Alternative 7 Site for Dam Construction

From a geological, geomorphological and hydrological point of view, the location of proposed Sambor Alt_7 is found suitable at a concept level to build a hydropower dam. However, a full feasibility study would require a more refined site survey, including:

- A deeper survey of the geology by drilling core samples to evaluate the natural embankment solidity, especially on the island dividing the mainstream and the anabranch. Special attention must be paid to the areas encircled in Figure 2-15 with elevation between 35m and 40m above Ha Tien Zero[3] as the resolution of the contours is not high enough to guarantee that water will not spill over from the reservoir to the anabranch.
- More refined bathymetric surveys are needed as a basis for detailed hydraulic modeling and particularly to assess the high discharge levels during flood events, see Figure 2-14. This information is also needed for the final design of control structures, fish passes and the ship lock.
- The flow split between the mainstream and anabranch should be estimated with a 2-dimensional hydraulic model to verify the velocities through the inner channel and deep pool and relate them to sediment flushing and maintaining the inner channel as the major fish migration route. See Chapter 5, section 5.4.1 (Figure 5-7) regarding flow split at Sambor Alt_6, and Chapter 6, section 6.3 (Figure 6-14) regarding flow split at Sambor Alt_7.
- Potential bank erosion in the anabranch due to triple discharge should be modeled.

## Fishery Resources

### Species Richness of the Mekong Fishery at the Sambor Reach

According to the MRC (2015), the physical diversity and high level of biological productivity give the Mekong the second highest richness of species in the world after the Amazon River (Baran and Myschowoda, 2009; FishBase, 2009; Pauly and Froese, 2010) (Figure 2-16). This accords with an analysis of fish species present in 204 rivers worldwide recorded in FishBase (www.fishbase.org) and backed by a scientific study or publication (Baran, 2010).

[3] Ha Tien Zero is the mean sea level at the Ha Tien tide gauge.

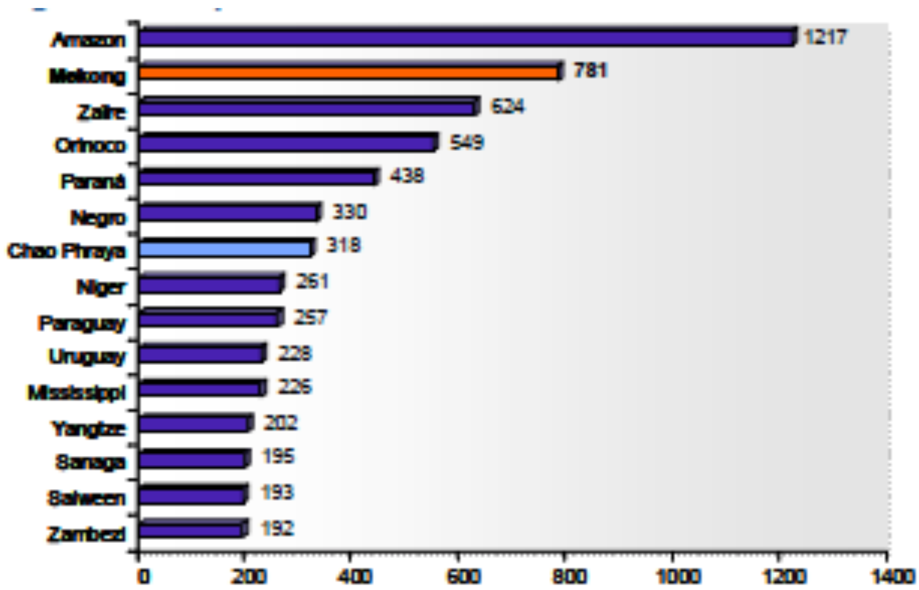



*Figure 2-16. Fish species richness for different rivers of the world. Source: FishBase, December 2009 cited in Pauly and Froese, 2010.*

## The Value of Mekong River Fisheries

Considerable fishing activity takes place in the reach of the mainstream Mekong that would be impacted by a dam at the Sambor site. The harvest is mainly the migratory fish species using large fishing gears such as bag nets, gill nets, lee traps. These gears can yield high catches, and are generally deployed during the period of upstream migrations. For most such species that occurs as the water levels rise at the beginning of the rainy season. However, the migratory species are not the only ones captured as evidenced by the diversity of finfish species found in the local markets; they also contain a broad range of other aquatic animals (OAAs), including amphibians, mussels and snails, which are the most frequent aquatic animals consumed by people after the fishes (Sjorslev, 2000). Impoundments of rivers reduces water velocity and allows accumulation of silt; most of these species of OAAs are adapted to a flowing river habitat and the change in habitat leads to their eradication.

The value of Mekong fisheries can be assessed in many ways: by total catch, by fiscal value and by number of people involved in the fisheries. Estimates have varied over the past 20 years because of different statistical methods, changes in data sampling and especially by steady increase in monetary value over the years. An overview can be found in (Nam *et al*., 2015).

Approximately 2-2.3 million tons of fish are landed each year in the LMB (Cowx, 2014; Hortle and Bamrungrach, 2015), in addition to almost 500,000 tons of other aquatic animals (OAAs) (Hortle, 2007). In terms of overall consumption, estimates of fish and OAAs in the LMB range from 2.56-3.8 million tons (Hortle, 2007; MRC, 2010a; Pukinskis and Geheb, 2012). Depending on the region, fisheries supply between 49-82% of the animal protein consumed in the LMB (Cowx, 2014). Average per capita consumption in Cambodia is the highest in the basin, ranging from 52.4-59.4 kg/capita/year (Figure 2-17) (Friend and Blake, 2009; Cowx, 2014; Nam *et al*., 2015). Fishing communities living within Tonle Sap Great Lake consume more than 70 kg/capita/year (Nam, 2010). "Fish are the cheapest source of animal protein in the region and any decline in the fishery is likely to significantly impact nutrition, especially among the poor" (Baird, 2009a; Baird, 2009b; ICEM, 2010; Baird, 2011; Bush, 2013 *cited in* Pukinskis and Geheb, *2012,* p. 3).

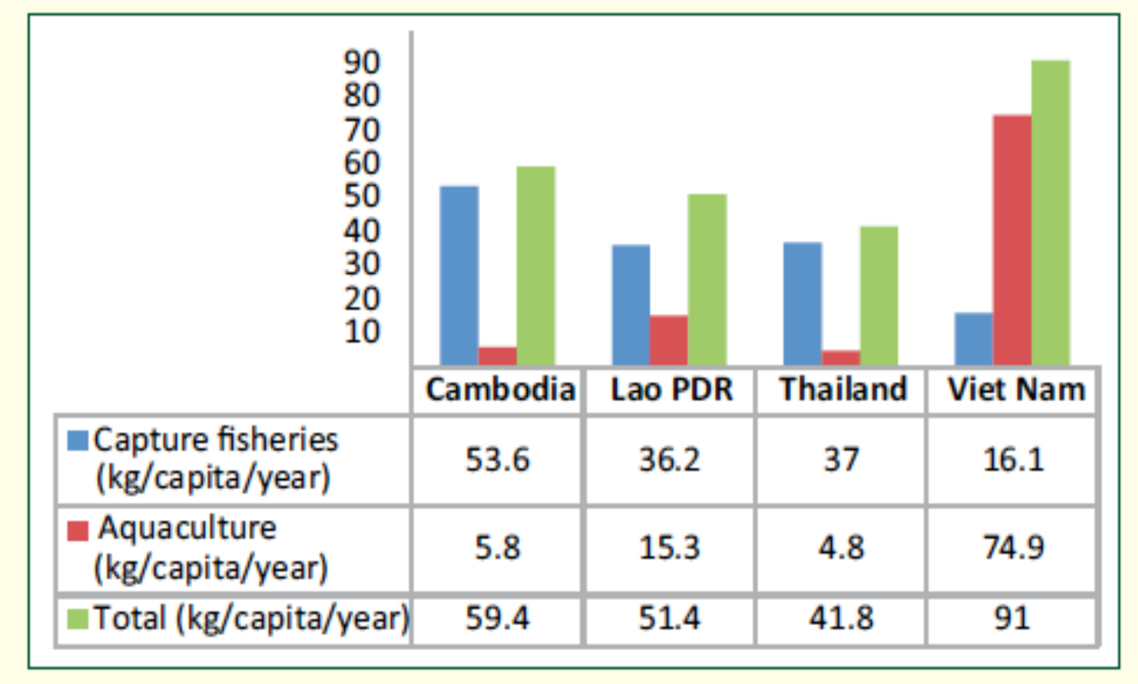



*Figure 2-17. Country fish consumption in LMB (2015). Source: MRC Member Country estimates of Basin population 63.2 million in 2003, 66.6 million in 2010, 68.9 million in 2015), cited in Nam et al., 2015, p. 5.*

The number of people involved in fisheries indirectly, in trade and processing equals more than one million people in each country (see Table 2-4). Relative to population size, this constitutes a large proportion of people in Cambodia and Lao PDR; and 18.0% and 12.8% respectively of their GDP (Nam *et al*., 2015). Other estimates of the number of rural people engaged in the wild capture fishery range up to 40 million, which is more than two-thirds of the rural population in the Lower Mekong Basin (ICEM, 2010).

*Table 2-4. People engaged in LMB fisheries (number).*

| | Cambodia | Lao PDR | Thailand | Viet Nam | LMB |
|---|---|---|---|---|---|
| Fishers | 1,009,190 | 526,300 | 1,065,900 | 689,910 | **3,291,300** |
| Fish farmers | 80,976 | 782,800 | 315,948 | 279,552 | **1,459,276** |
| Processors | 220,464 | N/A | N/A | 133,705 | **354,169** |
| Traders | N/A | N/A | N/A | 72,786 | **72,786** |
| TOTAL | 1,310,630 | 1,309,100 | 1,381,848 | 1,175,953 | **5,177,531** |

Source: National statistics (Cambodia, Lao PDR and Viet Nam) and Estimates base.

Estimates of the total economic value of the fishery also vary widely, between USD 3.9 to USD 7 billion a year (MRC, 2010b). "Wild capture fisheries alone have been valued at USD 2 billion a year" (Baran and Ratner, 2007). This value increases considerably when the multiplier effect is included. Based on first-sale prices in 2015, the value of wild catch in the Lower Mekong Basin is estimated at 11.15 billion USD, of which the Cambodian part is 2.76 billion USD, see Figure 2-18 (Nam *et al*., 2015).

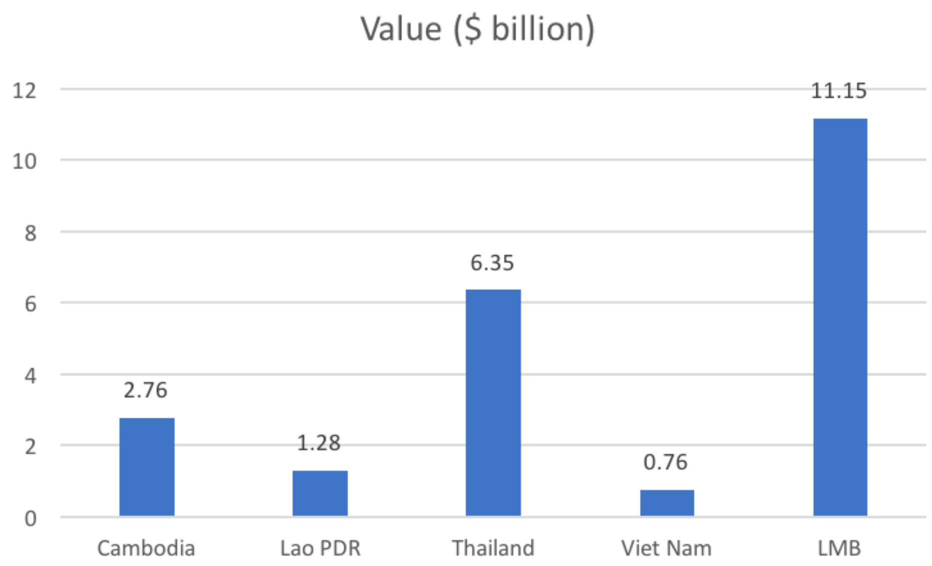



*Figure 2-18. Capture fisheries estimated value in the basin. Source: adapted from Nam et al., 2015.*

## Fish Migration in the Lower Mekong

The Sambor reach of the Mekong experiences one of the largest annual migration of fish biomass on the planet. This migration is vital for the completion of the life cycles of the migratory fish that characterize the most productive freshwater fishery in the world. The great diversity of fish species in the Mekong River exhibit also a great diversity and complexity of life cycles, many of which involve migration between different areas of the river, particularly upstream migration to spawning areas and floodplain nursery areas. Between 40 and 70% of the catch is of fish species that migrate long distances along the Mekong mainstream and into its tributaries (Barlow *et al*., 2008), and these fish stocks are extremely vulnerable to dams built in the middle and lower Mekong basin.

To complete these migrations requires unobstructed passage upstream, as well as the capacity for adults, larvae and juveniles to migrate or drift downstream. 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 the most important at the onset of the wet season (May-July), with the other peaks when the water is receding (November) and during the dry season (February-March) (Figure 2-19). Many of the abundant species caught in the lowlands of the Mekong River system spawn around the beginning of the wet season.

This behavior has been strongly selected for in the monsoonal 'flood-pulse' environment. Flood-related spawning results in the fish larvae and fry growing at a favorable time, when the available aquatic habitat is expanding and zooplankton (the essential food for most fish larvae) is becoming abundant.

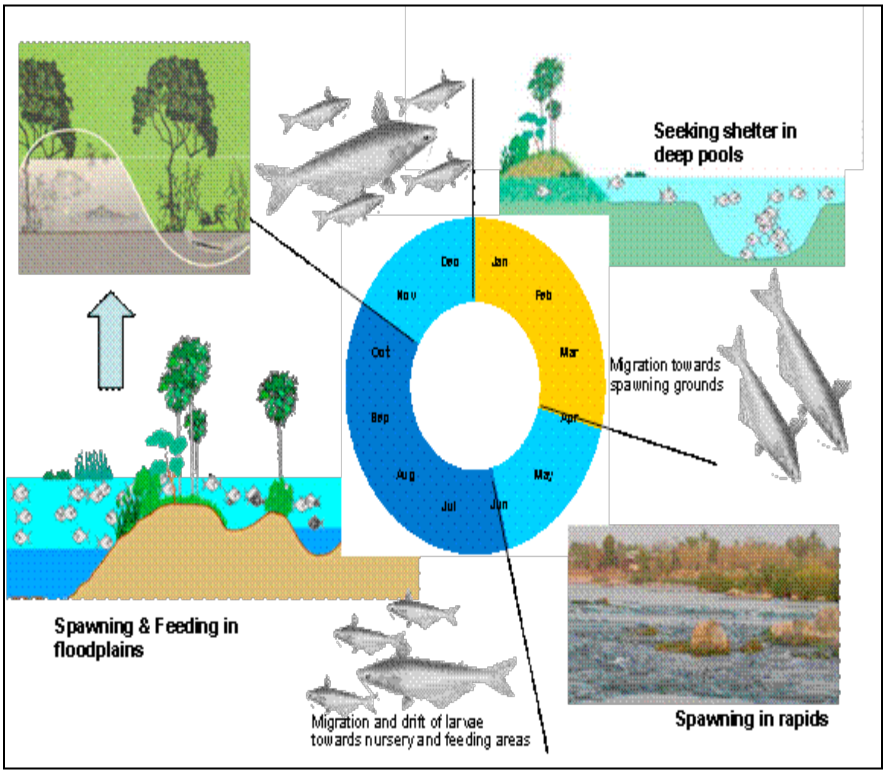



*Figure 2-19. Generalized life cycle of potamodromous (wholly freshwater) Mekong fish. Source: Sverdrup-Jensen, 2003.*

A large number of these species migrate through the Sambor site (Poulsen *et al*., 2002; Poulsen *et al*., 2004), and these constitute major fisheries both in the region and throughout the lower basin. Some 329 species (42% of all Mekong species in 10% of the area of the basin) have been recorded in this area and into the 3-S system. Fourteen of these are endangered. Eight-six fish species migrate from Tonle Sap and the Cambodian floodplains into the 3-S system, highlighting the importance of maintaining connectivity through the system (see Figure 2-20). The only migration route between these habitats 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 (see Figure 2-21 for examples). There are relatively far fewer species migrating in the delta, but a surprisingly steady number of species migrating along the mainstream up to Northern Laos.


*Figure 2-20. Fish migration in the LMB. Source: MRC.*

Importantly, migration of fish in the region occurs throughout the year (Figure 2-21 and Figure 2-22). The different species utilise different aspects of the hydrograph for both upstream and downstream migration. Significantly, the early life stages of eggs and larvae drift downstream to replenish and sustain the populations in the lower Cambodian floodplain and delta. This means that upstream and downstream migration must be maintained throughout the year if the fisheries are not to be compromised.

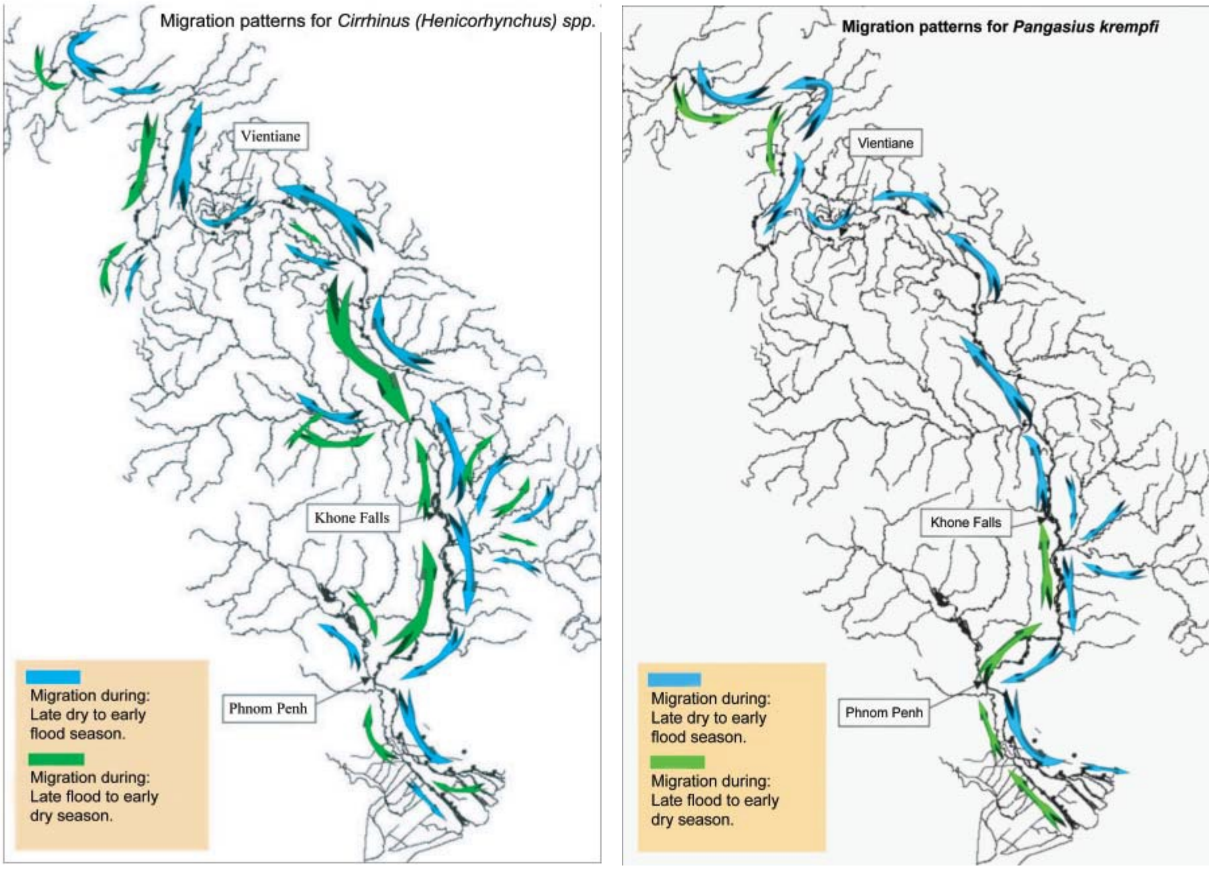



*Figure 2-21. Typical migration patterns of key species in the LMB to illustrate the importance of connectivity between the mainstem Mekong and the 3-S.*

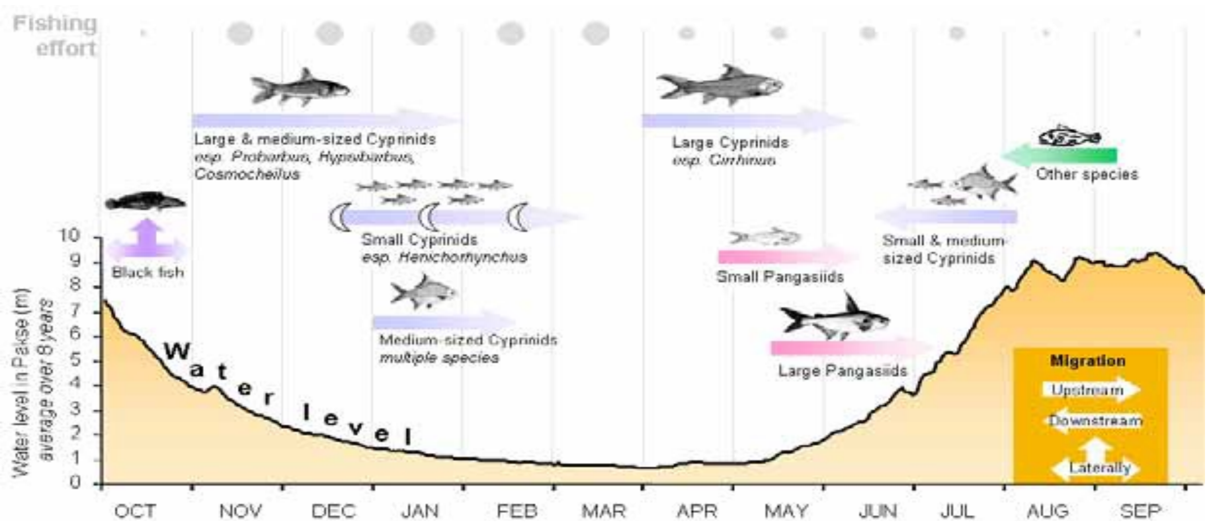



*Figure 2-22. Main migration patterns of fish in the lower Mekong in the Sambor, Lower Sesan Khone Falls region. Source: Baird, 2001.*

The general understanding of migration patterns in the Mekong is that there are three main groupings: the lower migration system LMS] (from the Delta up to Khone Falls), the middle migration system [MMS] (from Khone Falls up to Vientiane) and the upper migration system [UMS] (from Vientiane up to China), see Figure 2-23. These are overlapping and inter-connected systems

(Poulsen *et al*., 2002). Importantly, many species in Cambodia that migrate up to Khone Falls continue upstream and spawn in Lao PDF; hence the fisheries stocks of these two countries are intimately linked. The fish need to migrate as they cannot use just one habitat for all their functions of feeding, spawning, rearing and refuge. Therefore, the migration systems (LMS, MMS and UMS) are all defined by the need to migrate between the spatially separated locations for dry season refuge, flood season feeding/rearing and spawning grounds.

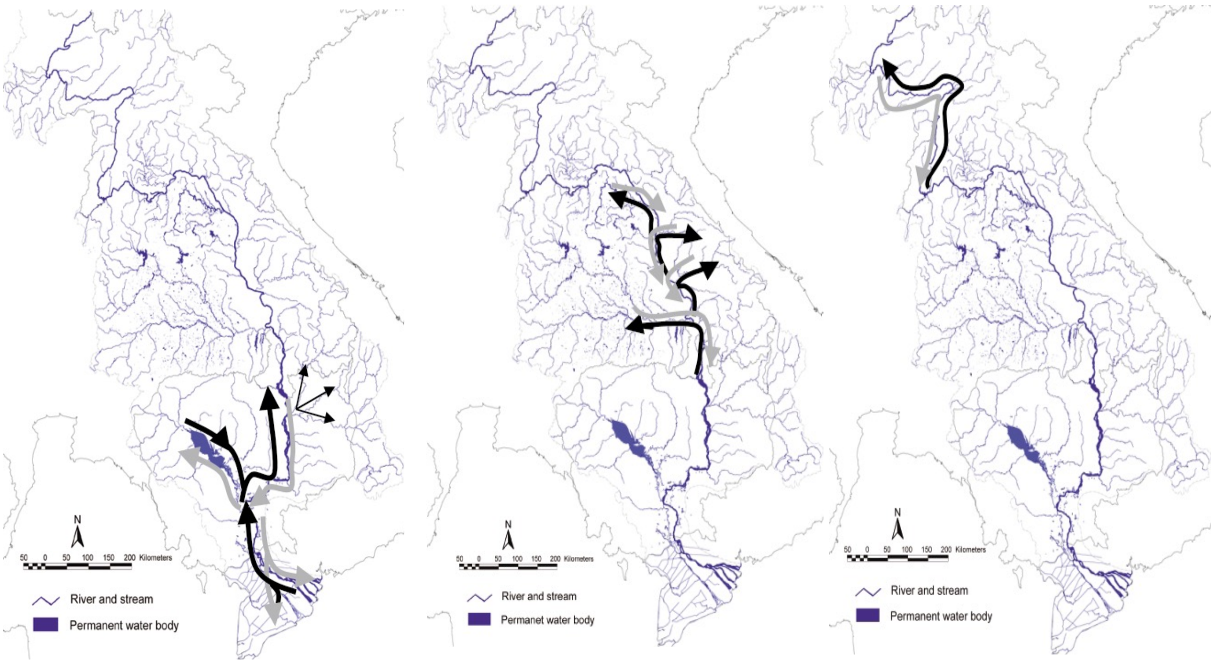



*Figure 2-23. Three maps showing the LMS, MMS and UMS migratory system of the Lower Mekong Basin. Source: Poulsen et al., 2002.*

## Lower Mekong Migration System (LMS)

The LMS includes the very large floodplains in Cambodia around the Tonle Sap Lake and the Vietnamese delta. The system includes lateral migration of species from the floodplains for refuge in the deep pools and longitudinal migration further upstream for spawning, primarily at the start of the wet season.

For the Tonle Sap system this happens when the Mekong flows reverse out of the lake. Some migrations are short distance, while some are long distance into the MMS and UMS and the 3S system (Se Kong, Se San and Sre Pok Rivers). Because of the large floodplains (up to 50,000 km$^2$), the LMS is the most productive system of the three. Many species spawn within the Mekong mainstream from Kratie to Pakse, and in the 3S tributaries at the beginning of the flood season in May-June. Eggs and larvae then drift downstream with the current to reach the floodplain feeding habitats in southern Cambodia and Viet Nam (Poulsen *et al*., 2002).

The MMS includes the large tributaries in Lao PDR and Thailand. The migration pattern is similar to the LMS with migration between floodplains, deep pools and rearing habitats, but here the floodplains are along the tributaries. This is a simplistic description as the MMS overlaps with both the LMS and UMS and many species pass the Khone falls both upwards and downwards. At different stages of the life cycle, migration can be in the LMS as juveniles and in the MMS as adults. Different populations and subspecies may also have different migration patterns (Poulsen *et al*., 2002).

The Sambor site is downstream of the intersection of LMS and the MMS systems, which is at Khone Falls and the Cambodian-Lao PDR border. What differentiates the LMS and the MMS is not spatial isolation but that, at the onset of the flood season, fishes migrate **downstream** in the LMS towards flood season habitats, whereas fishes migrate **upstream** in the MMS towards flood season habitats. In some cases, the same fish may participate in both migration systems at different stages of their life cycle. Spawning in both systems occurs all year round, but there appears to be greater spawning at the beginning of the wet season. Downstream drift of larvae in the MMS and LMS is a critical part of the life cycle, as these fish have high survival in the huge downstream floodplains of the Tonle Sap and Viet Nam delta. It is likely that drift of larvae for many migratory species is over hundreds of kilometers and larvae spawned near Pakse could utilize nursery habitats in the Tonle Sap (Poulsen *et al*., 2002).

In the UMS there are few floodplains and the major migration is longitudinal, in the mainstem and tributaries, up and downstream for spawning, feeding and refuge. The UMS is connected to both the MMS and LMS, but the connections are more attenuated, probably because it has a long stretch of river without many deep pools.

### Biological Importance of Deep Pools

A total of 419 deep pools are registered in the Mekong River mainstream from Cambodia to Lao PDR in the deep pool atlas (MRC, 1996; Halls *et al.*, 2013). The deep pools form an interconnected system of dry-season refugia that lie along the thalweg (deepest part of the river channel) (Figure 2-24, left). There are more than 20 deep pools forming the inner channel and thalweg between the Sambor Alt_7 proposed location and the anabranch split (see Figure 2-24).

The importance of the deep pools is documented in many reports (see MRC, 1996; Poulsen and Valbo-Jørgensen, 2000; Kolding *et al*., 2002; Poulsen et al., 2002; TAB, 2005; Viravong *et al*., 2006; Halls *et al*., 2013). The deep pools are the intermediate link in the chain between floodplains and spawning areas. In the major corridor for up and downstream migration through the Sambor reach, they serve as refugia during the dry season, as rearing ground for many resident species, as migration route for small and especially large fish species and as sanctuary and feeding ground for dolphins. Although the deep pools have their own fisheries, their principal importance lies in the role they play in the life cycle of migratory fish and the major upstream and downstream fisheries that target migrating fish (TAB, 2005).

There is a relatively large seasonal variation in catch composition from the deep pools which is most likely due to the seasonal migration (Viravong *et al*., 2006).

Results from the acoustic survey in 2002 suggest that the pools are used as a resting place or refuge during the day time and that the fish move out of the area or continue the up- stream migration at the onset of dark hours (Viravong *et al*., 2006).

‘Dolphins are known to spend most of their time in deep pools, from where they frequently undertake "hunting" migrations following groups of migratory fishes, which constitute their prey’ (Poulsen and Valbo-Jørgensen, 2000).

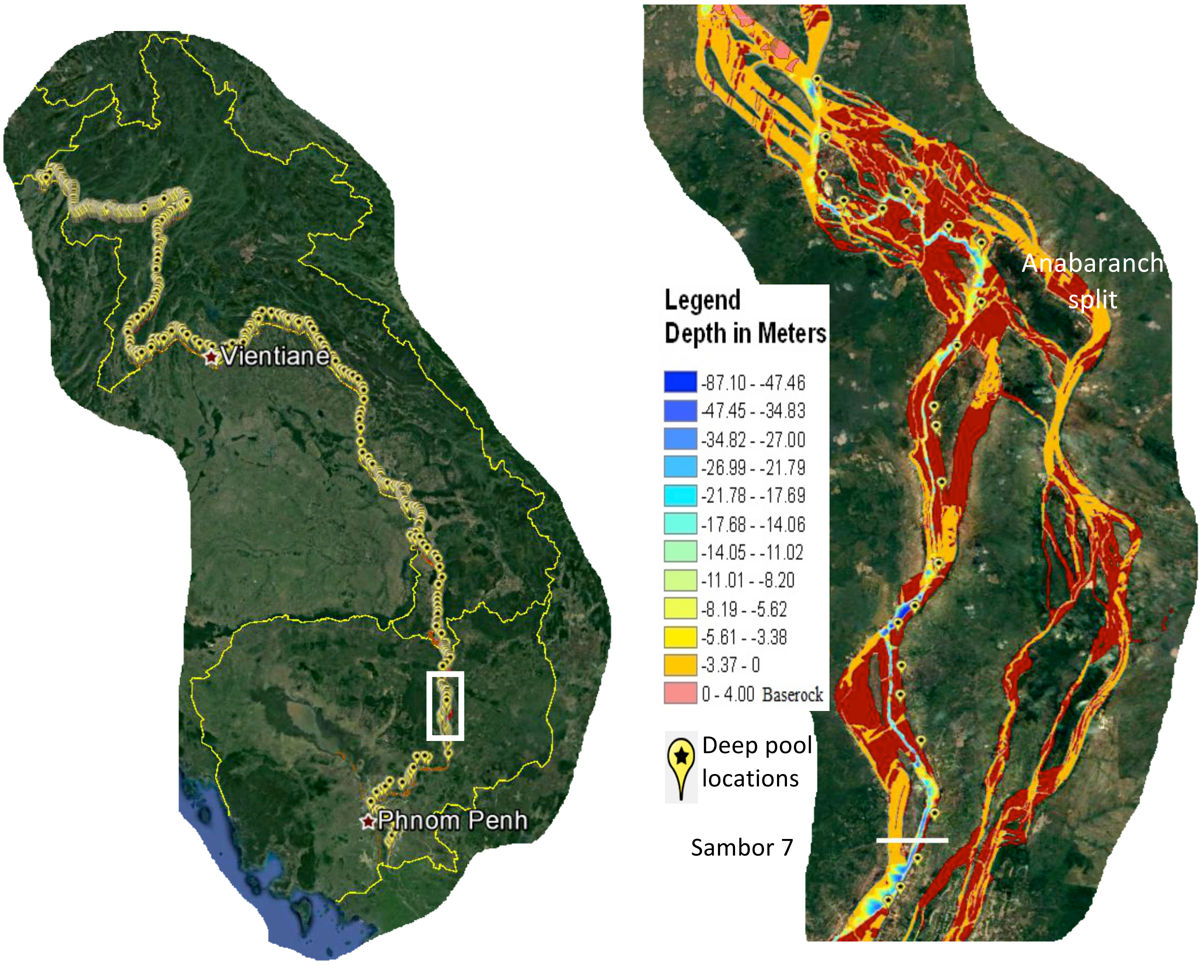



*Figure 2-24. (Left) 419 Deep pools identified on the Mekong River mainstream in Cambodia and Lao PDR. Deep pools and their interconnections makes an inner channel thalweg. (Right) Close up of the area around Sambor Alt_7-A and upstream to the anabranch split marked by white rectangle in left-hand image.*

## References


Adamson, P. T., Rutherford, I.D., Peel, M.C. and Conlan, I.A. 2009, The hydrology of the Mekong River, in The Mekong: Biophysical Environment of an International River Basin, edited by I. C. Campbell, pp. 53–76, Elsevier, Amsterdam.

Baird, I.G. 2001. Aquatic biodiversity in the Siphandone wetlands. Pp. 61-74 in Daconto G. (ed.) Siphandone Wetlands. Environmental Protection and Community Development in Siphandone Wetland Project, CESVI, Bergamo, Italy. 192 pp.

Baird, I.G. 2009a. The Don Sahong Dam: Potential Impacts on Regional Fish Migrations, Livelihoods and Human Health. Available from: http://polisproject.org/PDFs/Baird%_Don%20Sahong.pdf. (Accessed on 30 January 2012).

Baird, I.G. 2009b. Best Practices in Compensation and Resettlement for Large Dams: The Case of the Planned Lower Sesan 2 Hydropower Project in Northeastern Cambodia. Rivers Coalition in Cambodia.

Baird, I.G. 2011. The Don Sahong Dam. *Critical Asian Studies* 43(2): 211-235.

Baran, E. and Ratner, B. 2007. The Don Sahong Dam and Mekong Fisheries. Science Brief. WorldFish Center. p. 3.

Baran, E. and Myschowoda, C. 2009. Dams and fisheries in the Mekong Basin: *Aquatic Ecosystem Health & Management*, v. 12, p. 227-234.

Baran, E. 2010. Mekong fisheries and mainstream dams. Fisheries sections in: ICEM 2010. Mekong River Commission Strategic Environmental Assessment of hydropower on the Mekong mainstream, International Centre for Environmental Management, Hanoi, Viet Nam. 145 pp.

Baran, E., Guerin, E. and Nasielski, J. 2015. Fish, sediment and dams in the Mekong. Penang, Malaysia: WorldFish, and CGIAR Research Program on Water, Land and Ecosystems (WLE). 108 pp.

Barlow, C., Baran, E., Halls, A.S., and Kshatriya, M. 2008. How much of the Mekong fish catch is at risk from mainstream dam development? Catch and Culture: Mekong River Commission. Vol. 14, No.3. December 2008. p. 16-21. ISSN. 0859-290X.

Bush, S. 2003. "Give a man a fish..." Contextualising Living Aquatic Resources Development in the Lower Mekong Basin. Australian Mekong Resource Centre Working Papers No. 8.

Cowx, I.G. 2014. Critical Issues with Migratory Fish Mitigation at Hydropower Dams. Technical Report prepared for the Natural Heritage Institute under Cooperative Agreement AID-486-11-00002 with USAID for 'Maintaining the Productivity of the Mekong River by Improving Sediment Passage and Fish Passage through Hydropower Dams in Lao and Cambodia'.

China Southern Power Grid Co. (CSP) and Guangxi Electric Power Industry Investigation Design. October 2008. *Feasibility Study Report of Sambor Hydropower Station*. Prepared for The Kingdom of Cambodia.

FishBase. December 2009. www.fishbase.org - Tonle Sap ecosystem.

Friend, R.M. and Blake, D.J.H. 2009. Negotiating trade-offs in water resources development in the Mekong Basin: implications for fisheries and fishery-based livelihoods. *Water Policy Supplement I* (2009): 13-30.

Gupta, A. et al. 2002. Evaluation of part of the Mekong River using satellite imagery. *Geomorphology*, 44 (3-4): 221-239.

Halls, A.S., I. Conlan, W. Wisesjindawat, K. Phouthavong, S. Viravong, S. Chan and V.A.Vu. 2013. Atlas of deep pools in the Lower Mekong River and some of its tributaries. MRC Technical Paper No. 31. Mekong River Commission, Phnom Penh, Cambodia. 69pp. ISSN: 1683-1489.

Hortle, K.G. 2007. Consumption and the yield of fish and other aquatic animals from the Lower Mekong Basin: Mekong River Commission, Vientiane, Lao PDR.

Hortle, K.G. and Bamrungrach, P. 2015. Fisheries habitat and yield in the Lower Mekong Basin, MRC Technical Paper No 47, Mekong River Commission, Phnom Penh.

ICEM. 2010. MRC SEA for Hydropower on the Mekong River Mainstream. Fisheries Baseline Assessment Working Paper. International Center for Environmental Management (ICEM) report to MRC.

Koehnken, L. 2014. Discharge Sediment Monitoring Project (DSMP) 2009-2013: Summary and Analysis of Results, MRC, Office of the Secretariat in Vietnam, P.O. Box 6101, Vientiane, Lao PDR.

Kolding, J., Viravong, S., Phounsavath, S., Photthitai, C., Sverdrup-Jensen, S. and Warren, T. 2002. Monitoring of Deep Pools in the Mekong River: The potential of hydro-acoustic methods. Catch and Culture: Mekong River Commission. Vol. 7, No. 4. June 2002. ISSN 0859-290X.

MRC. 1996. "Hydrographic Atlas of the Lower-Mekong River (1:20 000), Volumes I-V." Mekong River Commission.

MRC. 2005. Overview of the Hydrology of the Mekong Basin. Mekong River Commission, Vientiane, November 2005. 73 pp. Available from: http://www.mekonginfo.org/assets/midocs/0001968-inland-waters-overview-of-the-hydrology-of-the-mekong-basin.pdf.

MRC. 2010a. Impacts on Fisheries. Assessment of Basin-wide Development Scenarios: Technical Note 11. Basin Development Plan Programme Phase 2. Vientiane, Lao PDR, MRC.

MRC. 2010b. State of the Basin Report 2010. Vientiane, Lao PDR, MRC.

Pauly, D. and Froese, R. 2010. A count in the dark. *Nature Geoscience* 3 (10): 662-663, doi:10.1038/ngeo973.

Piman, T., Cochrane, T.A., Arias, M.E., Green, A. and Dat, N.D. 2013. Assessment of flow changes from hydropower development and operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin. *Journal of Water Resources Planning and Management* 139 (6): 723-732.

Poulsen, A.F. and J. Valbo-Jørgensen (editors). 2000: *Fish migrations and spawning habits in the Mekong Mainstream – a survey using local knowledge*. AMFC Technical Report. Mekong River Commission.

Poulsen A.F., Poeu, O., Viravong, S., Suntornratana, U., and Thanh Tung, N. 2002. Fish migrations of the Lower Mekong Basin: implications for development, planning and environmental management. MRC Technical Paper No. 8. Mekong River Commission, Phnom Penh, Cambodia. 62 pp. ISSN: 1683-1489.

Poulsen et al. 2004. Distribution and Ecology of Some Important Riverine Fish Species of the Mekong River Basin. MRC Technical Paper No. 10. Mekong River Commission, Phnom Penh, Cambodia.

Pukinskis, I. and Geheb, K. 2012. The Impact of Dams on the Fisheries of the Mekong. State of Knowledge Series 1. Vientiane, Lao PDR, Challenge Program on Water and Food. Available from: https://cgspace.cgiar.org/rest/bitstreams/24817/retrieve.

Sjorslev, J.G. (ed.), 2000. Luangprabang Fisheries Survey, AMFC/MRC and LARReC/NAFRI; Vientiane.

So Nam. 2010. Fisheries Resources in Cambodia- An Overview. Inland Fisheries Research and Development Institute, Phnom Penh, Cambodia. 31 pp.

So Nam, Phommakone, S., Vuthy, L., Samphawamana, T., Hai Son, N., Khumsri, M., Peng Bun, N., Sovanara, K., Degen, P. and Starr, P. 2015. Fisheries Research and Development in the Mekong Region. *Catch and Culture*, Vol. 21, No. 3. December 2015. ISSN 0859-290X

Sverdrup-Jensen, S. 2003. Fisheries in the Lower Mekong Basin: Status and Perspectives. MRC Technical Paper No. 6. Mekong River Commission, Phnom Penh, Cambodia. 84 pp.

Technical Advisory Body for Fisheries Management (TAB). 2005. Deep pools as dry season habitats in the Mekong River Basin. Mekong Fisheries Management Recommendation No3. Mekong River Commission. August 2005. Available at: http://www.mrcmekong.org/assets/Publications/report-management-develop/TAB-Man-Rec-No3-deep-pools.pdf.

Viravong, S., Phounsavath, S., Photitay, C., Putrea, S., Chan, S., Kolding, J., Valbo Jørgensen, J. and Phoutavong, K. 2006. Hydro- acoustic surveys of deep pools in southern Lao PDR and Northern Cambodia. MRC Technical Paper no.11, Mekong River Commission, Vientiane. 76 pp. ISSN: 1683-1489.

Walling, D. E. 2008. The changing sediment load of the Mekong River. AMBIO, 37(3), 150–157.

# 3 How Dams 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 Mekong 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 in the Mekong both in terms of individual developments on local and basin wide scales and the cumulative impacts of multiple schemes. A dam at the Sambor site has the potential for the largest such impacts of any in the LMB, due to its location between the Tonle Sap and Viet Nam floodplains, and the middle Mekong above Khone Falls and the 3S (Se San, Srepok and Sekong) River basin. This corridor is of great importance as it connects upstream spawning habitat with downstream nursery habitats, which sustains the abundant fisheries of the Tonle Sap Great Lake and Mekong Delta.

## Alteration of Hydrology

Hydropower dams are non-consumptive. Except for evaporative losses, the same amount of water will flow through the Sambor site on an annual basis before or after a dam is built. But, hydropower dams may be operated to store and release water on a seasonal or daily basis or both. Their objective 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). Both fundamentally alter the natural hydrograph in the downstream river system.

Seasonal flow alteration is not likely to be a severe problem with a Sambor Dam, however, because the storage capacity of even a large Sambor reservoir would not be sufficient to capture a large enough fraction of the annual inflow, simply because of the volume of the river. Thus, even a large Sambor Dam would have to operate, more or less, as a run-of-river facility, where the daily discharge from the reservoir would be roughly equal to the daily inflow. Yet, while there would not be enough capacity for seasonal or inter-annual storage of water, there would likely be sufficient capacity to regulate the daily discharge pattern to maximize power generation at the time of greatest dam. This "hydropeaking" operation would create large and rapid variations in the downstream flow pattern. These distortions can be particularly damaging to the downstream fishery.

## Alteration of Hydraulics and Impacts on Fish

As noted, one of the most profound effects of a dam, and one that is often overlooked, is the shift from a river to a still-water lake environment. The large CSP Sambor Dam would convert up to 82 km of flowing river to a static pool. This would have three major impacts: i) inundation of spawning and feeding habitats, ii) prevention of passage of drifting larvae, and iii) siltation/sedimentation of habitats.

Mekong fish have a range of spawning strategies (see Chapter 2). Some spawn on the floodplains, but most riverine species, especially the valuable migratory ones, spawn in flowing water habitats. 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.

The hydraulic barrier of the reservoir, as described earlier, produces low water velocities that, among other impacts, are insufficient to maintain larval drift (Pelicice *et al,.* 2015). In a static reservoir, the larvae do not drift and therefore die. 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 as they are 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, riverine species generally decline in abundance because of inability to fulfill their life cycle, to be replaced by species that 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, despite the persistence of some fish species in reservoirs, the total fish productivity is greatly reduced compared to the natural river system, which can be further compromised due to eutrophication caused by elevated nutrient run-off from the lake hinterland where small-scale agriculture often develops.

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 to the point of discharge at the spillway or powerhouse; transporting the eggs and larvae through 99% 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. For many of the Sambor Dam alternatives evaluated, operating the hydropower dam to ensure these velocities will require that the reservoir levels be reduced with a consequent reduction in hydropower production.

In the Sambor reach of the mainstream Mekong, there are varying estimates in loss of fishery yield (and the lost cost of fish production) from the region due to planned hydropower dams (e.g., Cowx, 2014; ICEM, 2010; Baird, 2011). "If, by 2030, eleven dams are built on the Lower Mekong Basin mainstream, forecasted total fish losses would amount to 550,000 to 880,000 tons compared to the baseline year 2000 (a 26-42% decrease). This is a loss of approximately 340,000 tons compared to a situation in 2030 without mainstream dams" (Pukinskis and Geheb, 2012 cited in ICEM 2010). More importantly this threatens biodiversity, sustainable livelihoods and food security in the region.

## Fish Passage

The physical barrier of a dam prevents upstream fish migration, which ultimately may 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) but the combined abundance of the river downstream and the reservoir upstream is much lower (Oldani *et al.* 2007).

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%.

The challenges to providing downstream migration are often overlooked, apart from the passage of salmonid juveniles (smolts) in North America. In the Mekong River, 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[4] of fish to populations both upstream and downstream of the dam.

### Mortality at Hydropower Dams from Spillways and Turbines

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 migration at dams. Trash racks typically have spacing of 180-200mm which allow all small and medium fish to pass through to the turbines but not fish larger than 900-1000mm in length which would be impinged on the trash racks (Stuart *et al,.* 2008). 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 physical and 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

4 Survival of young.

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 were longer than one meter (Figure 3-1) (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.

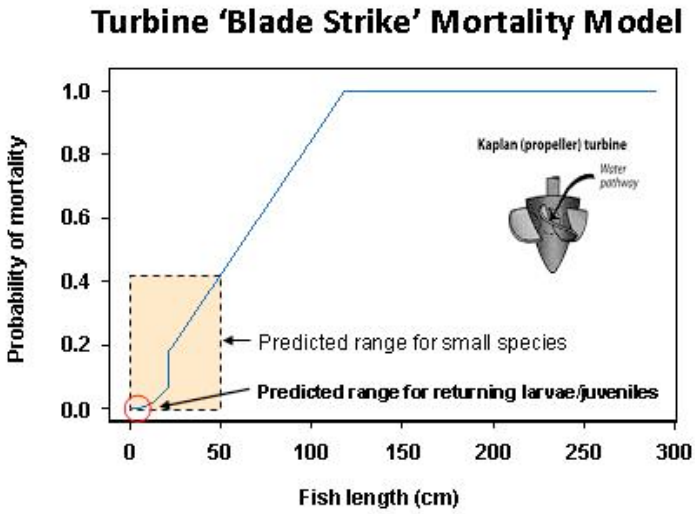



*Figure 3-1. Relationship between fish length and the probability of mortality due to a blade strike Source: Adapted from Halls and* Kshatriya, 2009.

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).

## Sediments

### Sediment/Nutrient Depletion and Alteration

For sediments and nutrients, the effects of dams and reservoirs are two-fold. They both alter the natural transport 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 vast majority mobilized during the largest storm events) and are then deposited in the floodplains, which keeps these habitats replenished and nourished. But, reservoirs are sinks for sediments and nutrients. When the inflowing water meets the still water of the reservoir, the velocity abruptly declines, causing sediments to drop out of suspension.

Reservoirs trap all the bedload (the coarse sand and gravel moving along the river bed) and a percentage of the suspended load (the finer sand and sediment carried in the water column, which is held in suspension by the current). 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 capacity to annual inflow of water (Brune, 1953). The reach downstream of the dam is characterized by sediment-starved, or 'hungry' water, which erodes the bed and banks, thereby regaining some of the former sediment load (Kondolf, 1997). These erosive flows commonly induce incision, coarsen the bed, and fundamentally altering aquatic food webs (Kondolf *et al*., 2012; Power *et al*., 1996).

## Why Sediments are Important

Sediment is essential to maintain the complex channel and floodplain morphology that provides the diversity of habitats needed by different species and life stages of fish and other aquatic biota. 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. Fine sediment deposited from overbank flows provide soil fertility for natural riparian forests and for floodplain agriculture.

The sediments carry the nutrients that fuel the aquatic food chain. Many nutrients are associated with fine sediment (organic particles, clay, and silt). These nutrients are essential to support the food web of the river and productivity of the nearshore coastal fisheries. In the Mekong, productivity of the system depends on these transported nutrients, especially in the delta area and coastal region.

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 2m above sea level and 37,000 $km^2$ is regularly flooded (Syvitski *et al.*, 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 *et al*., 2009).

Given that modelling scenarios of the delta with sediment reductions of 80% or more all had reductions in aggradation rates of more than 88% (Rubin, Kondolf and Carlin, 2014), under a full-build scenario in the Mekong basin, we expect an almost complete cessation of sediment deposition at the delta (Kondolf *et al.*, 2012). As such, land erosion and subsidence will be essentially uncontrolled and, combined with sea-level rise, would leave be few options available to mitigate coastal retreat (Rubin, Kondolf and Carlin, 2014). The combination sediment reduction and a 0.46 meter rise in sea level by 2100 would lead to a 50% increase in saltwater intrusion, with profound consequences for coastal populations in Vietnam (Chen *et al*., 2012; Syvitski *et al.*, 2009).

Sediment capture is also fatal to the reservoir itself. As the silt accumulates over time, the reservoir loses its storage capacity and thereby its ability to control variable flows for power production (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), but to date there are few examples of successful management. With many dams reaching the end of their original design life (Doyle *et al*., 2003), accumulation of sediment is becoming an increasingly important issue in reservoir management. Approximately 1% of storage volume in the world's reservoir is lost each year due to sedimentation (Morris and 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). That results in a progressive loss in hydropower generation.

### Techniques to Reduce 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.

First, 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 one.

Second, 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 that have a deep and confined channel and steep sides. And it will be most successful if it is employed relatively frequently.

Third, 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, such as the largest Sambor options, 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 Sambor Dam alternatives, as discussed below.

## References

Annandale, G., 2013. Quenching the Thirst: Sustainable water supply and climate change. CreateSpace Independent Publishing Platform. North Charleston, SC. ISBN: 1480265152.

Baird, I.G., 2011. The Don Sahong Dam. *Critical Asian Studies.* 43(2): 211-235.

Brune, G.M. 1953. Trap efficiency of reservoirs, Eos Trans. AGU, 34(3), 407–418. DOI: 10.1029/TR034i003p00407.

Chen, Y., Syvitski, J., Gao, S., Overeem, I. and A.J. Kettner. 2012. Socio-economic impacts on flooding: A 4000-year history of the Yellow River, China. *AMBIO* 41(7): 682-698. DOI: 10.1007/s13280-012-0290-5.

Cowx, I.G. 2014. Critical Issues with Migratory Fish Mitigation at Hydropower Dams. Technical Report prepared for the Natural Heritage Institute under Cooperative Agreement AID-486-11-00002 with USAID for 'Maintaining the Productivity of the Mekong River by Improving Sediment Passage and Fish Passage through Hydropower Dams in Lao and Cambodia'.

Doyle, M.W., Stanley, E.H., and Harbor, J.M. 2003. Channel adjustments following two dam removals in Wisconsin. Water Resour. Res. 39: 1–15. DOI: 10.1029/2002WR001714.

Ferguson, J.W., Absolon, R.F., Carlson, T.J., and Sandford, B.P. 2006. Evidence of Delayed Mortality on Juvenile Pacific Salmon Passing through Turbines at Columbia River Dams. *Transactions of the American Fisheries Society* **135**, 139-150.

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

ICEM. 2010. MRC SEA for Hydropower on the Mekong mainstream. Fisheries Baseline Assessment Working Paper. ICEM report to MRC.

ICOLD. 1989. Selecting Seismic Parameters for Large Dams - Guidelines. Bulletin 72. Committee on Seismic Aspects of Dam Design. ICOLD, Paris.

Jackson, D., and Marmulla, G. 2001. The Influence of Dams on River Fisheries. www.dams.org. World Commission on Dams.

Jepsen, N., Aarestrup, K., Økland, F., and Rasmussen, G. 1998. Survival of radiotagged Atlantic salmon (*Salmo salar* L.)–and trout (*Salmo trutta* L.) smolts passing a reservoir during seaward migration. *Hydrobiologia* **371**, 347-353.

Kawashima, S., Johndrow, T.B., Annandale, G.W. and Shah, F. 2003. Reservoir Conservation, vol. II, RESCON Model and User Manual, World Bank, Washington, D. C.

Keefer, M.L., Peery, C.A., Bjornn, T.C., Jepson, M.A., and Stuehrenberg, L.C. 2004. Hydrosystem, dam, and reservoir passage rates of adult Chinook salmon and steelhead in the Columbia and Snake rivers. *Transactions of the American Fisheries Society* **133**(6), 1413-1439.

Kondolf, G.M. 1997. Hungry water: Effects of dams and gravel mining on river channels. *Environmental Management* 21(4):533-551.

Kondolf, G.M., Rubin, Z.K., Minear, J.T., and Alford, C. 2012. Cumulative Sediment Reduction to the Lower Mekong River from Planned Dams. *American Geophysical Union*.

Kondolf, G.M. et al. 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents, Earth's Future, 2, 256–280, DOI: 10.1002/2013EF000184.

Larinier, M. 2001. Environmental issues, dams and fish migration. *FAO fisheries technical paper* **419**, 45-89.

Mallen-Cooper, M. 1992. Swimming ability of juvenile Australian bass, Macquaria novemaculeata (Steindachner), and juvenile barramundi, Lates calcarifer (Bloch), in an experimental vertical-slot fishway. *Australian journal of marine and freshwater research* **43**, 823-823.

Mallen-Cooper, M. 1994. Swimming ability of adult golden perch, Macquaria ambigua (Percichthyidae), and adult silver perch, Bidyanus bidyanus (Teraponidae), in an experimental vertical-slot fishway. *Australian journal of marine and freshwater research. Melbourne* **42**(2), 191-198.

Mallen-Cooper, M. 1996. Fishways and freshwater fish migration on South-Eastern Australia.

Mallen-Cooper, M. 1999. Developing fishways for non-salmonid fishes: a case study from the Murray River in Australia. *Innovations in fish passage technology*, 173-195.

Mallen-Cooper, M., and Brand, D. 2007. Non-salmonids in a salmonid fishway: what do 50 years of data tell us about past and future fish passage? *Fisheries Management and Ecology* **14**(5), 319-332.

Morris, G.L. and J. Fan. 1998. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use*. McGraw-Hill Book Co., New York.

Oldani, N.O., Baigún, C.R.M., Nestler, J.M., and Goodwin, R.A. 2007. Is fish passage technology saving fish resources in the lower La Plata River basin? *Neotropical Ichthyology* **5**, 89-102.

Palmieri, A., Farhed, S., Annandale, G. W., and Dinar, A. 2003. "The RESCON Approach: Economic and Engineering Evaluation of Alternatives Strategies for Managing Sedimentation in Storage Reservoirs." The World Bank, Washington, D.C.

Pelicice, F.M., Pompeu, P.S., and Agostinho, A.A. 2015. Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish and Fisheries* **16**(4), 697-715.

Piman, T., Cochrane, T.A., Arias, M.E., Green, A. and Dat, N.D. 2013. Assessment of flow changes from hydropower development and operations in Sekong, Sesan and Srepok Rivers of the Mekong Basin. Journal of Water Resources Planning and Management 139 (6): 723-732.

Power, M.E. *et al.* 1996. Challenges in the Quest for Keystones: Identifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems. *BioScience* (46)8: 609-620.

Pukinskis, I. and Geheb, K. 2012. The Impact of Dams on the Fisheries of the Mekong. State of Knowledge Series 1. Vientiane, Lao PDR, Challenge Program on Water and Food. Available from: https://cgspace.cgiar.org/rest/bitstreams/24817/retrieve.

Rubin, Z.K., Kondolf, G.M., Carling, P.A. 2014. Anticipated geomorphic impacts from dam construction. International Journal of River Basin Management, DOI: 10.1080/15715124. 2014.981193.

Stuart, I.G., Zampatti, B.P., and Baumgartner, L.J. 2008. Can a low-gradient vertical-slot fishway provide passage for a lowland river fish community? *Marine and Freshwater Research* **59**(4), 332-346.

Syvitski, J. P. M., A.J. Kettner, I. Overeem, E.W.H. Hutton, M.T. Hannon, G.R. Brakenridge, J. Day, C. Vörösmarty, Y. Saito, L. Giosan, and R.J. Nicholls. 2009. Sinking deltas due to human activities, *Nature Geoscience* 2(10), 681-686.

Turnpenny, A.W.H. 1998. Mechanisms of Fish Damage in Low Head Turbines: An Experimental Appraisal. In Fish migration and fish bypasses. (Eds. M. Jungwirth, S. Schmutz and S. Weiss) pp. 300-314. (Fishing News Books: Oxford, England).

39.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P. and J. Syvitski. 2003. Anthropogenic sediment retention: Major global-scale impact from the population of registered impoundments. *Global and Planetary Change* 39: 169-190.

White, R. 2001. Evacuation of sediments from reservoirs. Thomas Telford Publishing, London. 280 pp.

# 4 Original Sambor Dam Impacts

## Physical Description of the Dam and Dam Location

Sambor would be the downstream-most dam in the Lower Mekong Basin (LMB), located near Sambor village in Cambodia, between the 3S basin and the mainstream Mekong above Khone falls and the immensely productive floodplains at Tonle Sap and the Delta in Vietnam. The dam as originally proposed by China Southern Power (CSP) would be 23 meters high (difference in upstream and downstream water levels) and 18 km wide (Meynell, 2011). It would create a reservoir of 620 $km^2$ surface area and 465 $Mm^3$ of active storage (Meynell, 2011), backing water up some 82 kilometers, all the way to the 3-S confluence and the town of Stung Treng. The proposed installed capacity is 2,600 MW with 11,741 GWh of annual energy production (Meynell, 2011). Figure 4-1 shows the approximate location and cross section of proposed Sambor dam, and Table 4-1 shows some specifications. We call this alternative Sambor CSP as described in a 2008 pre-feasibility study prepared for CSP, the original Sambor Dam proponent.

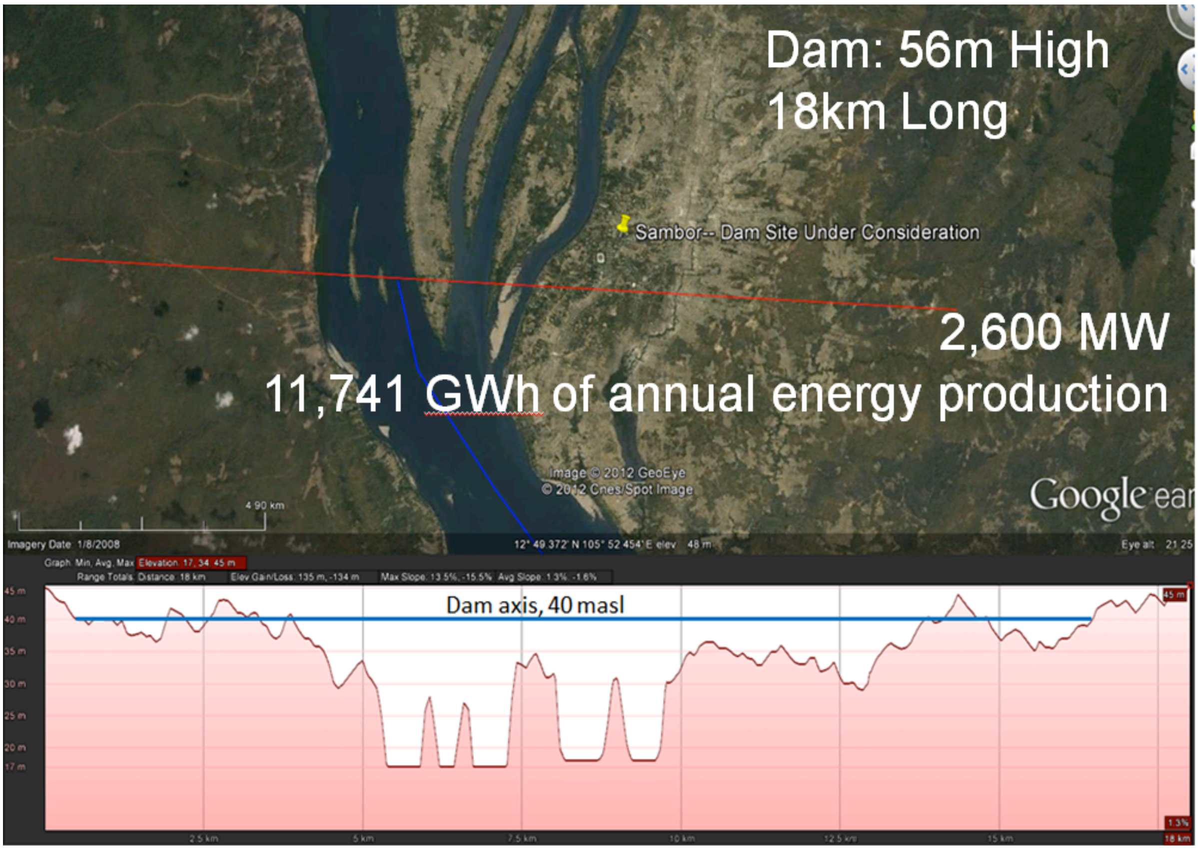



*Figure 4-1. Location of proposed Sambor dam site and cross section of the river channel (looking upstream).*

*Table 4-1. Reservoir Information of Proposed Sambor Dam (Meynell, 2011 and NHI Database).*

| Item | Units | Value |
|---|---|---|
| Total reservoir volume | mill $m^3$ | 5,206 |
| Bottom width of the dam | m | 5,000[5] |
| Top level of the reservoir | masl | 40.0 |
| Minimum bed level | masl | 17.1 |
| Available head | m | 22.9[6] |
| Reservoir length | km | 82 |
| Reservoir surface area | $km^2$ | 620.48 |
| Mean inflow | $m^3/s$ | 13,800 |
| Mean annual sediment inflow | tons/year | 81,000,000 |

## Location in River Corridor that Experiences One of the Greatest Migration of Fish Biomass in the World

Migratory fish form the majority of the fishery of the lower Mekong Basin and Sambor CSP is located between the spawning grounds upstream and the nursery habitats downstream (Figure 4-2). A huge volume of fish biomass pass through this river corridor every year, and that migration sustains the extraordinarily productive fishery of the lower Mekong, making the Sambor site the least suitable place for a physical barrier in the Mekong Basin. Thus, Sambor CSP poses extremely high risks for fish populations and food-security for the region.

If the original Sambor CSP Dam were built together with the other mainstream dams that have been proposed, "forecasted total fish losses by 2030 would amount to 550,000 to 880,000 ton compared to the baseline year 2000 (a 26-42% decrease). This is a loss of approximately 340,000 tons compared to a situation in 2030 without mainstream dams." (Pukinskis and Geheb 2012 *cited in* ICEM 2010). This also threatens biodiversity, sustainable livelihoods and food security in the region.

Upstream fish passage at the dam needs to accommodate adult fish migrating upstream to spawn, as well as juvenile fish dispersing upstream. Downstream passage needs to accommodate larvae drifting downstream as well as adult fish migrating back downstream to feeding area and refuge areas such as deep pools. A unique habitat of the Mekong River are the deep pools, which provide refuge for many species during the dry season. The impounded water of the proposed CSP Sambor dam would inundate numerous deep pools and change the hydrodynamics (variation in hydraulics) from a pool in a complex flowing river to a deep section of a larger reservoir. The ecological value of these key fish habitats would be lost due to the reduction in complexity. The low water velocity of the reservoir would lead to sedimentation of these pools and loss of these habitats. Despite the added depth provided by the reservoir it does not provide the refugia habitat of deep pools in a flowing river.

5 Top width of reservoir is 18,000 km.

6 The rated head range from 16.5m to 23m in the data sources available to Natural Heritage Institute.

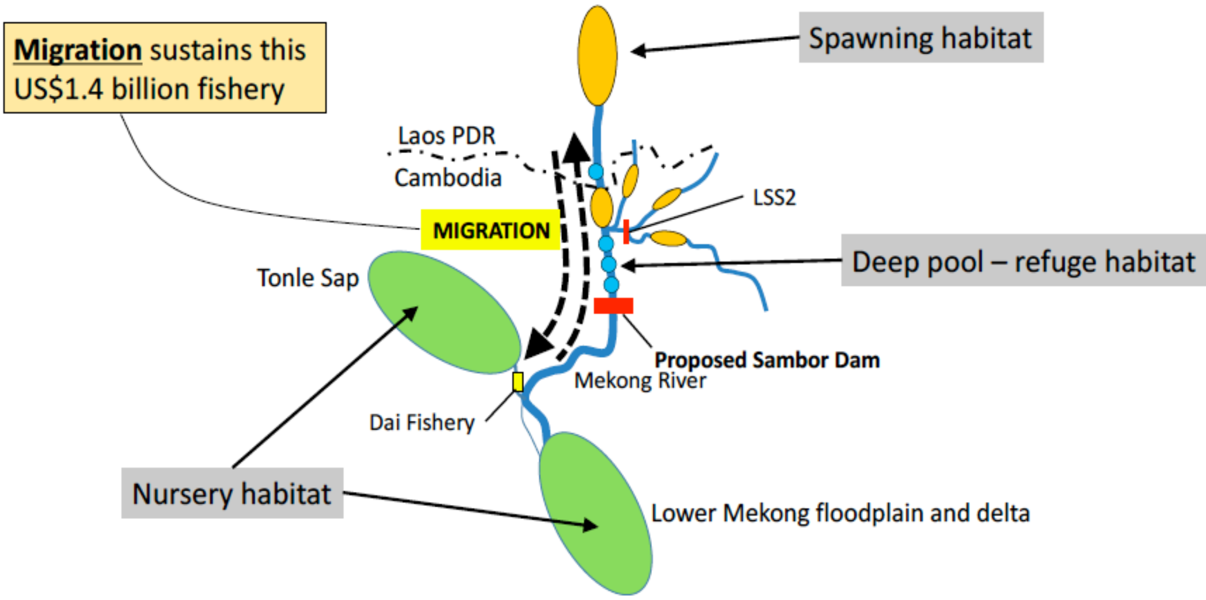



*Figure 4-2. Location of proposed Sambor Dam (CSP) depicted by small red rectangle; located in the key migratory fish corridor between the nursery habitats of the Tonle Sap and lower Mekong floodplain, and spawning habitats upstream.*

Sambor CSP creates an 82km long reservoir that will inundate spawning habitats. Some species will still spawn in the reservoir, but the majority of migratory riverine species require flowing water to spawn and that habitat would be permanently lost within the reservoir.

As proposed, Sambor CSP does not provide adequate measures for fish passage either upstream or downstream. The budget of $9 million for "fishway engineering", as proposed by CSP, is completely inadequate; typically, over $200 million would be required at a large dam solely for upstream passage. There is no specific indication that fish screens would be provided to divert fish from the turbine intakes.

Fish passage is very challenging at high dams in rivers with high discharge. In the Mekong, it may be possible to engineer fishpasses (also called fishways or fish ladders) for upstream migration for a 23m high dam, but to be effective it would need to be very large to accommodate the 10% of flow needed for fish attraction. It would also need to have a low gradient to pass the huge migratory biomass. There would also need to be three of these fishpasses, at the powerhouse and at each side of the spillway, where migratory fish congregate. The cost of such features would be relatively high. However, cost feasibility is a separate issue from engineering feasibility.

For downstream passage, adult fish could conceivably be screened and diverted at the turbines at considerable expense, and the turbines could be custom designed (noting that there are none currently available off-the-shelf) to reduce mortalities of adults, juveniles and larvae; but neither has been achieved in the Mekong River and both would require new designs and new technology with uncertain and untested performance.

The critical impact of Sambor CSP, however, and one that **cannot be mitigated**, is that effective downstream passage is required for larvae drifting through the reservoir. To survive, the larvae must drift through the reservoir – an 82km long body of nearly static water – the entire distance to the point of discharge at the turbines and/or the spillway. But the larvae cannot drift through the static water of the reservoir and will die. These larvae will then not return back down to the floodplains at Tonle Sap and the Delta where they mature into adult fish. The larval mortality of riverine species is likely to be close to 100%. This has been the experience with large hydropower dams in South America (e.g. Agostinho *et al*., 2007; Pelicice and Agostinho, 2008; Pompeu *et al*., 2011; Pelicice *et al*., 2015). This represents the gravest risk for fish populations in the Lower Mekong Basin and could likely lead to the collapse of the fishery.

Maintaining larval drift through the reservoir by maintaining water velocities can potentially be achieved by substantially lowering the reservoir level (e.g. by 10m) to re-create the flowing river, but it is extremely unlikely that an economically viable Sambor CSP could be operated to assure these minimum velocities could be maintained to keep the larvae in suspension.

Importantly, the cost of upstream passage, downstream screens at the turbines, the usage of >10% of flow for fish passage, and the operations to allow for larval drift, are not included in the Sambor CSP economic analysis.

## Impacts on Sediment

### Sediment Capture

Sambor CSP is not expressly designed for passage of sediment and would in effect capture most of the sediment recorded at Kratie. The dams already constructed in the Lancang Cascade (China), in the Sre Pok and Se San Rivers and in other tributaries to the Mekong River have significantly reduced the sediment load in the LMB. The annual average sediment load is currently estimated at between 72.5 Mt/yr (Koehnken, 2014) and 90 Mt/yr (this study), compared to 160 Mt/yr prior to development of dams (Kondolf *et al*., 2014).

The cumulative reduction in sediments and nutrients from these dams, and projected future dams such as Sambor CSP that are not designed or operated to discharge sediments, is shown in Figure 4-3 and Figure 4-4 below.

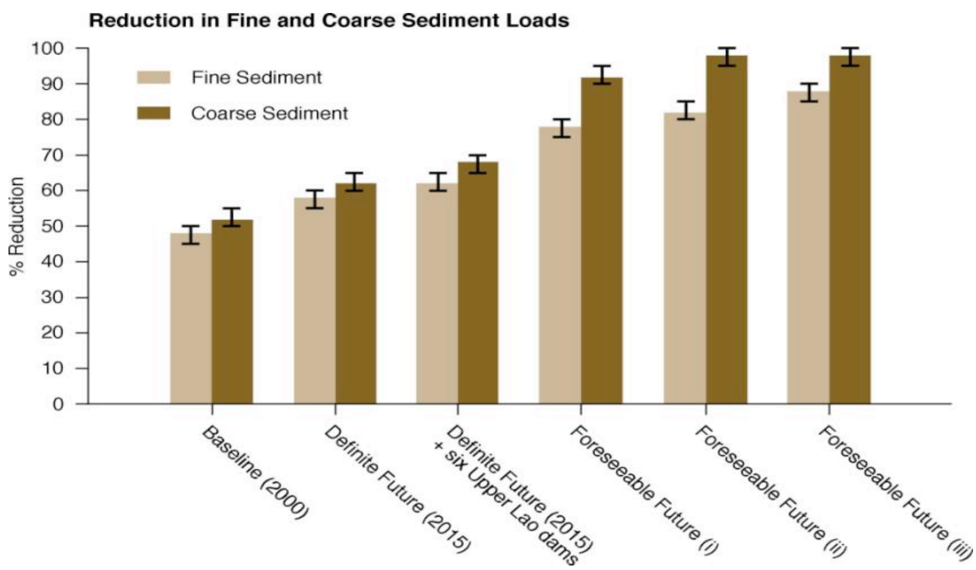



*Figure 4-3. Indicative estimates of future reductions in supply of fine & course sediment to the Mekong Delta due to sediment trapping in reservoirs with no mitigation measures. Source: Thorne et al., 2013.*

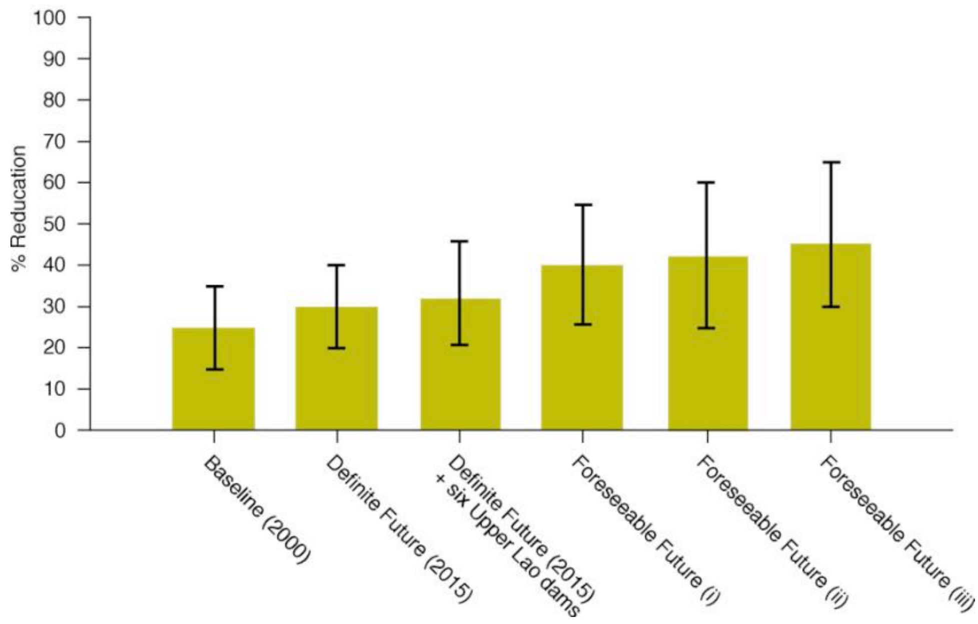



*Figure 4-4. Indicative estimates of future reductions in supply of nutrients to the Mekong Delta due to sediment trapping in reservoirs with no mitigation measures. Source: Thorne et al., 2013.*

The Mekong Delta Study (MDS) in 2015 indicated that sediment capture by the originally proposed Sambor dam would have been greater than 50%, which is deemed very high (HDR & DHI, 2015) and would have a significant impact on the Mekong Delta and biodiversity. This can be seen in Figure 4-5 below.

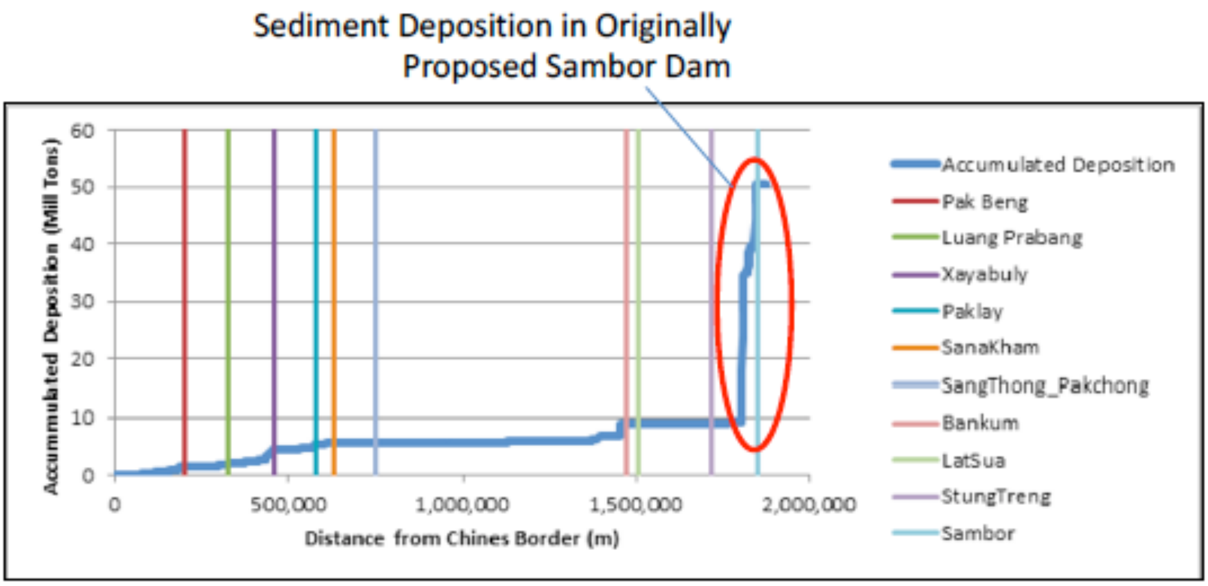



*Figure 4-5. Sediment capture at the original Sambor Dam. Source: HDR & DHI, 2015 (MDS).*

### Impacts on the Delta

There is widespread agreement in the literature that hydropower dams on the Mekong mainstream significantly affect the sediment and nutrient budget of the Mekong delta (Xue *et al.*, 2011; Fan *et* *al.,* 2015). These dams, together with uncontrolled sand mining, will aggravate the on-going erosion of the delta, and negatively impact the nutrient supply to the Mekong rice bowl. As noted in the recent literature review on the subject (Anthony *et al*., 2015), several modeling efforts aimed at assessing the response of the floodplain hydrology and sediment dynamics in the delta to anthropogenic and environmental changes have identified the critical role of hydropower development in further aggravating the combined effects of rise of the sea-level rise and the subsiding of the delta due to erosion of the land mass (see Manh *et al.,* 2015). Operation of all the planned hydropower projects on the Mekong will reportedly increase the sediment-trapping efficiency of dam reservoirs from 11–12 Mt/year to 70–73 Mt/year (Kummu *et al.*, 2010). Another study suggests that a cumulative sediment reduction of 51% and 96% to the delta will occur under a 'definite future' scenario of 38 dams (built or under construction) and full construction of all planned dams, respectively (Kondolf *et al*., 2014).

The prospects for the Mekong delta area as a consequence of sediment deprivation combined with sea level rise are grim. In a scenario of high greenhouse gas emissions, sea water levels could rise by almost a meter over the level observed in 1980-1999: most of the provinces in the Cuu Long River area of the delta would be submerged or face serious saline water intrusion (MoNRE, 2012). Simulations show loss of rice production in 10 provinces in the Mekong Delta hypothesized as the most affected areas, where 38% of land will be submerged under sea water, of which 31% is agricultural land, mainly allocated for rice production (Trinh *et al*, 2014). Results show that these areas will lose 7.6 million tons of rice per year (so almost a third of the total Mekong Delta rice production noted in Table 4-2). According to a recent summary of damaged rice areas in the Cuu Long Delta, water with a salinity level > 4% has intruded up to 93 km inland, and affected thousands of hectares of high-yield rice production (Directorate of Water Resources, 2016).

*Table 4-2. Production of paddy in Vietnam.*

| | | **2010** | **2012** | **2013** | **2014** | **2015** |
|---|---|---|---|---|---|---|
| Vietnam Total | 1000 tons | 40,006 | 43,738 | 44,039 | 44,975 | 45,215 |
| Mekong River Delta | 1000 tons | 21,595 | 24,320 | 25,021 | 25,244 | 25,699 |
| as % of Total | % | 54.0% | 55.6% | 56.8% | 56.1% | 56.8% |

*Source*: 2015 Statistical Yearbook of Vietnam, Table 172.

Figure 4-6 shows the area of the delta that is projected to be lost to sea level rise, salinization and storm surges by the end of this century due to global warming, depicted in blue. These impacts will be greater with less sediment from upstream and even the survival of the remaining areas is dependent on these sediments.

**Area Inundated in the Mekong Delta (Sea Level Rise = 1m)**
**(Source: MRC Technical Paper No. 24, September 2009)**

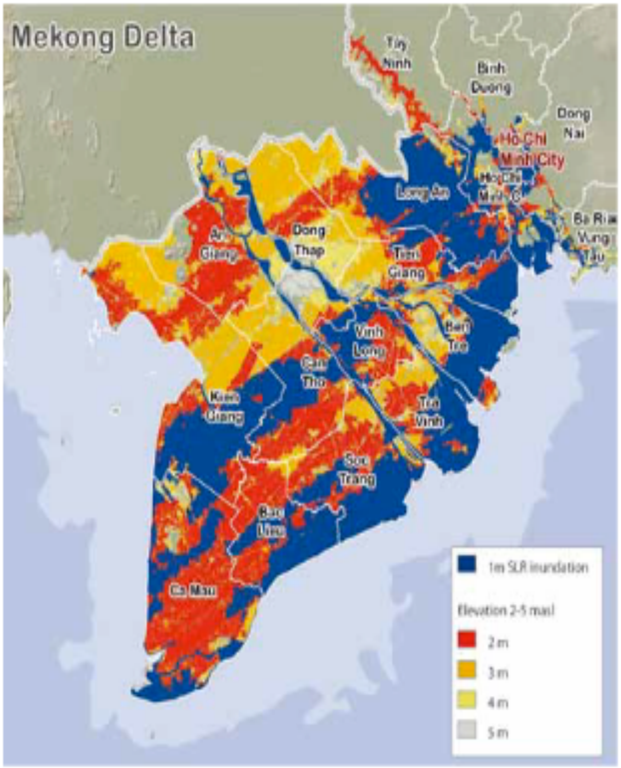
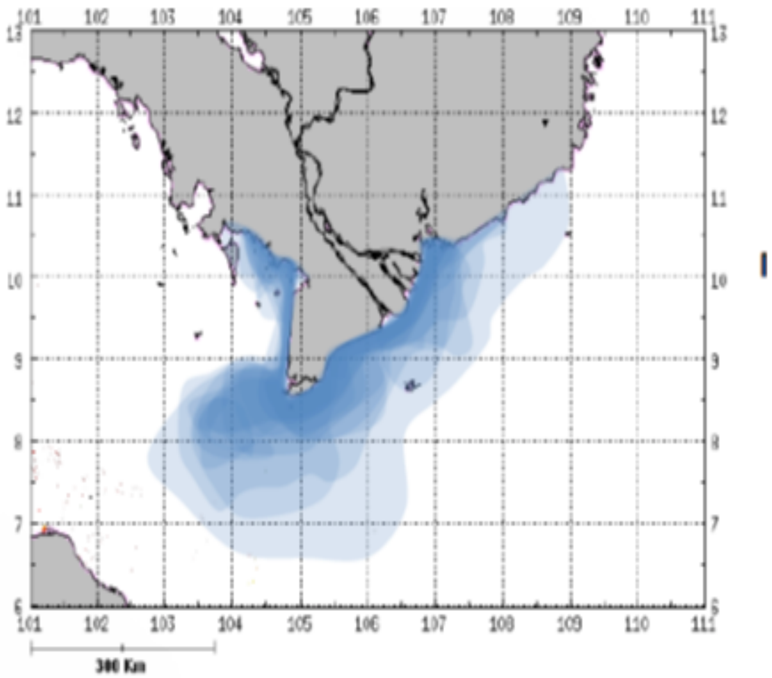



*Figure 4-6. Area inundated in the Mekong Delta region of Vietnam due to Sea Level Rise. Source: Carew-Reid, 2007 cited in MRC, 2009.*




Source: Mangin A., Loisel H. 2012 Measuring the colour of water using remote sensing to assess nutrient and sediments movement on the coasts. WWF workshop on sediment transport and discharge. Phnom Penh, 22-23 March 2012

*Figure 4-7. sediments and nutrients discharged into the near shore environment at the mouth of the Mekong River in the South China Sea. Source: Mangin and Loisel, 2012.*

### Impacts on Marine Fisheries

Figure 4-7 shows a satellite image of the plume of sediments and nutrients discharged into the coastal environment at the mouth of the Mekong River in the South China Sea. The influence of sediments from the Mekong is very widespread. This input of nutrients drives the off-shore marine fishery of Vietnam, which is as important for fish harvest as the freshwater fishery of the Mekong.

### Impacts on Tonle Sap

The consequences of sediment capture at Sambor CSP are not confined to the Delta. The Tonle Sap fishery is also at risk. Sediment capture at Sambor CSP would deplete the flow of sediments and nutrients into the Tonle Sap Great Lake, where the productivity of this fishery is directly correlated to the total flow through the lake, which also reflects the total sediments and nutrients from the Mekong inflows and the Tonle Sap catchment (Figure 4-8).

### Summary

In short, the Sambor CSP would present a major risk to the Tonle Sap fishery and aggravate the already serious threats to the food security of the Delta; hence raising strong opposition from the Government of Vietnam.

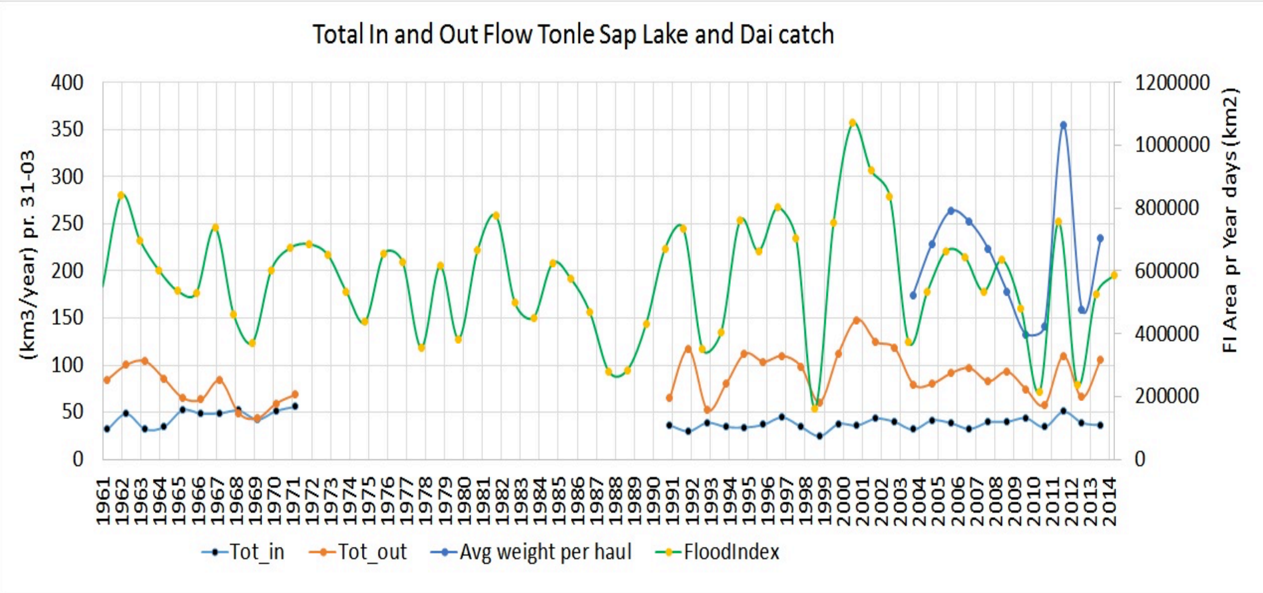



*Figure 4-8. Tonle Sap Lake total in and out flow, Flood Index and Dai catch by weight of all species. Note the constant inflow is around 40km$^3$/Y. Relating the catch weight per haul to the flood index and total flow gives high correlation coefficients. For the period 2004-2014 the coefficients are 0.78 and 0.81 (Jensen, 2016).*

## Removal of Accumulated Sediment at Sambor CSP is Not Feasible with Any Sediment Management Technique[7]

Sambor CSP is not designed and could not be operated to discharge sediment. However, the NHI team investigated the potential for modifying the design and operation of the dam to accomplish

7 Information and figures (unless noted otherwise) in this section are drawn from a report on sediment passage (November 2012) prepared for NHI by Golder Associates, and 'Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents' by Kondolf et al., 2014 prepared in conjunction with the NHI Mekong project.

this objective. Multiple sediment management techniques were considered during this preliminary evaluation. They included drawdown flushing (Atkinson, 1996), sluicing, density current venting (Morris and Fan, 1998), dredging, dry excavation, hydrosuction sediment removal system (HSRS) (Hotchkiss and Xi, 1995), a passive sediment collector, and bypassing. Each of these techniques are defined below. The net conclusion of this analysis is that NONE of these techniques would be practical or effective at Sambor CSP. In sum the sediment capture cannot be mitigated.

### Drawdown Flushing

During drawdown flushing a reservoir is brought to the original river-like condition by releasing reservoir flows through bottom outlets. The objective of drawdown flushing is to erode and remove previously deposited sediment from a reservoir and discharge it downstream. This is usually executed during a low-flow period, preferably just prior to the monsoon. By implementing drawdown flushing just prior to the monsoon allows the reservoir to be filled with water once drawdown flushing is complete.

It is important for flushing flows to freely discharge through the low-level outlets without damming; therefore, the need to implement drawdown flushing during low-flow periods. Sediment is eroded by water flowing in single or multiple channels through the sediment that previously deposited in the reservoir. The success of sediment removal by flushing depends on the reservoir size, geometry (such as width of the reservoir, the valley side slopes and longitudinal slope), location of the low-level outlets, the type of sediment deposited in the reservoir, and the magnitude of the flushing flows. Atkinson (1996) defines the reservoir long-term capacity ratio (LTCR) and sediment balance ratio (SBR) as the reservoir flushing criteria. LTCR is the ratio of the reservoir's long-term capacity to its original capacity and SBR is the ratio of sediment mass flushed from the reservoir to the sediment mass deposited in the reservoir over the period between flushing events.

### Sluicing

Sluicing is a sediment management technique implemented during floods, i.e. during the monsoon. The objective of sluicing is to minimize the amount of sediment that will deposit in a reservoir. This is done by creating flow conditions in a reservoir that are characterized by high sediment carrying capacity. In the ideal case, which is seldom accomplished, the sediment transport capacity in the reservoir will be equal to the sediment transport capacity of the river carrying sediment into the reservoir. Should it be possible to accomplish this goal the amount of sediment carried into a reservoir from upstream ($S_1$) will equal the amount of sediment discharged downstream ($S_2$), with no net amount of sediment depositing in the reservoir (Figure 4-9).

The sediment transport capacity in the reservoir is maintained at a high level by drawing down the water surface elevation at the dam as much as possible while flood waters flow through the reservoir. By doing so, the energy slope of the water flowing through the reservoir is increased, thereby maximizing the sediment transport capacity of those flows. The water surface elevation at the dam is drawn down by using low- and / or mid-level gates at the dam. It is obviously not possible to draw down the flows in a reservoir to the same extent required by drawdown flushing. The reason for this is that sluicing is implemented during high flows (the monsoon) during which time the rate of flow into the reservoir is normally larger than the free-flow discharge capability of low-level outlets.

Sluicing is best implemented in narrow reservoirs, located in relatively steep rivers where monsoon flow volumes are large relative to the reservoir volume. Successful flushing also requires provision of enough large mid- and low-level outlets in the dam that will allow the water surface elevation at the dam to be drawn down significantly during flood flows characteristic of the monsoon. Dams that are designed with the ability to significantly draw down the water surface elevation at the dam during the monsoon have a much greater potential to successfully transport large amounts of sediment through the reservoir without deposition; thus fulfilling the purpose of sluicing.

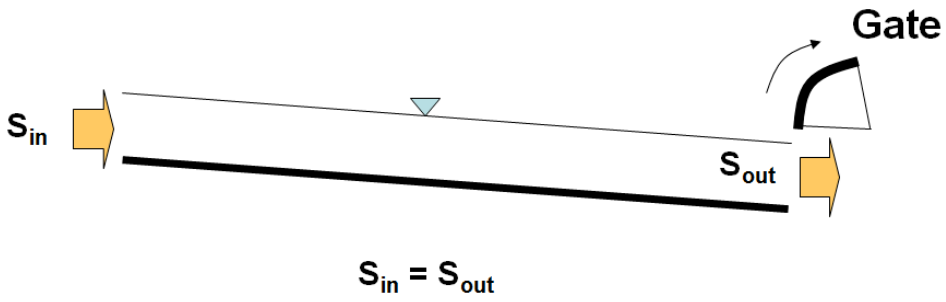



*Figure 4-9. Concept of sediment pass-through by sluicing.*

## Density Current Venting

Density Current Venting takes advantage of the differences in densities between the incoming flow and the impounded water to convey sediment through a reservoir without deposition. Flows with high sediment concentrations flowing into a reservoir have high densities compared to the water contained in a reservoir, characterized by low sediment concentrations. This causes the incoming high sediment-laden flow to plunge into the reservoir pool and travel along the bottom of the reservoir. The availability of a low-level outlet at the dam provides the opportunity to discharge the sediment carried by the density current downstream of the dam. Success of this technique depends on the reservoir size and geometry, the slope of the reservoir bed, and the sediment characteristics (i.e., concentration and size distribution of the sediment flowing into the reservoir). Figure 4-10 illustrates the concept of sediment pass-through by density current venting.

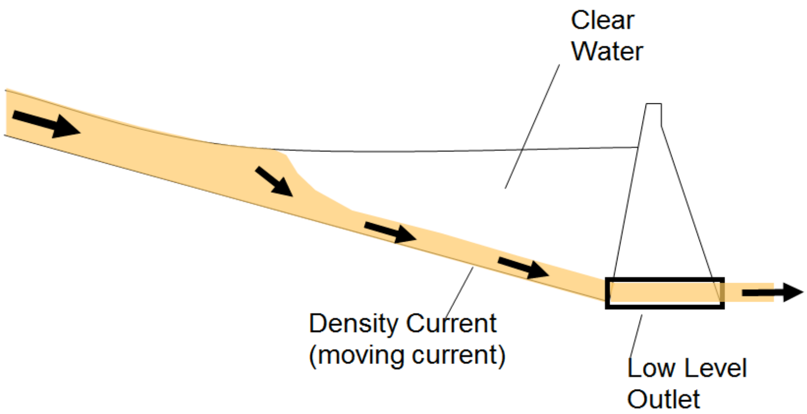



*Figure 4-10. Concept of sediment pass-through by density current venting.*

### Dredging and Dry Excavation

Dredging is a sediment removal technique that uses pump(s) to create a suction head at the bottom of the reservoir where the sediment is deposited. The sediment that is removed from the reservoir bed by suction is then slurried through a pipeline and deposited outside the reservoir. Dry excavation removes sediment from the emptied reservoir using heavy equipment.

Feasibility of sediment removal by dredging depends upon the size of the reservoir and feasibility of dry excavation upon its accessibility for the heavy equipment. The feasibility of using dry excavation as a sediment management technique also depends whether it is possible to empty the reservoir for an extended period of time.

### Hydro-suction Sediment Removal System

Hydro suction sediment removal system (HSRS) is similar to hydraulic dredging, except for the fact that the water head between the reservoir water level and the tail water level downstream of the dam is utilized to create the suction head (instead of using pumps, as is the case with hydraulic dredging). Feasibility of the system depends on the size of the reservoir, especially the length of the reservoir (i.e., 3 km is considered a threshold). Figure 4-11 demonstrates the concept of HSRS sediment removal.

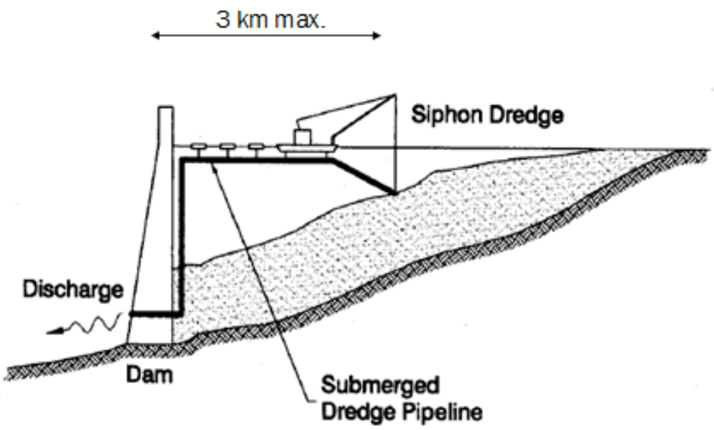



*Figure 4-11. Concept of sediment removal by HSRS.*

### Passive Sediment Collector

The passive sediment collector is an inline structure that collects bed load in its hopper. The sediment is removed from the hopper by using the available head in the flowing water. This system is usually applicable to small river systems (see: http://streamside.us/wp-content/uploads/2016/04/Collector_ProductSheet_0516.pdf/).

### Bypassing

Bypassing detours high sediment laden flows through a secondary channel or through a tunnel from upstream of the reservoir. Figure 4-12 illustrates the concept of sediment exclusion by bypassing.

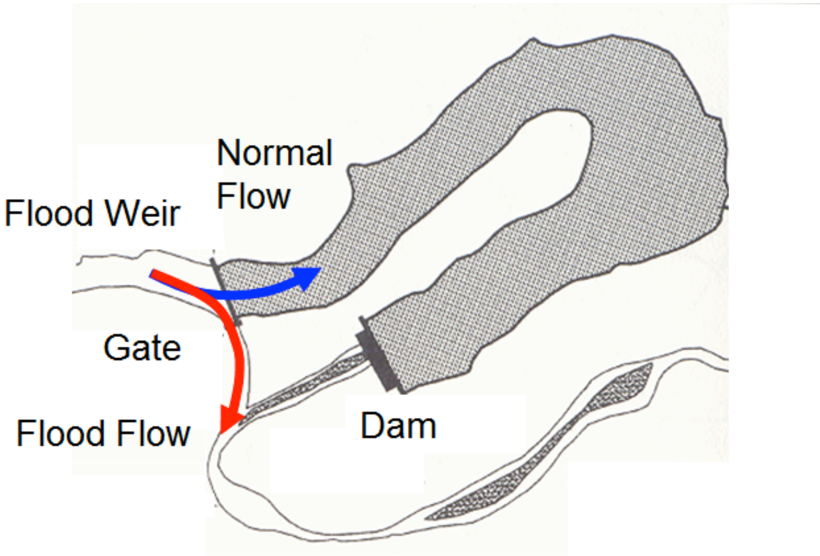



*Figure 4-12. Concept of sediment exclusion by bypassing.*

## Sediment Management Assessment

The Reservoir Conservation (RESCON) model (Palmieri et al., 2003) was applied to assess the feasibility of drawdown flushing, dredging, HSRS, and excavation, using the data in Table 4-1 above. The feasibility of other methods was assessed by hand calculation and engineering judgment. Flow and sediment data and the information on reservoir type and size were obtained from various sources (Meynell, 2011; ICEM, 2009; Hydropower Database, 2011). Additionally, Golder Associates obtained topographic information from Google Earth and from the University of Florida, Digital Collections (http://ufdc.ufl.edu/UF00075733/00001/thumbs) (Accessed on 11/07/2012) and developed site-specific topography at 5-m contour intervals.

### Results

*Table 4-3* presents Long-term capacity ratio (LTCR) and Sediment balance ratio (SBR) values, determined using the RESCON model, for various flushing flow magnitudes at the proposed Sambor Dam.

**Table 4-3. Proposed Sambor Dam- Drawdown Flushing Feasibility.**

| **Flushing Flow** | **LTCR** | | **SBR** | |
|---|---|---|---|---|
| | Result | Criterion | Result | Criterion |
| Average flow (13,800 $m^3$/s) | 0.13 | >0.35 | 1.78 | >1.0 |
| 1.5 times average flow | 0.16 | | 3.01 | |
| 2 times average flow | 0.19 | | 4.37 | |

LTCR and SBR are two indicators to determine drawdown flushing feasibility. LTCR, which is the ratio of the eroded valley area to the total valley area just upstream of the dam is a proxy for estimating the percentage of the original reservoir volume available in the long-term, when the sedimentation in a reservoir reaches equilibrium. RESCON documentation recommends a minimum value of LTCR as 0.35 for flushing to be feasible. SBR is the ratio of the sediment transport capacity of the flushing flow and the total amount of sediment discharging into the reservoir between drawdown flushing events. The recommended minimum value of SBR is 1.0.

The results in Table 4-3 indicate that although the sediment transport capacity of the average flow is high enough to transport the annual amount of sediment through the reservoir, it is not geomorphologically possible to remove the deposited sediment. The reason for this is that the expanse of the deposited sediment upstream of the dam will be much wider than the width of a channel that can be eroded into the deposited sediment. The LTCR, which represents the relative amount of deposited sediment that can be removed over the long term (as a decimal), is very low (0.13 to 0.19). This indicates that only about 13% to 19% of the original reservoir volume can be maintained in the long-term and that drawdown flushing is not a viable approach to evacuate the majority of the deposited sediment. Dredging, hydrosuction, inline sediment removal or dry excavation are not feasible because of the size of the reservoir (see Table 4-4).

The amount of data (i.e., sediment concentration and particle size distribution data) available to evaluate the feasibility of density current venting is inadequate. However, given the width and length of the reservoir, the anticipation is that density current venting may not be a practical sediment removal option for the proposed Sambor Dam.

Sluicing, not assessed, remains a potentially feasible solution, but it would involve a major sacrifice in hydropower output if found viable, and is unlikely to be implemented in practice for economical and operation reasons.

*Table 4-4. Feasibility of sediment management techniques.*

| Technique | Feasible? |
|---|---|
| Dredging | No |
| Hydrosuction (HSRS) | No |
| Dry Excavation | No |
| Sluicing | Unlikely |
| Bypassing | No |
| Drawdown Flushing | No |

### Cumulative Sediment Capture from Mainstream Dams—Sediment Management Upstream Nullified by Sambor

By virtue of its position downstream on the mainstem Mekong and by its shape as a wide reservoir creating a lake, the Sambor CSP Dam (as originally proposed) would trap about 50% of whatever sediment load is delivered to that point from upstream. Thus, even if sustainable sediment management were implemented in dams upstream in the basin, the benefits of these actions would be largely lost if the sediment were to be trapped in the Sambor CSP Dam.

### Sediment Management and Downstream Habitats

River sediment in the lower Mekong enables the high productivity of both the perennial aquatic habitats and the ephemeral terrestrial floodplains, but a key feature is the season of transport and deposition. A seasonal deposition of sediment, such as a pulse of sediment in the dry season, can cause high impacts on fish habitats downstream by smothering spawning and feeding habitats. The sediment management techniques described above vary in their extent that they accommodate the same seasonality of transport and deposition. We have not discussed the environmental implications of sediment management as the techniques are not feasible or practical for Sambor CSP, but we note, for example, that drawdown flushing potentially has the highest impact on downstream habitats while sluicing in the wet season would have the least.

## Summary – Sambor CSP Dam Option

*Text Box 4-1. Major Impact on Fish Migration.*

**Summary:**

- The critical impact of Sambor CSP on fish populations, and one that **cannot be mitigated**, is that fish larvae cannot drift – an essential part of the life cycle - through the static water of the 82km long reservoir; and most species will die.
- Effective upstream or downstream fishpasses not included in the Sambor CSP design.
- 82 km of static would inundate spawning grounds for many species.
- Extreme decline for migratory river fish.
- **Catastrophic decline (e.g. >80%) of fish productivity.**

## References

Agostinho, A.A., Marques, E.E., Agostinho, C.S., de Almeida, D.A., de Oliveira, R.J. and de Melo, J.R.B., 2007. Fish ladder of Lajeado Dam: migrations on one-way routes? *Neotropical Ichthyology* 5(2): 121-130.

Anthony, E., G. Brunier, M Besset, M Goichot, P. Dussouillez & Van Lap Nguyen, 2015. Linking rapid erosion of the Mekong River delta to human activities. *Nature Scientific Reports*, October 2015.

Atkinson, E. 1996. *The Feasibility of Flushing Sediment from Reservoirs*, TDR Project R5839, Rep. OD 137. HR Wallingford.

Directorate of Water Resources. March 2016. Summary of damaged rice area in cuu Long Delta in 2016 (Updates to March 9, 2016). Vietnam Ministry of Agriculture and Rural Development. Available from: http://en.wrd.gov.vn/News/catid/85/item/2678/summary-of-damaged-rice-area-in-cuu-long-delta-in. (Accessed on 7 June 2017).

Fan, H., He, D., and Wang, H. 2015. Environmental consequences of damming the mainstream Lancang-Mekong River: A review. *Earth Science Rev*iew 146, 77–91.

HDR and DHI. 2015. Study on the Impacts of Mainstream Hydropower on the Mekong River (Mekong Delta Study) – Final Report. Ministry of Natural Resources and Environment, Government of Vietnam.

Hotchkiss, R. H., and Xi, H. 1995. Hydrosuction Sediment Removal System (HSRS): Principals and Field Test. J*ournal of Hydraulic Engineering* 121(6): 479-489.

Hydropower Database: http://www.3sbasin.org/3SsDB/DB_HY/index.php?table_name= hydropower (Assessed in September/October 2011).

ICEM, 2009. MRC SEA for Hydropower on the Mekong River Mainstream, Volume I—Inception Report. International Center for Environmental Management (ICEM) report to MRC.

ICEM. 2010. MRC SEA for Hydropower on the Mekong River Mainstream. Fisheries Baseline Assessment Working Paper. International Center for Environmental Management (ICEM) report to MRC.

Jensen, E.D. 2016. Dai fisheries 1994-2014. Report for the Natural Heritage Institute.

Koehnken, L. 2014. Discharge Sediment Monitoring Project (DSMP) 2009-2013: Summary and Analysis of Results, Mekong River Commission. Vientiane, Lao PDR.

Kondolf, G.M. et al. 2014. Sustainable sediment management in reservoirs and regulated rivers: Experiences from five continents, *Earth's Future* 2, 256–280, DOI: 10.1002/2013EF000184.

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

Mangin, A., and Loisel, H. 2012 Measuring the colour of water using remote sensing to assess nutrient and sediments movement on the coasts. WWF workshop on sediment transport and discharge. Phnom Penh, 22-23 March 2012.

Manh, N. V. *et al*. 2015. Future sediment dynamics in the Mekong Delta floodplains: Impacts of hydropower development, climate change and sea level rise. *Global & Planetary Change* 127, 22–23 (2015).

Meynell, Peter-John. 2011. Mainstream Hydropower Dams in Cambodia and their Environmental Impacts (Report for IFREDI).

Morris, G.L. and J. Fan. 1998. *Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs and Watersheds for Sustainable Use*. McGraw-Hill Book Co., New York.

MRC. 2009. Adaptation to climate change in the countries of the Lower Mekong Basin: regional synthesis report. MRC Technical Paper No. 24. Mekong River Commission, Vientiane. Pg. 21.

Palmieri, A., Farhed, S., Annandale, G. W., and Dinar, A. 2003. "The RESCON Approach: Economic and Engineering Evaluation of Alternatives Strategies for Managing Sedimentation in Storage Reservoirs." Reservoir Conservation. Vol. 1. The World Bank, Washington, D.C.

Pelicice, F.M. and Agostinho, A.A. 2008. Fish-Passage Facilities as Ecological Traps in Large Neotropical Rivers. *Conservation Biology* 22(1): 180-188.

Pelicice, F.M., Pompeu, P.S. and Agostinho, A.A. 2015. Large reservoirs as ecological barriers to downstream movements of Neotropical migratory fish. *Fish and Fisheries.* 16(4): 697-715.

Pompeu, P.S., Nogueira, L.B., Godinho, H.P. and Martinez, C.B. 2011. Downstream passage of fish larvae and eggs through a small-sized reservoir, Mucuri river, Brazil. *Zoologia.* 28(6): 739-746.

Thorne, C., Annandale, G., Jensen, J., Jensen, E., Green, T., and Koponen, J. 2013. "Implications of Planned Mainstream and Tributary Dams in the Lower Mekong Basin for Future Supplies of Sediment and Sediment-related Nutrients to the Mekong Delta".

Trinh, M.V., Loan, B.T.P., Hang, V.T., Lien, L.T. and Them, L.T.T. 2014. Climate change scenarios for the study of regions and their impacts on rice productions with respect to droughts and salinity identified. Project report for "Climate change and impacts on rice production in Vietnam: Pilot testing of potential adaptation and mitigation measures." Ministry of Foreign Affairs and the Royal Norwegian Embassy, Hanoi. Available from: http://www.bioforsk.no/ikbViewer/Content/111855/D%201.1%20Climate%20Scenarios%20and%20impacts%20on%20rice%20production.pdf

Vietnam Ministry of Natural Resources and Environment (MoNRE). 2012. *Vietnam climate change and seas level rise*.

Xue, Z., Liu, J. P. and Ge, Q. 2011. Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: connection to dams, monsoon, and ENSO. *Earth Surface Process and Landforms* 36, 296–308 (2011).

# 5 Methodology for Sambor Alternatives Analysis and Assessment of Anabranch Dam

Because of the extraordinary value of the aquatic resources for the economy, livelihoods and food security of the region, and the very large threats to them that the original Sambor Dam proposal would impose, the task of identifying and assessing more benign alternatives called for a reversal of the conventional approach to hydropower development planning, as described below.

## Usual Order of Hydropower Feasibility Assessment

On the traditional path for pre-feasibility assessment of hydropower development on large rivers, the first step is to identify a dam site that maximizes energy production; followed by a concept design; followed by impact identification; and then development of mitigation options Figure 5-1. The underlying question is how the fishery and other natural and societal resources can be managed to accommodate the hydropower development. The result of this process is that it produces expectations of energy production as a function of capital cost first. This tends to compromise the mitigation options which will impose additional costs and thereby reduce the expected rate of return on investment. In the context of the Mekong basin, such subordination of mitigation to hydropower profits typically results in substantial impairment of the environmental productivity and social welfare.

In light of these realities, the NHI team inverted the standard paradigm and began its inquiry by first identifying the natural processes and environmental resources at risk, ascertaining the degree of impairment that they could sustain without significant functional loss, and then setting environmental performance standards to maintain these functions. The question for defining the hydropower development alternatives then became how hydropower could be sited, sized, designed and operated to meet these standards. The conventional and inverted paradigm are depicted in the Figure 5-1 below:

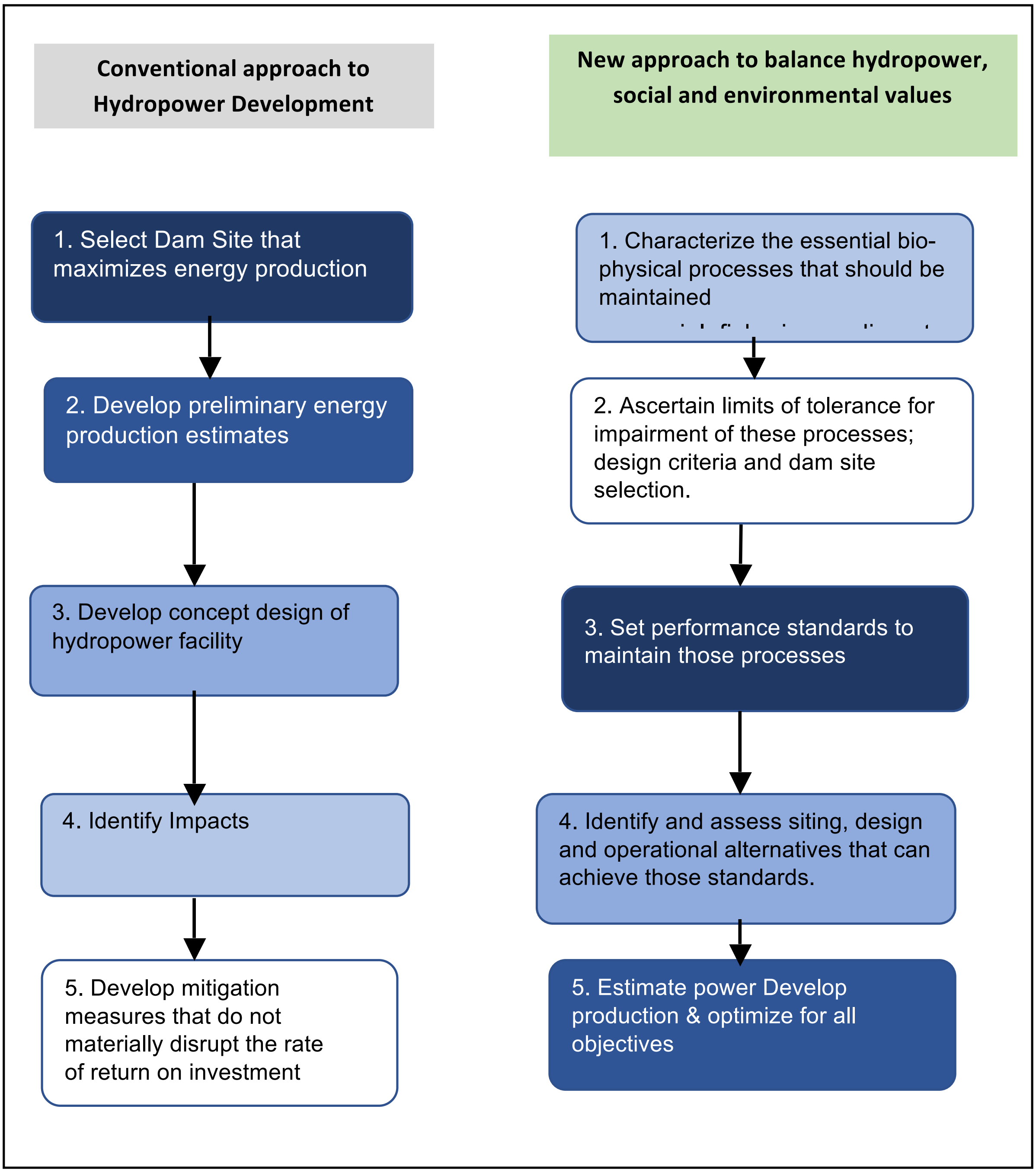



*Figure 5-1. Conventional methodology for hydropower development and the approaches used in the present study.*

For the Sambor Alternatives Assessment, the environmental performance standards derived from this approach are listed in Text Box 5.1:

*Text Box 5-1. Environmental performance criteria used for present study.*

- **Fisheries**
  - Fish Survival 95% at Sambor
  - Fish Passage
    - Up and Downstream
  - Larval Drift
    - Downstream Passage
    - Through Reservoir
    - Flow Velocity of Water ≥ 0.3m/s
  - Minimize Barotrauma Potential
    - Powerhouse
    - Spillway
  - Minimize Turbine Mortality
    - Blade Strike
    - Shear
- **Sediment**
  - Pass ~95 % of Suspended Sediment Annually
    - Nutrients – Sustain Fisheries
    - Mekong Delta – Agriculture and Food Security
  - Maintain Reservoir Storage over Long Term
    - Design to Remove Deposited Bed Load
  - No Significant Deposition in Deep Pools
- **Relocation**
  - Minimize the Number of People to be relocated
  - Use 100-year Flood as Criterion
  - No Additional Flooding in Stung Treng

These are the most exacting standards for hydropower development one can find. To our knowledge, no major hydropower dam in the world could presently meet them. As such they set a new global standard for sustainable hydropower. The rest of this report will show how the Sambor alternatives were formulated to meet these standards and the extent to which they do so.

In sum, the Sambor alternatives examine how hydropower development can accommodate the environmental and social resources, not how the environmental and social resources can accommodate hydropower development. Yet, it needs to be stated at the outset that the best outcome for the River would be no dam at all, as all dams and reservoirs alter the natural riverine functions to a greater or lesser degree.

As noted in Chapter 1, a "no dam" alternative is within the scope of the MoU between the Ministry of Mines and Energy and NHI, and the results of that assessment will be forthcoming by the end of 2017. That concept for that alternative is to increase the power production at Cambodia's largest hydropower facility at present, the Lower Se San 2 Hydropower Plant, by superimposing floating solar arrays on the reservoir and operating the facilities in a hybrid mode. At that time, a comparative evaluation of the Sambor Dam alternatives and the no-dam alternative will be presented to the to assist the RCG in satisfying it's "need to develop indigenous sources of clean, affordable and renewable electricity to replace dirty and expensive power generation from imported fossil fuels". Thus, the responsibility of NHI includes finding dam alternatives that can maximize power production in an economical manner while also achieving the environmental and social performance standards.

## Two Sambor Alternatives to Keep a Portion of the River Free-flowing

In its quest to satisfy that charge from the RGC, the NHI team assessed in some detail a total of 10 hydropower dam concepts to replace the originally Sambor Dam proposal by CSP (2008). This study is at pre-feasibility level as defined by the IFC (2015) (Figure 5-2), except for the fact that permitting needs and a market assessment has not been performed.

As previously noted, the originally proposed design provided no fish passage facilities; would have captured more than 50% of the suspended sediment reaching the upstream end of the reservoir; and would have relocated several tens of thousands of people. Although the power production potential of that design is very high it is not deemed a viable option because of its significant transboundary impacts. The alternatives studied would generate less power than the originally proposed Sambor Dam, but would substantially outperform it in the domains of environmental and social acceptability.

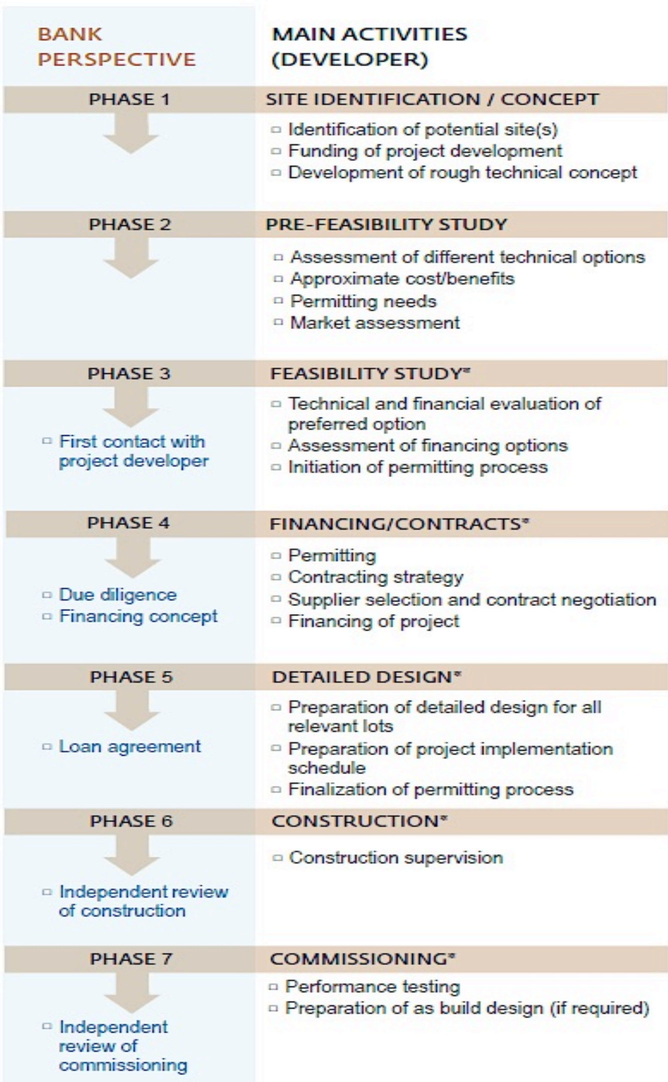



*Figure 5-2 Hydropower project development process. Source: IFC, 2015.*

## Reason for Siting Choices

The field of 10 alternatives narrowed substantially when the study team factored in the fishery objectives in addition to the sediment management objectives. What became clear, applying the new planning paradigm described above, was that the only viable alternatives would be those that would avoid creating an absolute barrier to the movement of migratory fish through the Sambor corridor. That insight led to an investigation of sites some 13km upstream of the original site. These are sites in the reach of the river where there are multiple channels incised in the bedrock formation. At this location, the NHI team applied data and field investigations on topography and bathymetry, hydrology, and geology to formulate a concept for a dam that would straddle the main channel, while leaving the side channels unobstructed for passage of fish and sediments/nutrients. This became known as Sambor Alternative 7 (see Figure 5-3), which is described at length in the rest of this report. At the suggestion of the Senior Minister of RGC, the Honorable Cham Prasidh, the NHI team also evaluated the option of placing the dam in the side channel (the anabranch) and leaving the main channel free-flowing. This became known as Sambor Alternative 6 (see Figure 5-3 and Figure 5-4).

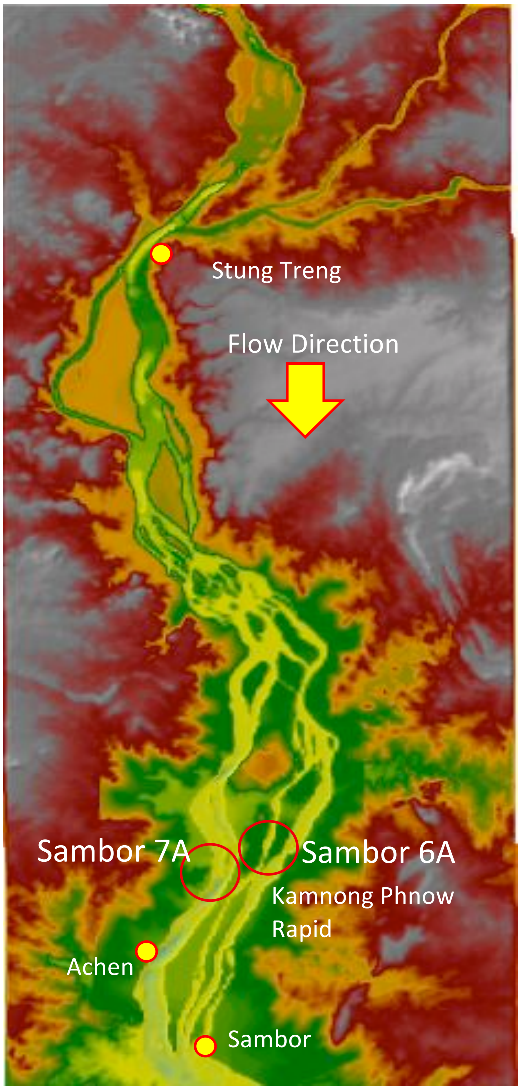



*Figure 5-3. Location of Sambor Alt_7 and 6.*

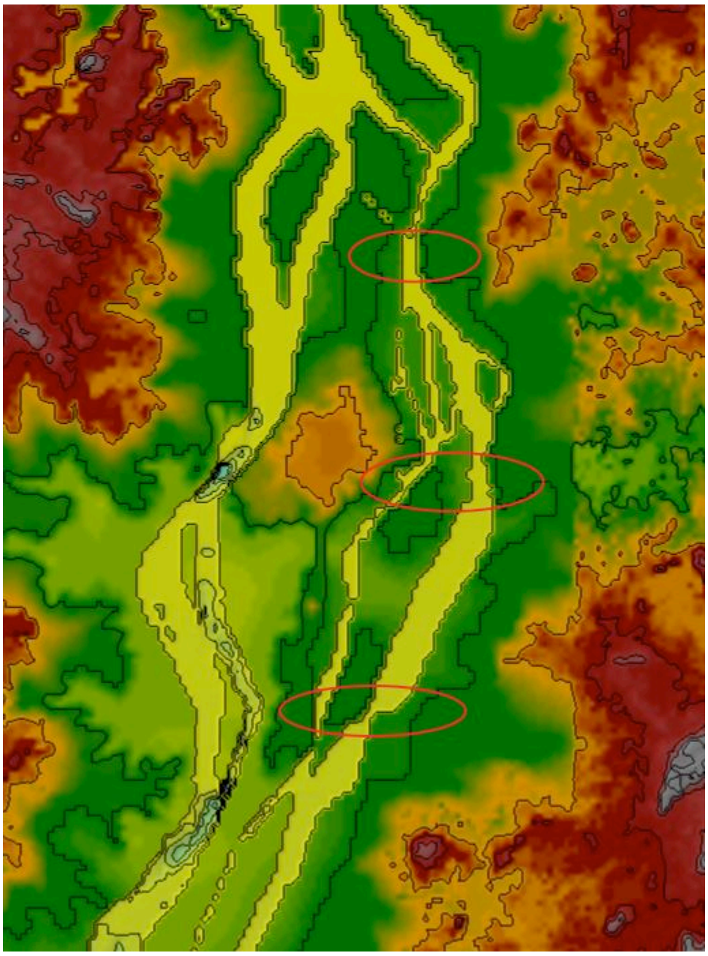


*Figure 5-4. Detail of the 3 locations considered for Sambor Alt_6.*

## Analysis and Rejection of Sambor Alternative 6

The viability of Sambor Alt_6 to be constructed in the anabranch channel of the Mekong River downstream of Stung Treng was investigated as an alternative to Sambor Alt_7-A. Three alternative sites were considered for Sambor Alt_6 as shown in Figure 5-4. It was obvious at the outset that Sambor Alt_7 would prove superior from the standpoint of power output, while Sambor Alt_6 would prove superior from the standpoint of the environmental and social performance standards. The main question was whether Sambor Alt_6 would also be viable from the financial perspective of potential investors; that is, would it provide a rate of return on investment that would make it competitive with Sambor Alt_7.

To compare the power output of these options, the team assessed the hydrology at these sites and, specifically, the flow split down the main and side channels with and without the dams.

### Hydrology

Hydraulic modeling indicated that the amount of water diverted to the main channel was very sensitive to the water surface elevation in the anabranch. This required careful analysis to maximize power potential. It was necessary to develop an operating rule providing the greatest potential for power generation (see Table 5-1 and Figure 5-5). The upper two sites were therefore eliminated as the amount of water flowing into the anabranch with a dam(s) at these locations was insufficient to generate a reasonable amount of power.

The focus therefore shifted to the most downstream site, which showed some potential. The finding that the upper sites were not viable indicates that the use of a cascade is not desirable.

*Table 5-1. Operating rule providing greatest amount of power at Sambor Alt_6*

| Operating Rule | |
|---|---|
| Anabranch Disch (m3/s) | Head WSE (masl) |
| 100 | 31.4 |
| 1000 | 31.4 |
| 1153.7 | 32.5 |
| 2300 | 34.8 |
| 3150 | 35.1 |
| 8000 | 35.1 |
| 11300 | 37.5 |

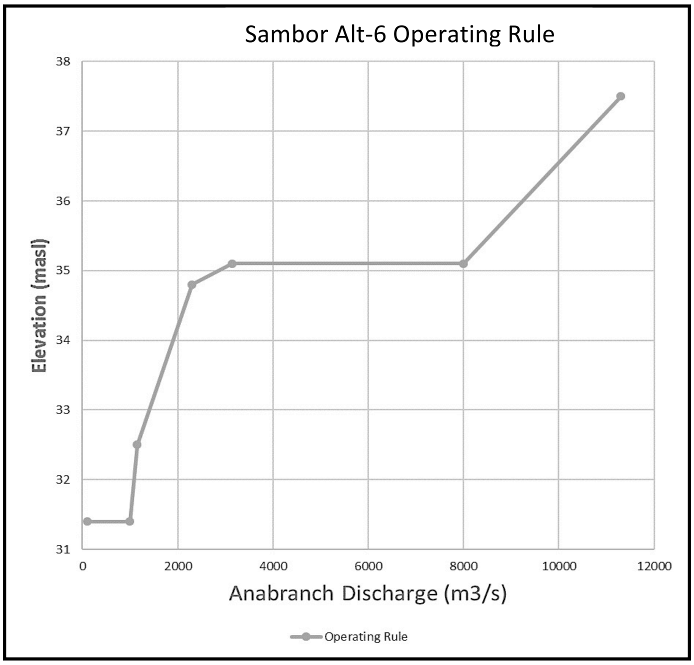



*Figure 5-5. Operating rule for Sambor Alt_6.*

The impact of this operating rule on flow in the anabranch channel is shown in Figure 5-6. It shows that flows reduction in the anabranch is minimized by implementing the rule.

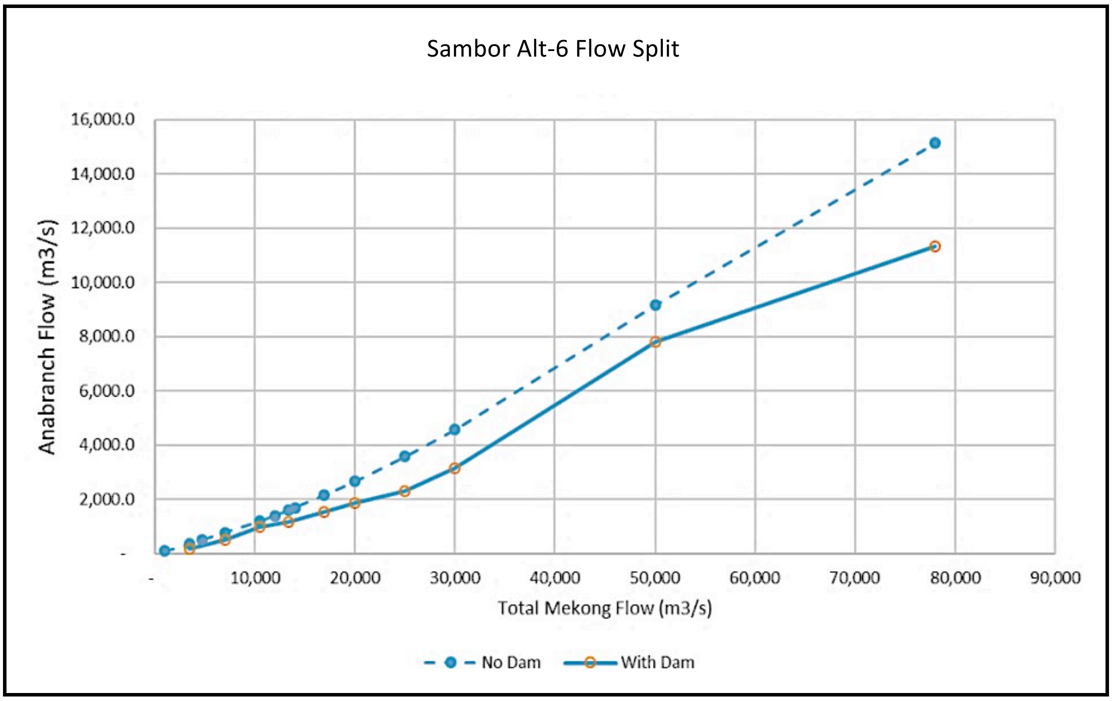



*Figure 5-6. Flow split between main and anabranch channels when implementing Sambor Alt_6 operating rule.*

The spillway was also designed to minimize backwater impacts upstream, as shown in Figure 5-7. For this condition, the radial gates at the spillway are fully open.

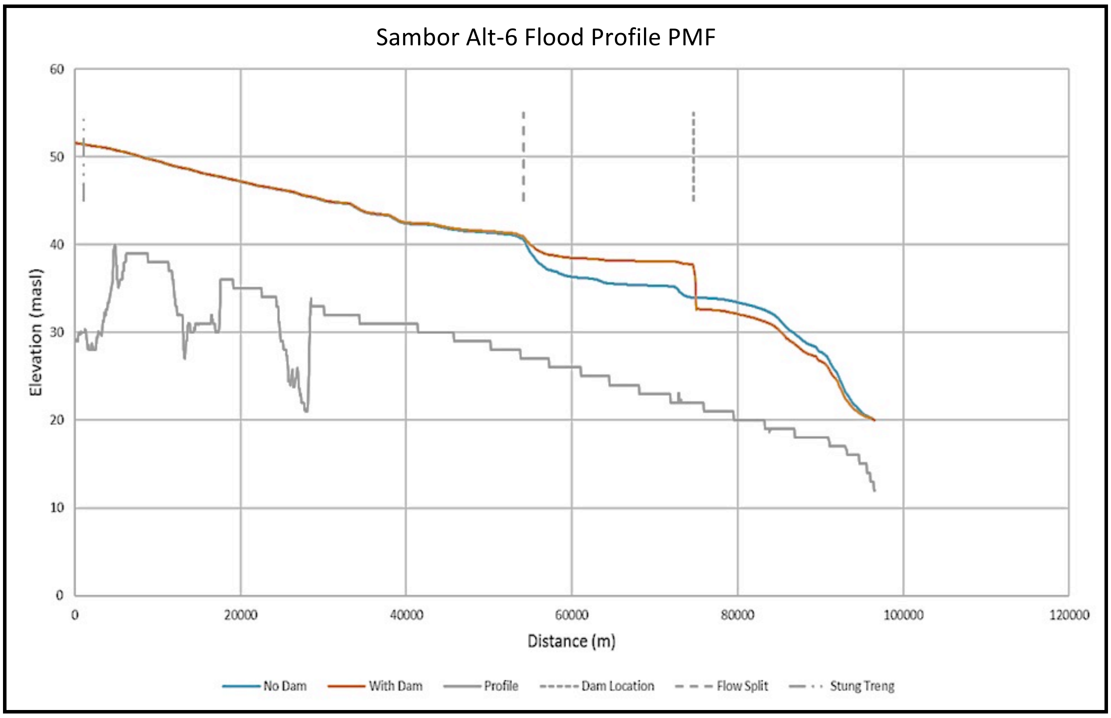



*Figure 5-7. Flood profile for PMF = 78,000m3/s.*

## Hydropower

The hydrologic and site conditions were used to size the turbines for the project. The analysis indicated that Kaplan turbines were optimal, in this case Kaplan turbines. Various combinations of turbines were considered, ranging from four to ten turbines (see Table 5-2). Project viability was determined by preparing a concept design for six turbines. Essential turbine characteristics are shown in Table 5-3.

*Table 5-2. Installed capacity and energy analysis results for Sambor Alt_6.*

| KEY PARAMETERS | | | | | |
|---|---|---|---|---|---|
| Number of Turbines | 10 | 8 | 7 | 6 | 4 |
| Energy/year (GWh) | 559 | 524 | 500 | 472 | 397 |
| At or abovedesign capacity (% of year) | 0% | 6% | 13% | 15% | 22% |
| Output (Max) (MW) | 203 | 181 | 165 | 152.5 | 132.9 |
| Output (Min) (MW) | 3 | 3 | 3 | 3.3 | 3.3 |
| Output (Max as % of Installed Capacity) | 97% | 108% | 113% | 122% | 159% |
| Installed Capacity (at design flow) | 209 | 167 | 146 | 125.4 | 83.6 |
| Head at design flow | 6.5 | 6.5 | 6.5 | 6.5 | 6.5 |
| Design Discharge | 3,500 | 2800 | 2450 | 2,100 | 1,400 |
| Max head | 9.4 | 9.4 | 9.4 | 9.4 | 9.4 |
| Min head | 3.8 | 3.8 | 3.8 | 3.8 | 3.8 |
| Max flow | 10,289 | 10,289 | 10,289 | 10,289 | 10,289 |
| Min flow | 50 | 50 | 50 | 50 | 50 |

*Table 5-3. Horizontal Kaplan Turbine characteristics.*

| | |
|---|---|
| Design discharge per turbine | 350m3/s |
| Net rated head | 6.5m |
| Minimum head | 4.4m |
| Maximum head | 9.4m |
| Runner diameter | 8.171m |
| Number of blades | 4 |
| Peak efficiency | 95.2% |
| Rotation speed | 54rpm |

## Design

The concept design for Sambor Alt_6 shown in Figure 5-8 consists of a 10 bay gates spillway with a stilling basin downstream, a power house with six Kaplan turbines and a ship lock. The gates in the spillway are 13m high by 15m wide radial gates with 3m high flap gates on the top to facilitate fish passage.

Completion of the design requires additional embankments to ensure that the water head is maintained upstream of the power house. Those embankments are not shown in Figure 5-3 and Figure 5-4.

No special allowance has been made for fish passage, except for providing flap gates on top of the radial gates and for providing a simple flat screen on the upstream side of the power intakes. The argument is that should this dam be built it leaves the main stem of the Mekong River entirely free for fish passage. If this option proceeded it is likely, however, that some form of simple upstream fish passage would be required, such as a side-channel connection to the main channel, similar in philosophy to the Don Sahong dam.

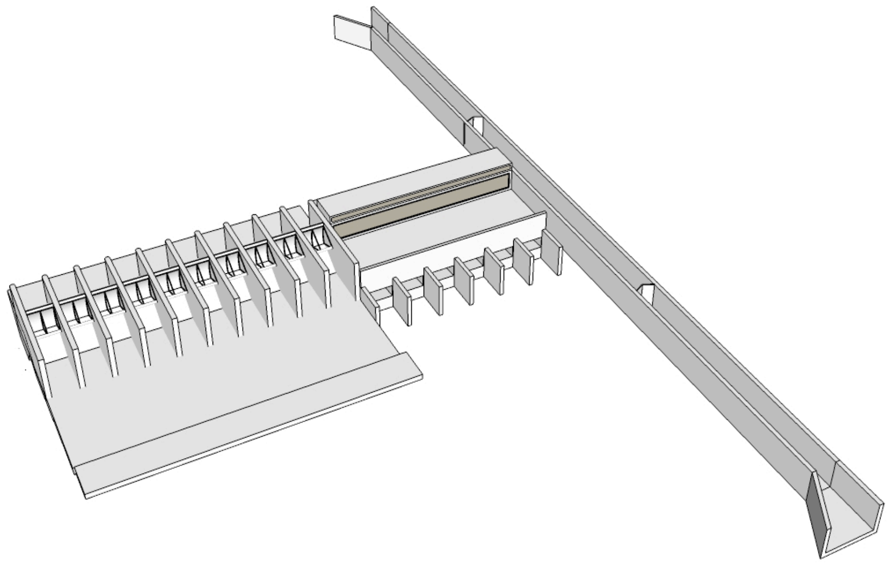


*Figure 5-8. Concept layout for Sambor Alt_6.*

## Cost

Table 5-4 provides a comparison between the cost of Sambor Alt_7-A and Sambor Alt_6, and indicates that the estimated cost for Sambor Alt_6 amounts to US$689,552,433. The cost per MW is US$5,498,823/MW, which is significantly higher than Sambor Alt_7-A and the cost range for viable projects, ranging between about US$1,000,000/MW and US$3,000,000/MW.

*Table 5-4. Cost comparison between Sambor Alt_7-A and Sambor Alt_6.*

| Alternative | Total Cost (USD) | Energy (GWh) | Installed Cap. (MW) | USD/MW |
|---|---|---|---|---|
| Sambor 7-A | $2,237,218,902 | 4,240 | 1,236 | 2,062,628 |
| Sambor 6 | $689,552,433 | 472 | 125 | 5,498,823 |
| Ratio | 31% | 12% | 12% | 267% |

## Conclusion

The final conclusion was that a dam on the anabranch would back so much water up into the main channel that there would not be enough flow through the turbines to generate sufficient power to justify the cost of construction. Specifically, that dam would only be able to produce 125 MW of power, whereas the construction costs would be US$5836/Kw. On that basis, the cost per kilowatt hour would be over 20 US cents/kWh, about twice as much as for Sambor Alt_7 with full mitigation.

## References

China Southern Power Grid Co. (CSP) and Guangxi Electric Power Industry Investigation Design. October 2008. *Feasibility Study Report of Sambor Hydropower Station*. Prepared for The Kingdom of Cambodia.

International Finance Corporation, 2015. Hydroelectric Power: A Guide for Developers and Investors. Prepared by Fichtner Management Consulting AG for International Finance Corporation. Accessed on 19 March 2017. Available from: http://www.ifc.org/wps/wcm/connect/06b2df8047420bb4a4f7ec57143498e5/Hydropower_Report.pdf?MOD=AJPERES.

# 6 Sambor Alternative 7

The alternative facility designed by the NHI Team, known as Sambor Alternative 7 (Alt_7), aims at significantly reducing the impact on fishery yield, bio-diversity and sediment passage, although significant risks remain, as documented in this Chapter and Chapters 11 and 12. Sambor Alt_7 would be a 1,236 MW, 4,240 GWh per year facility. Applying the new hydropower planning paradigm described in Chapter 5, it is designed to pass 95% of the sediment load through this stretch of the river and allow 95% survival of fish, including larvae, migrating up- and downstream.

Four versions of Sambor Alt_7 were assessed, each featuring a different combination of fishery mitigation measures. Common elements in all four are mitigation measures that include:

- Three upstream fishpasses located at the powerhouse and both sides of the spillway, where migrating fish would congregate.
- A bypass channel that links with a natural anabranch to pass >10% of river flow
- A navigation lock that also serves as a fish lock.
- Operations to enable a downstream drift of larvae through the reservoir by maintaining a minimum velocity of flow.
- A pressure acclimation weir in the intake channel to ensure fish volitionally acclimate to surface pressure before entering the turbine.
- Deep emplacement of the turbines in the tailwater to reduce pressure impacts (barotrauma).

The four versions of Sambor Alt_7 each incorporate various strategies for reducing mortality of fish passing downstream through the dam and turbines. These mitigation scenarios are:

1) **Sambor Alt_7-A:** Trash rack with standard turbines (as per Xayaburi Dam)
    - Fish up to 900-1000 mm would pass through these trash racks and enter the turbine intakes.
    - Turbines with low barotrauma and moderate shear and blade strike.

2) **Sambor Alt_ 7-B:** Trash rack (as per Xayaburi Dam) + low impact turbines
    - Trash racks with surface bypass but no fish screens on the turbine intakes
    - Low impact turbines (low barotrauma, low shear and low blade strike [thick-blade]) that safely passes larvae and fish < 300mm. We use Alden turbines for illustration. Other low-impact designs may also be considered.

3) **Sambor Alt_7-C:** Fish screens + standard turbines
    - Coarse fish screens to enable fish > 300 mm to bypass the turbines.[8]
    - Turbines with low barotrauma and moderate shear and blade strike.

4) **Sambor Alt_7-D:** Fish screens + low impact turbines.
    - Coarse fish screens to enable fish > 300 mm to bypass the turbines

[8] The project team also evaluated fine-mesh fish screens on the turbine intakes, which divert all fish except larvae from the turbines, but concluded that they were too expensive to be practical.

- Low impact turbines (low barotrauma, low shear and low blade strike [thick-blade]) that safely passes larvae and fish < 300 mm. We use Alden turbines for illustration. Other low-impact designs may also be considered.

The team also initially investigated a fine mesh fish screen which diverted all fish around the turbines but this proved uneconomic, so the decision was made to investigate combinations of coarser fish screens and less impactful turbines.

## Project Concept

Sambor Alt_7 is located in the stretch of the Mekong River between the town of Stung Treng and the village of Sambor. The river assumes a braided character with multiple channels flowing through rock bed, partially flanked by alluvial banks. The channels are not founded on alluvial material, providing the opportunity to locate the dam in the western channel (main channel), while keeping the eastern channel open (anabranch channel) for fish and sediment passage.

The dam concept of Sambor Alt_7 is designed so that the location and height:

i) minimize relocation of people;
ii) optimize the use of the anabranch channel as a natural fishpass, providing fish passage with no additional infrastructure (e.g. regulating weirs on the inlets) so that fish have an unimpeded natural path for migration;
iii) ensure >10% of flow passes down the anabranch/fishpass at all times of the year to provide for fish attraction at the dam and passage of high biomass;
iv) enable the dam to be operated to maintain water velocities in the reservoir for larval drift.

This results in a dam that "breathes" with the river: as river discharge increases the upstream and downstream water levels rise together, and as discharge decreases the upstream and downstream water levels fall together.

A suitable powerhouse site was identified in the dashed rectangle on Figure 6-1, with the detail presented on Figure 6-2. Damming the main channel as shown on Figure 6-1 creates a reservoir allowing water to flow into the anabranch channel if the water surface elevation is maintained based on the specified operating rule. Effective use of the reservoir therefore requires construction of a saddle dam in the valley between the main and anabranch channel to prevent the flow of water to the anabranch channel (see Figure 6-1).

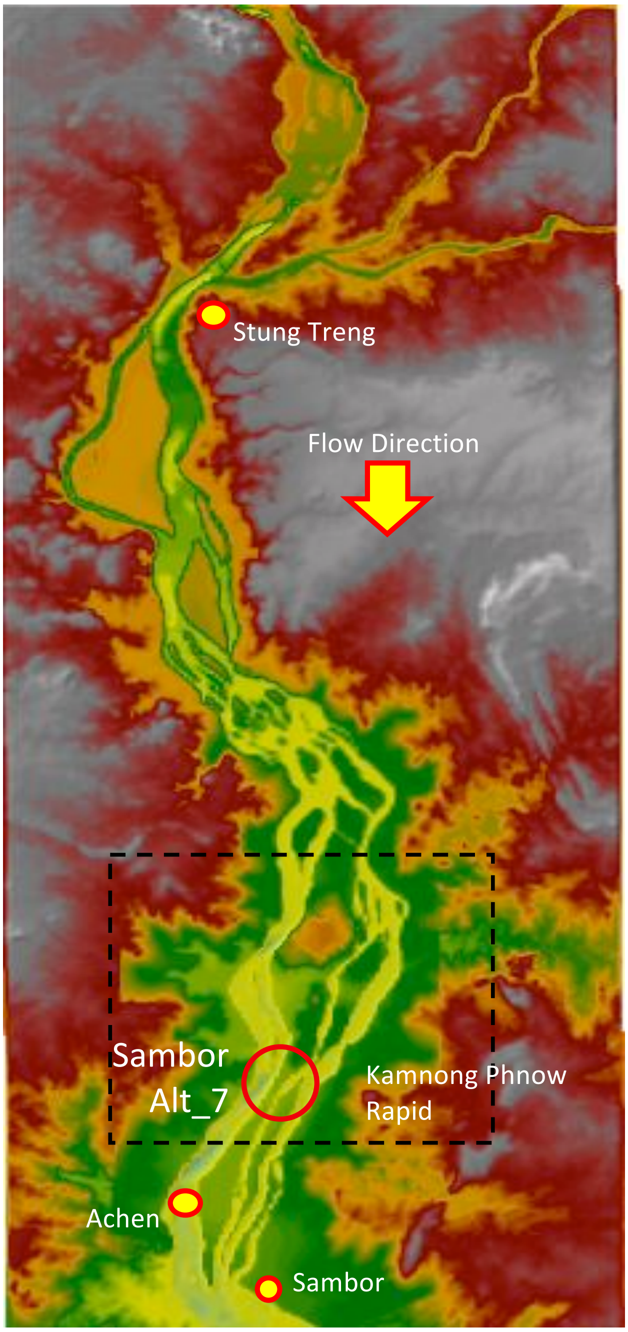



*Figure 6-1. Mekong River from Stung Treng to Sambor. Dashed square indicates location of topography shown on Figure 6-2.*

The locations of the dam and the spillway in the main channel on either side of an island facilitates construction of the project. A coffer dam can be constructed in the channel on the right side of the island (looking downstream) to allow construction of the spillway while water flows through the left channel of the island. Once completed, the coffer dam can be removed and another coffer dams can be constructed on the left side of the island, allowing construction of the powerhouse by diverting water through the spillway.

To facilitate up- and downstream fish passage, a fishpass channel (also called a fishway or fish ladder) would be constructed between the main and anabranch channels. The channel has been sized to pass large amounts of water to attract and convey the large volume of fish that will follow the attraction flows emanating from the fishpass channel and adjacent turbine discharge, allowing them to migrate upstream along the anabranch channel (Figure 6-2). Conveniently, the volume of material to be excavated from the channel balances the amount of material required for the saddle dam.

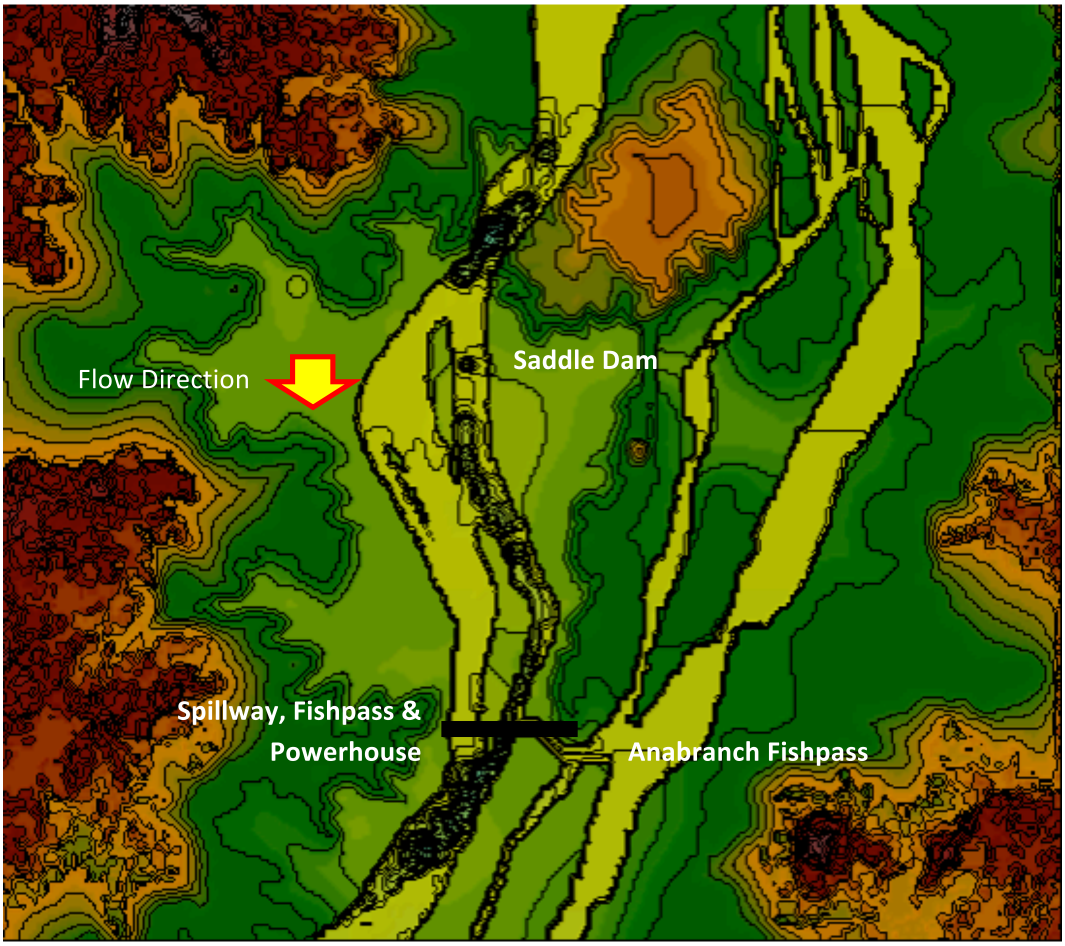



*Figure 6-2. Location of proposed Sambor Alt_7 hydropower facility.*

The constructed anabranch channel between the anabranch and main river channel uses the hydraulic head difference between the two channels to naturally divert water from the anabranch to the main channel. This can be accomplished without construction of a diversion structure in the anabranch channel, although detailed hydrodynamic and physical modelling would likely be required to confirm these design aspects. Flow through the anabranch fishpass allows for up- and downstream migration of fish and downstream migration of larvae. The proposed fish screens are not shown on Figure 6-3. More detailed descriptions and figures of these fishpass facilities are provided in Chapter 7.

A more detailed perspective of the hydropower plant is shown on Figure 6-3. It shows a pool-type fishpass facility on the right bank of the river (looking downstream), which is about 2,000 meters long and contains baffles in the channel, which creates a series of pools, to facilitate upstream fish passage. The right-bank fishpass is located next to the spillway so that fish attracted by spillway flows along the right bank will be guided into the right-bank fishpass for upstream passage. Some fish swimming downstream along the right river bank of the main channel will use the right-bank fishpass for downstream migration, but most fish will follow the majority of flow, either toward the powerhouse or over the spillway.

On the left side of the spillway is located a ship/fish lock specifically designed as a dual-function facility. It would facilitate upstream passage of fish attracted to the left side of the spillway where fish would enter a holding area from where they can migrate upstream through the ship/fish lock. Like the right-bank fishpass, there would be some downstream passage of fish and larvae along the left bank of the channel and through the ship/fish lock, but the majority of fish would migrate to the powerhouse or over the spillway.

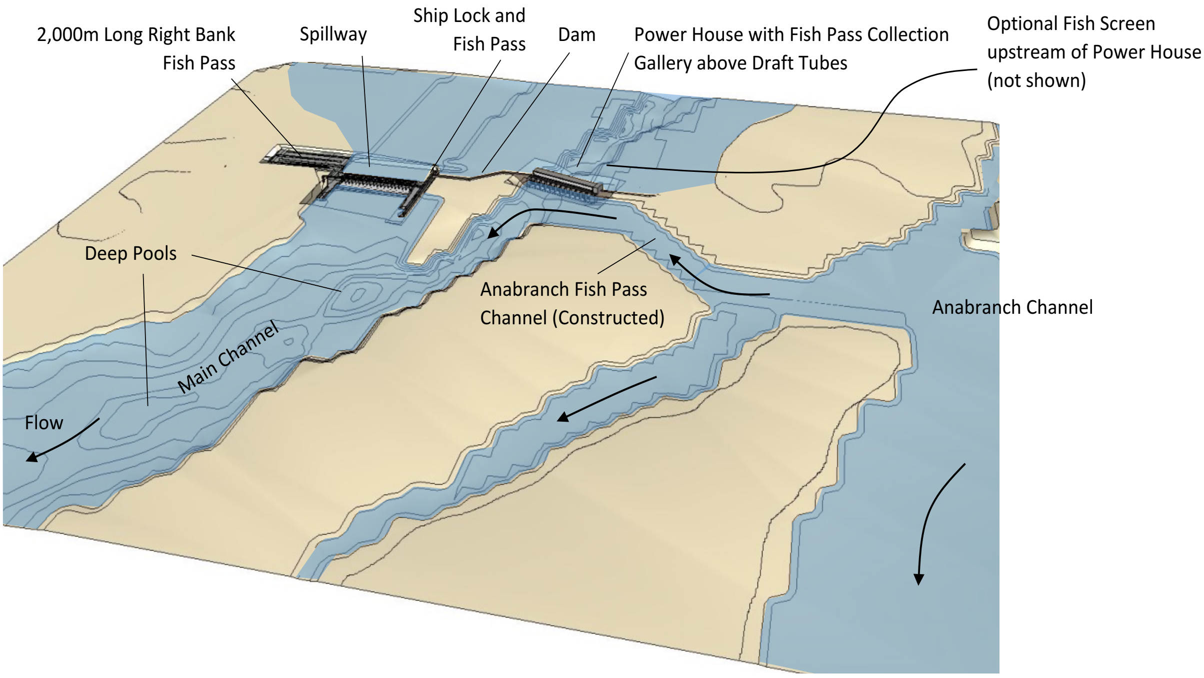



*Figure 6-3. Sambor hydropower project Sambor Alt_7-A. Perspective with topographic and bathymetric map.*

## Project Components

### Powerhouse and Turbines

The powerhouse (Figure 6-4) is located on the left side of the island in the main stem, just upstream of deep pools. The powerhouse as shown in this display contains twelve 103 MW vertical Kaplan turbines, although the project team also evaluated lower impact Alden-style turbines as explained above.[9] The turbines are set vertically to allow construction of a draft tube outlet that is deep enough below the tailwater surface to minimize the potential for barotrauma of fish, including larvae, passing through the turbines.

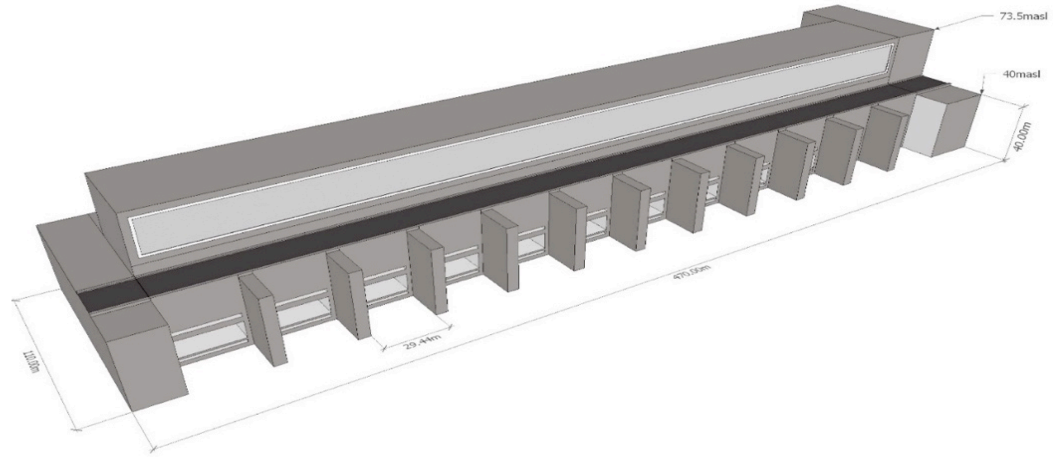
Turbines designs that are suitable for Sambor, in order of low fish impact first are: Alden, bulb, horizontal Kaplan and vertical Kaplan. Kaplan includes the Minimum Gap Runner (MGR) variation which reduces fish impacts from blade strike. Each of these designs would be a unique application at Sambor and can be modified to reduce impacts on fish. Factors such as number of blades and

9 The final configuration of turbines will be subject to more detailed engineering optimization at the detailed feasibility study stage. The powerhouse configurations shown in the drawings below that show twelve turbines are indicative only. The final design would likely have more turbines than shown here, particularly if Alden turbines were used.

rotation speed influence the impacts on fish. The Alden turbine with only three blades and a low rotation speed has the lowest impact; it also has the unique feature of the housing and blades rotating as one unit which eliminates friction and grinding of the blades against the housing. Although the Alden turbine has been extensively tested by Voith using a 1:3 scale model and CFD it has yet to be used in the field, largely because it has a higher capital cost (e.g. 30% greater than an equivalent Kaplan). All of these turbine designs, however, cannot protect large fish over 500mm, from high mortality from blade strike. If an objective is to protect these fish from turbines they need to be diverted by fish screens to a bypass.

Upstream-migrating fish are attracted to flow from the turbines so fishpass collection galleries are located on the downstream side of the powerhouse above all the turbine outlets, which collect and guide fish to the Anabranch Fishpass. Sediment flushing facilities are located below each turbine to flush deposited sediment from upstream of the powerhouse and turbine intakes.

The presence of the deep pools downstream makes it possible to design and construct turbine outlets that are deep enough below the tailwater surface elevation to minimize the effects of barotrauma on the fish and larvae that may pass through the turbines. This mitigation feature is described and depicted in Chapter 7.



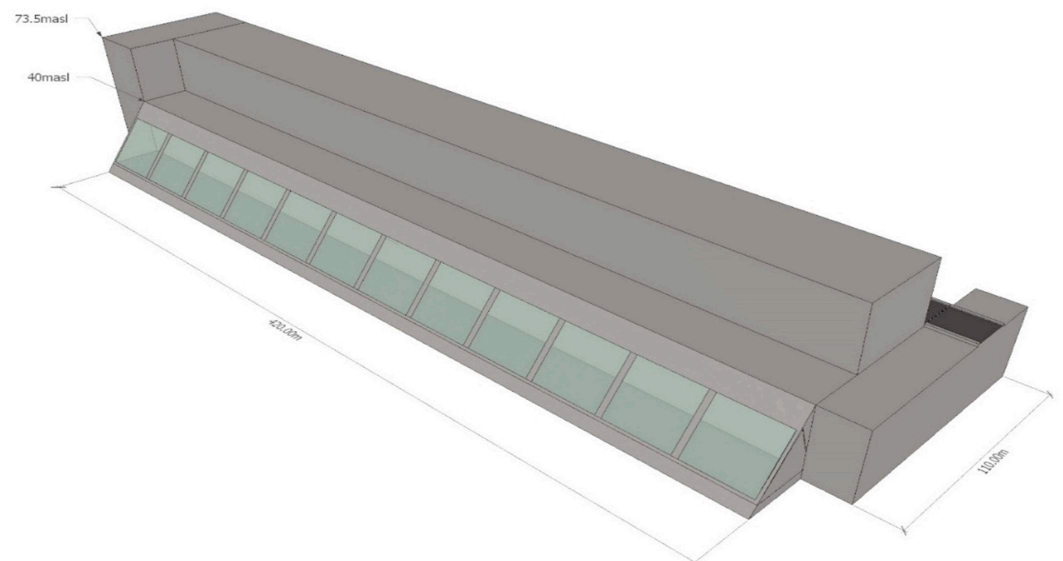




*Figure 6-4. Powerhouse from downstream (top image) and upstream (lower image).*

## Spillway

The spillway consists of 25 radial gates with flap gates on top. The radial gates are 13m high and the flap gates 3m high. The role of the flap gates is to facilitate downstream passage of fish and larvae. A concrete dam would be constructed on the island between the ship lock and the powerhouse to maintain the maximum operating water level at 39masl. The spillway (Figure 6-5) was designed to pass the 1:1,000-year flood.

*Table 6-1. Design discharges determined using data at Stung Treng gauging station 014501.*

| Flood Frequency | Discharge (m3/s) | Comment |
|---|---|---|
| 100-year | 73,448 | |
| 1,000-year | 78,550 | |
| 10,000-year | 88,300 | Not determined by frequency analysis in this study. Adopted from CSP (2008). |

The magnitude of the design flood upstream of the flow spilt between the main and anabranch channels is 78,550 $m^3$/s while that of the flow in the main channel is 54,000 $m^3$/s with the remainder flowing down the anabranch channel. The spillway consists of a 578m wide structure with 25 gates that are 20m wide x 16m high. The gates consist of 13m high radial gates with a 3m high flap gate on top.

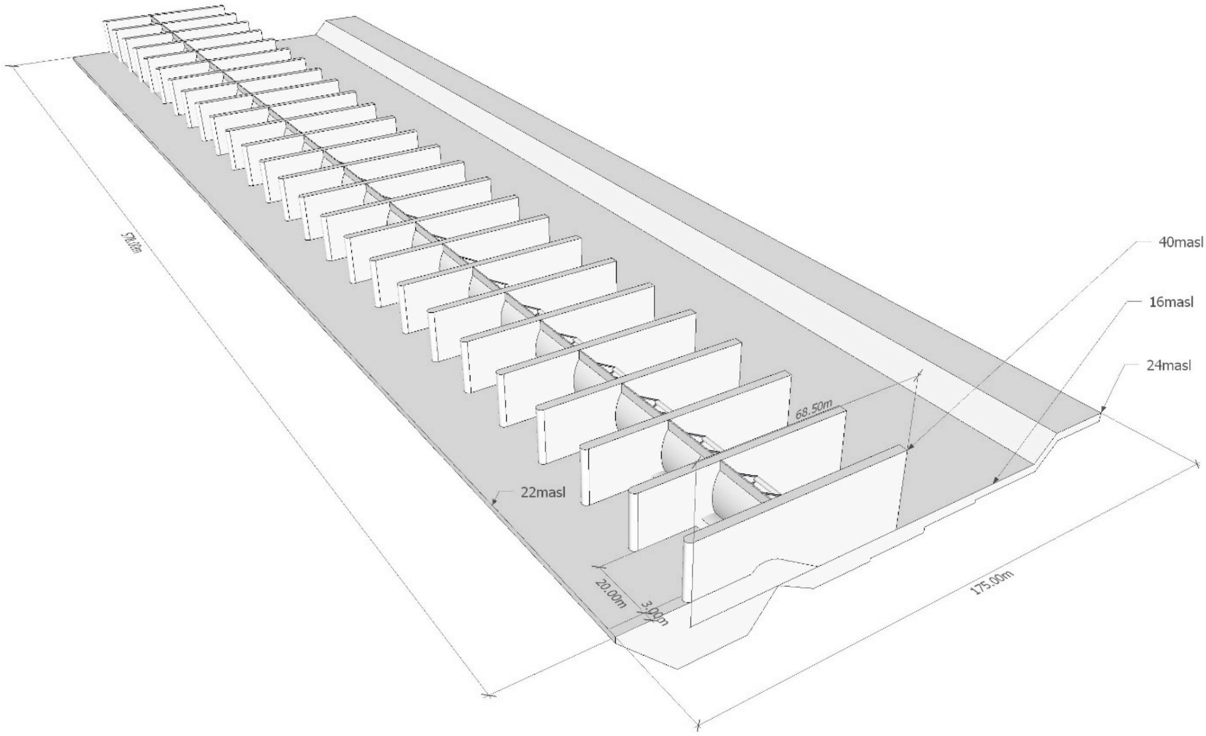



*Figure 6-5. Spillway - 578m with 25 spillway bays.*

The spillway is large enough to prevent incremental flooding at Stung Treng during the 1:1,000-year flood (Figure 6-6 and Figure 6-7). It is noted from Figure 6-7 that the flow levels increase downstream of the flow split between the main and anabranch channels. The reason for this is that the presence of the dam causes more water to flow down the anabranch channel than under natural conditions (see further on).

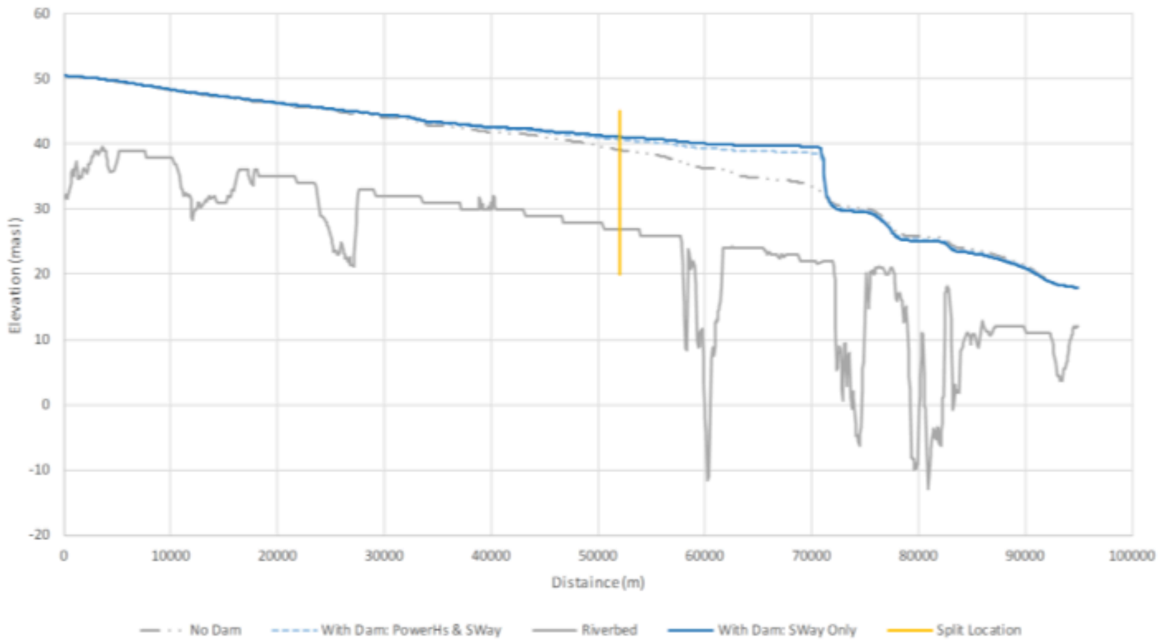



*Figure 6-6. Flood profile along the main stem up to Stung Treng at distance 0m for total Mekong River discharge equaling 78,550m$^3$/s (54,000m$^3$/s along the main stem).*

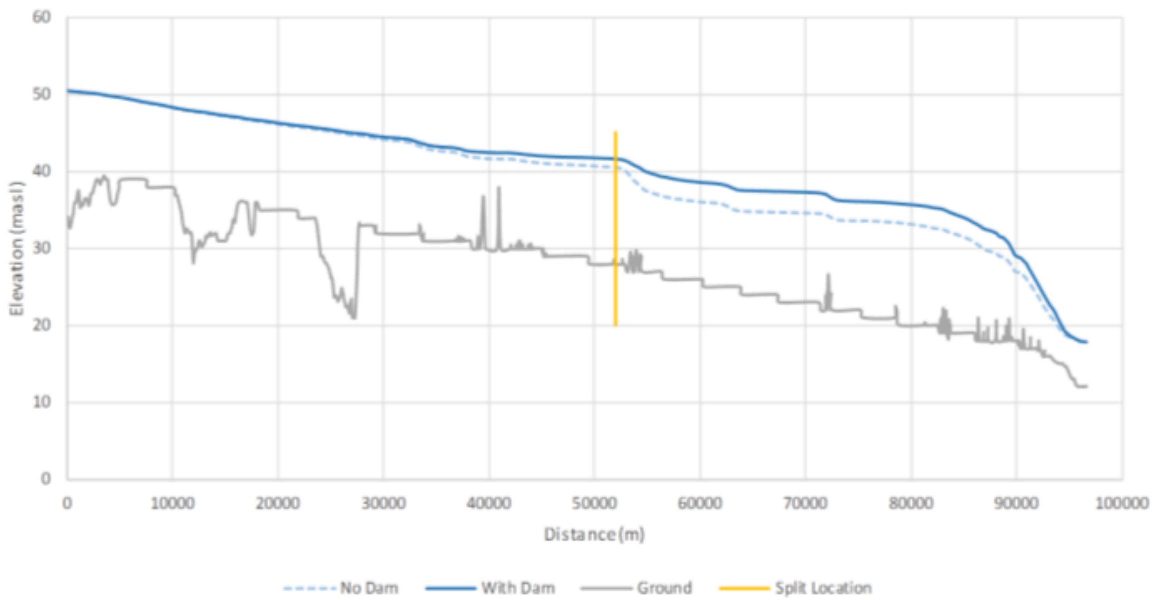



*Figure 6-7. Flood profile along the anabranch channel up to Stung Treng at distance 0m for total Mekong River discharge equaling 78,550m$^3$/s (24,000m$^3$/s along the main stem).*

The influence on flooding under the 1:1,000-year conditions is also shown in Figure 6-8 (without the dam) and Figure 6-9 (with the dam); showing only minor impacts in the reaches immediately upstream of the dam, with no impact in the vicinity of Stung Treng.

*Figure 6-8. Flood Extent for 1,000-year flood (78,550m$^3$/s) without Dam.*

*Figure 6-9. Flood Extent for 1,000-year flood (78,550m$^3$/s) with Dam.*

## Essential Project Statistics

The essential statistics of Sambor Alt_7-A (12.950586°N 105.990926°W) are presented in the following table. As noted, the turbine configuration is still preliminary, and particularly if Alden turbines were used, the final design may be somewhat different.

*Table 6-2. Essential project statistics for Sambor Dam Alt_7-A.*

| Item | Unit | Quantity | Comment |
|---|---|---|---|
| Hydrology | | | |
| 1. Basin Area | $Km^2$ | 810,000 | |
| 2. Years of record | Year | 72 | Daily Flow |
| 3. Mean Annual Flow | $m^3/s$ | 13,400 | Mean daily |
| 4. Maximum Recorded Flow | $m^3/s$ | 67,320 | |
| 5. Minimum Recorded Flow | $m^3/s$ | 1,076 | |
| 6. Design Flood | | | |
| a. 100 year (Total Mekong) | $m^3/s$ | 73,448 | Design - Weibull analysis |
| b. 1,000 year (Total Mekong) | $m^3/s$ | 78,550 | Weibull analysis |
| c. 10,000 year (Total Mekong) | $m^3/s$ | 88,300 | Check - 2008 Design Report |
| d. 100 year (Main Stem) | $m^3/s$ | 43,203 | Due to flow split |
| e. 1,000 year (Main Stem) | $m^3/s$ | 54,000 | Due to flow split |
| f. 10,000 year (Main Stem) | $m^3/s$ | 60,720 | Due to flow split |
| Reservoir | | | |
| 7. Normal Pool | masl | 39 | See Rule Curve |
| 8. Dead Water Pool | masl | 34 | See Rule Curve |
| 9. 100-year Level | masl | 39.24 | No Impact on Stung Treng |
| 10. 1,000-year level | masl | 39.4masl | No Impact on Stung Treng |
| 11. Reservoir Area | $km^2$ | 67 | |
| 12. Backwater Length | km | 37 | 100-year Design Flood |
| 13. Reservoir Volume | | | |
| a. Total Storage | $10^6m^3$ | 1,411 | |
| b. Normal Pool | $10^6m^3$ | 1,223 | |
| c. Regulating Pool | $10^6m^3$ | 589 | |
| d. Dead Storage | $10^6m^3$ | 634 | |
| 14. Regulating Mode | Run-of-River | | |
| Flood Releases Downstream | | | |
| 15. Maximum Discharge @ Design | $m^3/s$ | 54,823 | Spillway discharge + Anabranch Fishpass Flow |
| 16. Maximum Discharge @ Check | $m^3/s$ | 61,630 | No Attenuation |
| Power | | | |
| 17. Installed Capacity | MW | 1,230 | |
| 18. Average Annual Energy Output | GWh | 4,240 | |
| Resettlement | | | |
| 19. Inundated Farmland | ha | n/a | |
| 20. Inundated Forest | ha | n/a | |
| 21. Population relocated | person | 6,663 | |
| 22. Houses Demolished | $m^2$ | n/a | |
| 23. Relocated Cities and Counties | | 11 | Relocated villages |
| Main Structures | | | |
| 24. Dam and Powerhouse | | | |
| a. Type | | Concrete gravity | |
| b. Foundation characteristics | | Sandstone | |
| c. Seismicity | | Not accounted for in Concept Design | |
| d. Elevation of Dam Crest | masl | 40 | |
| e. Maximum Dam Height | m | ~40 | Approximate |
| f. Length of Dam Axis | m | 2,000 | |

| Item | Unit | Quantity | Comment |
|---|---|---|---|
| g. Length of Saddle Dam Axis | m | 1,262 | |
| 25. Spillway | | | |
| a. Type | | Radial w Flap | |
| b. Number of Gates | No | 20 | |
| c. Height of Gates | m | 13 + 3 | Radial = 13m; Flap = 3m |
| d. Width of Gates | m | 20 | |
| e. Invert of Gate | masl | 25 | |
| f. Elevation of Gate Top | masl | 40 | |
| g. Discharge per Gate | $m^3/s$ | 2,160 | |
| h. Mode of Energy Dissipation | | Hydraulic Jump | |
| Powerhouse | | | |
| 26. Type | | Dam / Water Retaining | |
| 27. Dimensions (length x width x height) | m x m x m | 470 x 110 x 73.5 | |
| Switch Yard | | | |
| 28. Foundation Type | | Earth Fill | |
| 29. Area (length x width) | m x m | 300 x 200 | |
| Navigation Structures | | | |
| 30. Type | | Ship Lock | |
| 31. Length | m | 560 | |
| 32. Width | m | 12 | |
| 33. Upstream Max Water Stage | masl | 39 | |
| 34. Upstream Min Water Stage | masl | 34 | |
| 35. Downstream Max Water Stage | masl | 35 | |
| 36. Downstream Min Water Stage | masl | 27 | |
| Main Electromechanical Equipment | | | |
| 37. Type of Turbine | | Vertical Kaplan | |
| a. Number of Sets | | 24 | |
| b. Rated Output | MW | 51.5 | |
| c. Rated Speed | r/min | 55 | |
| d. Max Operating Head | m | 12.6 | |
| e. Min Operating Head | m | 4.2 | |
| f. Rated Head | m | 11 | |
| g. Rated Flow | $m^3/s$ | 500 | |
| 38. Generator | | | |
| a. Number of Sets | | 24 | |
| b. Rated Capacity | MW | 51.5 | |
| c. Rated Speed | r/min | 55 | |
| d. Rated Voltage | kV | 138 | |
| e. Rated Frequency | Hz | 50 | |

## Hydrological Analysis

The Volume – Elevation curve of the reservoir upstream of the dam and spillway is presented in Figure 6-10 and the Area-Elevation curve is shown in Figure 6-11.

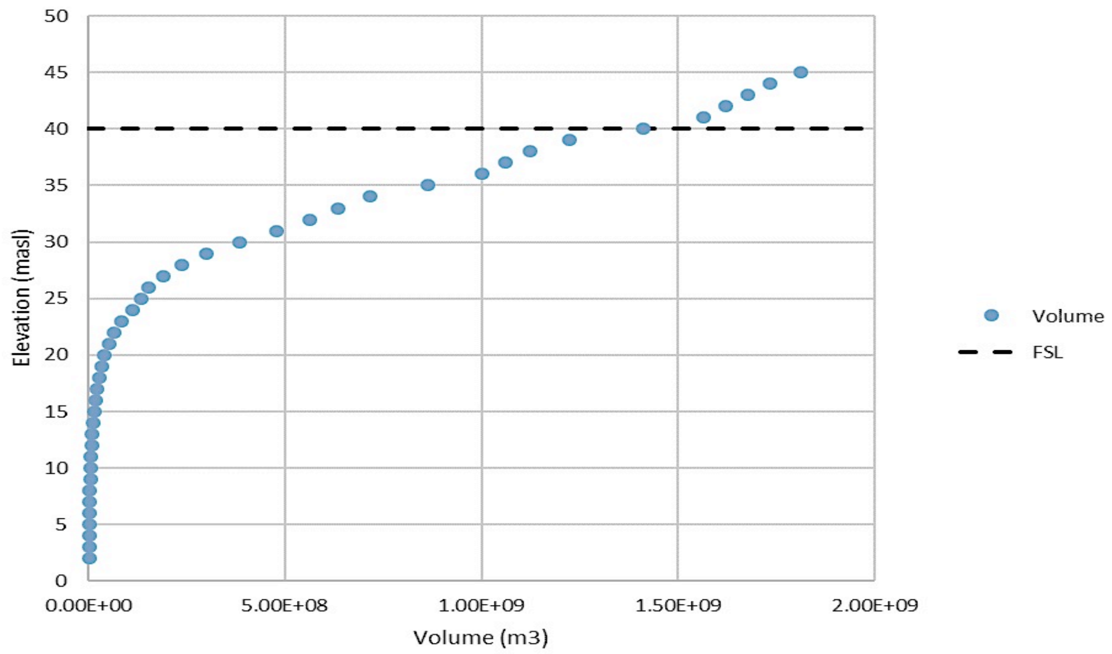



*Figure 6-10. Volume-elevation curve of the reservoir for Sambor Alt_7.*

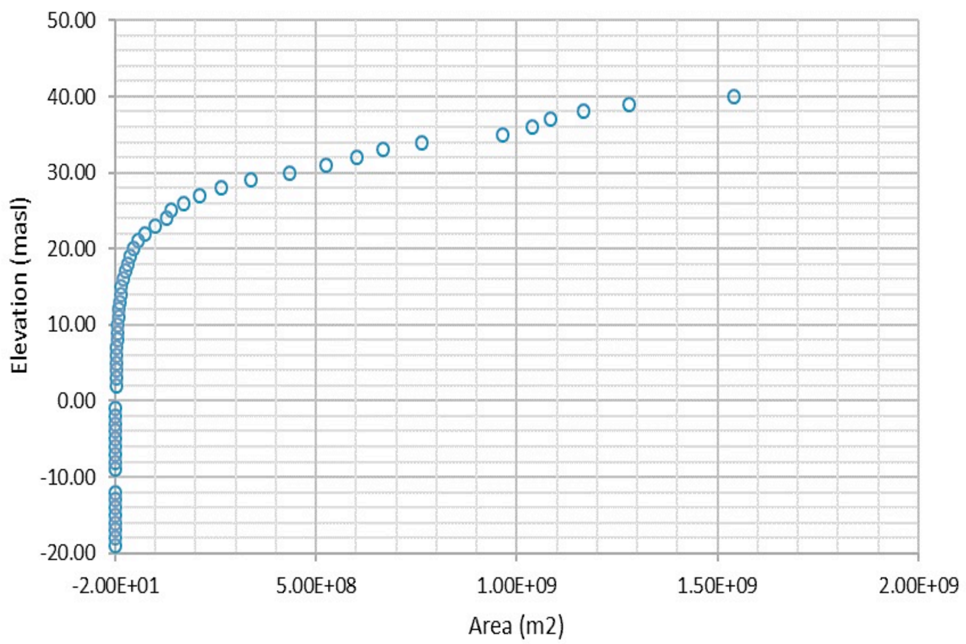



*Figure 6-11. Area-elevation curve of the reservoir for Sambor Alt_7.*

It is important to emphasize that operation of the Sambor Alt_7 reservoir is exceptionally dynamic and complex. First, the reservoir has three unregulated natural upstream channels discharging into the anabranch channel (Figure 6-12). Therefore, the reservoir's inflow is nonlinearly governed by the reservoir's water level and the main stem Mekong flow rate. Higher reservoir water levels result in lower proportions of the main stem flow entering the reservoir (and therefore more spillage into the anabranch). Conversely, lower water levels result in higher total reservoir inflows. In this sense, the reservoir is highly irregular, as reservoir inflows are dependent upon the reservoir's water levels. Given that the three natural channels in the reservoir's upstream reach are unregulated, it may be more difficult to maintain high water levels in the dry season, as significant spillage into the anabranch will occur.


*Figure 6-12. Satellite image of the upstream end of the Sambor Alt_7-A reservoir site, with blue arrows indicating natural spillways into the anabranch channel.*

The complex nature of the project hydraulics and hydrology render specifying an optimal reservoir operating policy difficult. To maximize energy production requires balancing the long-term product of hydraulic head and inflow by avoiding reservoir water levels that create excessive spillage into the anabranch channel. Figure 6-13 provides an example of an operating policy that attempts to maximize the long-term product of flow and hydraulic head, without using formal optimization.

The policy assumed in Figure 6-13 maintains a reservoir water level of approximately 34 masl at relatively low main stem flow rates. This is to avoid excess spillage into the anabranch channel, which would occur at very high rates if the reservoir was kept full during low main stem flow conditions. Water levels are not reduced below 34 masl to avoid the risk of cavitation of the turbines, which occurs when net hydraulic head (the difference between reservoir water level and water surface downstream of the powerhouse) drops below 7.6 m. The impact on the flows in the main stem and in the anabranch channel when implementing this operating rule is shown in Figure 6-14, Figure 6-15 and Figure 6-16.

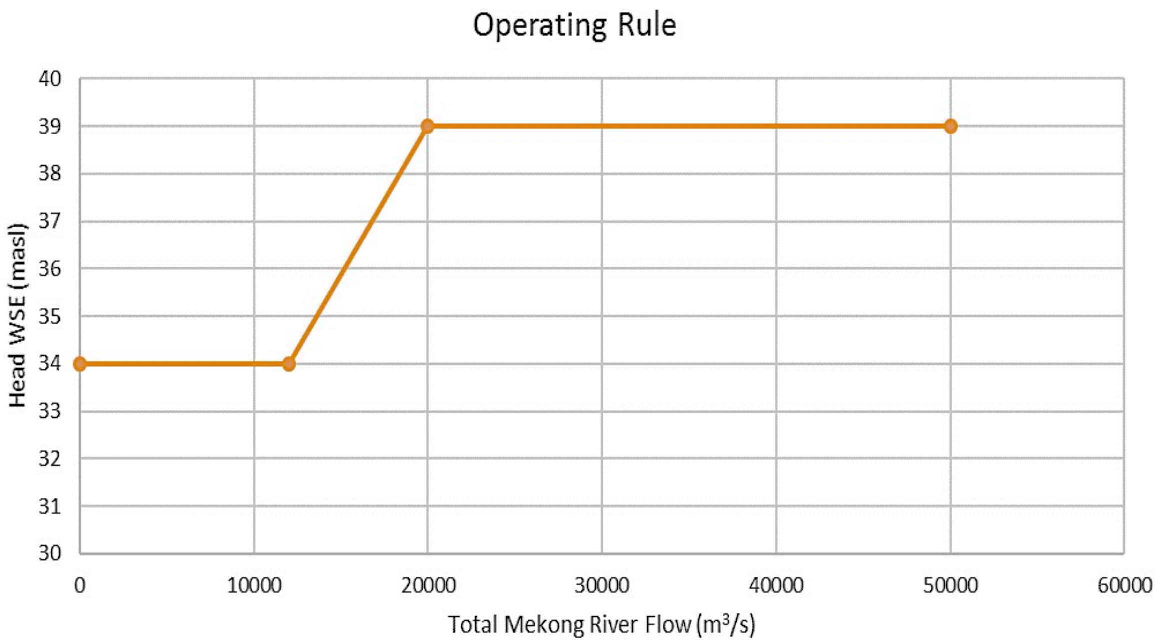



*Figure 6-13. Reservoir operating rule designed to maximize energy production. The rule specifies target reservoir water elevation (masl, meters above sea level) for different main stem river flow rates ($m^3/s$). Actual inflow values to the reservoir are less than the main stem flow rate, as spillage occurs into the anabranch channel.*

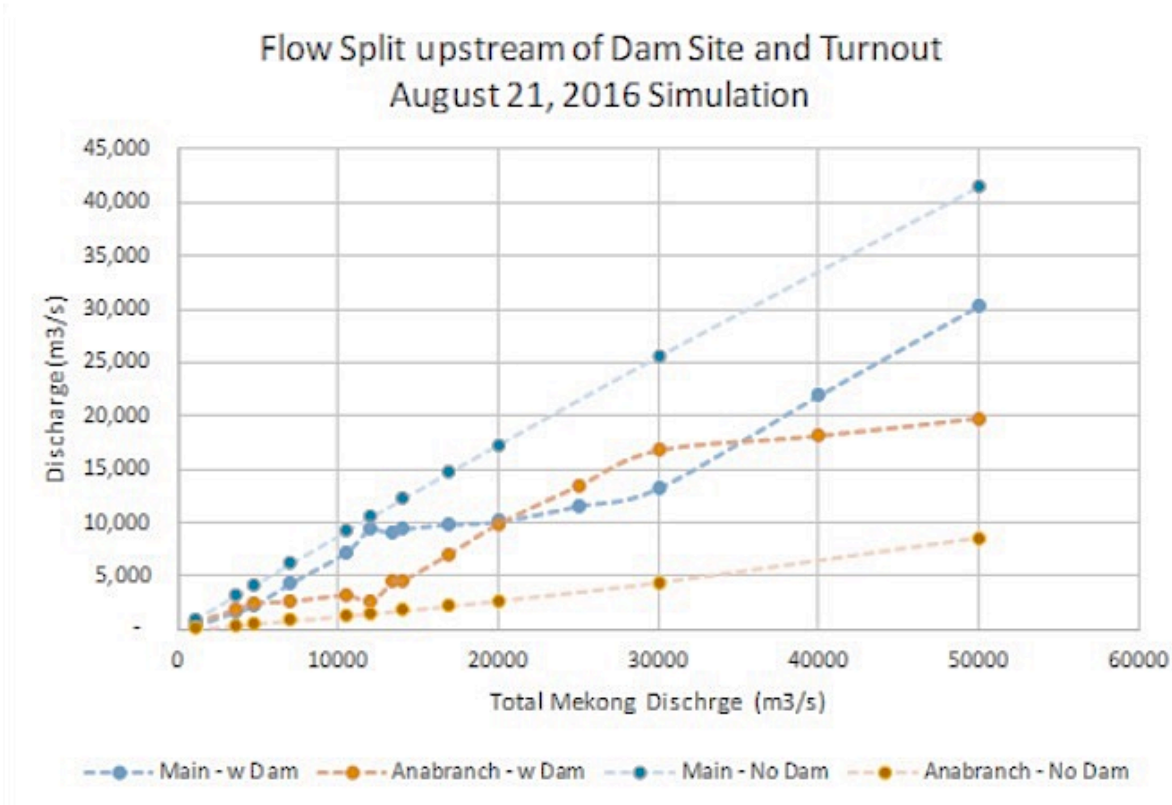



*Figure 6-14. Flow Split upstream of dam site and intake to the anabranch fishpass.*

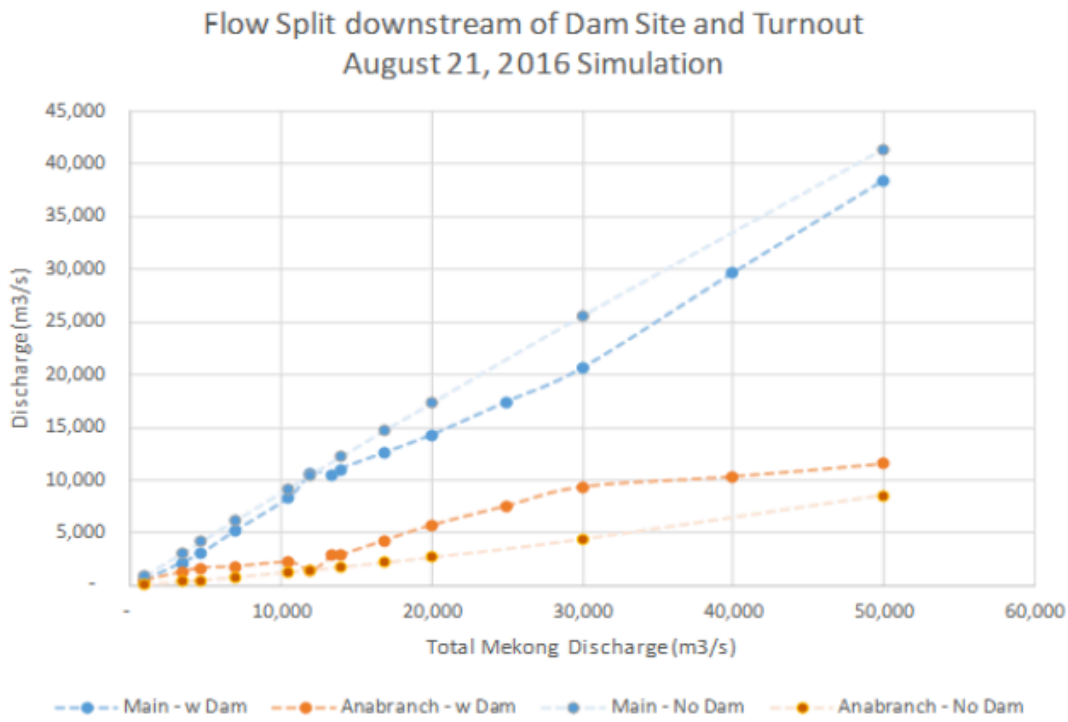



*Figure 6-15. Flows downstream of the dam and downstream of the anabranch fishpass.*

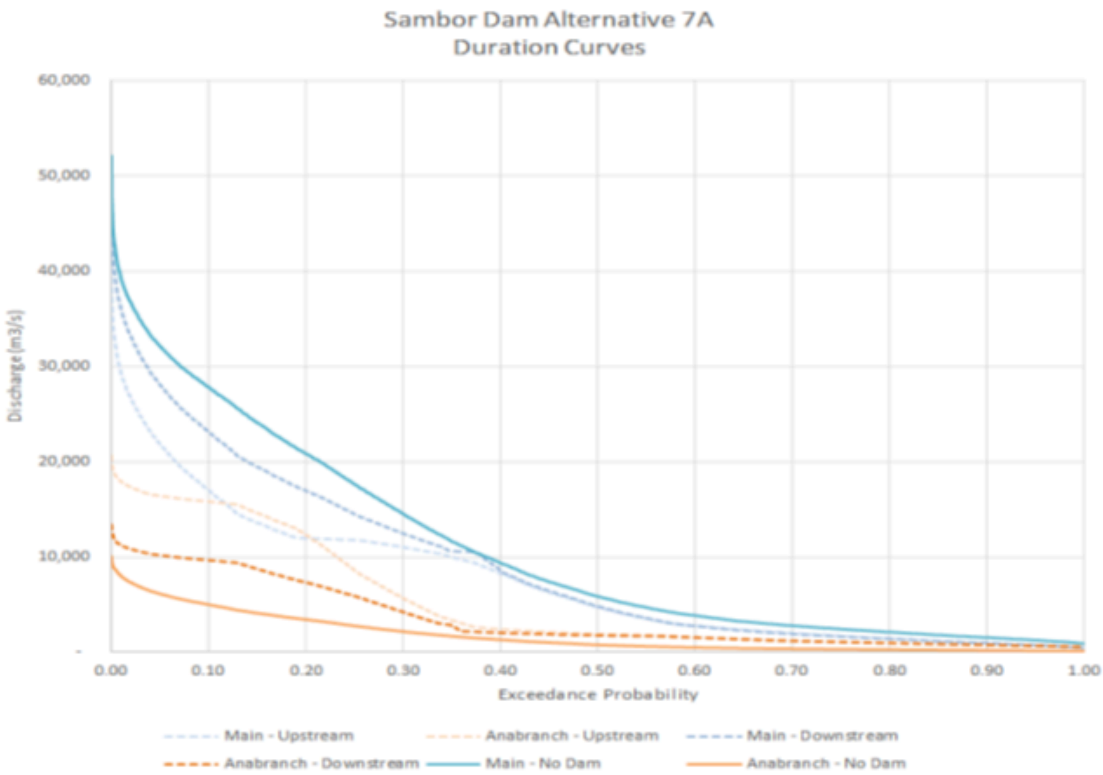



*Figure 6-16. Duration Curves for conditions with and without the dam and anabranch fishpass in place.*

The policy depicted in Figure 6-13 is one example of a reservoir operating policy. The HEC-RAS modeling results for the reservoir, presented in Figures 7-15 and 7-16 (in Chapter 7), suggest that this operating policy could maintain hydraulic conditions conducive to the passage of larvae through the reservoir. However, this result is uncertain, as it depends upon the split between anabranch and main channel flow and the spatial distribution of flow velocities in the reservoir. These factors will require additional survey and data collection, alternatively assessed by exploring the potential implications of relevant uncertainties.

Given the importance of maintaining natural larval drift (flow velocities exceeding 0.3 m/s), we explored conditions in which greater drawdown of reservoir water levels may be required to ensure site conditions that enable larvae passage. Policies maintaining lower water levels achieve higher inflows and thus higher velocities to pass larvae, but the reduced hydraulic head associated with those policies reduces energy production, thus creating a tradeoff. Appendix 6.1 (in Volume 4) presents the development and application of a stochastic simulation-optimization framework, called *PySedSim*, used to identify alternative reservoir operating policies and their resulting tradeoffs for a suite of objectives such as energy production, larvae passage, fish passage, and sediment passage.

The mainstream Mekong streamflow upstream of the Sambor 7A dam site (at Stung Treng gage station) is characterized by significant intra-annual variability. The figure below plots historical daily streamflow from 1910-2015 upstream of the reservoir, before flow is naturally partitioned between the anabranch channel and the reservoir as a result of site hydraulics. Each of the 107 blue lines represent a different year in the 106-year long hydrologic record at Stung Treng (1910-2015). Energy production and firm power production will be driven largely by dry season hydrology, which is characterized by very low inter-annual variability as shown in Figure 6-17.

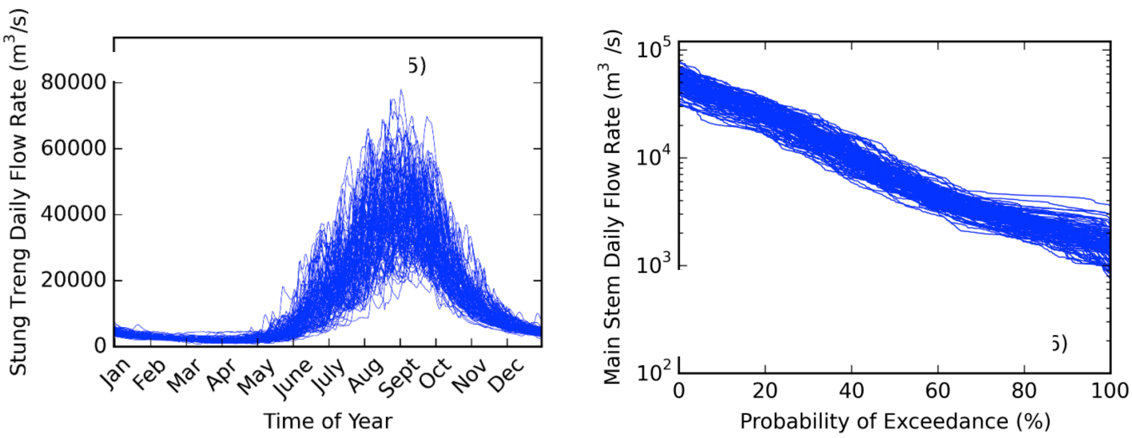



*Figure 6-17. Hydrograph for the Mekong River at Stung Treng (gauge station 014501) for the historical hydrologic record from 1910-2016. Each year from the historical record is plotted as a different line. (B) Annual flow duration curves for the Mekong River at Stung Treng (gauge station 014501). Each year from the historical record is again plotted as a different line, with daily flow values on the y-axis on a logarithmic scale, and exceedance probability plotted on the x-axis. Both figures serve to demonstrate that there is significant inter- and intra-annual variability in the hydrologic record at the site.*

## Elevated Flows in Anabranch Due to Sambor Alt_7—Effects on Erosion and Fish Passage

A Sambor dam at the location indicated for Alternative 7 will increase the discharge in the anabranch from a current maximum of about 8000 $m^3/s$ to a maximum of about 24,000 $m^3/s$, a threefold increase. For this increased discharge, the flow velocity will increase from a current average of about 0.6 to about 1.4 m/s, or more than double, see Figure 6-18. Increases in anabranch discharge will take place at other Mekong flows as well, although with different magnitudes (see Figure 6-15 above).

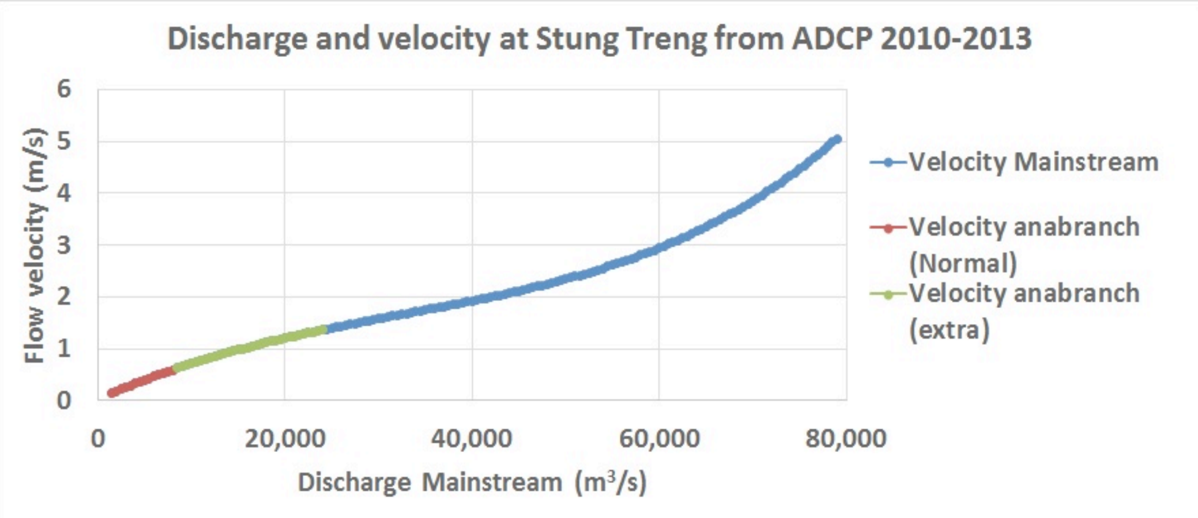



*Figure 6-18. Discharge and velocity at Stung Treng ADCP 2010-2013. Formula derived from ADCP survey at Stung Treng 2010 – 2013 to calculate average flow velocity from discharge.*

5E-20*X^4 + 9.84165E-15*X^3 - 1.30624521945E-09*X^2 + 0.0000808121411481233*X + 0.026302218610074

$R^2$ =0.998, (X is discharge $m^3/s$)

Red….: Normal anabranch flow (1500 - 8000 $m^3/s$),

Green: Extra anabranch flow with HP dam 8000 - 24000 $m^3/s$,

Blue…: Mainstream flow 24000 – 79000 $m^3/s$,

As the river bed is rock, the increased flow through the anabranch cannot erode the bed, but will tend to reestablish equilibrium between the flow and channel dimensions by laterally eroding the alluvial banks (Figure 6-19).

*Figure 6-19. Typical Mekong alluvial river bank. The bank has a very steep slope and is under erosion and no vegetation can cover it. Photos by Susannah Erwin, USGS*[1]*.*

We note however that the rock stratum containing the anabranch is overlain with sediment deposits that are quite thick in some places. This raises the question whether the increase in flows due to the Sambor Alt_7 dam on the main channel would cause this sediment to erode and the morphological consequences of such erosion both at the dam site and downstream.

For the anabranch, this erosion cannot easily be quantified as data is not available for detailed calculations, and available models are not sufficiently precise to specify in detail the likely channel width change, or which side will erode more. To account for this uncertainty, this study assumes that settlements in the area of the anabranch up to the 50-meter contour lines would be resettled to higher ground, and that assumption is used to estimate the number of persons that would be resettled.

It is recommended that a detailed morphologic study of bank composition and channel dimension be undertaken to better inform predictions of channel change, and that the initial channel response be monitored to inform adaptive management, to determine, for example, whether the setbacks need to be increased.

The elevated velocities of the current are mean channel velocities. These should not hamper fish migration or reduce the efficiency of this channel as a fishpass because the roughness along the sides will probably allow most fish to pass.

If a Sambor Dam proposal proceeds to a feasibility study, that should include 2-dimensional modeling (e.g., MIKE 21 or HEC-RAS 5.0) and physical modeling of the elevated flows and their effect on erosion and opportunities for fish passage.

## Sediment Passage

The amount of sediment passing downstream of the Sambor Alt_7-A reservoir is the sum of the sediment that flows through the reservoir and the sediment flowing through the anabranch channel. The sediment passing through the reservoir is determined by its trap efficiency, which is the fraction of inflowing sediment that is deposited in the reservoir. If the trap efficiency is 100% it means that 100% of the sediment flowing into a reservoir deposits. The trap efficiency of the Sambor Alt_7-A is very low.

Estimates of the trap efficiency can be made by using the Brune (1953,) and Churchill (1948) curves, as modified by Roberts (1982). The Brune curve (Figure 6-19) relates trap efficiency to the relative capacity of the reservoir. The relative capacity is equal to the reservoir capacity divided by the mean annual flow in the river. In the case of Sambor Alt_7-A, the relative capacity equals 0.4% (0.005). As the general character of the suspended sediment flowing into the reservoir is silt and clay, the lower bound curve in Figure 6-20 is used to estimate trap efficiency at ~10%.

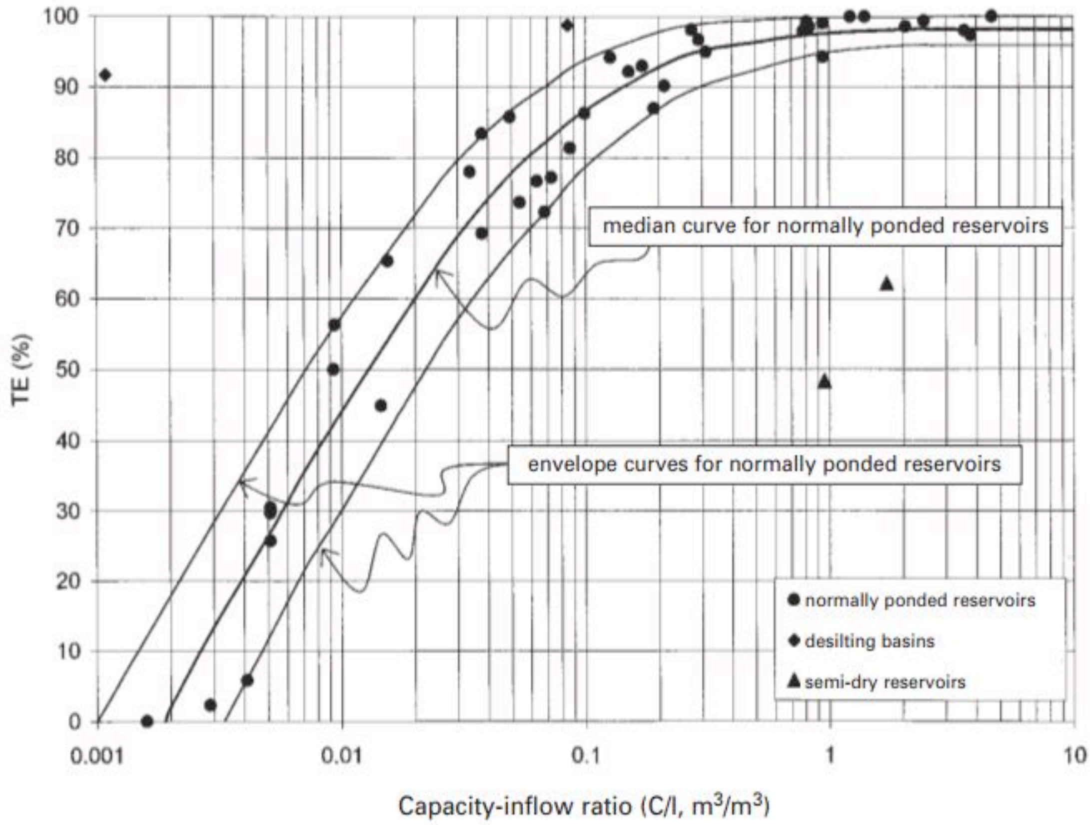



*Figure 6-20. Brune Curve (1953) to determine the trap efficiency of a reservoir.*

When using the Churchill curve (Figure 6-21) it is required to calculate a sedimentation index as shown on the figure; which in the case of Sambor Alt_7-A is 2.3 x $10^7$. With the suspended sediment flowing into the reservoir mainly consisting of silt and clay the upper curve in Figure 6-22 is used to estimate the amount of sediment flowing through the reservoir, which amounts to ~90%.

The Brune and Churchill methods of estimating sediment either trapped or flowing through the reservoir provide consistent results. In both cases, it is estimated that the amount of sediment flowing through the reservoir is on the order of 90%.

If this estimate of sediment flowing through the reservoir is combined with the sediment flowing through the anabranch the total amount of suspended sediment passing amounts to 93% (Table 6-3).

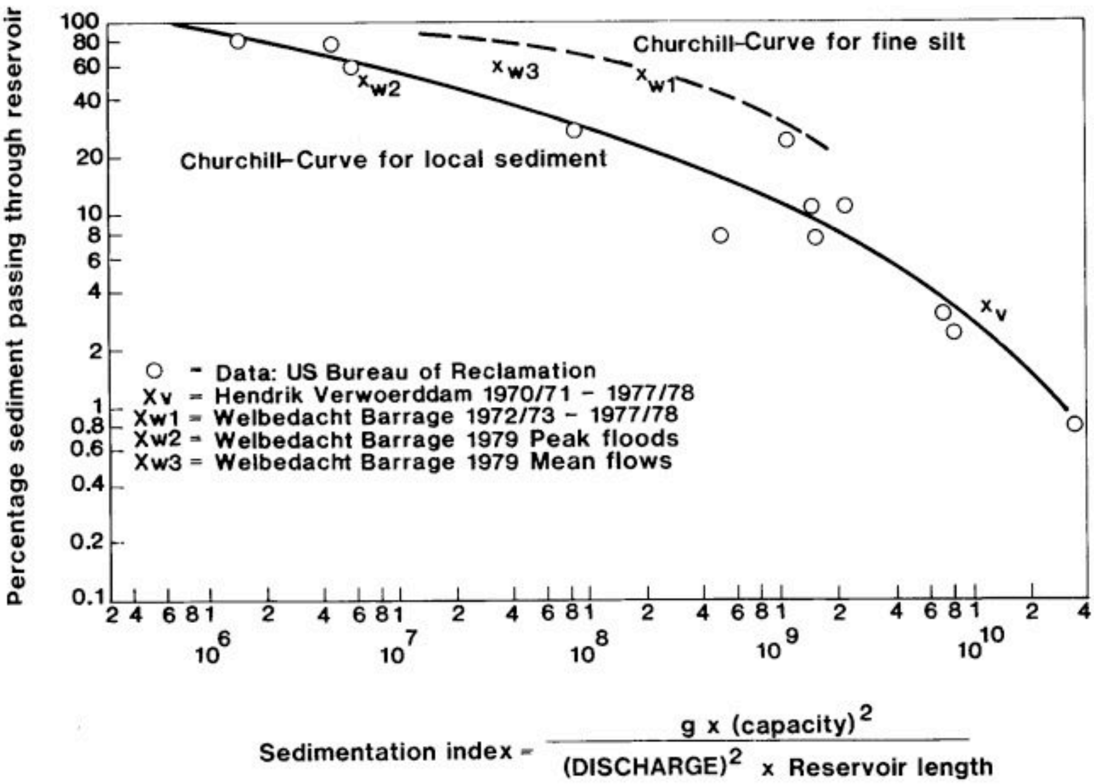



*Figure 6-21. Churchill (1948) curve as modified by Roberts (1982).*

*Table 6-3. Total amount of sediment passage through the Sambor Alt_7A hydropower facility.*

| Total Percent Passing (Entire River) | | |
|---|---|---|
| | Flow (m3/s) | Sed Pass |
| Mean Mekong Flow | 13,400.00 | |
| Main Stem Flow | 9,999.00 | 90% |
| Anabranch Flow | 3,401.00 | 100% |
| | | |
| Total Passing | | 93% |

The bed load in the Mekong River consists predominantly of fine sand, which is likely to deposit in the reservoir upstream of the Sambor Dam and spillway. However, the low-level gates in the spillway of Sambor Alt_7-A can be used to flush sediment through the system, resulting in minimal amounts of deposited sediment over the long term.

The design allows almost all the suspended sediment to pass through the reservoir. This is accomplished by sediment flowing unobstructed through the anabranch channel (east channel) and through the reservoir on the main channel (west). The reservoir is so small compared to the average flow in the river (i.e. only about 0.5% of the average annual flow in the river) that the sediment trap efficiency is very low. In total, it is estimated that 93% of the sediment will pass downstream. A comparison of the sediment capture at the original Sambor CSP with Sambor Alt_7 is depicted below in Figure 6-22.

The increased discharge of suspended sediment resulting from Sambor Alt_7-A design and operations modifications will benefit downstream geomorphology, increase the flow of nutrients to the lower floodplain fishery, and limit the subsidence of the Mekong delta landform in Vietnam. For example, a study by Schmitt *et al.* (2017) suggests that increasing the discharge of sediment from the Sambor Alt_7-A site by 60 Mt/yr would correspond to an improvement of 1.2 mm/yr of sediment deposition, which ultimately would prevent 31 m/yr of coastline retreat. This corresponds to the prevention of 2600 m of coastline retreat by 2100, and prevention of 2273 $km^2$ of delta land lost by the year 2100 (Schmitt *et al.*, 2017). Passing nearly all of the Mekong's current sediment load at Kratie would correspond to an improvement of 1.4 mm/yr of sediment deposition, which ultimately would prevent 37 m/yr of coastline retreat. This corresponds to the prevention of 3100 m of coastline retreat by the year 2100, and prevention of 2500 $km^2$ of delta land lost by 2100 (Schmitt *et al.*, 2017).

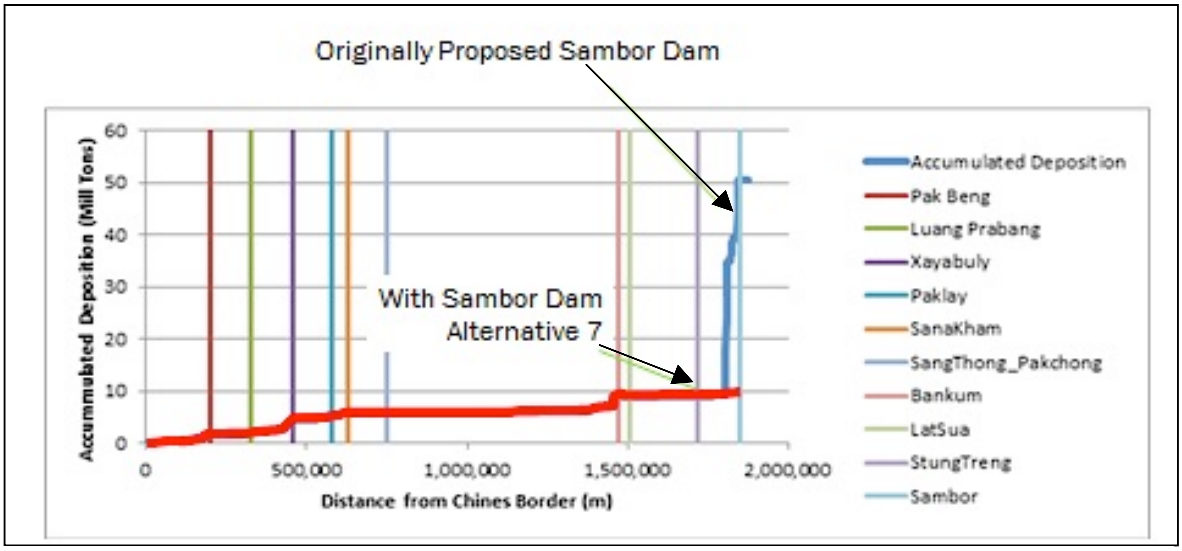



*Figure 6-22. Sediment capture at the original Sambor (CSP) & (b) Sambor Alternative 7. Source: HDR & DHI, 2015.*

## Energy Calculations

A reservoir operation model was used to evaluate the daily energy production potential of Sambor Alt_7 using daily flow data from Stung Treng gauging station (Table 6-4) for the period from 1910-2015.

*Table 6-4. Gauging stations.*

| Station Name | ID | Latitude | Longitude |
|---|---|---|---|
| Stung Treng | 014501 | 13.522047N | 105.933548W |
| Kratie | 014901 | 12.442324N | 106.024037W |

The energy output was estimated using the operating rule in Figure 6-13 and the tailwater curve immediately downstream of the dam (Figure 6-23). The presence of the anabranch fishpass results in more discharge occurring downstream of the powerhouse than what flows through the powerhouse, a fact that should be taken into account when estimating the hydropower potential of the facility.

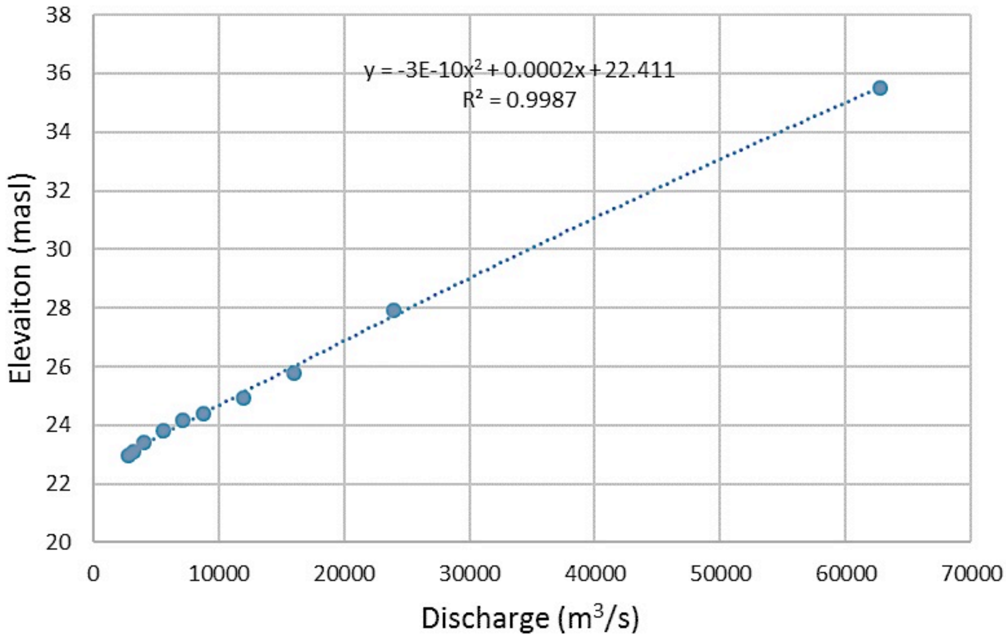



*Figure 6-23. Tailwater Curve downstream of Sambor Alt_7 derived from HEC-RAS modeling of Mekong River cross section downstream of Sambor by George Annandale.*

Relevant dam and reservoir specifications used to calculate the energy potential of Sambor Alt_7-A are shown in Table 6-5.

*Table 6-5. Relevant dam and reservoir specifications used to calculate the energy potential of Sambor Alt_7-A.*

| | | |
|---|---|---|
| Flow Period | 1992-20002 | |
| Full Supply Level | 39m | |
| Tailwater Level | variable m | |
| Efficiency | 0.95 | |
| Head | variable m | |
| g | 9.81 m/s$^2$ | |
| Design Flow (Main) | 10,580 m$^3$/s | |
| Average Flow (Main) | 7,557 m$^3$/s | |
| Initial WSE | 34.3 masl | |
| Max Volume | 1,223,262,000 m$^3$ | |
| **Dead Storage** | 634,165,200 m$^3$ | |
| Active Storage | 589,096,800 m$^3$ | |
| Minimum Operating Level | 34 masl | EL of Dead Storage |
| Minimum Head (Cavitation) | 7.619 m | |
| Maximum Head (Cavitation) | 17.142 m | |
| Design Head | 11 m | |
| Shiplock Fish Pass | 1% of Main Channel Flow | 50 m$^3$/s (max) |
| Right-Bank Fish Pass | 100 m$^3$/s | |

As previously discussed, only a fraction of the flow upstream of the reservoir site actually enters the reservoir, while the remainder is spilled into the anabranch channel at the reservoir's upstream end.

Figure 6-24 shows 106 years (i.e., from 1910-2015) of simulated daily flows entering the reservoir under the energy maximizing operating policy from Figure 6-13. (The remainder of flow was spilled into the anabranch channel). Importantly, the operating policy itself affects the inflow values given the complex site hydraulic configuration. That is, lower water levels result in higher inflows, whereas higher water levels result in lower inflows. Thus, the sequence of reservoir inflows depicted in Figure 6-24, which were used to estimate energy production potential, are applicable only for the particular reservoir operating policy discussed in Figure 6-13.

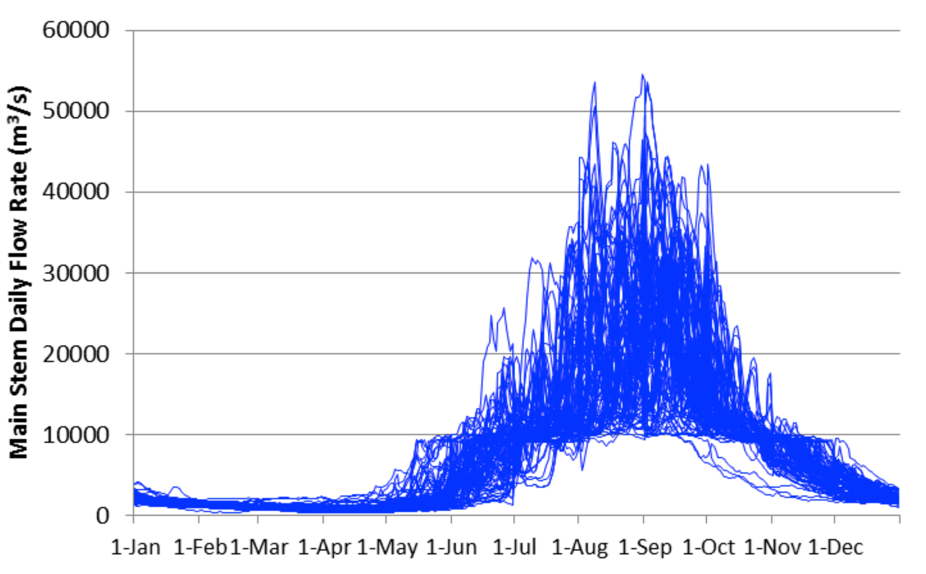



*Figure 6-24. Daily reservoir inflows over historical record with energy maximizing operating policy.*

The reservoir inflows from Figure 6-24 resulted in the simulated daily energy production time series shown in Figure 6-25 below. Note that during the wet season there are occasionally periods of time with no energy production. This occurs because during the wet season the combination of substantial reservoir releases and anabranch channel discharge create a tailwater level sufficiently high that danger of cavitation exists for the turbines considered in this study. Zero energy production is assumed to occur in these cases.

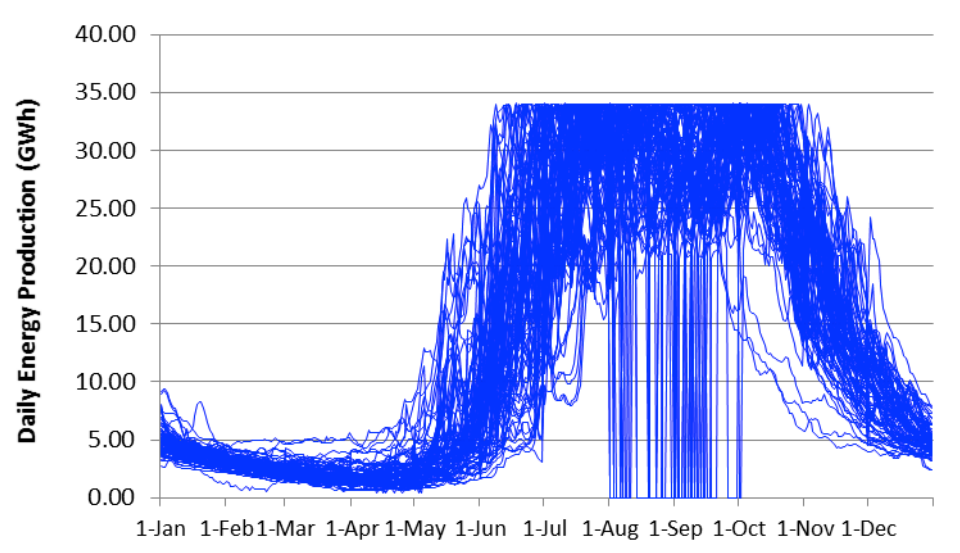



*Figure 6-25. Daily energy production for the operating policy in Figure 6-13 using the reservoir inflows from Figure 6-24.*

The daily energy production and power production exceedance probability plots resulting from this simulation appear below in Figure 6-26 and Figure 6-27, while the exceedance probability plot corresponding to powerhouse (i.e., turbine) discharge is shown in Figure 6-28.

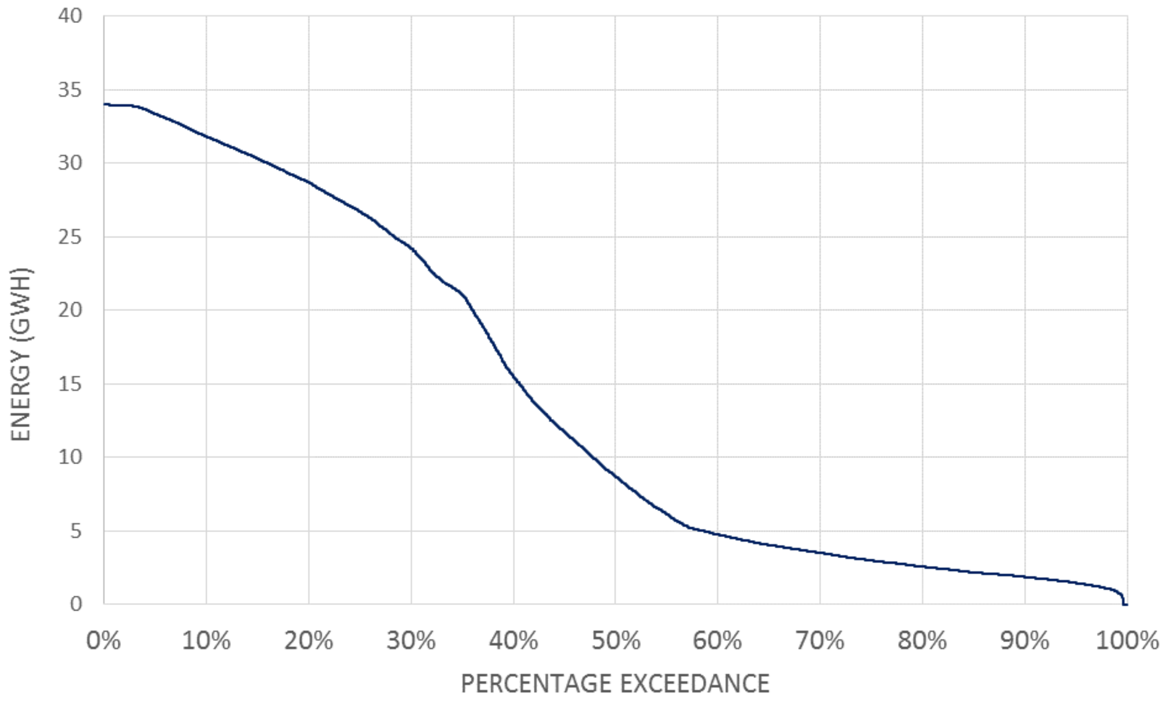



*Figure 6-26. Daily energy production (GWh) exceedance probability plot.*

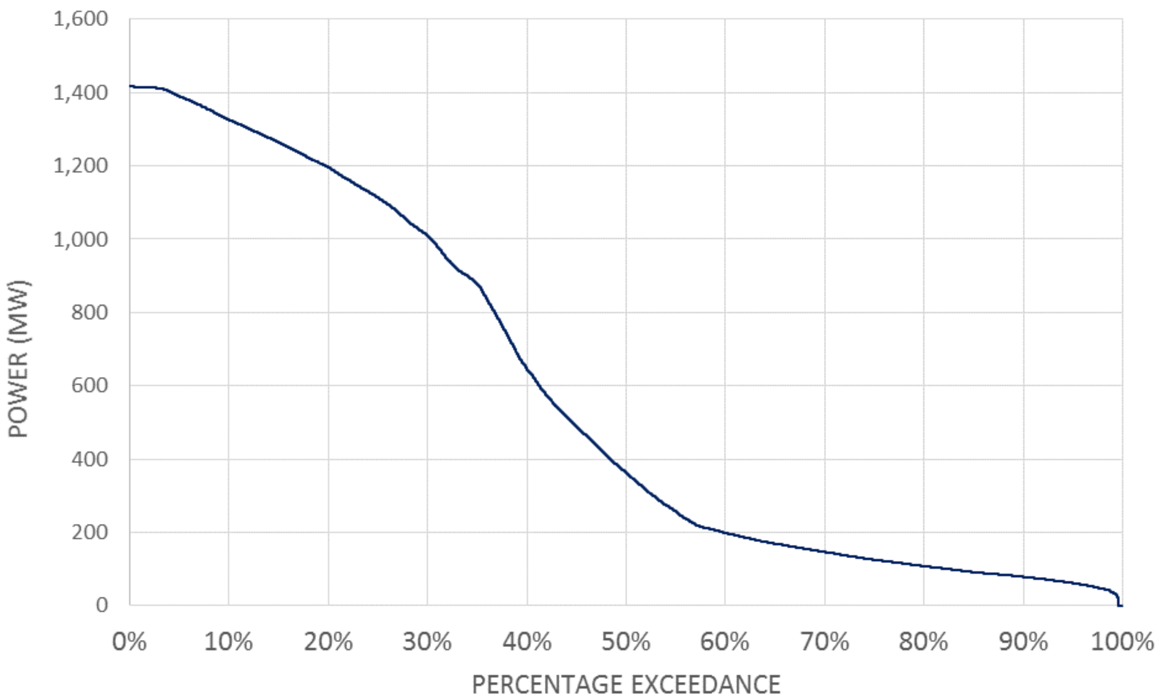



*Figure 6-27. Daily power production exceedance probability plot.*

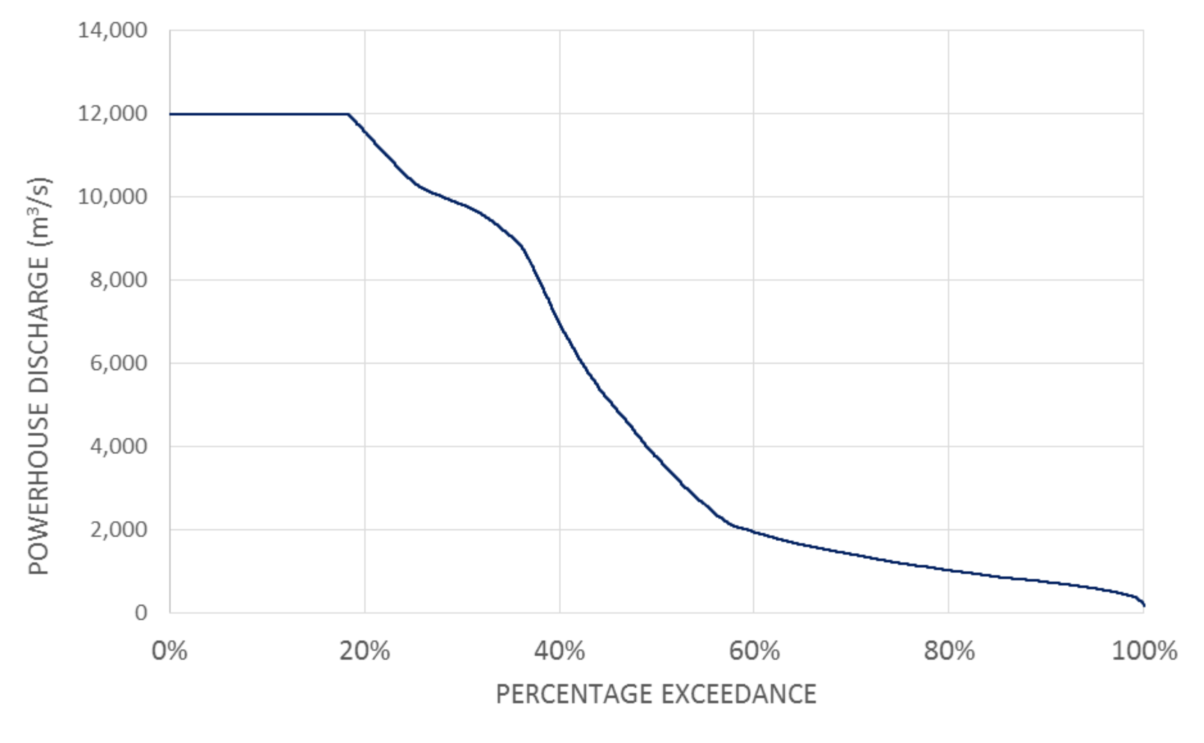



*Figure 6-28. Daily powerhouse discharge exceedance probability plot.*

A summary of the dam's energy production potential is provided and results in Table 6-6. Note that this energy and power production assessment assumes the reservoir is operated continuously (year-round for 24 hours per day) with no downtime.

*Table 6-6. Energy Potential of Sambor Alt_7-A.*

| | |
|---|---|
| Energy/year | 4,240 GWh |
| Firm daily energy (95% exceedance) | 1.46 GWh |
| Firm power output (95% exceedance) | 61 MW |
| At Design Capacity | 18 % of the year |
| Output (Max) | 1,417 MW |
| Output (Min) | 0 MW |
| Output (Max as % of Installed Capacity) | 115% |
| Output (at Design Flow) | 1,236 MW |
| Head at Design Flow | 11.0 m |
| Design Discharge | 12,000 $m^3$/s (Main Stem) |
| Max Head | 12.9 m |
| Min Head | 0.0 m |
| Max Flow | 46,815 $m^3$/s (Main Stem) |
| Min Flow | 345 $m^3$/s (Main Stem) |

## Electro-Mechanical Design

Figure 6-29 indicates the selection of the turbine type as a Kaplan turbine, which has been placed vertically in the proposed design. The installed capacity consists of twelve 103 MW turbines, for a total of 1,236 MW.

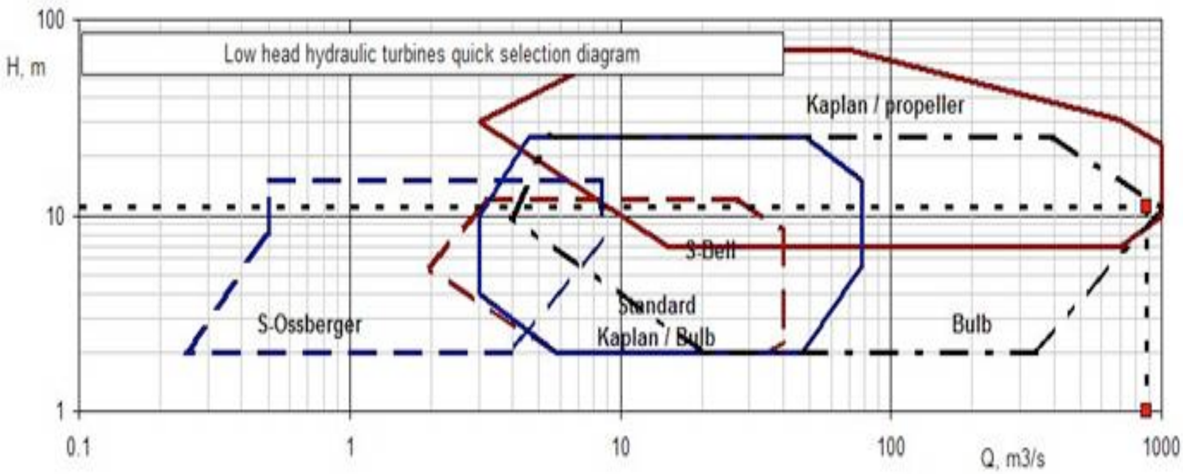



*Figure 6-29. Selection of turbine type (Escher-Wyss Turbine Chart).*

## Relocation Calculations

Relocation for Sambor Alt_7-A should be done from areas within the 40 meters' contour line. This will affect people within four communes: 1) Ou Mreah, 2) Siem Bouk, 3) Boeng Char and 4) Ou Krieng. In the 1998 village census, seven villages were registered within the 50 meters' contour lines above the dam site (see Figure 6-30). On the left bank, relocation should be considered for an additional 4 villages as discharge may exceed present day values.

Estimation of the number of people to be relocated is based on the 1998 village census and the 1998 and 2008 commune censuses (ODC). To estimate the population in the villages by 2016, the population growth in 11 communes was calculated for the years between 1998 and 2008. (Average 45.1%). The village population is then estimated as the 1998 population + (1.8*45.1%), assuming a similar growth in population during the 8 years from 2008 to 2016 (see Table 6-7). The estimated village population of 6,663 by 2016 is almost double from 1998. The village population estimate is a minimum as some people may live outside the villages but still within the 40 meters' contour line.

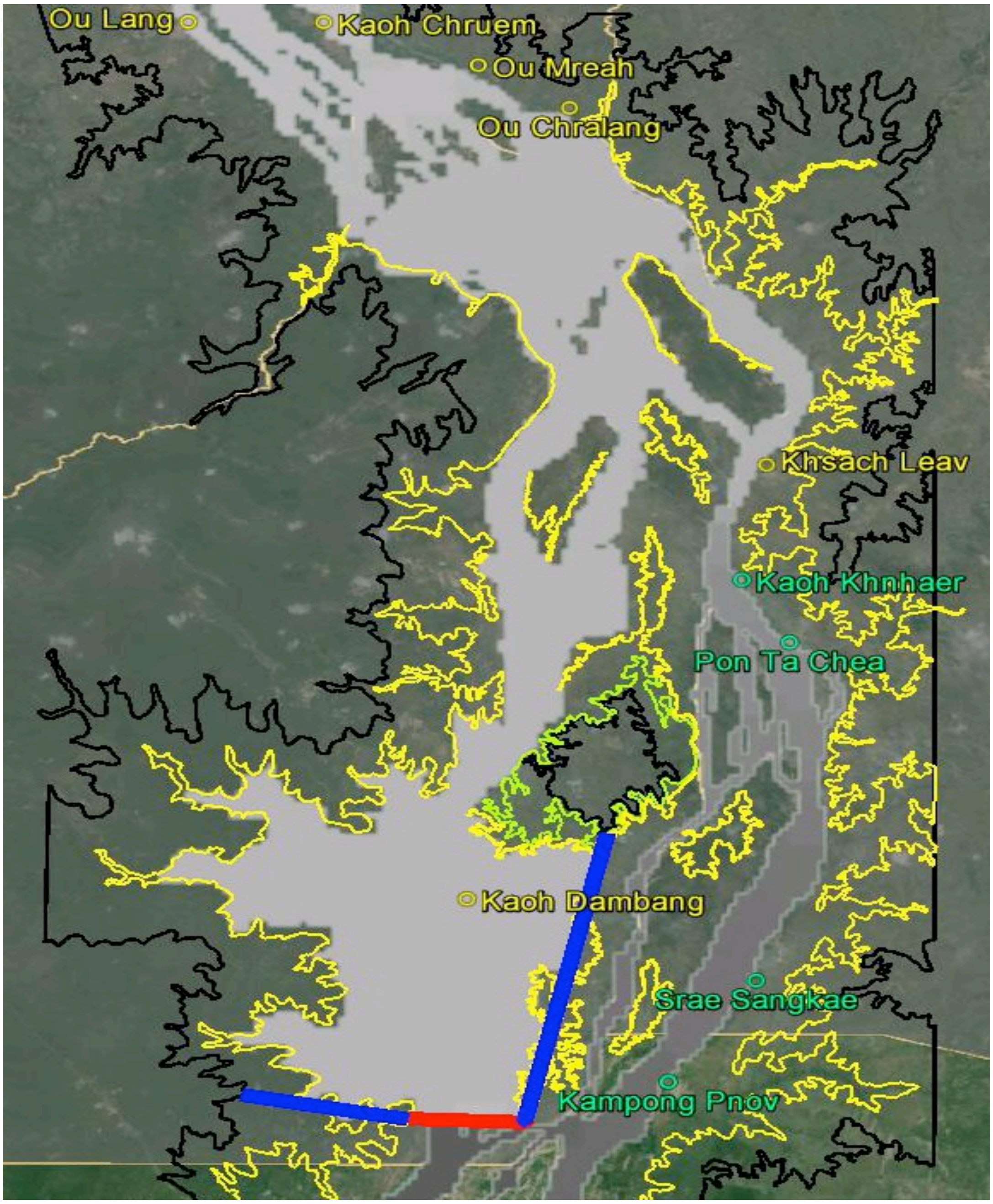



*Figure 6-30. Map of Sambor Alternative 7-A at Latitude: 12.948765°, Longitude: 105.998352°, showing villages where relocation is necessary (village names in yellow) or should be considered (villages names in green).*

The reservoir is delineated by the light grey shaded area equal to the 40 meters' contour line. In the dark grey area, water level may exceed present day values. Yellow contours: 40 masl Ha Tien, Black contour: 50 masl Ha Tien, Red line: Dam wall 3 km. Blue line left bank enforcement to 50 meters' contour lines 9 km. Blue line right bank enforcement to 50 meters' contour lines 4 km.

*Table 6-7. Estimation of relocation size (persons) for Sambor Alt_7-A.*

| | Population | Population |
|---|---|---|
| **Village Name** | **Census** | **Estimate** |
| | **1998** | **2016** |
| **Relocation needed** | | |
| Ou Lang | 552 | 1000 |
| Tboung Khla | 545 | 988 |
| Kaoh Chruem | 460 | 834 |
| Ou Mreah | 58 | 105 |
| Ou Chralang | 132 | 239 |
| Khsach Leav | 307 | 556 |
| Kaoh Dambang | 434 | 786 |
| *Total* | *2488* | *4508* |
| **Relocation considered** | | |
| Kaoh Khnhaer | 473 | 857 |
| Pon Ta Chea | 359 | 651 |
| Srae Sangkae | 79 | 143 |
| Kampong Pnov | 278 | 504 |
| *Total* | *1189* | *2155* |
| Grand total | 3677 | 6663 |

For location of Sambor Alt_7-A, see Figure 6-24 above.

Relocation categories are: villages where relocation is needed and villages where relocation is to be considered. Relocation should be considered in the dark grey area in the map in Figure 6-24 because discharge there may exceed present day values.

The Feasibility Report prepared in 2008 for the original Sambor Dam estimated that 19,034 people would be relocated if the originally proposed Sambor dam was constructed at the Sambor village. It would also cover the anabranch and the reservoir would be considerably larger than for a dam constructed at Alternative Alt_7-A. However, it would still be within the 40 meters' contour line (yellow contour on map in Figure 6-30).

For villages within the 40 meters' contour line above the original Sambor dam location, relocation calculations were based on the same principles as for Table 6-7, resulting in relocation of 16,622 people in 2007 numbers and 21,422 people in 2016 numbers (see Table 6-8). The number was 19,034 in the Feasibility Study (2008).

With a dam located at Sambor Alt_7-A, the needed relocation is 21% of the original Sambor dam, or 31% if villages where relation should be considered is included in the estimate.

*Table 6-8. Relocation estimates (in persons) based on same principles as Table 6-7. The estimate for the originally proposed dam at Sambor village, using 2016 numbers, is 21,442 people relocation, compared to the estimate of 19,034 in (The Kingdom of Cambodia, 2008).*

| Village name | Population Census 1998 | Estimated population 2016 | Estimated Population 2007 | | Population Census 1998 | Estimated population 2016 | Estimated Population 2007 |
|---|---|---|---|---|---|---|---|
| Kaoh Khnhaer | 473 | 857 | 665 | Kaoh Phdau | 654 | 1185 | 920 |
| Pon Ta Chea | 359 | 651 | 505 | Samphin | 1145 | 2075 | 1610 |
| Kaoh Dambang | 434 | 786 | 610 | Cheung Peat | 935 | 1694 | 1315 |
| Srae Sangkae | 79 | 143 | 111 | Svay Chek | 682 | 1236 | 959 |
| Kampong Pnov | 278 | 504 | 391 | Bay Samnom | 657 | 1191 | 924 |
| Kaoh Chbar | 611 | 1107 | 859 | Doun Meas | 761 | 1379 | 1070 |
| Ampil Tuek | 846 | 1533 | 1190 | Kaoh Real | 478 | 866 | 672 |
| A Chen | 1001 | 1814 | 1407 | *Khsach Leav* | 307 | 556 | 432 |
| Tonsaong Thleak | 1414 | 2562 | 1988 | *Ou Chralang* | 132 | 239 | 186 |
| Kampong Krabei | 576 | 1044 | 810 | Total | 11383 | **21422** | 16622 |

## References

Brune, G.M., 1953. Trap Efficiency of Reservoirs. Trans. of American Geophysical Union 34(3), 407-418.

Churchill, M. A., 1948. Discussion of paper by L. C. Gottschalk ''Analyses and use of reservoir sedimentation data,'' in Federal Inter-agency Sedimentation Conference Proceedings, pp. 139–140, U.S. Geological Survey., Denver, CO.

China Southern Power Grid Co. (CSP) and Guangxi Electric Power Industry Investigation Design. October 2008. *Feasibility Study Report of Sambor Hydropower Station*. Prepared for The Kingdom of Cambodia.

HDR and DHI, 2015. Study on the Impacts of Mainstream Hydropower on the Mekong River (Mekong Delta Study) – Final Report. Ministry of Natural Resources and Environment, Government of Vietnam.

OpenDevelopment, Cambodia http://www.opendevelopmentcambodia.net/maps/downloads/.

Roberts, C.P.R., 1982. Flow Profile Calculations. *HYDRO 82*, University of Pretoria. Pretoria, South Africa.

Rosgen, D.L., 2001. A Practical Method of Computing Streambank Erosion Rate. Wildland Hydrology, Inc., Pagosa Springs, Colorado. Available at: https:/semspub.epa.gov/work/01/554370.pdf.

Schmitt, R.P., Rubin, Z., Kondolf, G.M., 2017 (in press). Changing Drivers Affecting the Sediment Budget of the Mekong Delta. *Geomorphology. DOI:* http://doi.org/10.1016/j.geomorph.2017.04.029.

# 7 Fish Passage Design at Sambor Alternative 7

## Objective of Fish Passage Design

In this Chapter, we describe and assess the effectiveness of state-of-the-art mitigation measures that were designed with the objective of achieving passage of 95% of the fish and other aquatic animals (OAA) in the Mekong/Tonle Sap ecosystem - after the reductions expected from the Lower Sesan 2 Hydropower Project (LSS2). The LSS2 will potentially reduce fish production by 9% (Ziv *et al.*, 2012)[10]; hence, the LSS2 plus a new Sambor Alternative 7 Dam that maintains 95% of fish passage will still result in ~14% reduction in fish production. This Chapter, and Chapters 8 and 11 also estimate the risks that this performance goal will not be met, and the potential consequences. Our analysis (see Chapter 8) is that if Sambor Alternative 7 (Sambor Alt_7) proceeded with mitigation measures that provide only a conventional level of success, fish production could potentially be 30-70% less than current production.

We set the following performance objectives for the mitigation measures described in this report.

- **Fish Passage Objectives:** Pass 95% of fish upstream and downstream, which follows MRC guidelines (MRC, 2009) for mainstream Mekong dams. Note that some species will likely require more than 95% passage to maintain populations, such as threatened species with very low population numbers (e.g. Mekong giant catfish) and obligate long distance migrations, while other species that are common and have short distance migrations will likely require less than 95% to maintain populations.
- **Dolphin Objectives:** 100% survival. This standard reflects the extremely low population number such that any mortality has a major impact on the population (See Chapter 9).

We have noted in Chapter 5 that attaining these standards requires departing from the conventional paradigm for feasibility studies of hydropower projects on large rivers. Under that paradigm, the planning process starts with a dam site and conceptual design that maximizes energy production. Environmental impacts are then assessed and mitigation measures defined. The problem with this approach is that it requires the fishery to accommodate the power generation rather than requiring the power production to accommodate the needs of the environment. That conventional paradigm, whatever its justification in ordinary circumstances, cannot be justified at Sambor Alt_7 site with its extraordinary fishery value.

For the Sambor Alt_7 project we have changed this methodology and put *identifying impacts* and *mitigations* first, before dam site selection and energy estimates. Hence, these factors are integrated into the project from the beginning (see Figure 5.1 in Chapter 5).

## Background to Fish Passage in Tropical Rivers

The key mitigation for the impacts on upstream migration are fishways (also called fishpasses and fish ladders). Fishways were historically developed for adult salmon and trout in temperate climate rivers, with relatively low species diversity. Salmon and trout are strong swimmers and fishways

[10] This predicted reduction applies only to the biomass of migratory *whitefish* species. The loss expressed as a proportion of the total yield of all species (blackfish+ grey fish + whitefish) may therefore be significantly less: approx. 3 %, if it is assumed that migratory *whitefish* species form about 38% of the total yield/biomass following the modeling assumptions reflected in Chapter 8 of this Report.

designed for these fish have performed very poorly where they have been used in tropical or temperate rivers with different fish species and sizes migrating (Mallen-Cooper, 1996; Mallen-Cooper and Brand, 2007). Fishways for non-salmonid fishes in temperate and tropical rivers systems need to be designed to be compatible with the swimming ability and behavior of the species present (Mallen-Cooper, 1999). Understanding these aspects has led to very effective fishways for temperate and tropical non-salmonids at weirs up to 6m in height (Mallen-Cooper, 1992; Mallen-Cooper, 1994; Barrett and Mallen-Cooper, 2006) with more recent effective examples at high dams up to 30 m (Berghuis, 2008). However, these high-dam examples have been in rivers with relatively low to moderate discharge and low migratory biomass. The examples of fish passage at high dams in large tropical rivers are mainly from South America and these have consistently performed poorly (Agostinho *et al*., 2007). The fundamental reason is that the financial that have been negotiated with the investors, the power customer(s) and the national government terms are agreed before the details of the fishway design are determined. Those terms seek to minimize the costs of dam construction and operations, whilst maximizing power output.

The reasons for the poor performance of fish passage facilities in large tropical rivers (Agostinho *et al*., 2007) are well known. The design and operations have been based on a misunderstanding of the biology and migratory ecology of the fish species, leading to:

- facilities that are too small for the volume of biomass encountered (Oldani and Baigún, 2002).
- facilities that provide only for upstream passage, not downstream passage.
- fishpass entrances being at a location that the fish cannot readily find.
- water dedicated to the fishpass being inadequate (< 1% of total flow) to provide the flow that can attract the fish and accommodate their biomass.

All these issues for upstream migration are potentially solvable in the initial design and operational decisions. Downstream migration, however, is more complex and presents greater challenges.

## Principles of Fish Passage Design

There is great diversity among freshwater fish species in large tropical rivers, and comparably large variation in their migration patterns. Yet, there are common approaches and principles that can be applied to fish passage designs for all these fish species and river systems. These are described in detail in Appendix 7.1 and summarized in Text Box 7-1.

*Text Box 7-1. Principles of fish passage design*.

| | |
|---|---|
| **Principle 1.** | Assess fish passage in a regional context of habitats, migrations, and existing and proposed dams. |
| **Principle 2.** | Integrate Biology, Hydrology and Hydraulics. |
| **Principle 3.** | Address Upstream and Downstream Migration. |
| **Principle 4.** | Design for Fish Attraction and Passage. |
| **Principle 5.** | Size the Fishway to meet the Biomass and Flows of the River System. |
| **Principle 6.** | Document Assumptions and use Adaptive Management. |

## Conceptual Basis for Fish Passage Design at Sambor Alternative 7

Following Principle 1 above, a prerequisite to designing a hydropower dam that minimizes impacts on fish populations, and hence food security and livelihoods, is to understand the ecology and life cycles of fish. The conceptual basis for the design of the fish passage mitigation measures at Sambor Alt_7 are presented in detail in Appendix 7.2. The major points are summarized here.

Fish migration is an essential part of the life cycle of many fish species, especially key commercial species in the Lower Mekong River. For example, it is common for adult and sub-adult fish to migrate upstream; larvae to drift downstream to nursery areas on inundated floodplains; and adults and sub-adults to return upstream or downstream to refuge areas, including deep pools. In the Lower Mekong, migrating fish range in size from 30-3000 mm and there is a very high migratory biomass, especially during the onset of the wet season. These characteristics need to be accommodated in fish passage facilities, as well as the varying swimming ability and behavior of each species and life stages. Text Box 7-2 outlines specific fish passage requirements that apply to hydropower dams in the lower Mekong and specifically at Sambor Alt_7 site.

*Text Box 7-2. Fish passage requirements for hydropower in the lower Mekong and specifically at Sambor Alternative 7.*

- 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.

## Fish Passage for Sambor Alternative 7 – Design Criteria & Concepts

### Upstream Passage

#### *Concept*

Based on the requirements listed in ***Text Box 7-2***, the design concept for the Sambor Alt_7 option is to provide three upstream fishpasses:

i) utilize 30km of natural anabranch to provide a low-gradient natural fishpass that passes >10% of flow in all months; the anabranch would be connected to the dam directly by a large channel cut in rock,

ii) a specifically-designed combination dual navigation/fish lock, that passes fish attracted to the left-hand side of the spillway, and

iii) a large pool-type fishpass, that passes fish attracted to the right-hand side of the spillway, with integrated auxiliary flow to attract and guide fish.

Operation of these three fishpasses would vary. The bypass channel would operate continuously, passing > 10% of flow. The twin navigation/fish lock would operate when used for navigation and when water is available, including when the dam is spilling. The pool-type fishpass would operate when the dam is spilling.

### *Bypass channel fishway using the anabranch*

The site and design of the Sambor Alt_7 dam allows the anabranch to serve as a natural fishpass for both upstream and downstream migrating fish (Figure 7-1). The height of the dam backs water up to the inlet of the anabranch. The anabranch would be linked to the river immediately below the dam and powerhouse by a channel cut into the rock, which would mimic the habitat and hydraulics of the anabranch channel (details in Text Box 7-3). The entrance of the channel would be beside the powerhouse, so that migrating fish attracted to the powerhouse and dam would be diverted into the anabranch (*Figure 7-1*, Figure 7-2, and Figure 7-3). Both the anabranch and channel would have a low-gradient (e.g. 1:200) with turbulence and water velocities that are similar to the Hou Sahong channel, which is known to be satisfactory for passing Mekong fish species. Most of the anabranch will likely require little modification, but physical modelling in detailed design may reveal areas that require additional rocks or excavation and widening.

*Text Box 7-3. Details of the orientation of the rock channel (between the powerhouse and the anabranch) and of the powerhouse.*

The rock channel:

- would be 150m wide for dry season flow, and a 300m wide for wet season flow.
- would receive > 10% of the total river flow at all times.
- would have an entrance that is oriented to align with the river channel. physical modelling is needed to finalize the design.
- have an exit located at the upstream limit of migration, which is immediately adjacent to the draft tubes of the powerhouse.

The power house:

- Is aligned to guide fish to the channel.
- would include a fish collection gallery (Figure 7-2), which is a series of fishpass entrances and a channel on the draft tubes of the powerhouse that direct migrating fish to the rock channel.

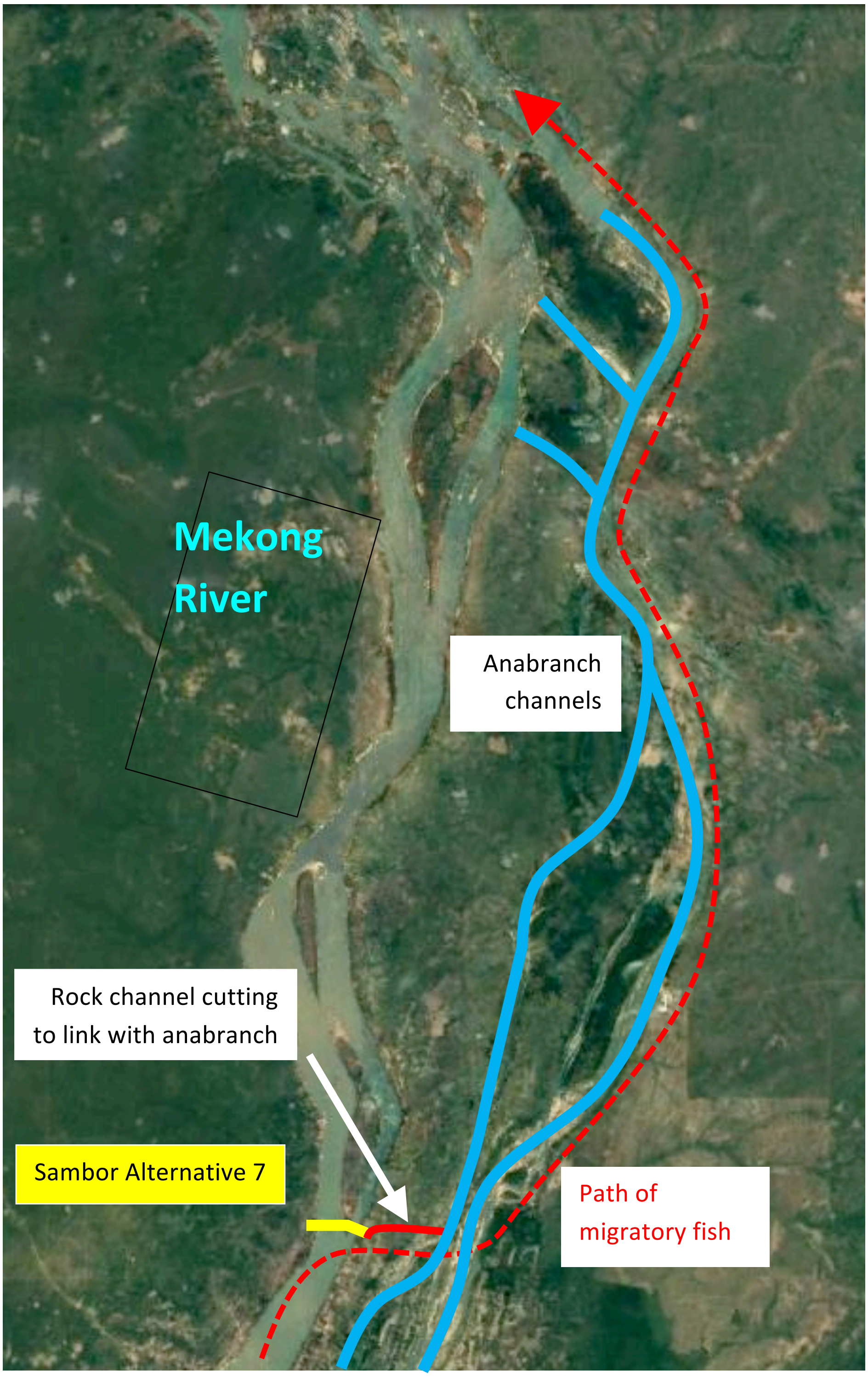



*Figure 7-1. Google Earth image showing the fish passage concept of using the anabranch as a fishpass and cutting a channel from the dam.*

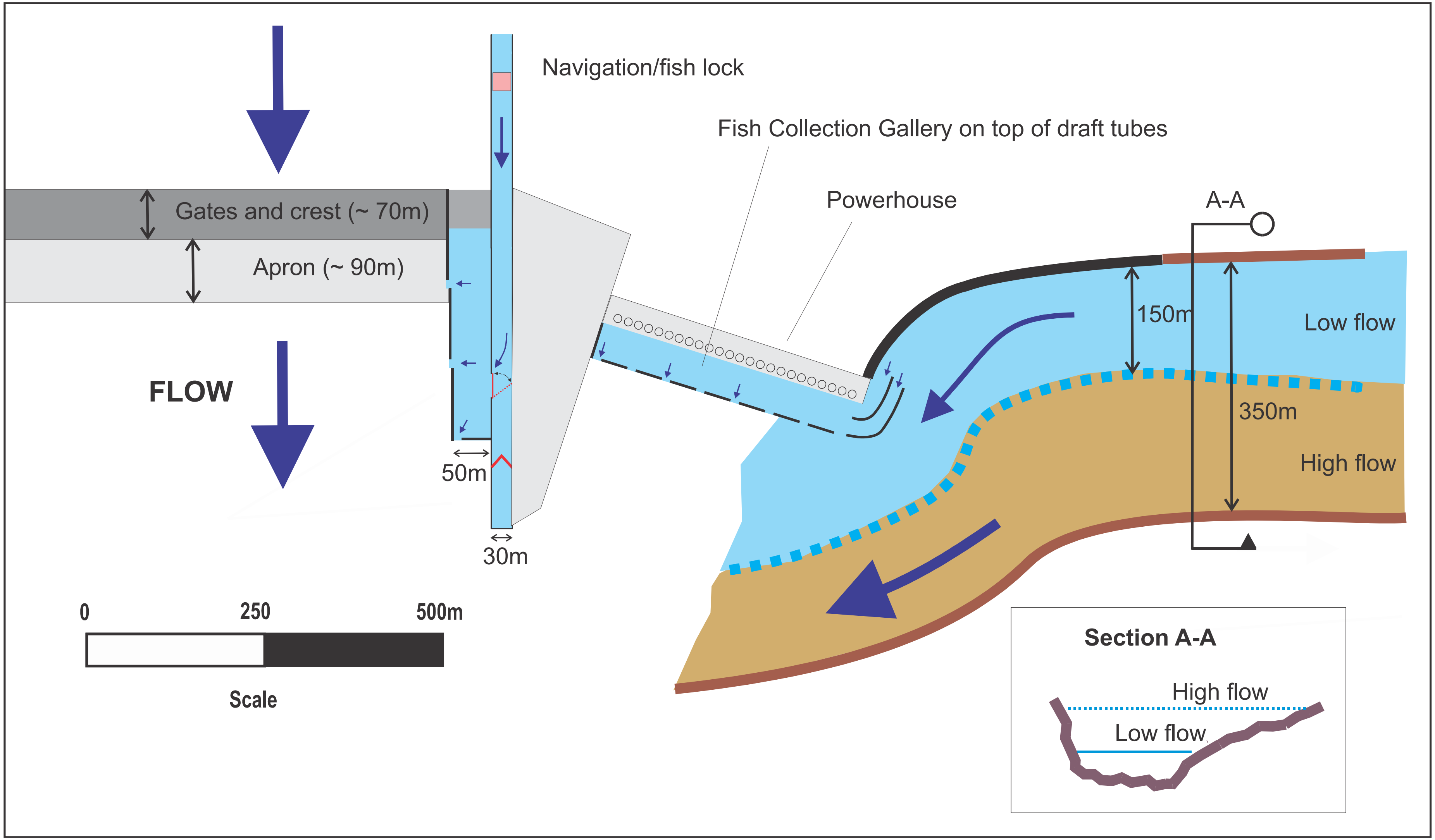



*Figure 7-2. Concept plan of Sambor Alt_7-A option showing the bypass channel fishway that links with the anabranch.*

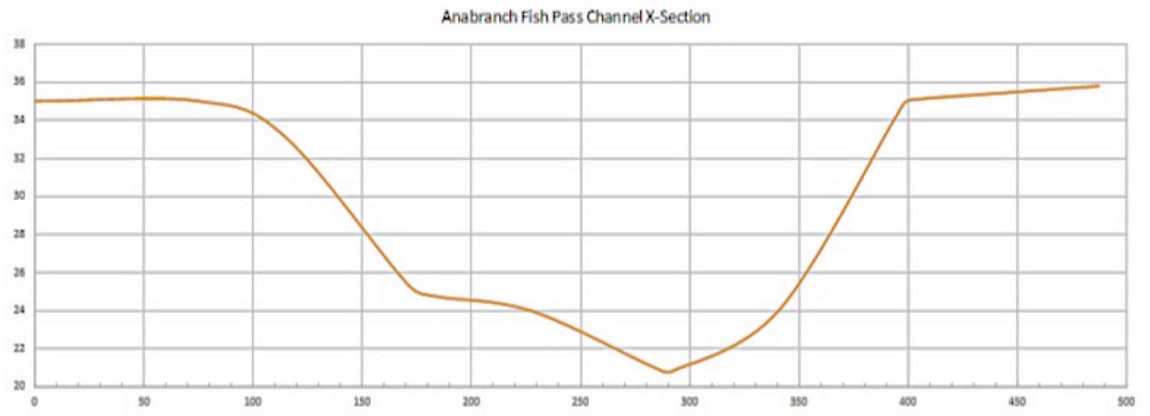



*Figure 7-3. Detailed Section A-A from Figure 7-2 showing the cross-section of the cutting to the anabranch channel.*

## *Navigation/fish lock*

The concept for Sambor Alt_7 includes a combined navigation/fish lock which can be operated in:

- "ship mode", to pass boats;
- "fish mode", to pass fish (if there is no navigation traffic); and
- "hybrid mode" to pass both.

The MRC guidelines (2009) on fish passage and navigation recommend at least one navigation lock but note that two locks are preferable. We have included one in the drawings and cost calculations for Sambor Alt_7, but acknowledge that two would be preferable so that one can be transferring fish upstream while the other is releasing flows to continuously attract fish. In addition, the lock should be as wide as possible; the MRC guidelines have minimum dimensions for navigation locks of 120m long by 12m wide by 4m deep. The combined navigation/fish lock for Sambor Alt_7-A has a width of 30m to enable high flows to attract fish, and provide low turbulence that fish can swim against. Wider locks would pass more fish in the peak migration season.

In *Figure 7-4*, the operation of a generic fish lock is shown to demonstrate the four phases of operation – attraction, filling, exit and draining – and how these operations pass fish upstream.

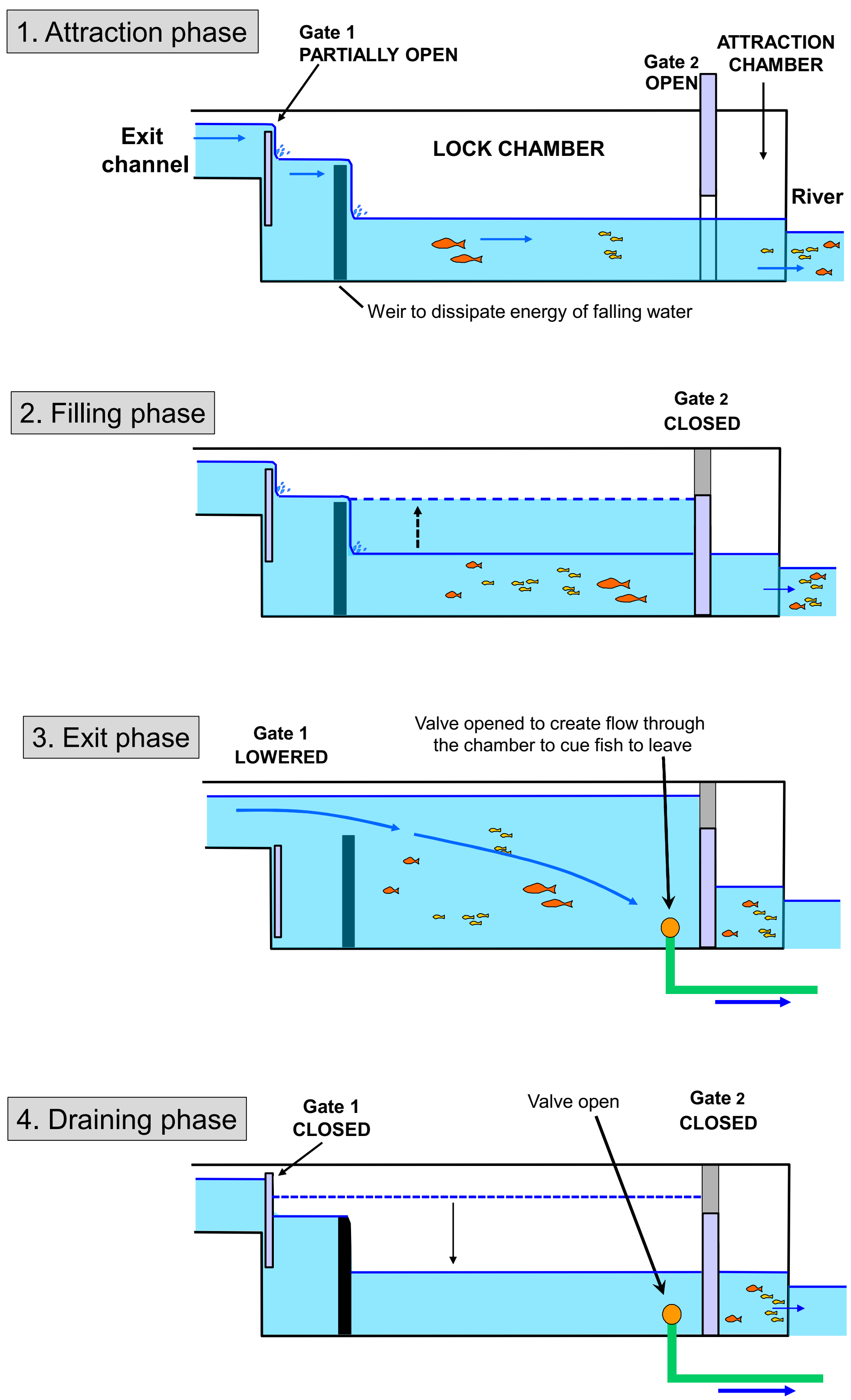



*Figure 7-4. Generic diagram of a fish lock, showing the phases of operation.*

The specific components of the navigation/fish lock design for Sambor Alt_7 are shown in *Figure 7-5* and *Figure 7-6*. The design includes:

- A large overshot gate at the upstream end to pass high flows. Internal weirs or a diffuser system may be necessary to dissipate the energy of the high discharge, so that it is suitable for fish attraction and passage.
- The length of the chamber would be determined by the safe unobstructed passage required for boats so they are not affected by turbulent spillway flow. At Xayaburi Dam the downstream training wall is 400 m long to protect boats.
- There is a fish lock gate as wide as the fish lock chamber which is opened when in "fish mode" to pass water and attract fish, and which connects the lock chamber to the fish entrance pool beside the spillway. This gate has a maximum head differential of 0.3 m when open and full head differential when closed.
- Water from the fish lock passes into an entrance pool which has three entrances at different distances from the spillway, intended for low, medium and high spillway flow. These entrances pass approximately 100 $m^3 s^{-1}$ to ensure fish are attracted into the entrance pool.

  Each entrance is 12m wide and has a 5m offset to create an area of low water velocity and turbulence which becomes the upstream limit of migration, where migrating fish will aggregate. The exact location of the entrances will need to be determined by physical modelling if the project proceeds.
- The navigation/fish lock has traditional angled (mitre) gates at the downstream end to pass boats.

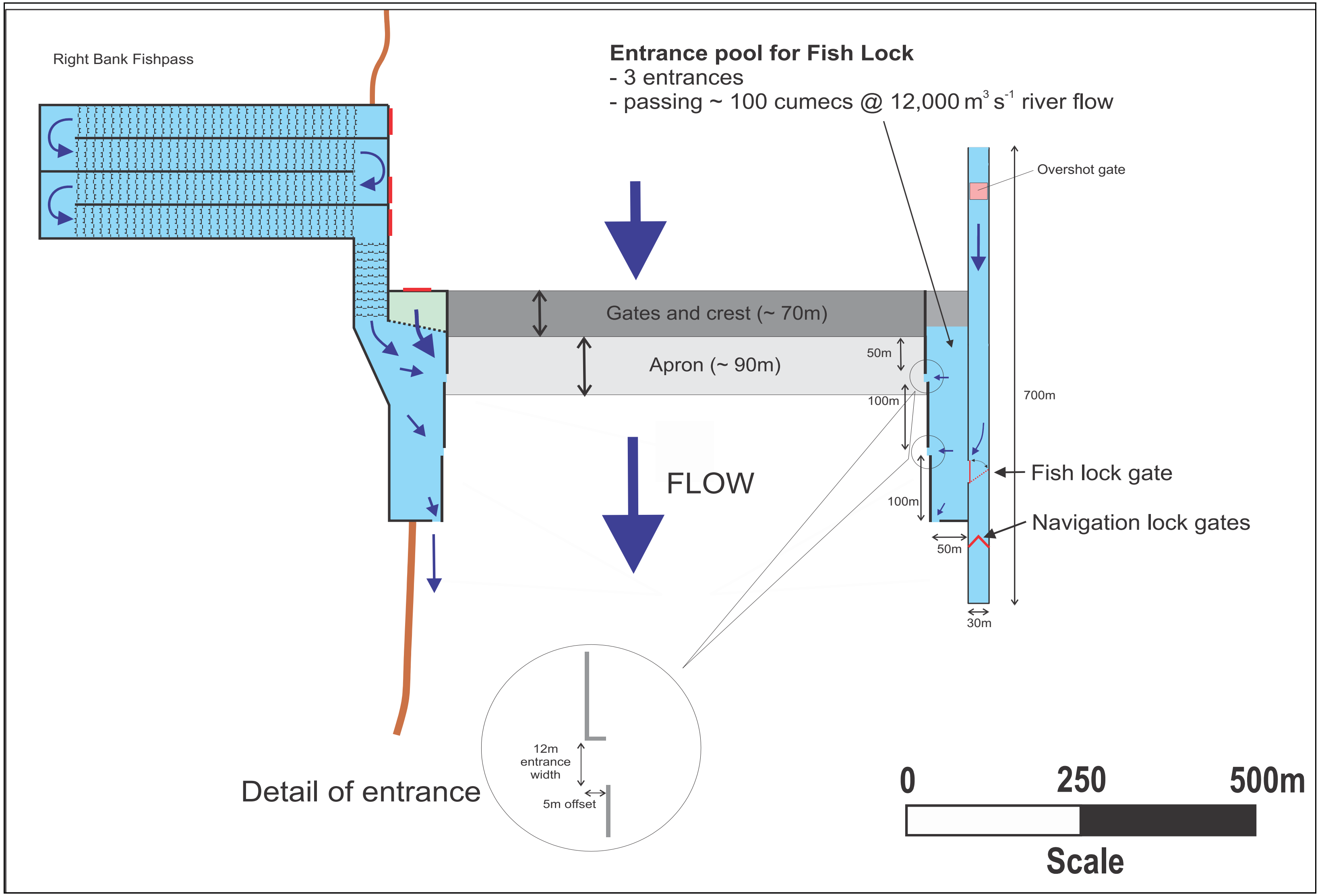



*Figure 7-5. Plan view of navigation/fish lock showing the location with respect to the dam spillway and the right bank fishpass. Powerhouse not shown.*

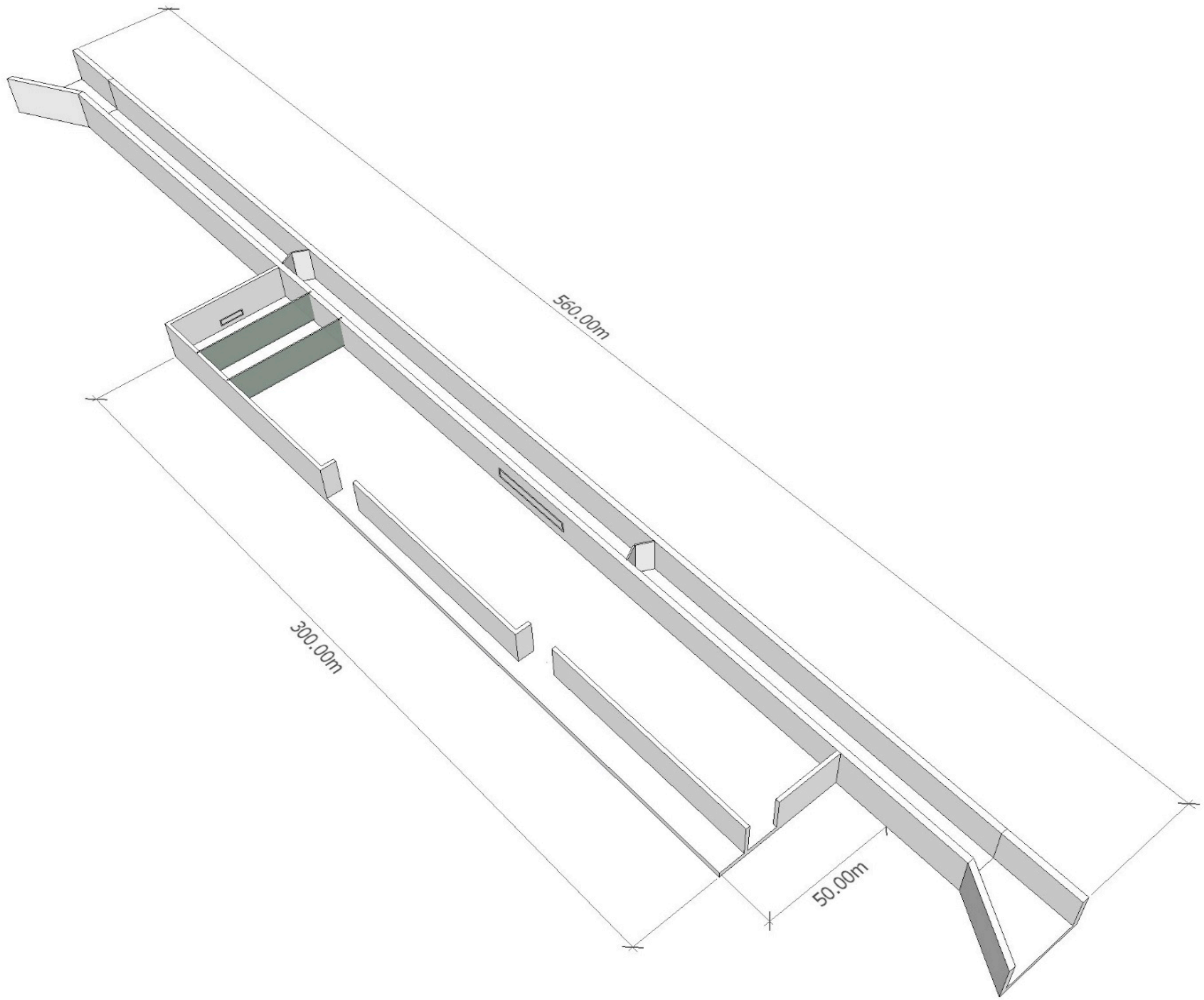



*Figure 7-6. Oblique view of navigation/fish lock showing the lock chamber and entrance pool with 3 entrances.*

*Figure 7-7* shows the operation of the Sambor Alt_7 navigation/fish lock as proposed, in "fish mode". It follows the generic fish lock in Figure 7-4, but shows how the upstream tilting gate, fish gate and downstream valves are coordinated.

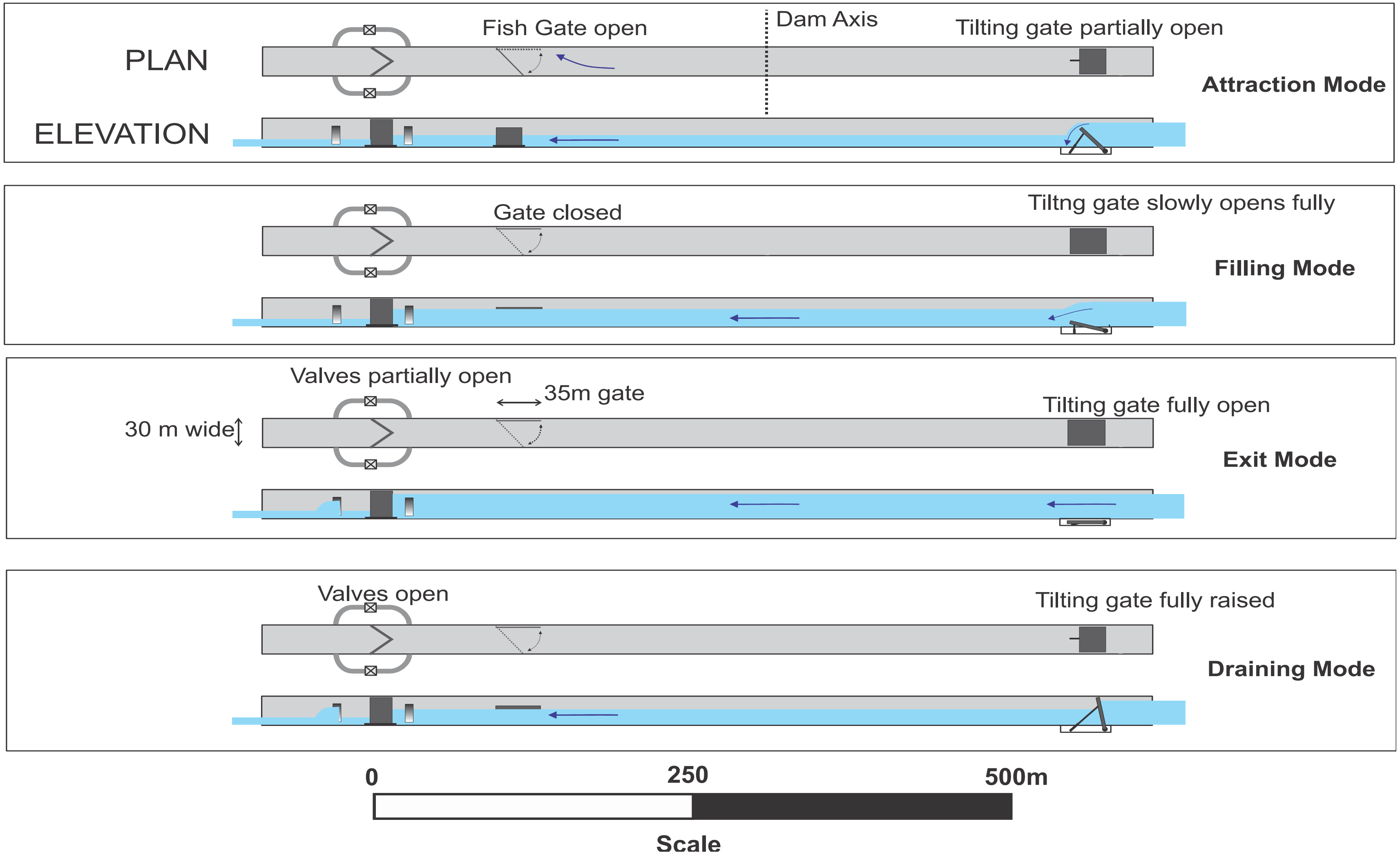



*Figure 7-7. Operation of navigation/fish lock in "fish mode".*

### *Pool-type fishpass*

Sambor Alt_7 would be designed and operated to have a variable headwater. The most suitable fishpass for this condition is a variation of a vertical-slot design (Figure 7-8, Figure 7-9), which maintains constant water velocity and turbulence. Four key design parameters determine the size and biomass of fish that can negotiate a pool-type fishpass:

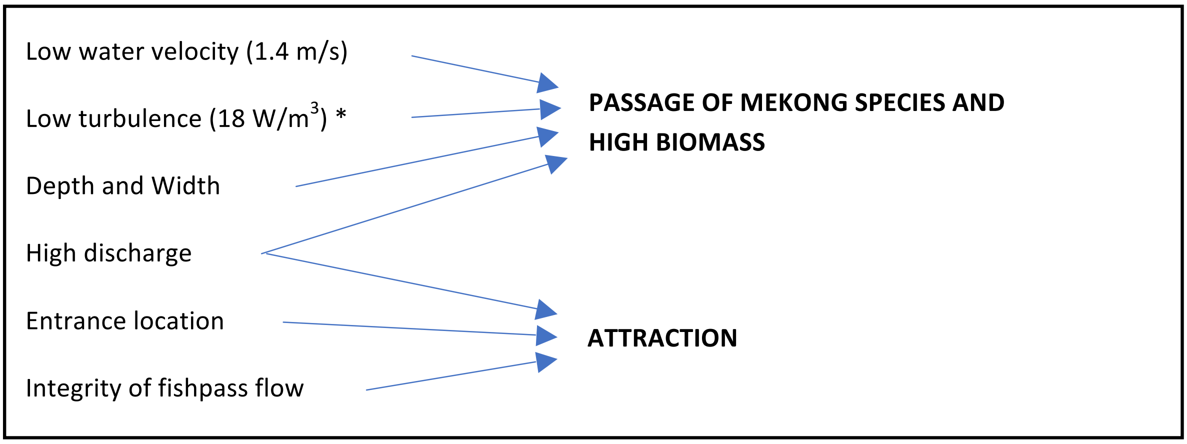
i) maximum water velocity,
ii) turbulence in each pool,
iii) depth and width, and
iv) discharge.

The three key design parameters that help determine fish attraction into the fishpass are:

i) discharge
ii) entrance locations, and
iii) integrity of fishpass flow (that is, a discrete flow that is easily distinguished by fish).

Text Box 7-4 summarizes the design objectives of Sambor Alt_7 based on these parameters for fishpasses.

*Text Box 7-4. Design objectives for Sambor Alt_7 pool-type fishpass.*




*see Appendix 7.3 for calculations

The maximum water velocity in a pool-type fishway is determined by the difference in water level between pools (i.e. through the baffles), which is called the "head loss". For Sambor Alt_7 we are using a baffle head loss is 0.1m, which provides a maximum velocity 1.4 m $s^{-1}$ (Figure 7-8, Figure 7-9). Further explanation for the calculation is provided in Appendix 7.3. This criterion is known to provide passage of small tropical species and would aid passage of high biomass. The baffle design would need computer modelling (CFD) as well as physical modelling to refine the design.

Preliminary design criteria for the pools are 50m wide and 12m long. Minimum depth is 4 to 5 meters, and the gradient is 1:120, depending on baffle thickness. Turbulence in the pools is very low at approximately 18 W/m$^3$ but could be slightly higher (e.g. up to 30 W/m$^3$) in detailed design depending on the final baffle design.

Multiple exit gates would be required for the variable headwater (Figure 7-10). Only one gate is open at one time. The dam could have up to eight meters of headwater variation which would likely require four exit gates. The final number of gates and the headwater variation would need to be determined is an optimization study in detailed design, if the project proceeds. For a maximum differential head of 14m there would be 140 pools and the fishway channel would be 1.4km long. Auxiliary flow for the pool-type fishway would be provided in the entrance pool to enhance fish attraction (Figure 7-10, Figure 7-11). There are three entrances for low, medium and high flow, following the same offsets as described for the navigation/fish lock, to ensure migrating fish can locate the entrance at all spillway flows.

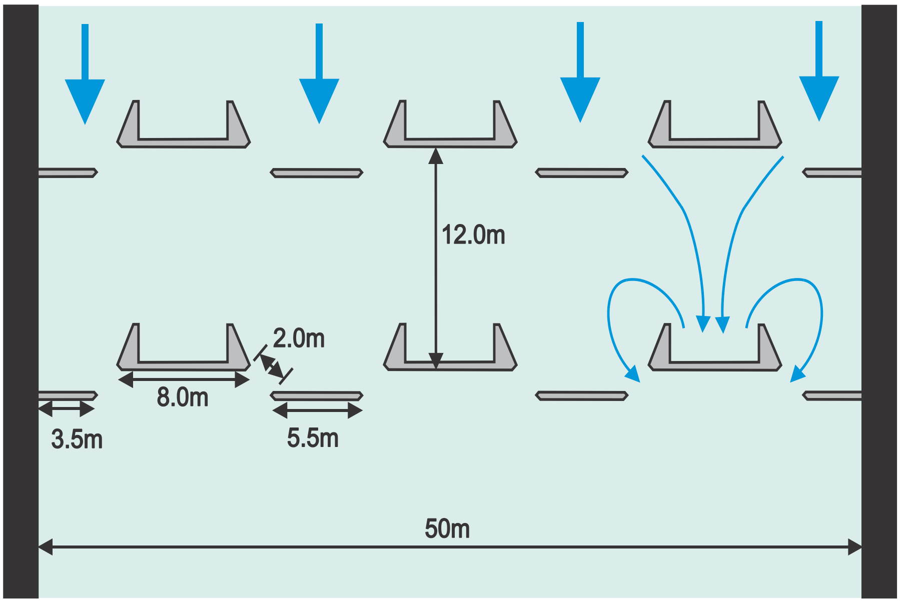



*Figure 7-8. Detailed plan view of baffles in right-side fishpass. Each pool is 4m deep and has 0.1 difference in water level (head loss) between each pool.*

*Figure 7-9. Example of a dual-slot vertical slot fishpass on the River Elbe in Germany. The proposed design for Sambor Alt_7 replicates the dual-slot three times (Figure 7-8) to ensure sufficient biomass of fish can pass.*

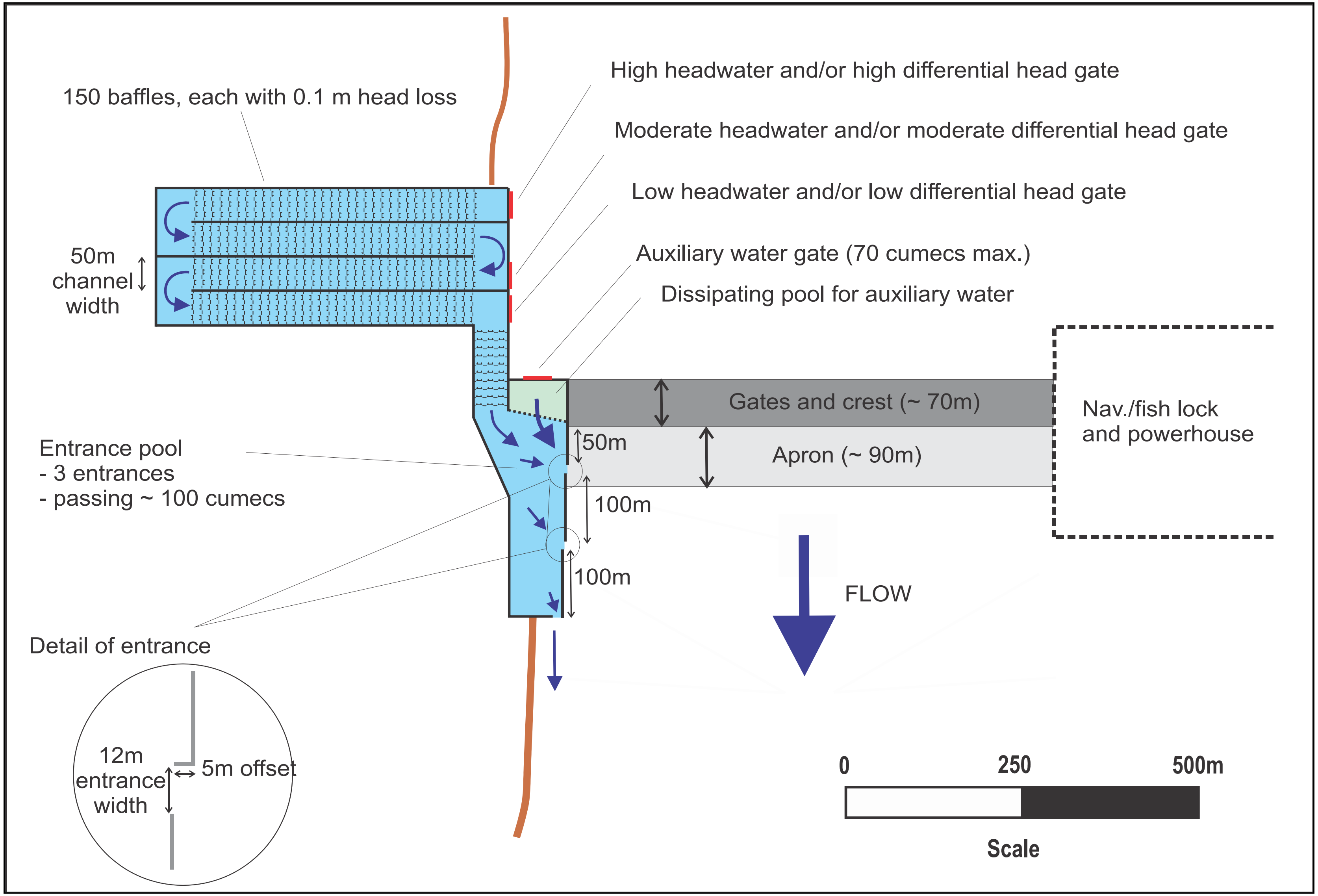



*Figure 7-10. Plan view of the layout of the right-bank fishpass.*

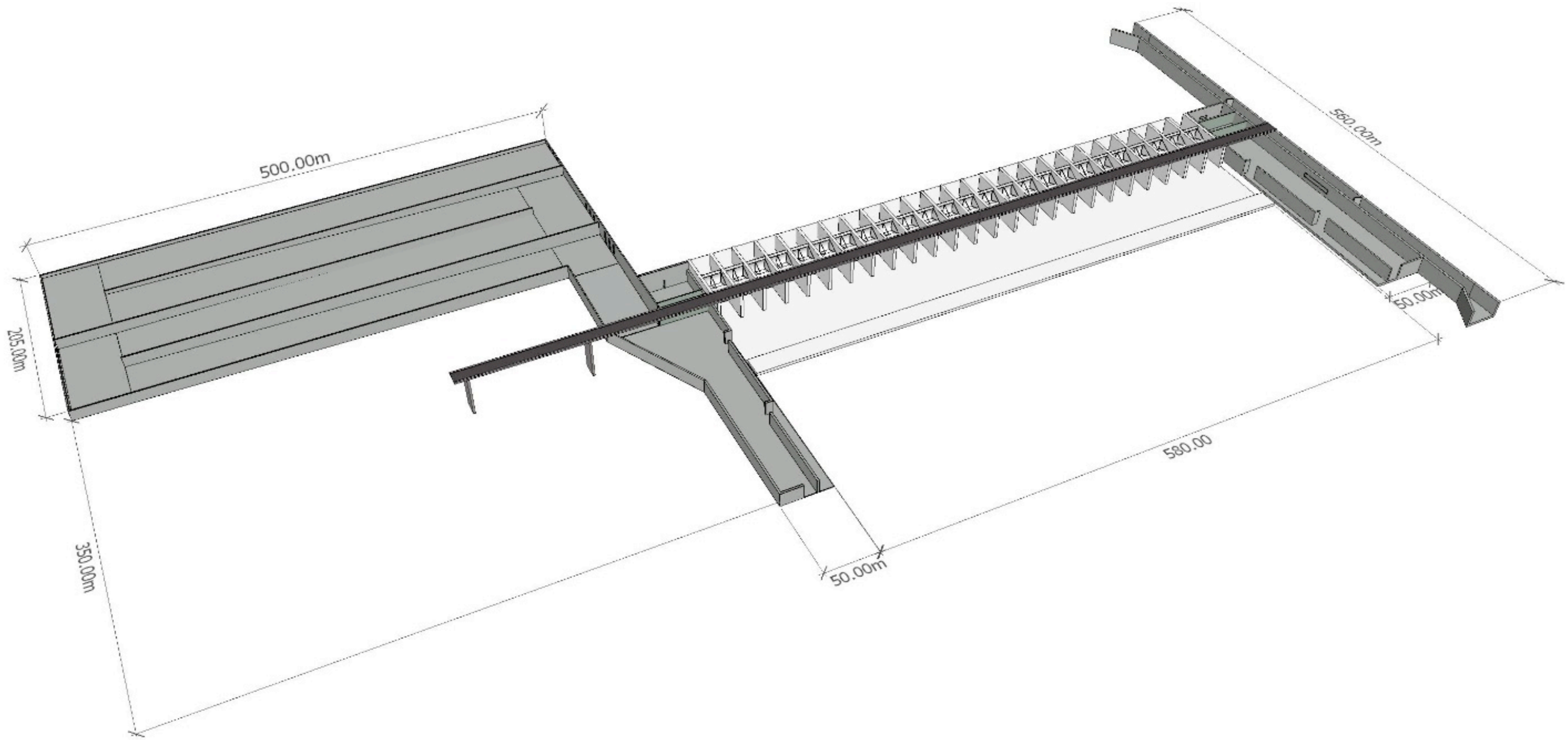



*Figure 7-11. Oblique view of the right-bank fishpass shown with spillway and navigation/fish lock. Fishpass is shown without internal baffles.*

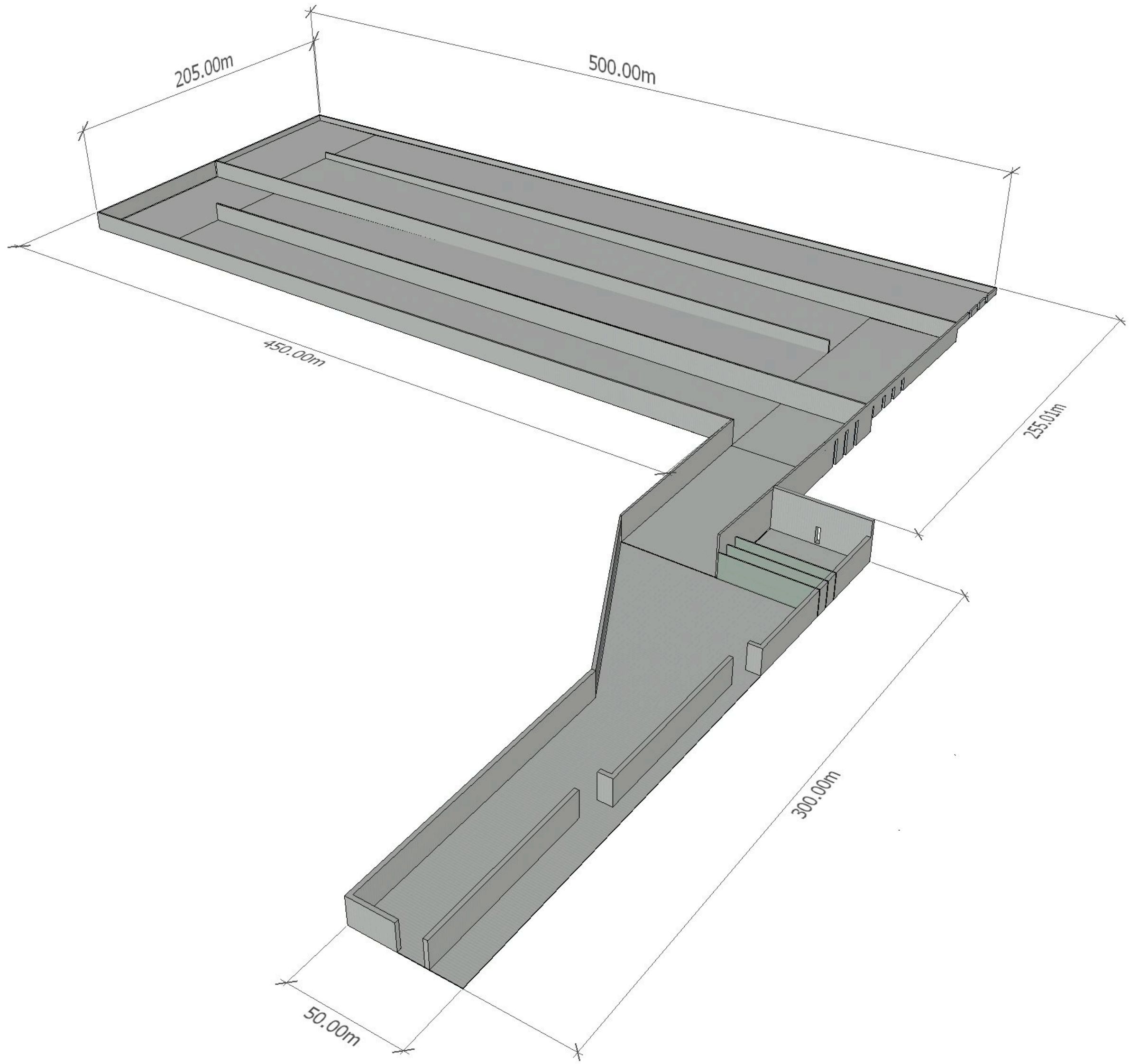



*Figure 7-12. Detailed oblique view of the right-bank fishpass channel, shown without internal baffles.*

## *Layout*

There are two possible layouts for the fishpass design of Sambor Alt_7. The first layout (Option 1) is shown in Figure 7-13, and the second layout (Option 2) is shown in Figure 7-14. Physical modelling would be required to select the most effective option.

Option 2 has greater attraction of migratory fish and, if feasible from an engineering viewpoint, should be considered the preferred option for fish passage. It has a large auxiliary spillway to pass up to 3,250 $m^3 s^{-1}$ to attract fish; the shape and gaps in the right-hand abutment training wall would need to be developed in physical modelling. The NHI technical team considers that this option has a high likelihood of meeting the MRC guidelines (2009) of 95% upstream passage. This option also has the powerhouse oriented to guide fish more effectively to the cutting and anabranch.

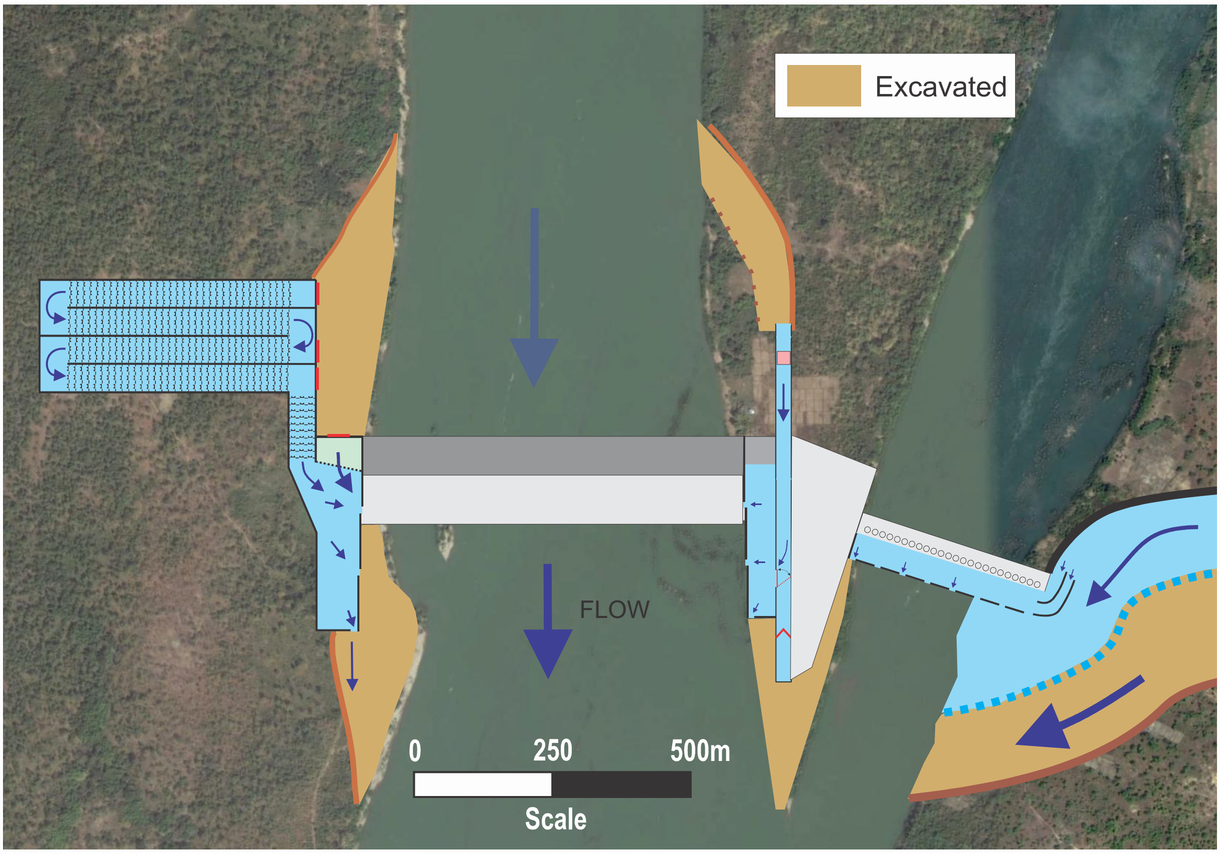



*Figure 7-13. Option 1— conceptual overview of upstream fishpasses for Sambor Alt_7.*

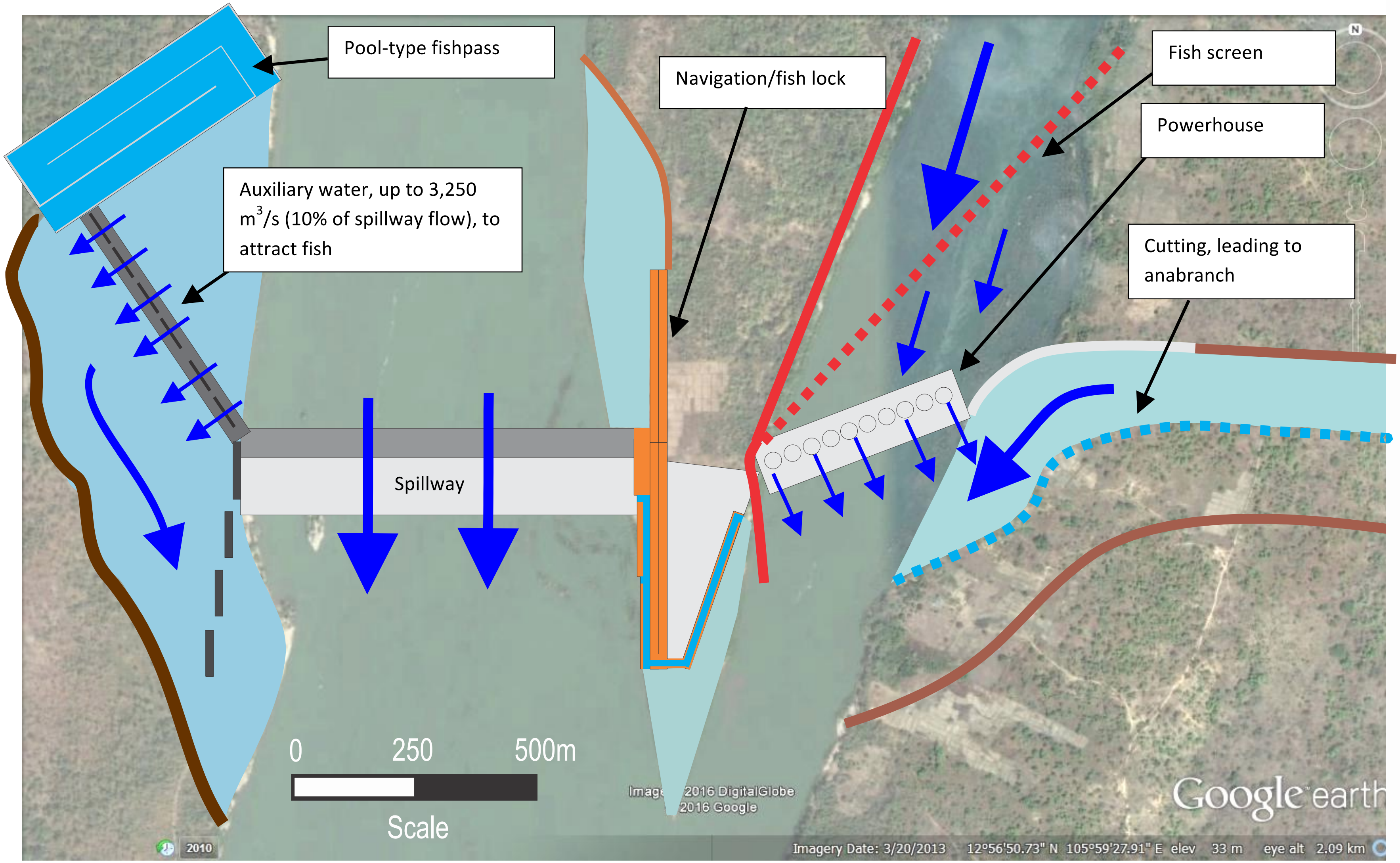



*Figure 7-14. Option 2 – conceptual overview of upstream fishpasses for Sambor Alt_7.*

## Downstream Passage

### *Concept*

Downstream passage of drifting larval fish, juvenile fish and adult fish would be accomplished through both the anabranch and the reservoir and the turbines or spillway. Some fish would also pass down the navigation/fish lock and the right bank fishpass but the flow through these two structures is small compared to the turbines and spillway, so relatively few fish will use them. The measures for achieving 95% survival in downstream passage are:

i) Use of the anabranch to pass some fish around the dam. The number of fish passing in this manner are likely to be proportional to the flow passing through the anabranch. However, the larger fishes that use the deepest channel in the river (thalweg) are more likely to enter the reservoir where they are vulnerable to pass downstream through the spillway or turbines.

ii) Divert medium to large fish around the turbines (as these fish have high mortality in turbines from blade strike), using fish screens and a bypass.

iii) Provide sufficient water velocity for drifting larvae to be transported through the reservoir, based on ADCP measurements of the Mekong main channel at different flows.

iv) Minimize impacts on larvae and small fish in the turbines by:

   a. providing a *pressure acclimation weir* in the intake channel of the power house. This is a submerged weir which forces larvae and juvenile fish on the river bottom to the surface (e.g. upper 2 m) and acclimates them to surface pressure which reduces impacts of pressure change in turbines (barotrauma).

   b. locating the turbines at depth which, when combined with a *pressure acclimation weir*, will largely mitigate pressure change in the turbines.

   c. Installing turbine that reduce impacts of *blade strike* and *shear*.

v) Design the spillway gates to pass fish safely.

### *Larval drift*

As discussed earlier, reservoir water velocities required to sustain larvae drift were assessed using ADCP data of the Mekong River in Cambodia at Stung Treng gauge station (below the Mekong 3-S confluence) at different flows. The minimum mean water velocity in the channel during the dry season is 0.3 m $s^{-1}$. Our approach was to develop a 2D hydraulic model of the reservoir in HEC-RAS, and evaluate the ability of the reservoir to maintain hydraulic conditions exceeding this 0.3 m $s^{-1}$ criterion at a minimum. Reservoir velocities depend on both the reservoir inflow rate, the reservoir water level, and the cross-sectional area of the river, so multiple scenarios were simulated in which the inflows and dam crest elevations were varied. Examples of two modelling runs are shown in Figure 7-15 and Figure 7-16. More details justifying this top-down approach to creating flowing water (lotic) reservoir conditions, rather than modelling the numerous larvae mortality factors such as starvation and predation, is provided in Appendix 7.1.

The modelling shows water velocities of 0.4 to 0.5 m $s^{-1}$ are achieved in the dry season and 0.8 to 1.0 m $s^{-1}$ are achieved in the wet season for the preferred reservoir operating policy (see Chapter 6) that is intended to maximize hydropower production while maintaining larval drift. An example of the proportional discharge through the powerhouse, spillway and fishpasses is shown in Table 7-1 under the operating scenario featured in Chapter 6. The range of mean channel velocities in the anabranch are shown in the table; however, much lower water velocities would be present along the sides of the anabranch due to roughness provided by rocks and vegetation. These would be suitable for fish passage.

Sambor Alt_7 has been designed so that it can be operated to provide the minimum velocity needed to maintain larval drift, but it can also be operated to achieve a wide range of velocities so that it can adapt to improvements in knowledge of the required parameters (e.g. change in season of larval drift). The HEC-RAS modelling results strongly suggest that year-round larvae passage is likely while generating continuous energy from an economically viable project.

However, this conclusion is uncertain as actual reservoir velocities will ultimately depend upon factors such as the river's bathymetry, which controls the flow of water into the reservoir and the spatial distribution of velocity within the reservoir. Until the bathymetry is better known, we show in Appendix 6 how this uncertainty can be dealt with by using an alternative scenario in which the dam would be operated to maintain higher velocities to improve the likelihood of larvae passage, but with a sacrifice of some power production.

To show the complex trade-offs between energy production and fishery objectives, we developed a simulation-optimization framework to test multiple alternative reservoir operation strategies (Appendix 6). These results show that a significant sacrifice in energy production could ultimately be required to improve hydraulic conditions for larval passage, as a result of reduced reservoir water levels. Further hydrodynamic modelling would be required to test the sensitivity of these results to the assumptions.

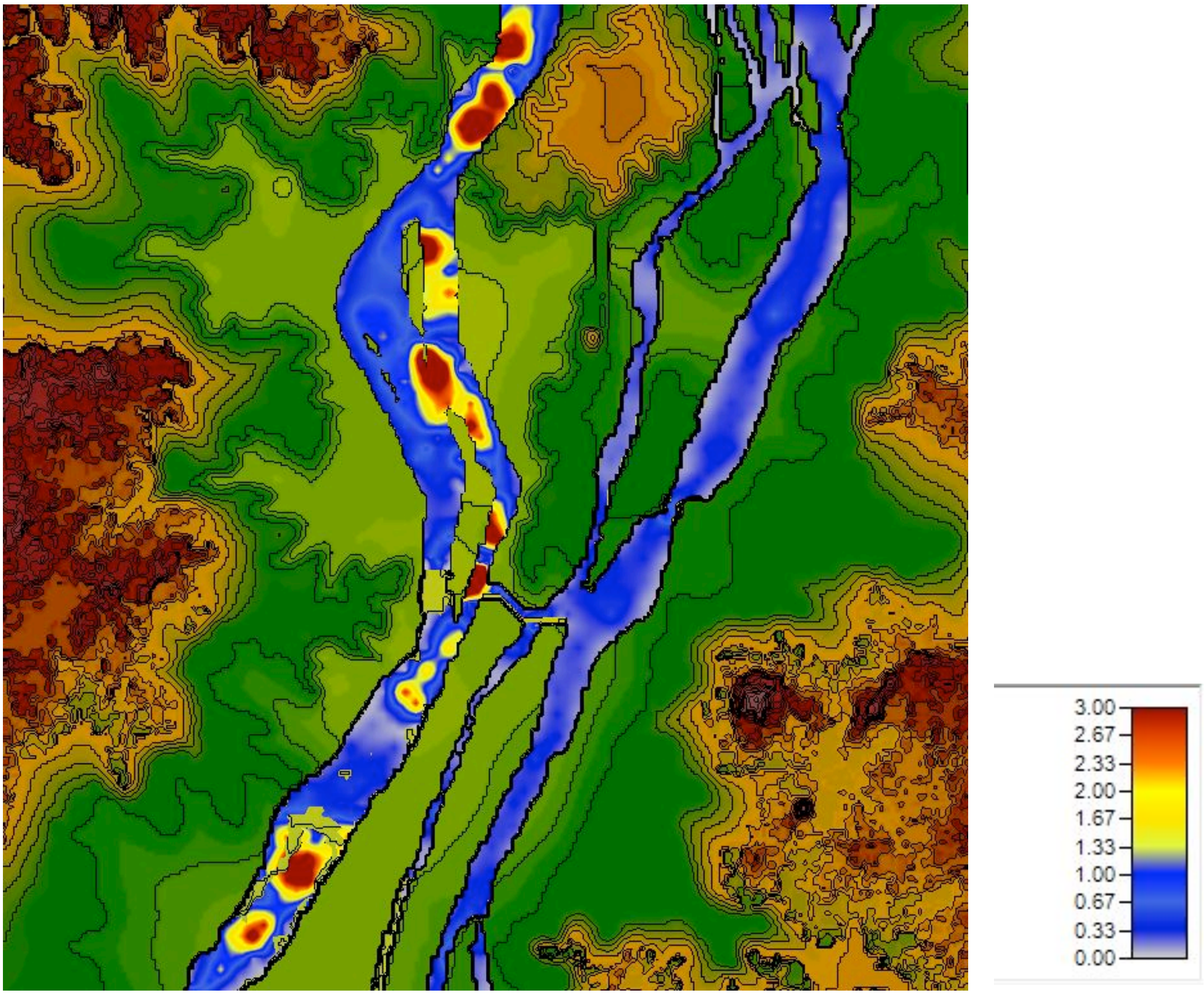



*Figure 7-15. Modelled water velocity (m $s^{-1}$, see colorbar) in the Sambor Alt_7-A reservoir for total Mekong River flow rate of 1000 $m^3$ $s^{-1}$ (see Table 7.1), as modelled in HEC-RAS. Per the reservoir operating rule described in Chapter 6 (Fig. 6-14), which dictates target reservoir water level as a function of total Mekong River flow upstream of the reservoir, the reservoir's water surface elevation is 31.64 masl in the velocity results shown above. Significant areas of the reservoir and anabranch channel maintain velocities above the 0.3 m/s threshold required to create the lotic conditions that ensure natural larvae drift through the site.*

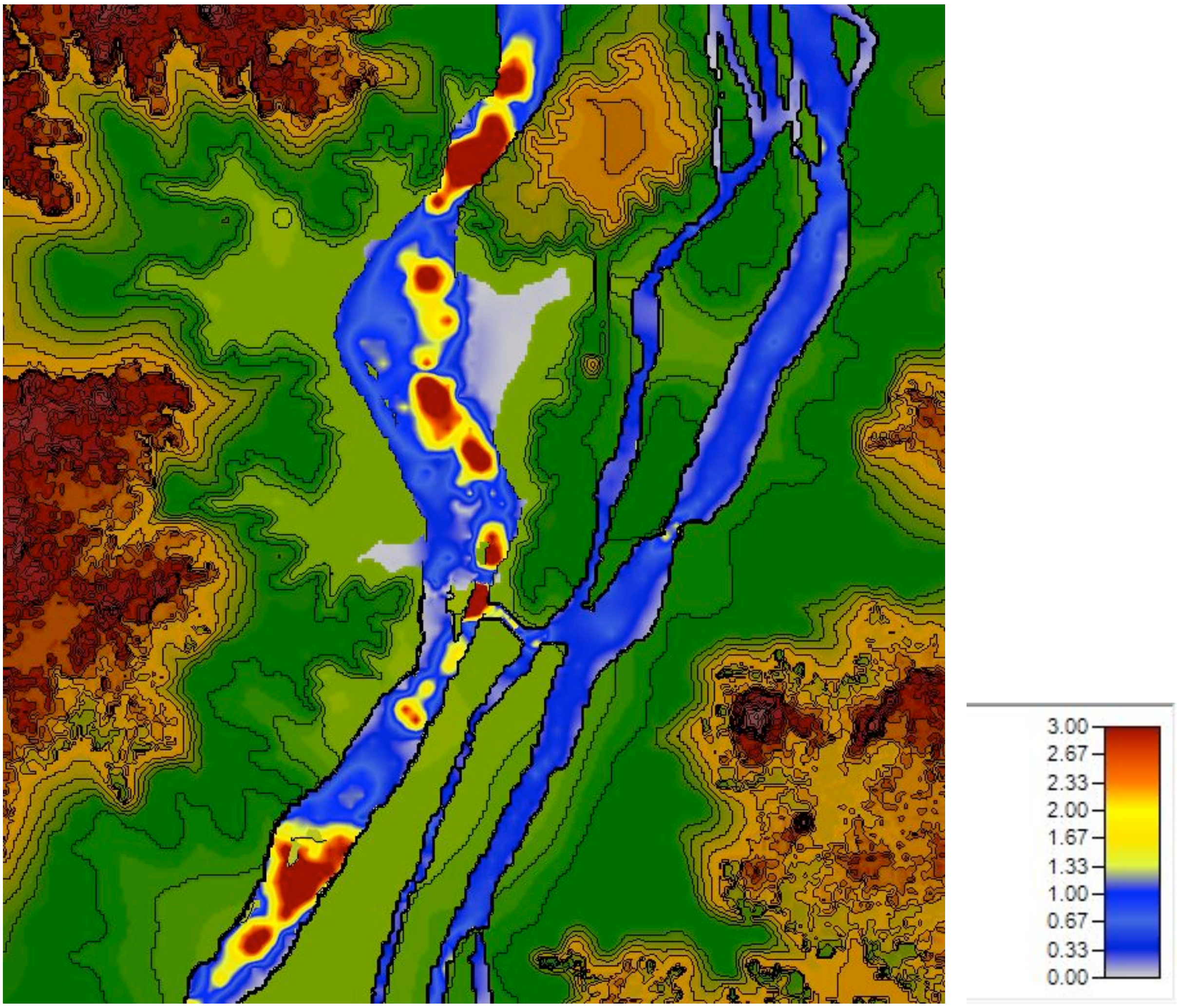



*Figure 7-16. Modelled water velocity (m $s^{-1}$, see colorbar) in the Sambor Alt_7-A reservoir for a total Mekong River flow rate of 4700 $m^3$ $s^{-1}$ (see Table 7-1), as modelled in HEC-RAS. Per the reservoir operating rule described in Chapter 6 (Fig. 6-14), which dictates target reservoir water level as a function of total Mekong River flow upstream of the dam, the reservoir's water surface elevation is 34.07 masl in the velocity results shown above. Significant areas of the reservoir and anabranch channel maintain velocities above the 0.3 m/s threshold required to create the lotic conditions that ensure natural larvae drift through the site.*

*Table 7-1. An example of discharge through the main pathways under the operating scenario featured in Chapter 6.*

| | Upstream | | | Anabranch Fish Pass | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Plan No | Total Discharge (m3/s) | Q main (m3/s) | Q Anabr (m3/s) | Desirable Q in Anabr Fish Pass (m3/s) | Simulated Q in Anabr Fish Pass (m3/s) | Simulated Fish Pass Flow (% of Main) | Head Water EL (masl) | TW EL w Fish Pass (masl) | TW EL No Fish Pass (masl) | TW Difference (m) | Velocity in Anabr Fish Pass (m/s) |
| 25c | 1000 | 318 | 682 | 31.84 | 151 | 47% | 31.64 | 21.77 | 21.51 | 0.26 | 0.29 to 0.90 |
| 26c | 3500 | 1,638 | 1,862 | 163.79 | 537 | 33% | 33.40 | 23.14 | 22.81 | 0.33 | 0.58 to 1.29 |
| 27c | 4700 | 2,233 | 2,467 | 223.30 | 783 | 35% | 34.07 | 23.61 | 23.12 | 0.49 | 0.77 to 1.37 |
| 28c | 7000 | 4,326 | 2,674 | 432.59 | 842 | 19% | 34.04 | 24.54 | 23.85 | 0.69 | 0.78 to 1.23 |
| 29c | 10500 | 7,249 | 3,251 | 724.90 | 1,054 | 15% | 34.19 | 25.4 | 24.73 | 0.67 | 0.86 to 1.38 |
| 30c | 12000 | 9,383 | 2,617 | 938.30 | 1,210 | 13% | 34.41 | 25.73 | 25.02 | 0.71 | 0.68 to 1.29 |
| 31c | 13400 | 8,977 | 4,423 | 897.70 | 1,556 | 17% | 35.17 | 25.97 | 25.18 | 0.79 | 0.96 to 1.50 |
| 32c | 14000 | 9,429 | 4,571 | 942.92 | 1,626 | 17% | 35.25 | 26.1 | 25.37 | 0.73 | 1.01 to 1.52 |
| 33c | 16900 | 9,879 | 7,021 | 987.87 | 2,703 | 27% | 36.90 | 26.43 | 25.41 | 1.02 | 1.18 to 2.10 |
| 34c | 20000 | 10,136 | 9,864 | 1,013.63 | 4,120 | 41% | 38.07 | 26.76 | 25.55 | 1.21 | 1.50 to 2.70 |
| 35c | 25000 | 11,583 | 13,417 | 1,158.33 | 5,829 | 50% | 38.49 | 27.36 | 25.59 | 1.77 | 2.00 to 3.27 |
| 36c | 30000 | 13,239 | 16,761 | 1,323.86 | 7,381 | 56% | 39.03 | 27.94 | 26.07 | 1.87 | 2.06 to 3.72 |
| 37c | 40000 | 21,887 | 18,113 | 2,188.65 | 7,766 | 35% | 39.00 | 29.47 | 27.58 | 1.89 | 2.00 to 3.60 |
| 38c | 50000 | 30,251 | 19,749 | 3,025.11 | 8,181 | 27% | 38.99 | 30.76 | 28.90 | 1.86 | 2.06 to 3.51 |

### *Knowledge gaps*

At the concept level of analysis reported in this study, several critical uncertainties must be acknowledged in the results that will require a more definitive level of analysis to resolve, should this project progress into a full feasibility study. These include:

- The accuracy of the hydrodynamic modelling.
- The 3-dimensional hydrodynamics near the dam wall (larvae could drift to within a few hundred meters of the dam wall and then fall out of suspension).
- The behavior of larvae in low velocity edge habitats. At the level of analysis reported in this study, we have assumed that larvae are active and will re-enter the flowing water.

### *Screen and bypass 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 and trash racks, fish screens with a bypass at the turbine intake would be needed.

The study included an investigation of fish screens for which the functional objective is to screen and pass fish of all sizes safely to prevent their entry into the turbines. The detailed results of the screen investigation are included in Appendix 7.4. Two screens designs were investigated:

i) Flat horizontal screen (no moving parts)

ii) Vertical screen (moving parts).

*Fish screen design*

These screens divert fish to one side of the powerhouse where they bypass the turbines and pass downstream via a sluicing flow. However, the mesh of the screens is not likely to be not fine enough to be effective for larvae and very small fish. The study investigated a screen suitable for up 12,500 $m^3/s$. While the latest powerhouse design has reduced the maximum discharge to 10,580 $m^3/s$, all the findings still apply. Significantly, the screen is filtering a discharge that is 35 times greater than the largest fish screen built to date. The screen sizes are:

- 1.25 $km^2$ for a flat horizontal screen, or
- 15 km long for a vertical screen.

*Fish screen costs*

The cost to screen 10,580 $m^3/s$ (i.e. the present design) would be approximately:

- Flat horizontal screen: USD \$1.75 billion (USD ~\$175,000/$m^3/s$)
- Vertical screen: USD \$5.29 billion (USD ~\$529,000/$m^3/s$)

The cost of the screen depends partly on the minimum size of fish that the screen diverts. If the minimum size of fish was increased to 0.3m or 0.6m, the flat horizontal screen could cost USD $1.00 billion. The cheaper screen would then require more sophisticated turbines with thicker blades to pass larger fish safely (Figure 7-17).

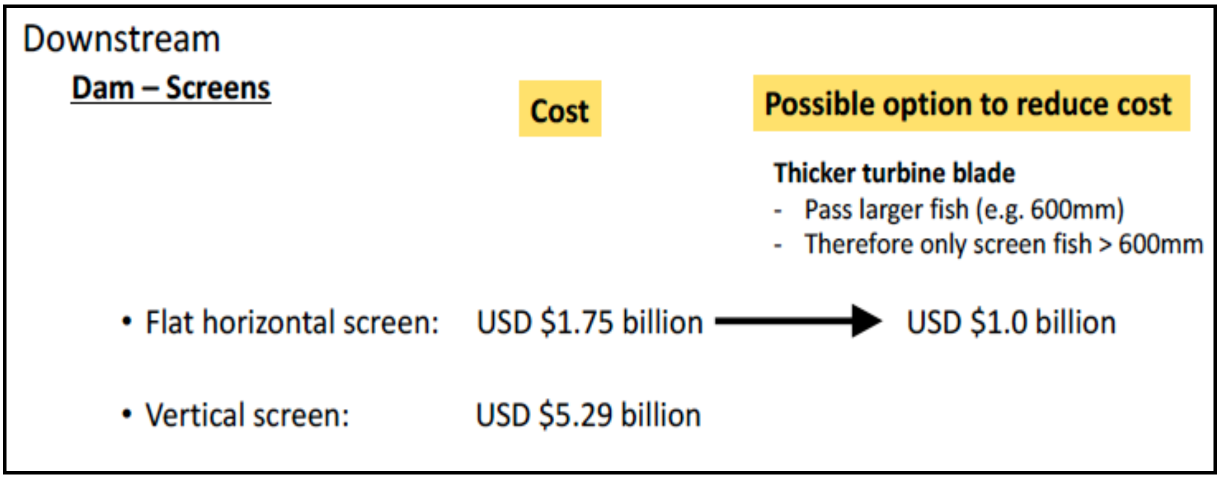



*Figure 7-17. Cost of fish screens & possible option to reduce cost.*

The conclusions from this work are that (***Figure 7-1***):

- fish screens bear the largest cost of any of the mitigation measures at USD $1.75 billion to screen most fish or USD $1.0 billion to screen fish > 0.3m long; and
- it is the mitigation measure with the highest technical risk because it is unprecedented.

## Turbines

### *Design Criteria*

For Sambor Alt_7, conservative turbine design criteria for Mekong fishes were developed with the objective of meeting a performance standard of 95% survival. These criteria are listed in Table 7-3. These criteria address the three impacts of turbines on fish:

i) pressure changes (barotrauma),
ii) blade strike, and
iii) shear.

These criteria were sent 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[11]. 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 optimize 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.

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 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 section.

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, for Sambor 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.

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

*Table 7-2. Preliminary turbine design criteria for passage of Mekong fish species fish including larvae, juveniles and adults; that are diverse in size, shape, and swim bladder morphology. The objective is to enable >95% survival of fish passing through turbines.*

| | **Very high probability of survival (e.g. >99%)** | **High probability of survival (e.g. >95%)** | **Comments / Notes** |
|---|---|---|---|
| Pressure of nadir<br><br>(on suction side of turbine | 100 kPa<br>(Atmospheric) | > 80 kPa | • Note: Siting the turbine below tailwater improves/increases nadir. |
| Ratio of Pressure Change (acclimation /exposure) | 1.0<br><br>(99% of paths) | 0.8<br><br>(99% of paths) | • A ratio of one describes *no pressure change* from acclimation to exposure to the fish but can include rapid compression and decompression, returning to the same pressure.<br>• Note: Siting the turbine below tailwater improves ratio of pressure change. |
| Shear stress (strain rate) | 150 cm $s^{-1}$ $cm^{-1}$<br>for 99% of paths through the turbine | < 600 cm $s^{-1}$ $cm^{-1}$<br>for 99% of paths through the turbine | • Applies to larvae without a yolk-sac; most Mekong larvae drifting in the main stem do not have a yolk-sac.<br>• Note: yolk-sac larvae are very vulnerable to shear stress. |
| Blade speed<br><br>(peripheral runner speed) | < 2 m/s<br>(not possible in design; fish screens may be necessary) | < 6 m/s<br>(not possible in design; fish screens may be necessary) | • Depends on fish length and thickness of leading edge of blade. |
| Thickness of leading edge of blade | = or > fish length<br>e.g. 50 cm thick for 50 cm long fish | > 75% of fish length? | • Assume large fish are screened.<br>• Possible screening for Mekong: > 500 mm fish. |
| Number of blades | Minimize; depends on blade strike model | Minimize; depends on blade strike model | |
| Flow passage openings in the runner | Maximize | Maximize | |
| Tip Gap | unknown | unknown | |
| Hub Gap | unknown | unknown | |

*Turbine Options*

As discussed above, the turbine design directly influences fish mortality. Of existing turbine designs in practice for low to medium head (5-30m) dams, bulb turbines have the lowest mortality, followed by horizontal axis Kaplan turbines and then vertical axis Kaplan turbines (Hadderingh and Bakker, 1998). The Minimum Gap Runner (MGR) design is a variation of a Kaplan, which is considered by the industry to have the least impact on fish of the Kaplan designs. These turbines have been installed at Bonneville and Wanapum dams and initial results indicate higher fish survival.

Fewer blades and a low rotation speed reduces impacts on fish. The design that optimizes these aspects is the Alden-Voith turbine, which has yet to be applied to a site. It is a radically different design, with three blades in a corkscrew shape that has a decreasing radius (***Figure 7-18***). It has been under development by the US Department of Energy and the Electric Power Research Institute (EPRI) since the 1990s (EPRI, 2011), with the primary objective of passing fish as safely as possible. The design is market-ready for application.

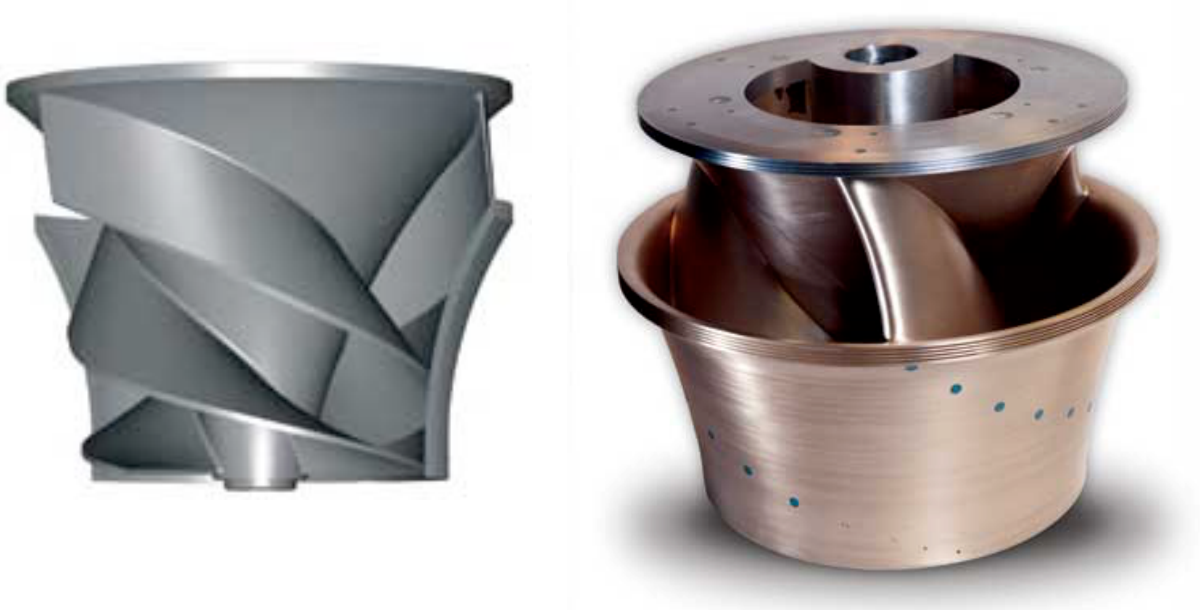


*Figure 7-18. Diagrams of Alden turbine, considered to have the least impact on fish. Source: Perkins et al., 2013.*

The key design features that reduce risks for fish are: i) three blades (the minimum possible), 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.

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 but these have been North American species and mainly been fish less than 200mm. 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.

Because of the potential to minimize impacts on fish, NHI commissioned Alden Labs to assess the feasibility of the design for Sambor Alt_7-B and D. The assessment from Alden Labs concludes that:

i) The Alden turbine is as feasible for the site as Kaplan or bulb turbines,
ii) The constructability would be similar to installing Kaplan turbines,
iii) The power conversion efficiency of 90% would be comparable to a Kaplan turbine but with a slightly larger diameter (10m Alden, 9.5 m Kaplan),
iv) The combined cost for turbine and generator would be USD 40 million.

Alden assessed the hydrology of the site with the NHI concept plan and provided a preferred configuration of 23 turbines each with 10m diameter (Table 7-3).

*Table 7-3. Preliminary Specifications of Alden turbines applicable to Sambor Alt_7-A.*

| | |
|---|---|
| Head (m) | 11 |
| Diameter (m) | 10 |
| Rotational Speed (rpm) | 34 |
| Flow per unit ($m^3$/sec) | 466.1 |
| Power per unit (MW) | 46.3 |
| Power conversion efficiency % | 90% |
| No. Units required for Sambor Powerhouse | 23 |
| Total Powerhouse Capacity ($m^3$/sec) | 10,720 |
| Total Powerhouse Capacity (MW) | 1,066 |
| Approximate turbine and generator cost | USD 40 million |

If the project proceeds the Alden turbine should be considered a preferred option to minimize fishery resource damage. At the feasibility stage of analysis, a detailed CFD analysis should be done to provide a more direct comparison of the Alden, Kaplan MGR and bulb turbines.

## Barotrauma Study

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 7-19, Figure 7-20, Figure 7-21). 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, Computational Fluid Dynamics) (Figure 7-22).

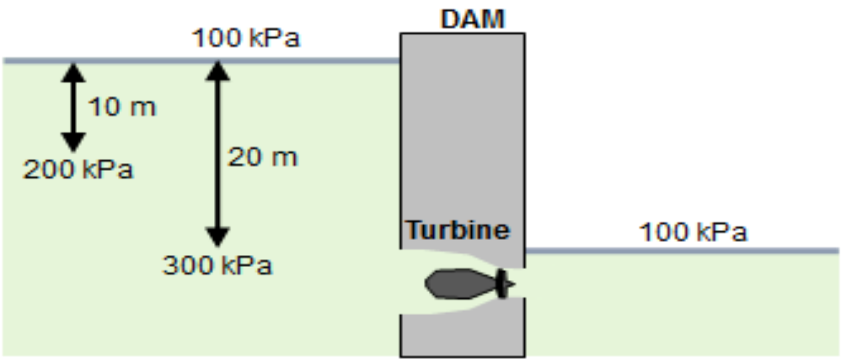



*Figure 7-19. Schematic of pressure changes (barotrauma) experienced by fish at a typical 20 m high hydropower dam.*

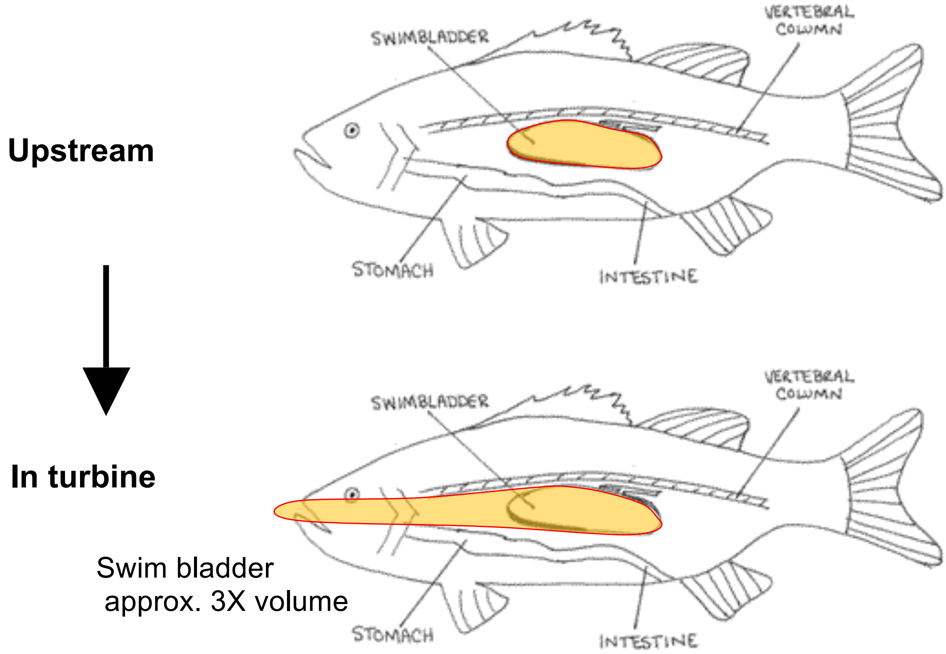



*Figure 7-20. Example of barotrauma at a typical 20m high hydropower dam. Upstream of the dam the swim (or gas) bladder is normal size but as the fish passes through a turbine it typically experiences very low (sub-atmospheric) pressure which expands the swim bladder up to three times.*

*Figure 7-21. Example of barotrauma at a hydropower dam, showing the swim bladder protruding from the mouth (Photograph courtesy of Luiz Silva).*

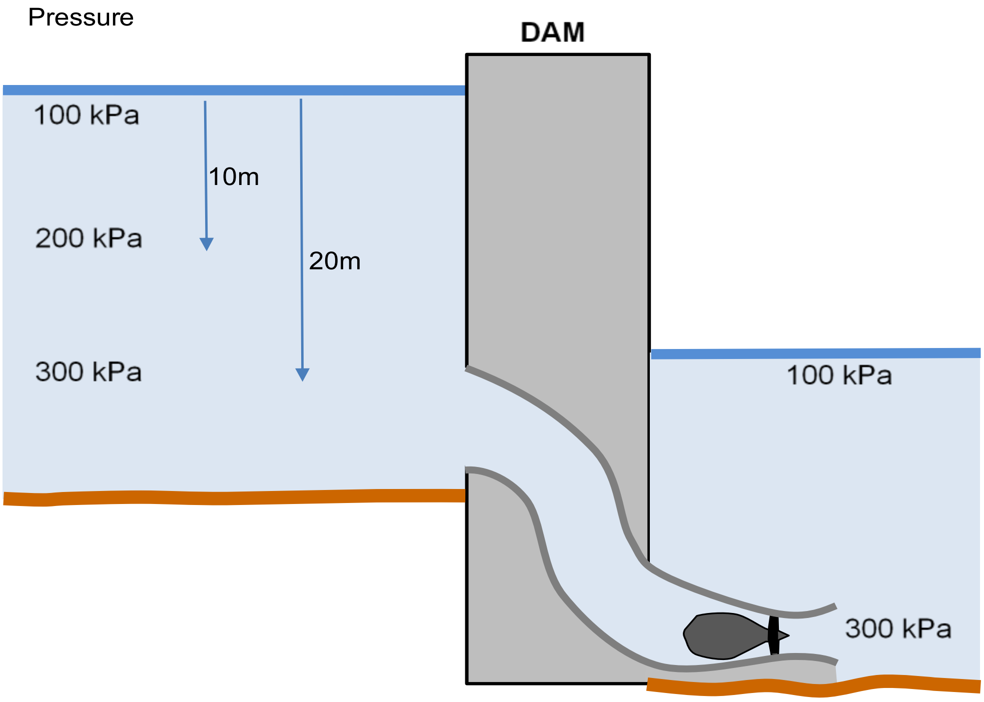



*Figure 7-22. Concept of deep turbine, showing the pressures that fish would potentially experience. Note that fish passing through the turbine potentially do not experience a lower pressure than upstream, and hence do not have decompression or barotrauma.*

### 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 7-23***). The dimensionless value of y+ indicates the required resolution of the grid spacing in the boundary laminar layer.

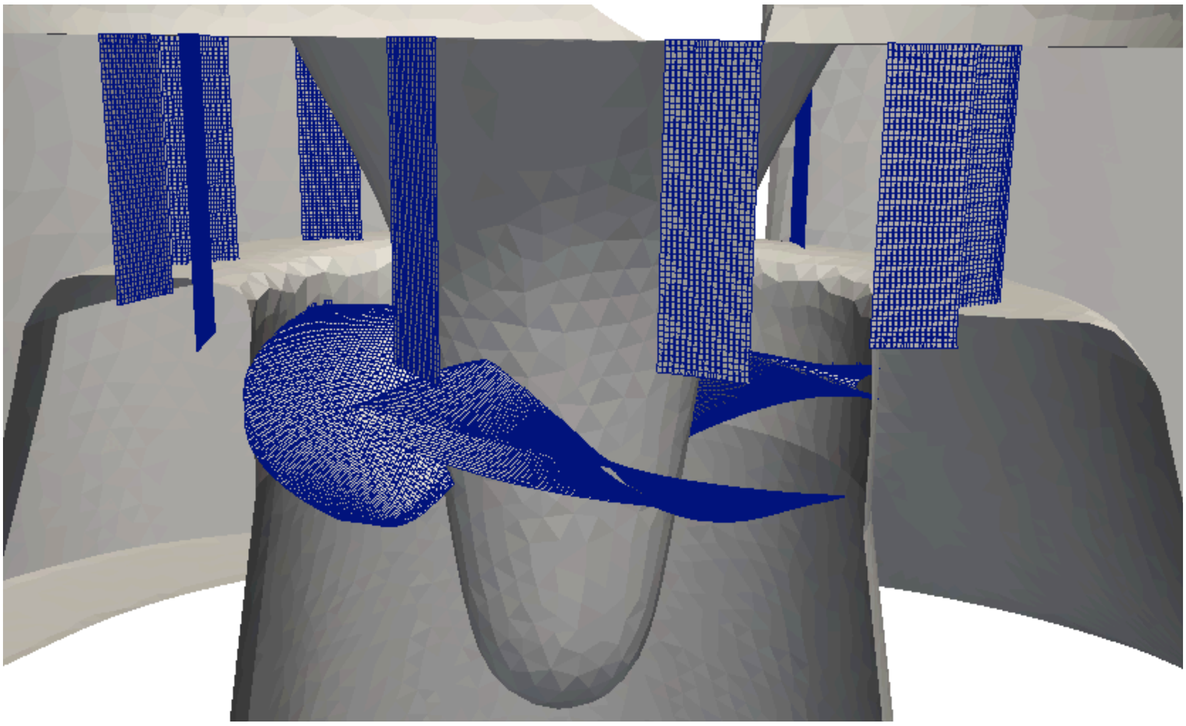


*Figure 7-23. Sample of CFD mesh used to model pressure in a Kaplan turbine.*

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 20m below the tailwater and with the dam having a total head of 20m.

### Results

The study showed that deep turbines, such as Kaplans, can theoretically greatly reduce – possibly even eliminate - pressure impacts (barotrauma) on fish. Figure 7-24 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.

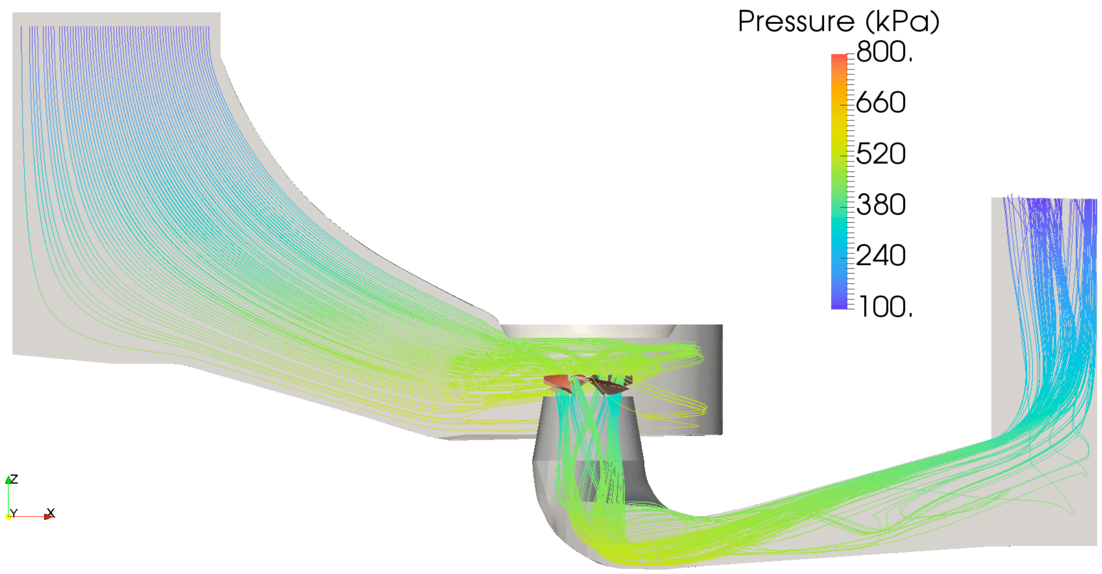



*Figure 7-24. Cross-section of 3D CFD model showing pressure in a deep Kaplan turbine. Note that there are no blue lines near the turbine, indicating that there are no sub-atmospheric pressures, which cause injuries in fish.*

Figure 7-25 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.

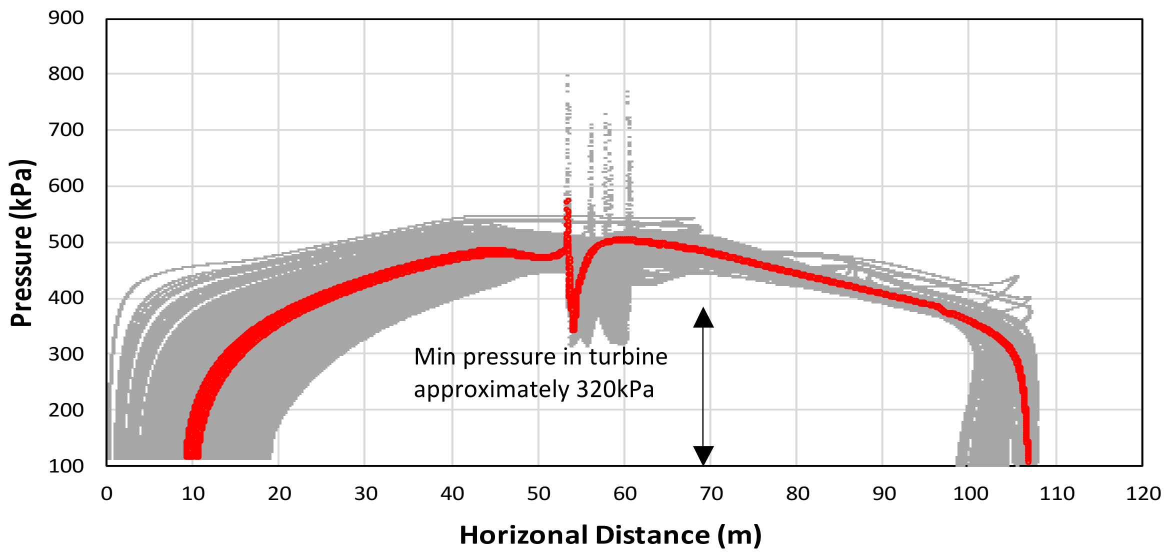



*Figure 7-25. Summary of 100 paths through a deep Kaplan turbine, with the median path in red. The figure shows that no path is sub-atmospheric (<100kPa) in the turbine, while fish entering and leaving the turbine start and finish at atmospheric pressure, with no net change.*

## *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.

### Spillway and Gate Design

To pass fish safely spillways need to be designed to provide a relatively laminar flow over a smooth surface (not a stepped spillway), with no sudden deceleration, or sudden transitions. Generally, this is a "ski-jump" shaped 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. The Sambor Alternative design includes with large "overshot" radial gates. At higher flows the whole radial gate would be opened fully.

## Assumptions for Fish Population Modelling

### Introduction

A critical aspect of the mitigation measures proposed above is to assess their actual impacts on the fish population and the productivity of the fishery. Modelling fish populations enables estimates to be made of these impacts although, due to the complexity of modelling, only a select number of species can be modelled. Modelling also enables different parameters to be used so that, for example, different rates of fish passage can be assessed. Importantly, it can enable the sensitivity of different aspects of the design to be assessed. One round of modelling has been done for the present project, which identified critical assumptions. The modelling was used to quantify the impacts on the fishery, specifically the Maximum Sustainable Yield, which has been used in the economic analysis.

Modelling of biological populations requires assumptions to be made about different aspects of the life cycle and impacts on fish at the dam. The following section outlines the rationale behind some of the key aspects and assumptions required for modelling. It describes the *present assumptions* which were used for the modelling and has *recommended assumptions for future modelling*.

### Migration - Regional

Adult migratory fish ("whitefish") in the lower Mekong migrate upstream to spawn and migrate downstream to feed and seek deep pools for refuge in the dry season (Poulsen *et al.,* 2004). Sambor is located in the lowlands of the Mekong with deep pools upstream and downstream. Spawning is known below Khone Falls and near Pakse. It is unlikely that all adult fish would seek feeding habitats and deep pools downstream of the dam site but the proportion of fish that remain upstream of Sambor is unknown.

#### *Assumptions*

*Present modelling*

i) All adult fish pass the dam each year.

*Recommendations for future modelling*

Adopt two cases:

i) All adult fish pass the dam each year.
ii) 20% of the adult fish remain upstream of the dam each year.

## Migration – Downstream at Dam

Fish that are migrating downstream have different distributions across the river channel. The significance of this is that fish that use the anabranch and not the main stem of the river bypass the dam turbines and spillway, and have no mortality above natural. Larvae can be assumed to be passive particles in a fast-flowing river and hence are uniformly distributed across the river channel. Although it should be noted that larvae can make daily vertical migrations and can be denser on the sides of rivers.

Large fish that are migrating make active choices about their position in the river and typically utilize the deepest part of the river channel (thalweg). For these fish, it is prudent to assume that most (95%) will use the thalweg and not use the shallower anabranch.

### *Assumptions*

*Present modelling*

i) Assume larvae will drift with the flow and hence use the proportion of flow in the main stem (Table 7-4) and anabranch as a surrogate for the proportion of larvae in each.

*Recommendations for future modelling*

Adopt two values:

i) Assume larvae will drift with the flow and hence use the proportion of flow in the main stem (Table 7-4) and anabranch as a surrogate for the proportion of larvae in each.

ii) Assume that 95% of large-bodied (> 50 cm) adult fish that are migrating downstream will use the thalweg in the main stem.

*Table 7-4. Modelled monthly proportion of flow at Sambor with dam in place.*

| Month | Proportion anabranch flow | Proportion of flow in main stem | Proportion of total flow in turbines | Proportion of total flow in spillway |
|---|---|---|---|---|
| **J** | 0.526 | 0.474 | 0.449 | 0.000 |
| **F** | 0.547 | 0.453 | 0.414 | 0.000 |
| **M** | 0.567 | 0.433 | 0.380 | 0.000 |
| **A** | 0.566 | 0.434 | 0.387 | 0.000 |
| **M** | 0.507 | 0.493 | 0.454 | 0.003 |
| **J** | 0.415 | 0.585 | 0.496 | 0.037 |
| **J** | 0.438 | 0.562 | 0.374 | 0.108 |
| **A** | 0.468 | 0.532 | 0.278 | 0.169 |
| **S** | 0.469 | 0.531 | 0.264 | 0.182 |
| **O** | 0.441 | 0.559 | 0.383 | 0.083 |
| **N** | 0.359 | 0.641 | 0.552 | 0.035 |
| **D** | 0.440 | 0.560 | 0.535 | 0.001 |

## 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. Mutilation ratio (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 (4m) 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 10-30m 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. Mortality values for barotrauma are listed in *Table 7-5* for physoclists, physostomes and fish with chambered swim bladders. These values were provided and reviewed by experts (Drs Baumgartner, Boys, Mallen-Cooper); however, no pressure profiles or modelling of the turbine were available, so these represent opinion.

### *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).

Main-stem Mekong dams would have trash racks which would exclude large fish, possibly over 50-75 cm, depending on the bar spacing. Hence, mortality of fish in typical Mekong turbines could be up to 25%.

### *Assumptions*

#### *Present modelling*

i) Use a calculated mortality from a blade strike model plus estimates for shear and barotrauma. (see Table 7-5 for values).

#### *Recommendations for future modelling*

Adopt two cases:

i) Use a calculated mortality from a blade strike model plus estimates for shear and barotrauma. (see Table 7-5 for values).

ii) Assume a total turbine mortality of 25% for fish > 300 mm and 15% for fish < 300 mm, which sets a defensible upper bound for a Kaplan or bulb turbine with a 7-12m head.

*Table 7-5. Proposed parameters for population modelling.*

| Passage | Modelling Case | Conditions | **Scenario 1.** **Full mitigation:** Full upstream fishpasses, Coarse fish screen (diverts fish > 300mm), Deep, low-impact turbine (protects fish <300 mm) | **Scenario 2.** **Partial mitigation:** Full upstream fishpasses, Trash racks with surface fish collector/bypass (e.g. Xayaburi) Deep, low impact turbine (protects fish <300 mm) | **Scenario 3.** **Minimal fish passage:** Full upstream fishpasses, Trash racks (no fish diversion) Deep, moderate impact turbine |
|---|---|---|---|---|---|
| **Upstream Passage Success** | Case 1 | High | 95.0% | 95.0% | 95.0% |
| | Case 2 | Medium | 80.0% | 80.0% | 80.0% |
| | Case 3 | Low | 40.0% | 40.0% | 40.0% |
| **Downstream Passage Mortality** | | | | | |
| **1. Larval drift** | | Anabranch | 0.1% | 0.1% | 0.1% |
| | | Reservoir (95% drift) | 5.0% | 5.0% | 5.0% |
| **2. Intake screens** | | | | | |
| 2.1 Impingment mortality: fish screens | | Fish length < 300mm | | | |
| | | fish length 300-600 mm | 1.0% | | |
| | | fish length > 600mm | 1.0% | | |
| 2.2 Impingment mortality: trash racks | Case 1 | 10% mortality | | 10.0% | 10.0% |
| | Case 2 | 50% | | 50.0% | 50.0% |
| | Case 3 | 90% | | 90.0% | 90.0% |
| **3. Turbine Passage** | | | | | |
| 3.1 Set mortality | Case 1 | fish < 300 | 2.0% | 2.0% | 15.0% |
| | | fish 300-600mm | | 25.0% | 25.0% |
| 3.2 Calculated mortality | Case 2 | | | | |
| Blade strike | | fish length <300mm | 2.0% | 2.0% | % from blade strike model |
| | | Fish length 300mm - 600mm | | % from blade strike model | % from blade strike model |
| Shear | | Larvae/Fry/Juveniles (First length class) | 5.0% | 5.0% | 25.0% |
| | | Sub-adults and adults | 1.0% | 1.0% | 5.0% |
| Barotrauma | | Catfish and physostomes (larvae) | 0.1% | 0.1% | 0.1% |
| | | Carp and Notopteridae (larvae ) | 1.0% | 1.0% | 1.0% |
| | | Physoclists (larvae) | 1.0% | 1.0% | 1.0% |
| **3. Spillway and gate passage** | | | | | |
| 2.1 Barotrauma | | Catfish and other physostomes | 0.1% | 0.1% | 0.1% |
| | | Carp and Notopteridae | 2.0% | 2.0% | 2.0% |
| | | Physoclists | 2.0% | 2.0% | 2.0% |
| 2.2 Shear | | Larvae/Fry/Juveniles (First length class) | 5.0% | 5.0% | 5.0% |
| | | Sub-adults and adults | 0.5% | 0.5% | 0.5% |

## Fish Screen Impingement and Mortality

The Sambor options being investigated either have: i) a coarse fish screen that diverts fish > 300 mm to a bypass around the turbines and allows fish < 300 mm to pass through the screen and turbines, or ii) a standard trash rack with 120-240 mm bar spacing that allows fish up to 300 mm and possibly 750 mm to pass directly through to the turbines, while larger fish risk being impinged.

For trash rack impingement, there are three bodies of literature:

i) Field data on impingement.

These studies show that the issue of fish impingement has been recognized for a long time (Hanson *et al.,* 1977) and over a wide geographic area including Russia (Pavlov, 1989), Europe (Hadderingh *et al.,* 1983; Bryhn *et al.,* 2013), Great Britain (Greenwood, 2008), Pakistan (Moazzam and Niaz Rizvi 1980), North America (Taft, 2000), and Taiwan (Chen *et al,.* 2015)

Almost all cases are cooling water screens for intakes of power stations with a minority on screens for irrigation offtakes. We are not aware of any studies of impingement of fish on hydropower trash racks although there are confirmed reports of large fish 500-1000 mm in length on hydropower trash racks in Australia (Stuart *et al.,* 2010) and published photographs from elsewhere (Figure 7-26).

*Figure 7-26. Impingement of Adult American shad on a powerhouse trash rack. Source: Larinier, 2001.*

The above studies of cooling water clearly demonstrate impingement of fish on trash racks (screens) in rivers is on a large scale – with millions and tons of fish impinged or entrained – but the proportion of the population impacted, or the long-term population impacts, are rarely quantified (Turnpenny, 1988). Cooling water generally takes a small proportion of the river flow, or estuarine volume, so the impacts on populations do not appear to be significant (Barnthouse, 2013). This differs from the situation of hydropower in rivers where a large proportion of the flow passes to the turbines via trash racks.

In all these studies the fish impinged are mainly less than 100mm long and apply to relatively fine mesh trash racks (debris screens) that prevent this size class of fish passing through. Larger fish are either not impinged or are not reported. There appear to be no studies of impingement on coarsely-spaced trash racks at riverine hydropower sites.

In summary, the field studies of impingement do not:

i. indicate the proportion of the population impinged,
ii. include medium- or large-bodied fish,
iii. apply to the coarse mesh/spacing of trash racks,
iv. include riverine hydropower sites.

Hence, it is not possible to incorporate a trash rack impingement and mortality – that is, a proportion of the population – as a single <u>quantitative</u> or stochastic factor in a fish population model of Sambor Dam.

ii) Laboratory swimming experiments.

Laboratory swimming experiments on screen design to quantify impingement of existing trash racks or design screens to protect fish, has a long history (Rulifson, 1977). These mainly test fish at various water velocities for various times and screen designs (Zydlewski and Johnson, 2002; Peake, 2004; Boys *et al.,* 2013). There is one measurement of water velocities on a fish screen *in situ* at a hydropower dam (Hughes *et al*., 2011). All these studies recommended water velocities from 0.1 to 0.3 m/s, although one used a DIDSON acoustic camera (Boys *et al.,* 2013) in the field and suggested that 0.5 m/s had potential to effectively screen fish in a river.

Significantly, all of these studies tested or observed small fish less than 100 mm. Hence, these data are not useful for developing impingement mortality of large fish on trash racks.

iii) Technical guidelines by government agencies.

There are numerous technical guidelines for screen designs to protect fish (Katopodis, 1992; Clay, 1995; National Marine Fisheries Service, 1997; Armstrong *et al,.* 2010). These are almost entirely in temperate rivers and in the northern hemisphere, often focused on salmonids and entirely on small fish. However, effective screening for small fish would presumably protect stronger swimming larger fish.

> These guidelines all recommend approach velocities for small salmonids of 0.12 to 0.24 m/s and for other small fish up to 0.4 m/s. There are no guidelines or data for larger fish although large eels can be impinged at 0.5 m/s (Redeker, 2011).
>
> These guidelines are focused on small fish but a practical upper limit to detect initial impingement at Sambor would be 0.4 to 0.5 m/s.

All of the above studies do not directly relate to trash racks or to large fish. However, the approach water velocities on the trash racks at Sambor would be 0.5 to 0.8 m/s (using screen area and discharge and a Cd of 0.7) which strongly suggests that impingement is a high risk.

#### *Assumptions*

##### *Present modelling*

i) 10% impingement mortality on trash racks

ii) 1% mortality on fish screens (a nominal value to allow for the unprecedented size of the screens)

##### *Recommendations for future modelling*

i) Adopt three cases of 10, 50 and 90% impingement mortality on trash racks.

ii) 1% mortality on fish screens (a nominal value to allow for the unprecedented size of the screens)

## Conclusion

For fish populations in the lower Mekong, Sambor Dam is in a critically vulnerable location; sited between the nursery grounds of the Tonle sap and Mekong delta, and spawning grounds upstream. The fishery has extraordinary value commercially, for food security, and for livelihoods, which calls for the highest level of impact mitigation if the concept of "sustainable hydropower" is to be satisfied. In light of this, the NHI team started the work on identifying alternatives to the original, highly impactful, Sambor CSP (China Southern Power) proposal by specifying environmental performance standards deemed sufficient to sustain the extraordinary fishery values in the Sambor reach. Those performance standards are described in Chapter 5 of this Report.

Next, the NHI team formulated fish passage and sediment/nutrient mitigation measures sufficiently demanding to attain these performance standards. The fish passage mitigation measures are described in this Chapter and are unprecedented in hydropower development.

Some of these measures are more vital than others in the sense that failure to attain them fully would have larger consequences than others for fish abundance and biodiversity in the Mekong River system. Most notably, modelling of fish populations (Halls and Kshatriya, 2009) suggests that the success of the facilities for passing upstream migrating fish is the largest determinant of the yield of the Mekong fishery. At 95% passage, the impacts are likely to be far from negligible but may be regarded as tolerable to the RGC decision makers. But, at lower levels of success, the adverse effects on fish yield may become much larger and may well become catastrophic. These impacts will be examined in detail, specifically for Sambor, in Chapter 8.

Mitigating downstream migration is costly. Using only a coarse trash screen would save a large fraction of the capital costs for screening, but would increase the costs of the turbines and significantly reduce their efficiency and, hence, power output. A third option is to use a cheaper, coarser fish screen. So, the economic trade-offs may be more significant than the fishery protection trade-offs. These trade-offs are shown, at a coarse level, in Table 7-6.

*Table 7-6. Matrix of fish mortality, capital cost, and energy generation.*

| | Fine fish screen<br><br>Low angle | Coarse fish screen<br><br>Low angle | Very coarse trash racks<br><br>High angle |
|---|---|---|---|
| Deep turbine | Mortality Low<br><br>Screen cost 1.8 bill<br><br>Power 4100 GWH | N/A | N/A |
| Deep turbine, thick bladed | N/A | Mortality Low<br><br>Screen cost <1.0 bill<br><br>Power < 4100 GWH<br><br>(poss. reduction < 10%) | Mortality High<br><br>Screen cost <0.1 bill<br><br>Power < 4100 GWH<br><br>(poss. reduction < 10%) |

For other mitigation measures, there is a more pronounced trade-off between fishery protection and hydropower generation. The most notable example here is the relationship between the degree of confidence in maintaining a velocity of flow in the reservoir sufficient to keep the eggs and larvae in suspension **all the way to the point of discharge** at the powerhouse and/or spillway, and the power output under various operating policies. Those relationships are presented in Chapter 6.

A second important point about the mitigation measures presented in this Chapter goes to the degrees of confidence that they will achieve the performance goals for which they are designed (Text Box 7-5). While it is the considered professional judgement of the experts in the NHI project team that each of them should do so in theory, in fact none of these have proven results in the actual world for the simple reason that each of them are unprecedented. For instance, these mitigation measures include fish screens that are 35 times larger than any that have ever been deployed; the deep turbines to mitigate barotrauma have never been tested; the advanced turbine designs to avoid blade strike have not been modelled and are not yet available, and, most important of all, the three upstream fishpasses with the large fraction of flow dedicated to them avoid all of the design defects that have limited the success of fishpasses historically, but our confidence in their performance has not yet been put to the test. And, as noted, population modelling suggests that even a small deviation from the performance standard that we have established could have significant population impacts. This gives rise to probabilities of risks (summarized in Text Box 7-5) and consequences that are assessed in Chapter 11.

*Text Box 7-5. Risks.*

| **Any of the following can cause decline of the fish population:** |
|---|
| • **Upstream fishpasses do not pass sufficient fish to maintain the fishery**<br>• **Velocity in reservoir not adequate for drift of larvae**<br>• **Fish screens impractical**<br>• **Turbine/spillway mortality underestimated** |

The concepts presented in this report seek to address the major failings of tropical fish passage. Key innovations include:

1. Upstream passage using 10% of dry season flow and up to 30% of wet season flow
    - This would set a new global standard for large tropical dams that has not been achieved anywhere previously.
    - Past Practice: 0.25 to 1% (maximum) of flow has been used in tropical fishpasses at large dams, which has proved ineffective.
    - Industry Standard: 10%.

2. Downstream passage of larvae through the reservoir
    - Operating Sambor Alt_7 to maintain velocities sufficient to keep larvae in suspension all the way to the point of discharge is unprecedented.
    - Past Practice: This mitigation strategy has never been addressed previously.
    - Industry Standard: None.

3. Fish screens
    - A first for any tropical or high discharge dam.
    - Past Practice: Screens have been used to divert fish at many sites but never at a high discharge hydropower dam. The proposed screen will be 35 times the largest presently installed.
    - Industry Standard: Velocity and mesh size well established.

4. Turbines
    - First approach to turbine manufacturers design for fish first, energy production second.
    - Sambor Alt_7 is the first time that deep turbines are proposed to mitigate pressure impacts.
    - Past Practice: Turbines either cause mortality of fish or “fish friendly” designs have been used with the objective of reducing mortality, but these are not based on biological criteria for tropical species. Turbine designers have been compromised in getting the best outcome for fish because energy outputs have already been agreed to in the PPA.
    - Industry Standard: Not developed.

It is the fish screens which are the single most expensive mitigation and the limiting factor in determining whether the project is economically viable and can sustain fish populations. The innovations listed above probably represent the best outcome for fish passage at this site, or equivalent site globally, but two questions remain:

i) Is the best outcome for fish passage, of >95 % passage upstream and downstream, still sufficient to maintain the population?

This will be considered in Chapter 9 on fish population modelling.

ii) Is the hydropower project economically viable if the full mitigation required for fish (screen or screen plus turbine, Table 7-3) is included?

This is considered in Chapter 11 on economics.

The present project is pre-feasibility and as such it is acknowledged that significant knowledge gaps remain.

## References


Agostinho, A.A., Marques, E.E., Agostinho, C.S., de Almeida, D.A., de Oliveira, R.J., and de Melo, J.R.B. 2007. Fish ladder of Lajeado Dam: migrations on one-way routes? *Neotropical Ichthyology.* 5(2), 121-130.

Armstrong, G., Aprahamian, M., Fewings, G., Gough, P., Reader, N., and Varallo, P. (2010) Environment agency fish pass manual: guidance notes on the legislation, selection and approval of fish passes in England and Wales. *Environment Agency, Rio House Waterside Drive, Aztec West Almondsbury, Bristol BS32 4UD*.

Barnthouse, L.W. (2013) Impacts of entrainment and impingement on fish populations: A review of the scientific evidence. *Environmental Science & Policy* **31**, 149-156.

Bell, C.E., and Kynard, B. (1985) Mortality of Adult American Shad Passing Through a 17-Megawatt Kaplan Turbine at a Low-Head Hydroelectric Dam. *North American Journal of Fisheries Management* **5**(1), 33-38.

Boys, C., Baumgartner, L., and Lowry, M. (2013) Entrainment and impingement of juvenile silver perch, Bidyanus bidyanus, and golden perch, Macquaria ambigua, at a fish screen: effect of velocity and light. *Fisheries Management and Ecology*.

Bryhn, A.C., Bergenius, M.A., Dimberg, P.H., and Adill, A. (2013) Biomass and number of fish impinged at a nuclear power plant by the Baltic Sea. *Environ Monit Assess* **185**(12), 10073-84. [In eng].

Chen, H., Liao, Y.-C., Chen, C.-Y., Tsai, J.-I., Chen, L.-S., and Shao, K.-T. (2015) Long-term monitoring dataset of fish assemblages impinged at nuclear power plants in northern Taiwan. *Scientific data* **2**.

Clay, C.H. (1995) 'Design of Fishways and Other Fish Facilities, 2nd edn.' (Lewis Publishers: Boca Raton, Florida).

Deng, Z., Carlson, T.J., Ploskey, G.R., Richmond, M.C., and Dauble, D.D. (2007) Evaluation of blade-strike models for estimating the biological performance of Kaplan turbines. *Ecological Modelling* **208**(2-4), 165-176.

Ferguson, J.W., Absolon, R.F., Carlson, T.J., and Sandford, B.P. (2006) Evidence of Delayed Mortality on Juvenile Pacific Salmon Passing through Turbines at Columbia River Dams. *Transactions of the American Fisheries Society* **135**, 139-150.

Ferguson, J.W., Ploskey, G.R., Leonardsson, K., Zabel, R.W., and Lundqvist, H. (2008) Combining turbine blade-strike and life cycle models to assess mitigation strategies for fish passing dams. *Canadian Journal of Fisheries and Aquatic Sciences* **65**(8), 1568-1585.

Greenwood, M.F.D. (2008) Fish mortality by impingement on the cooling-water intake screens of Britain's largest direct-cooled power station. *Marine Pollution Bulletin* **56**(4), 723-739.

Hadderingh, R., and Bakker, H. (1998) Fish mortality due to passage through hydroelectric power stations on the Meuse and Vecht rivers. In Fish migration and fish bypasses. (Eds. M Jungwirth, S Schmutz and S Weiss) pp. 315-328. (Fishing News Books: Oxford, England).

Hadderingh, R.H., van Aerssen, G.H.F.M., Groeneveld, L., Jenner, H.A., and Van Der Stoep, J.W. (1983) Fish impingement at power stations situated along the rivers Rhine and Meuse in The Netherlands. *Hydrobiological Bulletin* **17**(2), 129-141.

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

Hanson, C.H., White, J.R., and Li, H.W. (1977) Entrapment and impingement of fishes by power plant cooling-water intakes: an overview. *Marine Fisheries Review* **39**(10), 7-17.

Hughes, J.S., Deng, Z.D., Weiland, M.A., Martinez, J.J., and Yuan, Y. (2011) Water Velocity Measurements on a Vertical Barrier Screen at the Bonneville Dam Second Powerhouse. *Energies* **4**(11), 2038-2048.

Katopodis, C. (1992) Fish screening guide for water intakes. *Working Document, Freshwater Institute, Fisheries and Oceans Canada, Winnipeg, Man*, 5.

Larinier, M. (2008) Fish passage experience at small-scale hydro-electric power plants in France. *Hydrobiologia* **609**(1), 97-108.

Larinier, M. 2001. Environmental Issues, Dams and Fish Migration. Rome, Italy. (Ed. G Marmulla), pp. 45-89.

Mekong River Commission, 2009. Preliminary Design Guidance for Proposed Mainstream Dams in the Lower Mekong Basin. Final Version. 31 August 2009. Available at: http://www.mrcmekong.org/assets/Publications/Consultations/SEA-Hydropower/Preliminary-DG-of-LMB-Mainstream-dams-FinalVersion-Sept09.pdf.

Moazzam, M., and Niaz Rizvi, S.H. (1980) Fish entrapment in the seawater intake of a power plant at Karachi coast. *Environmental Biology of Fishes* **5**(1), 49-57.

National Marine Fisheries Service (1997) Fish Screening Criteria for Anadromous Salmonids. *National Marine Fisheries Service, Southwest Region.(Available from NOAA Fisheries., Habitat Conservation Division, 777 Sonoma Ave., Room 325, Santa Rosa, CA 95404)*.

Oldani, N., and Baigún, C. (2002) Performance of a fishway system in a major South American dam on the Paraná River (Argentina-Paraguay). *River Research and Applications.* 18(2), 171-183.

Pavlov, D.S. (1989) Structures assisting the migration of non-salmonid fish: USSR. pp. 1-97. (Food and Agriculture Organization of the United Nations: Rome, Italy) .

Peake, S. (2004) Effect of approach velocity on impingement of juvenile northern pike at water intake screens. *North American Journal of Fisheries Management* **24**(2), 390-396.

Perkins, N., Dixon, D. A., Dham, R., and Foust, J. 2013. Development Status of the Alden Fish-Friendly Turbine. *Power Engineering, 117*(6).

Pracheil, B.M., DeRolph, C.R., Schramm, M.P., and Bevelhimer, M.S. (2016) A fish-eye view of riverine hydropower systems: the current understanding of the biological response to turbine passage. *Reviews in Fish Biology and Fisheries* **26**(2), 153-167.

Redeker, M. (2011) Fish protection in Germany: first steps on a long and rocky road. *Transactions on State of the Art in Science and Engineering* **71**, 31-40.

Rulifson, R.A. (1977) Temperature and water velocity effects on the swimming performances of young-of-the-year striped mullet (Mugil cephalus), spot (Leiostomus xanthurus), and pinfish (Lagodon rhomboides). *Journal of the Fisheries Board of Canada* **34**(12), 2316-2322.

Stuart, I.G., Koehn, J.D., O'Brien, T.A., McKenzie, J.A., and Quinn, G. (2010) Too close for comfort: a fishway exit and a hydro-power station inlet. *Marine and Freshwater Research* **61**, 23-33.

Taft, E. (2000) Fish protection technologies: a status report. *Environmental Science & Policy* **3**, 349-359.

Turnpenny, A.W.H., S. Clough, K.P. Hanson, R. Ramsay, and D. McEwan. (2000) *Risk Assessment for Fish Passage Through Small, Low-Head Turbines*. Final Report. Energy Technical Support Unit, Harwell, United Kingdom.

Turnpenny, A.W.H. (1988) Fish impingement at estuarine power stations and its significance to commercial fishing. *Journal of Fish Biology* **33**, 103-110.

von Raben, K. (1957) "Regarding the problem of mutilations of fishes by hydraulic turbines." Originally published in *Die Wasserwirtschaft* (100):4,97. *Fisheries Research Board of Canada Translation Series*, No. 448, 1964.

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

Zydlewski, G.B., and Johnson, J.R. (2002) Response of Bull trout fry to four types of water diversion screens. *North American Journal of Fisheries Management* **22**, 1276-1282.

# 8 Potential Impacts on Fish Populations

## Introduction

### Study Purpose

The purpose of this chapter is to estimate and compare the impacts of a range of fishery mitigation scenarios for Sambor Dam Alt_7 on the mortality, population growth rates and potential yield of migratory species of fish caught for commercial and subsistence purposes in Cambodia and in the other riparian countries of the LMB. An initial round of modeling was performed in late 2016, and the results vindicated the analytic methods. However, in the ensuing month before the preparation of this Final Report, information for estimating the mortality of fish passing through the reservoir and dam have improved, and the range of feasible mitigation strategies have evolved to provide a better comparison of choices within the decision space that the Ministry of Mines and Energy (MME) will have on a Sambor Hydropower Dam. For those reasons, NHI recommends another round of modeling be performed, before any commitment is made to a Sambor Dam, to assess the impacts of a new set of mitigation strategies on the fishery yield. To do this remodeling productively, a narrowing of the range of uncertainties associated with the input parameters may be necessary.

The scenarios that will be evaluated in the new round of modeling each feature a different set of fishery mitigation measures in the design of the dam. All assume that the dam would be operated to achieve 95% larval passage. The results of this study are intended to inform the selection of the best dam design to sustain fisheries for migratory *whitefish* species.

### The Four Scenarios

All of the fishery mitigation scenarios feature mitigation measures for both upstream and downstream migration. Common elements in all four are mitigation measures that incorporate innovations driven by the behavior, life cycle, high diversity and high biomass of Mekong fishes. These common measures include:

- Three upstream fishpasses (also called fishways or fish ladders) located at the powerhouse and both sides of the spillway, where migrating fish would congregate.
- A bypass channel that links with a natural anabranch to pass >10% of river flow Designing the navigation lock as a combined fish lock.
- Downstream drift of larvae maintained through the reservoir by maintaining a minimum velocity through dam design and operation.
- A pressure acclimation weir in the intake channel to ensure fish volitionally acclimate to surface pressure before entering the turbine.
- Locating the turbines deep in the tailwater to reduce pressure impacts (barotrauma).

In addition, the four mitigation scenarios would incorporate various strategies for reducing mortality of fish passing through the dam and turbines.

The four scenarios for downstream fish passage mitigation are:

5) **Sambor Alt_7-A:** Trash rack with standard turbines (as per Xayaburi Dam)
   - Fish up to 900-1000 mm would pass through these trash racks and enter the turbine intakes.
   - Turbines with low barotrauma and moderate shear and blade strike.

6) **Sambor Alt_ 7-B:** Trash rack (as per Xayaburi Dam) + low impact turbines
   - Trash racks with surface bypass but no fish screens on the turbine intakes
   - Low impact turbines (low barotrauma, low shear and low blade strike [thick-blade]) that safely passes larvae and fish < 300mm. We use Alden turbines for illustration. Other low-impact designs may also be considered.

7) **Sambor Alt_7-C:** Fish screens + standard turbines
   - Coarse fish screens to enable fish > 300 mm to bypass the turbines.[12]
   - Turbines with low barotrauma and moderate shear and blade strike.

8) **Sambor Alt_7-D:** Fish screens + low impact turbines.
   - Coarse fish screens to enable fish > 300 mm to bypass the turbines
   - Low impact turbines (low barotrauma, low shear and low blade strike [thick-blade]) that safely passes larvae and fish < 300 mm. We use Alden turbines for illustration. Other low-impact designs may also be considered.

These fishery mitigation strategies are described in detail in Section 7 of this Report. Figure 8-1 illustrates the upstream and downstream fish passage routes for these scenarios.

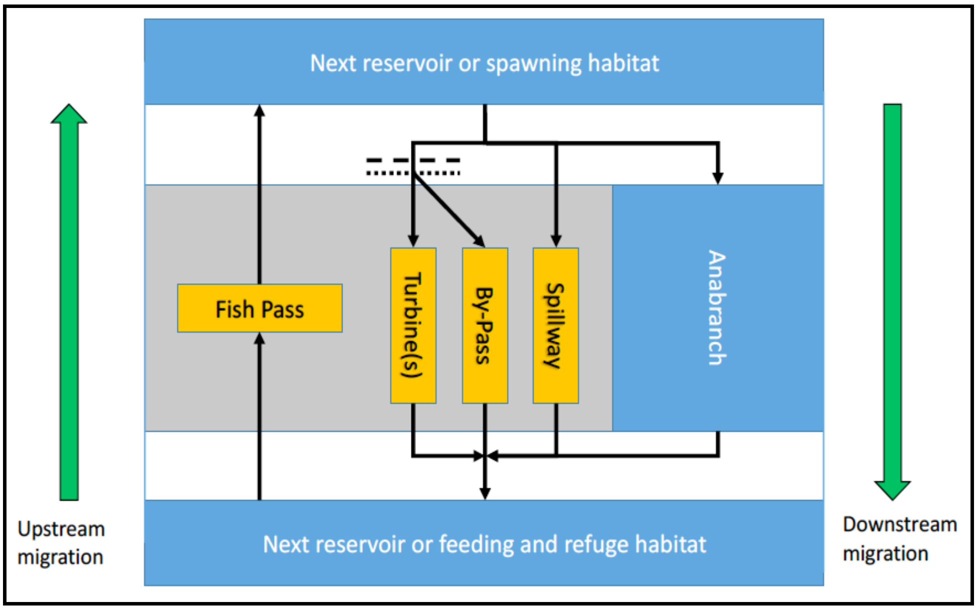



*Figure 8-1. Dam Passage for All Mitigation Scenarios.*

## Materials and Methods

### Modelling Approach

As for the precious round of population modeling, the additional modeling of these scenarios may adopt the approach described by Halls and Kshatriya (2009). This employed a length-based

[12] The project team also evaluated fine-mesh fish screens on the turbine intakes, which divert all fish except larvae from the turbines, but concluded that they were too expensive to be practical.

projection matrix model to describe the dynamics of simulated populations of migratory species in response to variable passage success (determined by fishpass efficiency) to upstream spawning habitat via fishpasses or anabranches of the river, and elevated downstream passage mortality rates on adults and juveniles returning to downstream feeding and refuge habitat via dam turbines, by-pass channels, spillways, or the anabranch. The original model builds upon published research and model development for dam impact and assessment purposes, particularly for systems in North America (Columbia River basin) and Sweden. Downstream mortality was described using a blade-strike using a model developed for Kaplan type turbines that has been installed into the Xayaburi Dam, Lao PDR, and initially proposed for Sambor.

The population model described by Halls and Kshatriya (2009) is able to predict change to the growth rate of the fish population (λ) in response to rates of upstream passage success and downstream passage mortality where:

$$\lambda = \frac{N_{t+1}}{N_t}$$

Where $N_t$ is the total number of individuals in the population at time *t.*

These can be compared with the estimates of the natural (baseline) growth rate of the fish population (λ) to determine the impact of the dam design on fish population sustainability and fish yield.

If, under the proposed design:

$\lambda > 1$, then the population is growing and can still be harvested but at a reduced rate.

If $\lambda = 1$, then the population is viable (constant size)

If $\lambda < 1$, then the population is at risk (shrinking in size).

The model can therefore be applied to determine the minimum upstream passage rate (or fishpass efficiency) that would be necessary to maintain viable or harvestable populations ($\lambda \geq 1$) given the predicted downstream passage mortality experienced by the population.

$\lambda$ is the discrete-time population growth rate. The continuous-time growth rate equivalent is denoted by *r*, and also called the intrinsic rate of population growth – defined as the rate at which a population increases in size if there are no density-dependent forces regulating the population.

$$r = \ln(\lambda)$$

In fisheries, *r* indicates the maximum rate of exploitation and *rK*/4 indicates the maximum sustainable yield (MSY) of the population, where *K* is the unfished stock size (virgin biomass or $B_0$).

Relative changes to the value of *r* can therefore be used to determine relative changes in fish yield (catch).

## Modifications to the Model

Halls and Kshatriya (2009) modelled only the effects of turbine blade strike on downstream passage mortality rates on adults and juveniles returning to downstream feeding habitat and ultimately population viability.

For the modeling of the Sambor mitigation scenarios, the effects of the following factors on downstream passage mortality rates will also be included:[13]

(i) reservoir passage (drift);
(ii) impingement on turbine intake screens and trash screens;
(iii) turbine shear and barotrauma;
(iv) spillway shear and barotrauma

## Model Assumptions

The main assumptions underlying the model are explained as follows:

1. *Longitudinal distribution of critical habitat*: All spawning habitat is located upstream (above) Sambor dam, and all feeding and nursery habitat is located downstream of (below) the dam. Hence, all adult fish pass upstream and downstream through the dam every year, and all juvenile fish spawned upstream pass downstream. Potential impacts will be highly sensitive to this assumption.
2. *Population structure*: The species of fish included in this study are assumed to comprise a single population in the LMB. Again, potential impacts will be highly sensitive to this assumption.
3. *Downstream migrations of adults and juveniles occur in August.* The effect of lower survival rates of drifting larvae in the reservoir in June caused by lower flows, was also examined.
4. *Upstream passage of adults to spawning grounds.* It is assumed that individuals experience no additional mortality or diminished reproductive capacity associated with upstream passage via ladders or other passes. In reality, some mortality and diminished reproductive capacity might be expected due to the high energetic costs associated with passage and the increased likelihood of predation in dam vicinity, hence our predictions of impact may have been underestimated.
5. *Turbine passage mortality from blade strike* can be accurately estimated using existing blade-strike models applied to the Sambor turbine geometry and operational characteristics.
6. *Fish screens* are assumed to be 100 % effective in preventing entrainment into the turbine intakes for the specialized size class of fish.
7. *Downstream passage mortality rates* for trash screen impingement, fish screen mortality, barotrauma, and shear derived from experience in other systems and expert judgement (see Chapter 7), are applicable and accurate.
8. *Other sources of downstream mortality*, such as predation after turbine passage and gas supersaturation in the tailwater, were assumed to be negligible. There are no quantitative data and little expert opinion on these aspects of mortality that can applied to the model, but in reality, they may be significant and hence our predictions of impact may have been underestimated.

9. *All life stages of fish have a uniform density in the* flow such that the number of fish passing through each dam structure is proportional to the flow through each structure.
10. *Fishing mortality:* Little is known about rates of fishing mortality (*F*) in the Mekong, and few estimates have been published. We assumed that fish populations in the LMB are exploited at rates that maximize yield ($F=F_{msy}$).

## Migratory Fish Species Selected for Modelling

Given time and resource constraints, we selected only five of the 10 species selected by Halls and Kshatriya (2009) to represent small, medium, and large migratory species (Table 8-1). These five species made up about 16% of the catch in the MRC fisher catch monitoring program between November 2003 and December 2004 (Halls and Kshatriya, 2009). Except for *Pangasius concophilus* (a pangasid catfish), the remaining species are all cyprinids.

## Model Parameters

### Fish Population Parameters

The model population parameter estimates for the five selected species are provided in Table 8-1.

*Table 8-1. Fish population parameters for the five model species. Source: Halls and Kshatriya, 2009.*

| Species name | Size category | L∞ (cm) | K (y-1) | Lm (cm) | W-L model | | $\lambda_{baseline}$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | | | | | a | b | $\lambda_{low}$ | $\lambda_{med}$ | $\lambda_{high}$ |
| *Henichorynchus lobatus* | Small | 15 | 0.550 | 9.8 | 0.012 | 3.026 | 1.07 | 1.19 | 1.64 |
| *Henichorynchus siamensis* | | 20 | 0.454 | 13 | 0.030 | 2.8 | 1.11 | 1.19 | 1.65 |
| *Hypsibarbus malcolmi* | Medium | 50 | 0.246 | 32.5 | 0.027 | 2.909 | 1.05 | 1.10 | 1.18 |
| *Pangasius concophilus* | Large | 120 | 0.137 | 78 | 0.021 | 2.86 | 1.02 | 1.05 | 1.17 |
| *Probarbus jullieni* | | 150 | 0.118 | 97.5 | 0.016 | 3.0 | 1.02 | 1.03 | 1.05 |

## Flow Proportions

This modeling will assess predicted flows through the main channel and anabranch, and via the main dam structures during the month of August when the model shows that adults and larvae are migrating downstream, and also flows predicted for June were assessed to test the sensitivity of the model predictions to flow proportion values (

*Table **8-2***). Flows through the fishpass and navigation locks (if present) are deemed negligible (<0.3%) and therefore excluded. The model assumes that all life stages of the species modelled have a uniform density in the flow such that the number of fish passing through each dam structure is proportional to the flow through each structure.

*Table 8-2. Proportions of the river flow via the reservoir, anabranch, powerhouse/bypass and spillway for each scenario.*

| Scenario | Flow month | Proportion of total river flow to reservoir | Proportion of total river flow to anabranch | Proportion of reservoir flow to powerhouse | Proportion of reservoir flow to spillway |
|---|---|---|---|---|---|
| 1, 2 | August | 0.51 | 0.49 | 0.57 | 0.43 |
| 1, 2 | June | 0.59 | 0.41 | 0.93 | 0.07 |
| 3 | August | 0.88 | 0.12 | 1.00 | 0.00 |

## Predictions of Results

From the previous round of modeling, some preliminary predictions can be made of the results of the next round of modeling: rates of downstream passage mortality are likely to be relatively low for the partially and fully mitigated scenarios due to the mitigating effects of fish screens, and the improved design of the turbines, with thicker blades and slower rotation, but at a sacrifice of power production.

The preliminary modeling suggested that the decline in potential yield is very sensitive to upstream fishpass efficiencies, with zero potential yield if fishpass efficiency was in the order of 45% - 50%. A decline in fish yield is inevitable following the construction of any dam as the intrinsic rate of population growth of species of fish, *r* is reduced by a combination of elevated mortality rates during downstream passage, and diminished reproductive rates (success) as fewer adult fish are able to access their spawning grounds. The results presented here suggest that the impact on fish yield is particularly sensitive to the latter in response to fishpass efficiency. Therefore, whilst the fishery yield impact modeling will be focused on the effects of downstream passage mortality caused by shear, barotrauma, blade strike, and reservoir drift, it would appear that fishpass efficiency is the key factor determining impact. It is illustrative that for the previous round of modeling of downstream fishery impact mitigation strategies, the minimum fishpass efficiency minimum required to prevent population declines was estimated to be in the order of 45%-50% for unexploited stocks and about 70% - 80% if the stocks were currently exploited at rates that would maximize yield. Efficiency would need to be greater if stocks are currently overexploited.

These findings pose the question: Can 95%, or even 50% fishpass efficiency be achieved?

The fishpass proposals for the Sambor dam are unique in terms of their scale and design, and therefore the relevance of the existing empirical evidence concerning fishpass performance needs to be considered. A review of the fishpass literature, published between 1960 and 2011 (65 papers), found that average upstream fish pass efficiency has been only 42% Noonan *et al.* (2012). After excluding salmonid species, for which average pass efficiency was approximately 60%, mean fish pass efficiency was found to be only 21%, and about 30 % for cyprinids.

However, the paper grouped fishways built in 1940 with those since 2000, and also grouped together high and low gradient fishways. Importantly, cost was not specifically evaluated in the assessment. Hence, the study also noted that "more expensive fishways are…the most effective" and that "…the very best designed fishways are approaching 100%". The study included 'natural' fish passes which were found to be less efficient than pool-type. The authors of the study concluded that "…current fishways are not achieving their primary conservation goal of restoring the connectivity of freshwater ecosystems" (Noonan *et al.*, 2012).

Whilst Noonan *et al.* (2012) were able to identify statistically significant factors and covariates affecting fish pass performance (e.g. slope, fish pass length, flow velocity…etc.), a great deal of variance in fish pass performance remained unexplained. This unexplained variance coupled with poor pass performance achieved to date suggests that the science of fish pass design is still at an early stage of development. As one reviewer stated: "It would hubris to assume that engineering solutions – no matter how well-intentioned – would mitigate all effects of a proposed dam on the fishery resources. If the Cambodian people value the fishery in the vicinity of the proposed Sambor Dam, then the risk (to the fishery) of constructing a dam is high. The highly uncertain question is the magnitude of the potential effect. Absent additional data, the precautionary principle is the most risk-averse approach."

The previous modeling results may have overestimated the potential impact of the dam because it did not account for potential compensatory mechanisms that might be operating in the population, but this strategy effectively generated protective, more precautionary advice. The extent of any overestimation is impossible to determine, may be marginal, and countered to some extent by the fact that the model did not include other sources of mortality (e.g. caused by delays to upstream migration).

These predictions about the barrier and passage related impacts of Sambor dam assume that the modelled species are obliged to spawn only in locations above the dam and must return downstream to feed and seek refuge every year in order to maintain their populations.

Given our poor knowledge and understanding of fish ecology in the Mekong, it remains highly uncertain if these assumptions are valid, but reflect our precautionary approach to the assessment. In reality, some or all spawning habitat may lie below Sambor dam, or some adult fish may remain upstream of the dam and reservoir. The potential for adaptation can only be determined after the construction of the dam and impacts may then be irreversible. Determining the distribution of spawning habitat and migration patterns in the LMB is therefore a research priority at least for those species which form the majority of the catch of highly migratory species.

A carefully designed larvae density sampling program might therefore be considered with intensive sampling undertaken simultaneously at perhaps 20-30 stations along the length of the Mekong and in the mouths of tributaries during the main spawning period (June-September). Such a program would need to be complemented by environmental and hydrological surveys to help identify and explain spawning location selection. Genetic studies and/or mark-recapture methods could also be employed to determine the population structure and the geographic range of species.

Because of lack of data and knowledge, the study also assumed that upstream migrating adults experience no additional mortality or diminished reproductive capacity associated with upstream passage via ladders or other passes. In reality, some mortality and diminished reproductive capacity might be expected due to the high energetic costs associated with passage and the increased likelihood of predation in dam vicinity, hence our predictions of impact may have been underestimated.

Knowledge of fish population resilience in response to dam construction would benefit from a better understanding of the prevailing rates of exploitation in the LMB. Here we assume that rates are equivalent to those that would generate MSY. In reality, fish populations may be over-exploited and in deterministic decline. In which case, we have underestimated the population vulnerability to this proposed development. The proposed sensitivity analysis would help better understand the implications of this uncertainty.

Estimation of fishing mortality rates would require sampling of the catch of low selectivity gears (perhaps the Cambodian *dai* fishery) to determine the size distribution of fish populations supported by ageing studies or the analysis of length frequency data to estimate the age distribution of the populations. Fishing mortality could then be determined from the age distributions after accounting for natural mortality rates which can be estimated from fish growth parameters.

*Text Box 8-1. Priority Research*.

- The potential impacts predicted by this study are very sensitive to the assumptions concerning the distribution of critical habitat above and below the proposed dam location.
- It remains highly uncertain if these assumptions are valid.
- In reality, some or all spawning habitat may lie below Sambor dam, or it may be that fish can adapt to spawn in locations below the dam.
- The potential for adaptation can only be determined after the construction of the dam and impacts may then be irreversible.
- Determining the distribution of spawning habitat in the LMB is therefore a research priority at least for those species which form the majority of the catch of high migratory species.
- The reliability of model predictions could also be improved with better estimates of the fecundity or intrinsic population growth rates of migratory species inhabiting the Mekong basin, as well as rates of exploitation.
- ***Programs to address these research priorities are urgently required.***

## References

Halls, A.S. and Kshatriya, M. 2009. Modelling the cumulative barrier and passage effects of mainstream hydropower dams on migratory fish populations in the Lower Mekong Basin *MRC Technical Paper,* **25,** 104.

Noonan, M.J., Grant, J.W.A. & Jackson, C.D., 2012. A quantitative assessment of fish passage efficiency. *Fish and Fisheries,* **13,** 450-464.

# 9 ASSESSING THE IMPACTS ON MEKONG RIVER IRRAWADDY DOLPHINS FROM THE SAMBOR HYDROPOWER ALTERNATIVES

## Background

The Sambor reach of the Mekong River is renowned for a small population of Irrawaddy dolphins, *Orcaella brevirostris*. This Chapter reports on the estimates by a team of dolphin ecology experts on the incremental impacts that the various Sambor alternatives are likely to have on the long-term viability of the Irrawaddy dolphin population that inhabits the Mekong River within Cambodia (hereafter Mekong dolphin population).

Impacts on the Mekong dolphin population were assessed – considering siting, design and operations – for the Sambor CSP (China Southern Power) Dam and the screened and unscreened alternatives examined by NHI for mitigating the impacts of fish passing through the reservoir and the dam. These are discussed at length in Chapter 7. The screened scenarios would prevent the adult fish and dolphins from entering the turbines. However, the unscreened scenarios would be equipped with trash racks which would also prevent the dolphins from entering the turbines.

## Dolphin Project Objectives

The objective of this study is to determine potential impacts on the Mekong dolphin population from the various hydropower dam designs, and to inform the Royal Government of Cambodia (RGC) of trade-offs between energy requirements and Mekong dolphin conservation.

The scope of this study investigates the feasibility of hydropower options that:

- Do not cause significant changes in sedimentation or hydrology, such that important dolphin habitats are degraded;
- Do not cause direct mortality of individuals within the Mekong dolphin population;
- Maintain Mekong dolphin gene flow and connectivity so that the remaining population (Kratie to the Cambodia-Lao PDR border) is not fragmented;
- Do not cause long-term habitat displacement or behavioral changes which may subsequently affect survivability of the remaining population;
- Do not significantly affect the species on which the dolphins prey, which are essential for dolphins' long-term survival.

## Mekong Dolphin Population Biology and Conservation Status

### Background on Mekong River Dolphins

The Mekong River of southern Lao PDR and Cambodia is home to a critically endangered population of the Irrawaddy dolphin, *Orcaella brevirostris* (Smith and Beasley, 2004; Reeves, 2008). Irrawaddy dolphins are poorly understood, and little is known of their genetics or biology. Irrawaddy dolphins inhabit marine and freshwater habitats in South and Southeast Asia, including the Mahakam River in Borneo, the Ayeyarwaddy River in Myanmar and Mekong River of southern Lao PDR and Cambodia. Until 2005, the species was considered also present in Australia, until the Australian snubfin dolphin *Orcaella heinsohni* was recognized as a separate species (Beasley *et al.*, 2005). Recent research suggests that the Mekong dolphin population is likely to be genetically distinct from other Irrawaddy dolphins, and may show sufficient difference to be considered a new sub-species (Krutzen *et al*., in review).

Historically, the Mekong dolphin population ranged from the Khone-Phapeng Falls on the Cambodia-Lao PDR border, south to the delta in Vietnam, and into the Tonle Sap and Sekong sub-basin, (Baird and Mounsouphom, 1997; Baird and Beasley, 2005; Beasley, 2007). Today, Mekong dolphins are primarily found in a 190km stretch of the main-stem Mekong River between Khone-Phapeng Falls and Kampi Pool, in Kratie Province, Cambodia (Figure 9-1. Dolphin & Figure 9-2; Beasley, 2007).

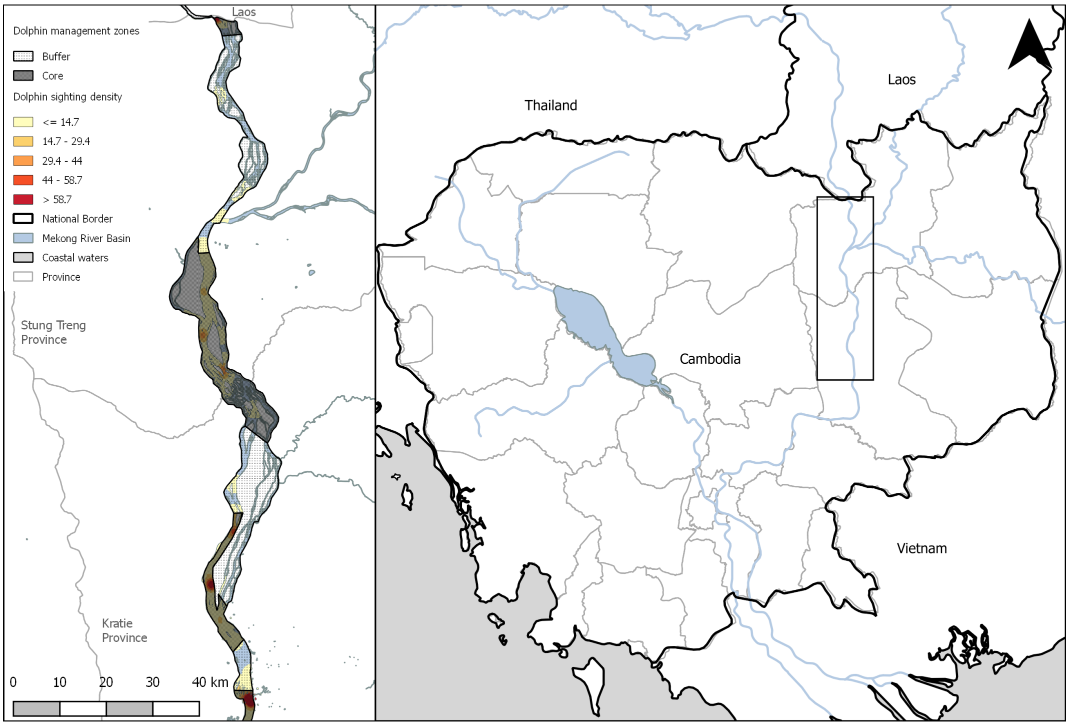



*Figure 9-1. Dolphin range in the Mekong River showing dolphin management zones in Cambodia and relative dolphin sighting densities, and right, black rectangle showing location within Cambodia. Sighting density based on Beasley and colleagues (2013), Ryan and colleagues (2011), and Beasley unpublished data.*

The Mekong dolphin population has been a focus of research and conservation efforts for around 20 years. Early efforts in the 1990's occurred mainly in Lao PDR (Baird and Mounsouphom, 1997; Baird et al*., 1994)* focussing on the group of dolphins resident in the Cambodia-Lao PDR border area (hereafter trans-boundary subpopulation). Recent surveys and conservation activities have been conducted in Cambodia and southern Lao PDR (Baird and Beasley, 2005; Ryan *et al.*, 2011; Beasley *et al.*, 2013; Dove, 2009, Beasley, 2007), with some surveys in Vietnam (Beasley, 2007). Key conservation actions have included:

1) efforts to curb entanglement in gill nets through legislation, enforcement, and awareness raising,
2) the provision of livelihood opportunities that reduce reliance on gill net fishing, and
3) research on mortality and population dynamics (Kratie Declaration, 2012; Beasley, 2007; Ryan *et al.*, 2011).

Recent efforts suggest the conservation work is having a positive effect and that the population is recoverable if efforts continue (Phan *et al*., 2015).

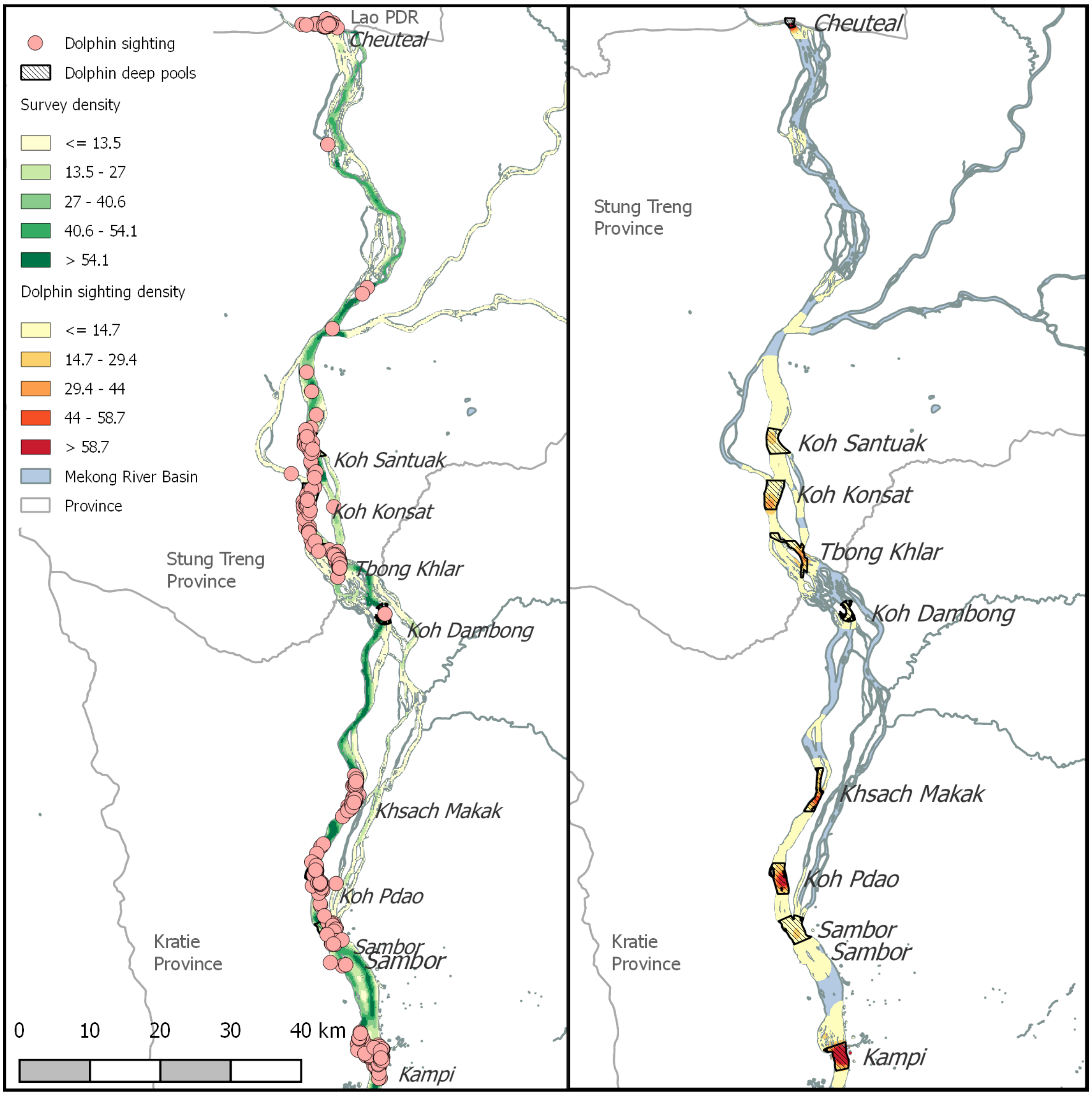



*Figure 9-2. Dolphin range in the Mekong River (see inset in fig. 1), with dolphin sightings 2001-2010, and relative survey effort (left), and relative density of dolphin sightings and key deep pool areas (right). Sighting density based on Beasley and colleagues (2013), Ryan and colleagues (2011), and Beasley unpublished data. See also Figure 5–3 in Chapter 5 of this report for a closer image of the proposed dam sites.*

## Habitat

Irrawaddy dolphins are facultative river dolphins, meaning they are found in both freshwater and marine habitats. Obligate river dolphins live only in fresh water. Of the two obligate Asian river dolphin species the baiji (*Lipotes vexillifer*) in the Yangtze River of China is now considered functionally extinct (Turvey, 2009; Smith *et al.*, 2008). The South Asian River dolphin (*Platanista gangetica*) is found in the Indus River of Pakistan and the Ganges River of Nepal, India and Bangladesh. The South Asian River dolphin population has declined dramatically in recent years and much of their range has been lost, primarily due to bycatch in fisheries and water development infrastructure (Smith *et al*., 1998; Reeves *et al.*, 2000b; Braulik, 2006, Braulik *et al*., 2014; Smith and

Braulik, 2012). Water infrastructure such as dams has also fragmented river dolphin populations in South America (Araújo and Wang, 2015; Pavanato *et al*., 2016).

Hydrological complexity is a key feature of river dolphin habitat. Riverine dolphins typically use areas around confluences, deep water, and counter-current eddies, particularly in low water seasons (Gomez EN.CITE.DATA es, particularly in low water seasons habit). This is likely to be a mechanism allowing them to conserve energy by escaping the need to contend with laminar flow (i.e. when water flows straight down the river without turbulence). Similar complex features are known to be important for other riverine biota such as fishes (Schiemer *et al*., 2000; Poulsen *et al*., 2002).

Deep pools are an important feature of the Mekong River (Poulsen *et al.*, 2002; Halls *et al.*, 2013), and are habitats where dolphins most often occur (Ryan *et al.*, 2011; Beasley *et al.*, 2013; Stacey and Hvenegaard, 2002). In particular, nine deep pool areas are key dolphin habitat over the dry season, corresponding to most of the deep-water areas within dolphin distribution (Figure 9-2 & Figure 9-3). Dolphins are found in water averaging >10 m depth (Beasley, 2007), which is much deeper than the average dry season depth of much of the river (Figure 9-3). In the Ayeyarwaddy River in Myanmar, Irawaddy dolphins are also known to favour deeper water (Smith *et al.*, 1997).

Habitat use in the wet season is less known, however counter-currents remain important. In particular confluences appear to be especially important. For example, dolphins' resident in Kampi Pool are generally observed at the Prek Krieng tributary above the Kampi site, where the flow is complex, turbulent, and the stream flows backwards into the floodplain for part of the wet season (GER pers. obs.). Counter-intuitively, dolphins are found in shallower habitats in the wet season than dry season (Beasley, 2007). This likely due to the dolphins using shallow areas and the river-banks during the wet season to escape the high velocity water-flows.

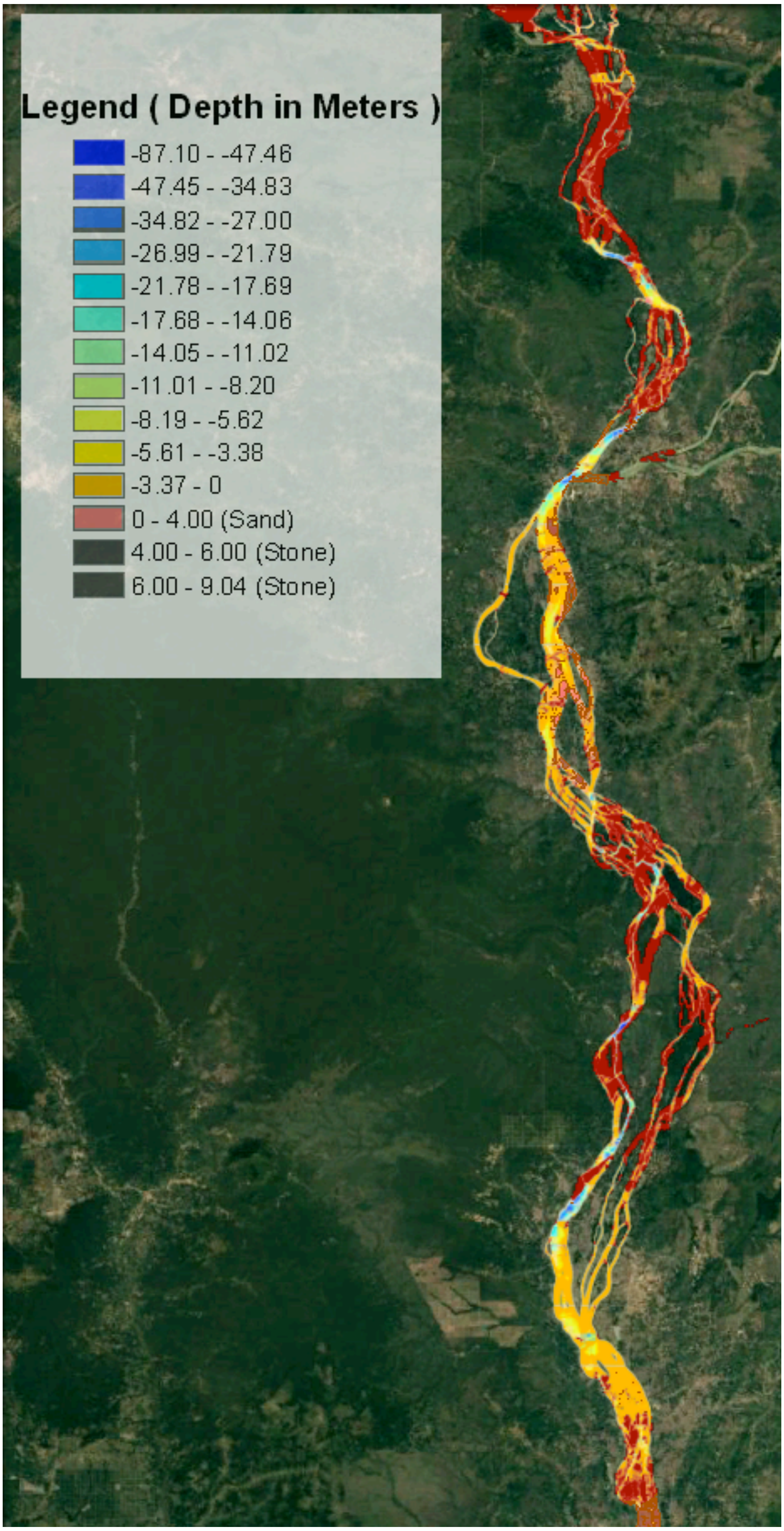



*Figure 9-3. Water depth in the Mekong River from "Atlas of deep pools in the Mekong River and some of its tributaries"; Halls and colleagues (2013). Depth is based on surveys in dry seasons in 1992 and 1992. Areas unable to be mapped due to substrate at or above water level are shown in red, as sand (light red) and rock (dark red).*

## Vocalizations and Communication

Like all cetaceans, Irrawaddy dolphins must use, and rely upon, complex biosonar to communicate, navigate and forage (Tyack, 2008).

While the biosonar signals of many marine toothed dolphins have been studied extensively, little is known about river dolphins (Hamilton *et al*., 2001). Although no detailed acoustic studies have been conducted on the Mekong dolphin population, studies have been conducted on Irrawaddy dolphins in the Sundarban mangrove forest of Bangladesh (Bahl *et al.*, 2007; Jensen *et al.*, 2013). Irrawaddy dolphins in riverine systems of the Sundarbans were found to produce echolocation clicks with a high repetition rate and low source level compared to marine species, perhaps reflecting an adaptation to a shallow, acoustically complex freshwater habitat with high reverberation and acoustic clutter (Jensen *et al.*, 2013).

Studies on the Irrawaddy dolphin's close relative the Australian snubfin dolphin, which inhabits coastal environments of northern Australia, found acoustic repertoires similar to marine Irrawaddy dolphins, with click trains (above 22kHz in frequency, primarily during foraging and socialising), burst pulse or creaks (above 22kHz in frequency, primarily during foraging) and whistles which were narrow-band, frequency-modulated (all were short in duration, low in frequency ~ 1 to 8 kHz and simple in form (Soto *et al.*, 2014; Van Parijs *et al.*, 2000).

Because dolphins rely solely on biosonar to communicate, navigate, and hunt, any excess underwater noise can cause significant stress to populations. The potential impacts of underwater noise are discussed further is Section 9.6.2.3. 'Construction and excavation', where effects can range from behavioural changes (including interruption of feeding, breeding, nursing) through to direct death (Ketten, 1995; Richardson and Würsig, 1997). Previously, the primary source of underwater noise that potentially caused disturbance to the Mekong dolphin population was outboard noise from boats, particularly boats engaged in dolphin-watching activities (Beasley *et al.*, 2010, Beasley *et al.*, 2009). Recent more significant underwater noise exposure has been during the construction of the Don Sahong Dam on the Lao-Cambodian border, where extensive construction and blasting noise may be significantly affecting the remaining trans-boundary subpopulation, causing the dolphins to move away from the site into unfavourable habitat (RFA, 2016). Because recommended mitigation protocols were not followed by the Don Sahong Dam proponents to mitigate for noise exposure (Beasley, 2014a) there are now grave concerns about the viability of this trans-boundary subpopulation (Ryan, 2012; RFA, 2016; WWF, 2016).

## Population Size and Demography

The Mekong River dolphin population is very small and is declining. The population has been subject to long-term monitoring through photographic capture-mark-recapture research since 2001 (Beasley, 2007; Beasley *et al.*, 2013; Ryan *et al.*, 2011; Phan *et al.*, 2015). This process has been externally reviewed and refined, and now represents one of the best long-term monitoring programs for any species in South-east Asia (Gray *et al.*, 2012). The process involves repeat surveys over the entire species range in the Mekong River, in which high-powered lenses are used to photograph individual dolphin dorsal fins, and individual dolphins are recognized by the unique patterns on the fin. Records of sightings of known and unknown individuals are modelled using well-established statistical techniques to estimate the abundance of individuals in the Mekong River (Beasley *et al.*, 2013; Ryan *et al.*, 2011).

Results of the key published estimates of the abundance, growth rate, and survivorship of Irrawaddy dolphins in the Mekong River is summarised in Table 9-1. The population was estimated to be 93 individuals (with a 95% confidence interval of 86–101) in 2007, based on research from 2004-2007 (Beasley *et al*., 2013). By 2010, the population was estimated to be 85 individuals (95% CI 78–91) (Figure 9-4), based on data from 2007–2010 (Ryan *et al.*, 2011). The most recent research, which continues the Ryan *et al.*, 2011 data to April 2015, estimated 80 individuals, though the uncertainty around this estimate is relatively larger (95% CI 64–100, Phan *et al.,* 2015). Between 2007 and 2015, 93 unique individual dolphins were identified. All studies show a consistent picture of a very small and declining population.

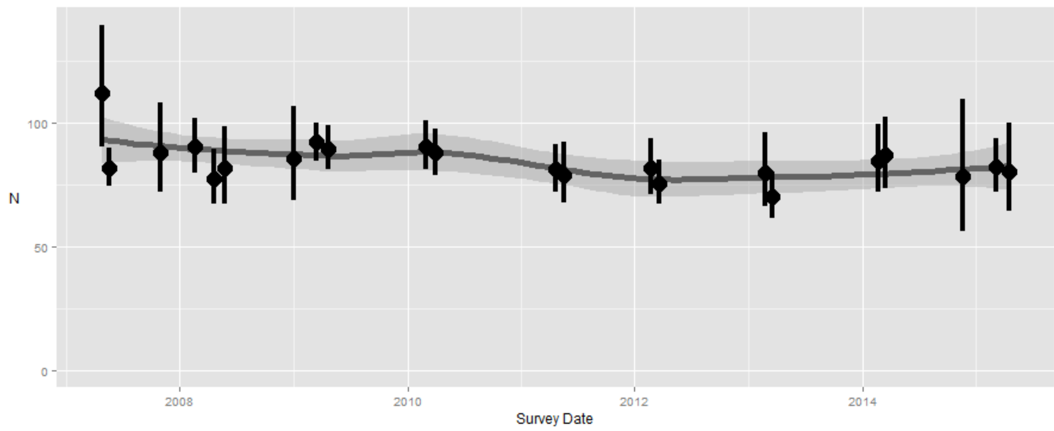



*Figure 9-4. Estimated abundance of dolphins in the Mekong River from 2007-2015. Source: Phan and colleagues (2015).*

The findings from Phan *et al.* (2015) suggest the decline may have slowed or stabilised in recent years. This is supported by slightly higher estimates of the number of unmarked individuals in the population, which are likely to be younger or juvenile animals. However, the population remains in a critical condition. For instance, the trans-boundary population was estimated at seven or eight individuals in 2010 (Ryan *et al.,* 2011), six in 2012 (Ryan, 2012), and three in late 2016 (WWF, 2016).

*Table 9-1. Abundance estimates of dolphins in the Mekong River from 2004-2015.*

| | Beasley *et al.* (2013) | Ryan *et al.* (2011) | Phan *et al.* (2015) |
|---|---|---|---|
| Years covered | 2004–2007 | 2007–2010 | 2007–2015 |
| Abundance estimate in last year | 93 | 85 | 80 |
| 95% CI | 86–101 | 78–91 | 64–100 |
| Population annual growth rate* | 0.887 (0.88–1.007) | 0.978 (0.883–1.074) | 0.984 |
| Individual annual survivorship** | 0.88 | 0.977 | 0.976 |

* Population growth rate *r*, where population $N_{t+1} = r \times N_t$

**Individual survivorship is the probability that an individual alive at time *t* is alive at time *t+1*.

## Mortality

Research on dolphin mortality in the Mekong has been running since the 1990s. Early work in Lao PDR found entanglement in gill nets and illegal explosive fishing to be the main sources of mortality in the trans-boundary area (Baird *et al.*, 1994; Baird and Mounsouphom, 1997). A carcass collection and mortality monitoring programme has been conducted in Cambodia since 2001, with 131 recorded mortalities up to October 2012 (Gilbert and Beasley, 2006; De La Fuente Marquez, 2012). The mortality rate appears to be continuing at a similar rate (Chheng, 2016).

While there were very large numbers of dead calves in 2004–7, from 2008–2012 the average recorded mortalities were 3.4 calves, 0.6 juveniles, and 2.6 adults per year. This represents around 8% of the population, and does not include those mortalities that go undetected.

Gill net entanglement is consistently a source of mortality of adults over this period (Gilbert and Beasley, 2006; Kratie Declaration, 2012; De La Fuente Marquez, 2012). Gill nets are a cheap plastic fishing net often left unattended underwater, and are a common source of dolphin mortality world-wide (Read et al., 2006).

The majority of recorded mortalities from the Mekong River are calves, although evidence suggests bycatch of calves is very rare (Gilbert and Beasley, 2006; De La Fuente Marquez, 2012). A variety of possible explanations for the calf mortality, and unexplained mortality have been put forward which include disease, inbreeding depression, infanticide, and dynamite and electro-fishing. However, no single or definitive conclusion has yet been reached (Dove, 2009, Kratie Declaration, 2012; De La Fuente Marquez, 2012).

### *Potential biological removal*

'Potential biological removal' (PBR), developed under the US Marine Mammal Act, provides a robust estimate of the maximum number of individuals that may be removed from a population without depleting. The aim is to provide a conservative estimate that accounts for uncertainty to provide a high degree of confidence that mortality up to this level by anthropogenic stressors would not deplete the population (Wade, 1998). PBR is calculated such that:

$$PBR = N_{min}\frac{1}{2}R_{max}F_r$$

Where
$N_{min}$ = the minimum population estimate
$\frac{1}{2}R_{max}$ = half of the maximum theoretical or estimated net productivity rate (product of net recruitment rate and population size; see (Wade, 1998).
$F_r$ = a recovery factor (Wade, 1998).

The minimum population estimates is estimated as 64 individuals, based on the lower bound of the 95% confidence interval from the most recent population estimate (Phan *et al.*, 2015). Following Beasley, 2007 for this population, 0.04 is used as the default value of $R_{max}$ for cetaceans, and 0.1 as the value of $F_r$ for a threatened species. Thus, the PBR is calculated as equal to 0.128 dolphins/year.

This suggests that a safe allowable level of anthropogenic mortality for dolphins in the Mekong River is 0.128 individuals per year (or approximately one dolphin every eight years), a number currently far exceeded by gill net deaths alone.

### Distribution, Structure and Ranging

Irrawaddy dolphins historically ranged throughout the Mekong River below the Khone Phapeng Falls, including the Tonle Sap in Cambodia, the Sekong-Sesan-Srepok sub-basin Northeast Cambodia and Lao PDR, and downstream in Vietnam. Presently the Mekong dolphin population is only distributed from Kampi Pool in Kratie Province, Cambodia, north to the trans-boundary deep-pool on the Lao PDR-Cambodia border, known as Cheuteal pool (Figure 9-1. Dolphin & Figure 9-2). In 2002, two individuals were trapped in floodplains near Phnom Penh during the wet season. Both dolphins were released back into the mainstream Mekong River near Phnom Penh, with at least one of them returning upstream to Kampi based on photo-identification confirmation (Beasley, 2002; Beasley, 2007). The most recent record of dispersal outside of this range was an individual killed by fishermen in the Srepok River in 2005 (Gilbert and Beasley, 2006). Other recent records outside this range are either of carcasses presumed washed downstream, or sick animals known to have died shortly afterward (GER pers. obs.). Tentative evidence suggests that even within this extent from Kampi to Cheuteal, the area actually used by dolphins may be decreasing (see Appendix 9.2: Figure A9.2.1., Figure A9.2.2. and Figure A9.2.3.).

Surveys for dolphins have covered almost all channels of the Mekong River between Kampi and Cheuteal (Figure 9-2 & Figure 9-7). While initial exploratory surveys by Beasley, 2007 (Figure 9-2 & Figure 9-7) and Ryan *et al.,* 2011 (not shown) covered a variety of side channels, very few observations of dolphins were made outside the main channel. The apparent limited occurrence in side channels was supported by ongoing consultation with people living in these areas by research and outreach teams. The anabranch channels to the east of Koh Rongeav are especially relevant to the Sambor Alt_7 dam proposal. Sok *et al.* (2012) spent approximately four years working on other projects in this area and found no evidence (neither sightings nor reports) of dolphins utilising the anabranch channels. These channels are likely to be too shallow for dry season use, and contain few deep pool areas (Figure 9-3). The channels that were not surveyed were either too shallow in the dry season for small boats to pass, and/or too shallow or dangerous to pass through in the wet season. These channels are unlikely to be used by dolphins during the dry season because of the very shallow water (Figure 9-3). The majority of survey work for dolphins has therefore focussed on the main channel.

Seasonally, Mekong dolphins are found to use slightly deeper water in the dry season than in the wet season (Beasley, 2007), corresponding to use of deep pools refuges (Poulsen *et al.*, 2002). In the dry season, dolphins stay generally close to deep pools, whilst ranging throughout the river in the wet season (Beasley, 2007).

Within the current populations' range from Kampi to Cheuteal pools, there is clear social structure and strong home-ranging patterns focussed around the deep-pools (Beasley, 2007), as shown in Figure 9-2. The following is based on Beasley, 2007 and Ryan *et al.,* 2011 and associated unpublished data. Dolphins are generally observed in one of four primary subgroups.

**Cheuteal**: these individuals are only found in the trans-boundary area around Cheuteal pool, immediately below the under-construction Don Sahong Dam in Lao PDR (Figure 9-2). This is the smallest group (currently estimated to be only three individuals; WWF 2016), and likely to be extirpated in the near future (Ryan, 2012, 2014). Dry season extent of occurrence is estimated to be only 2km (Beasley, 2007).

**Siembouk**: These animals range throughout the Koh Santuak, Koh Konsat, Tbong Khlar, and Koh Dambong pools (Figure 9-2) of Stung Treng Province (currently estimated to be around 30 individuals). There is some substructure within these groups, and Tbong Khlar is the most significant habitat. Dry season extent of occurrence is estimated to be linear 21km (based on Beasley, 2007).

**Sambor**: These animals range between the Sambor and Koh Pdao area, and a small number stay predominately in Ksach Makak-Sampan (currently estimated to be around 20-30 individuals). Maximum dry season habitat use is estimated to be linear 20km for the majority of individuals (based on Beasley, 2007).

**Kratie**: This is the largest single group of dolphins in the Mekong River (currently estimated to be around 20-30 individuals). Maximum dry season habitat use is estimated to be linear 2km for the majority of individuals (based on Beasley, 2007).

Only approximately 10 individuals are known from photographic identification studies to move between the Kratie and Siembouk groups, and such movements are rare (GER unpublished data). For these individuals, their maximum dry season habitat use is 32 linear km). It is likely that the shallow water and rocky substrate between these groups is a significant barrier to movement (Figure 9-3). Genetic evidence suggests that there is no genetic structure to the population, supporting at least some long-term mixing of these groups (Krutzen *et al.* in review). It is likely that although photographic identification studies suggest stable social groups in specific areas, the animals targeted by these studies are adults. It is likely that dispersal among groups occurs through the dispersal of sub-adult males seeking mates. It is this infrequent exchange among groups that maintains genetic diversity and connectivity.

It is important to note that within these linear distances covered by these group ranges, a few very small areas are disproportionately highly used, namely those areas around deep pools (Figure 9-2 & Figure 9-3).

## Tourism

Dolphins in the Mekong River hold significant cultural and monetary values. Traditional folklore has legends of the human origin of Mekong dolphins in both Cambodia and Lao PDR (Baird and Beasley, 2005). Dolphins are also a significant source of tourism revenue. Organized dolphin-watching tourism operates currently out of two major sites: at Kampi, and at Cheuteal from both the Cambodian and Lao PDR sides of the river. Smaller ad hoc operations also run at Koh Pdao, Tbong Khlar, and Koh Santuak. Although tourism can be a threat to dolphins, primarily from harassment by boats (Beasley *et al*., 2010), it is also a source of impetus in their protection in Cambodia (Kratie Declaration, 2012).

Kampi is the most valuable site for dolphin-watching tourism in Cambodia, with almost 10,000 domestic and 15,000 foreign tourists going on dolphin-watching boats at Kampi in 2014 (Mustika *et al.*, 2016). It is hard to judge the exact revenue from this as the ticket price depends on the number of people on the boat. O'Connor and colleagues (2008) suggest around US$50 is spent per tourist in both direct and indirect costs in a visit to see dolphins in Kratie, corresponding to around US$1.25 million spent in the local economy.

Around 10,000 tourists were estimated to visit the Cheuteal dolphin population in 2005 (O'Connor *et al.*, 2009). If the expenditure figures in this area are similar to Kampi, this suggests a potential further USD 500,000 into the local economy. The numbers are likely to have risen significantly since 2005 (G. Ryan pers. obs.), however most of this is likely to be spent in Lao PDR. US$50 per person (from O'Connor *et al.,* 2009) may be an overestimate of the expense related to dolphin-watching in Lao PDR, as the Siphandone region is a well-known tourist attraction in its own right.

There is no known data on dolphin tourism elsewhere in Cambodia, however it is likely to be only very small scale.

## Status and Regulations

This section is intended as an indication of relevant laws regarding dolphins and the proposed Sambor dam development, but not intended to constitute legal advice. The full legal implications of this process should be explored by an appropriate specialist legal advisor.

### International

Irrawaddy dolphins occur in brackish and coastal areas in South and Southeast Asia, and three major rivers; the Ayeyarwady River in Myanmar, the Mahakam River in Borneo, and the Mekong of southern Lao PDR and Cambodia. Mekong dolphins are now considered functionally extinct in Vietnam. All riverine populations of Irrawaddy dolphin are classified on the IUCN Red List of Threatened Species as Critically Endangered (Jefferson *et al.*, 2016; Smith, 2004; Smith and Beasley, 2004). Globally, the Irrawaddy dolphin is classified as Vulnerable. IUCN Red List classifications correspond with probability of extinction (Keith *et al.*, 2004), and critically endangered corresponds to the highest level of threat.

Irrawaddy dolphins are listed on the Convention on International Trade in Endangered Species of Wild Fauna and Flora, Appendix I (CITES, 2016). This prevents all international trade in the species.

### National

Irrawaddy dolphins are considered a "Fishery resource" under Article 4 of Fishery Law, which includes "any freshwater or marine organisms", and therefore management of the species is governed by the Fisheries Administration (Royal Government of Cambodia, 2007).

Irrawaddy dolphins are classified as 'Critically Endangered' under the Sub-Decree on the Determination of Types of Fisheries and Endangered Fisheries Products (Royal Government of Cambodia, 2009), which among other regulations, prevents the killing, trade, trafficking, or ownership of the species in Cambodia.

Irrawaddy dolphin habitat in the Mekong River is also protected under four legal instruments:

- Fishery Law (Royal Government of Cambodia, 2007) considers "permanent waters, the Mekong Flooded areas" as part of the "Fishery Domain" (Chapter 3, Article 8), and therefore governed by Fishery Law.
    - "Fishery Management Areas comprising *inter alia* rapids and deep pools in rivers…shall be classified as Protected and Conservation Areas of Fishery Resources" (Chapter 5, Article 18).
    - "Building dams/dykes across…rivers…that could cause disastrous damage to fishery resources in fishery domain shall be studies or evaluated by the Ministry of Agriculture, Forestry, and Fisheries, and concerned institutions" (Chapter 5, Article 25)
    - Both the Sambor CSP and Sambor Alt_7 sites are within "Fishery Domain" and are likely to be in "Protected Conservation Areas" by virtue of being over deep pool areas.

- The Sub Decree on the Creation of the Mekong River Dolphin's Managerial Protection Zones (Royal Government of Cambodia, 2012, Figure 9-1. Dolphin , see also **Error! Reference source not found.**), which prevents a variety of activities including some fishing types, and large-scale infrastructure development within the zone.
    - Both the original Sambor CSP and the Sambor Alt_7 sites are within areas designated as 'core zone' under this sub-decree (see **Error! Reference source not found.**). It is unclear if either option could proceed given this legislation.

- The Proclamation on the Creation of Fisheries Biodiversity Management Area designates a protected fisheries management area within a 50 km stretch of Mekong River mainstem and all channels in an area between the towns of Stung Treng and Kratie (*specifically between Indian-Thailand 1960 Map Datum UTM 1425761 in the south and 1475366 in the North*; see Appendix 9.2: Figure A9.2.4, MAFF 2013).
    - The Sambor Alt_7 site is within this zone. The original Sambor CSP site is not, however its reservoir would inundate much of this protected area.

- A Ramsar site covers most of the river between Stung Treng town and Cheutal (Timmins, 2006).
    - Neither proposed Sambor dam site lies within this zone.

### Obligations under International Conventions

Cambodia acceded to Convention on Biological Diversity in 1995, legally binding it thus to the treaty, and has accepted all protocols (CBD, 2016). The CBD has wide-ranging measures to protect biodiversity, notable among which are the so-called 'Aichi Targets', directing efforts to protect biodiversity between 2010 and 2020 (COP10, 2010). Goals require parties to "*Address the underlying causes of biodiversity loss by mainstreaming biodiversity across government and society*", "*Reduce the direct pressures on biodiversity and promote sustainable use*", and "*Improve the status of biodiversity by safeguarding ecosystems, species and genetic diversity*" (COP10, 2010).

Under these strategic goals, several specific targets are relevant (from COP10, 2010):

- Target 5: By 2020, the rate of loss of all natural habitats, including forests, is at least halved and where feasible brought close to zero, and degradation and fragmentation is significantly reduced.
- Target 12: By 2020, the extinction of known threatened species has been prevented and their conservation status, particularly of those most in decline, has been improved and sustained.

## Background to Hydropower Dams and Dolphins

Freshwater ecosystems are among the most important and threatened on the planet, however disentangling the effects of many simultaneous stressors is difficult (Vörösmarty *et al*., 2010). Hydropower dams come into conflict with dolphins in many large river basins (Braulik *et al.*, 2014; Araújo and Wang, 2015; Baruah *et al.*, 2012; Smith *et al*., 1998; Turvey, 2009), but almost always in the presence of other threatening processes, making determining cause and effect difficult. For example, although fishery interactions were probably the primary cause of the baiji (or Yangtze River dolphin, *Lipotes vexillifer* demise), the construction of extensive flood control, hydropower, and irrigation projects in the Yangtze River and its tributaries, resulting in extensive habitat loss, was almost certainly a contributing factor (Huang *et al.*, 2012; Turvey, 2009; Smith and Reeves, 2012), particularly the Gezhouba (2.71 GW; completed in 1989) and Three Gorges (22,500 MW; completed in 2012) dams on the mainstream Yangtze River (Zhang *et al.,* 2003). Construction of the Don Sahong Dam (260 MW), on the Laos/Cambodian border began in 2015, and appears to be already impacting the small group of three Irrawaddy dolphins that now inhabit the trans-boundary pool (Ryan, 2014; RFA, 2016).

Asian rivers provide heterogeneous habitat that supports high biotic diversity. The features that make river systems suitable for dolphins are hydraulic refuge, the seasonal availability of the floodplain, the lateral exchange of materials between the floodplain and main channel, and abundant prey *(Reeves et al.*, 2000a). Counter-current pools are the primary habitat of river dolphins in all river systems *(Reeves et al.*, 2000a).

As a result of river dolphins reliance on suitable riverine habitats and adequate prey for long-term survival, there are five primary reasons why dams result in reduced breeding/survival, increased stress, or death for river dolphin populations (Leatherwood and Reeves, 1994):

1. **Fragmenting dolphin populations into smaller groups**, which are genetically isolated and more vulnerable to extinction;
2. **Loss of microhabitats in the river**, which are critical to dolphin survival. Dams cause changes in river flow dynamics and sedimentation patterns which alter dolphin habitats, especially counter-current or eddy pools which are the primary habitat for dolphins and also support prey species;
3. **Reduced abundance and diversity of prey fish species**. Dams may block fish migration routes and degrade habitats for fish breeding and shelter;
4. **Short-term disturbance during dam construction** (e.g. noise from blasting, increased sediment loads) may disrupt dolphin social breeding, navigation and foraging behavior. Increased stress may result in increased susceptibility to disease (Bezuijen *et al.,* 2007);
5. **Direct death**, from construction and explosive trauma, being entrained into in the dam turbines, or injury during passage through structures such as spillways and navigation locks,

and/or starvation from lack of prey.

This study assesses the impacts of the Sambor dam proposals on the Mekong dolphin population through the above mechanisms.

## Potential Impacts of the Proposed Sambor Dam to the Mekong Dolphin Population

As a result of comprehensive studies since 1997, the Mekong dolphin population is now one of the best-studied river dolphin populations worldwide (Baird and Beasley, 2005; Ryan *et al*., 2011; Beasley *et al.,* 2013). However, many biological aspects of the Mekong dolphin population remain unknown, such as wet season movements and distribution, important breeding areas (although assumed to be deep pools), diet, life history, causes of mortality, and effects of dolphin-watching tourism on long-term survival.

Although there is a lack of some information on the Mekong dolphin population, inferences about the level of impact and risk, from the proposed Sambor Dam construction, operation and decommissioning activities can be assessed from other similar species. Such examples are widely available from river dolphin populations exposed to water development projects, as well as coastal and marine mammal populations exposed to the impacts of habitat degradation, developments, underwater noise and associated disturbance.

Important considerations when assessing potential impacts and mitigation strategies affecting the Mekong dolphin population are:

- Cambodian laws prevent the killing of Irrawaddy dolphins,
- Dolphin and other conservation areas in the proposed sites restrict infrastructure development,
- the Mekong dolphin population is listed as Critically Endangered by both the IUCN and Royal Government of Cambodia, which means that it has a high probability of extirpation in the near future, even under near-ideal circumstances;
- the remaining population is small (i.e. an estimated 80: 95% CI 64-100 individuals), inhabiting only 190 km of the upper Cambodian Mekong river (including the trans-boundary pool on the Lao PDR-Cambodian border);
- Mekong dolphin survival depends on suitable habitat and adequate prey. If either of these components degrade substantially, the Irrawaddy dolphin population will not survive in the Mekong River;
- the stretch of river where the Sambor dam is planned is listed within the Sub Decree on the Creation of the Mekong River Dolphin's Managerial Protection Zones (Royal Government of Cambodia 2012; Figure 9-1), which prevents a variety of activities being undertaken, including large infrastructure projects. Given that the Sambor dam would almost certainly be considered to be a large infrastructure project, this development may be in violation of existing Cambodian Government legislation.
- The safe allowable level of anthropogenic mortality for dolphins in the Mekong River is 0.128 individuals per year (one dolphin every eight years); a number currently far exceeded by gill net deaths alone. The death of even a single dolphin (directly or indirectly) from the dam construction and operation would contribute to population decline.

The following sections discuss which activities associated with construction and operation of the Sambor dam alternatives (see also Chapter 6) could impact the Mekong dolphin population. An associated level of risk is provided for each activity.

## Potential Construction and Operational Phase Impacts

Construction and operational phase requirements for both the original Sambor Dam and the NHI Sambor Alt_7 alternatives have been discussed by CSP (2008) and NHI (2016) respectively (also see Table 6-2 in this report). Based on these documents, and existing literature from other similar projects, the following are the major concerns related to construction and operational phase impacts on the Mekong dolphin population.

### *Construction waste and increased domestic garbage and sewage*

All Dam Options:

As stated within CSP, 2008, an inevitable impact of construction (for all dam options) will be construction waste and increased domestic garbage and sewage. All three potential products can cause impacts to the Mekong dolphin population through increased contamination levels, ingestion and entanglement in plastics and debris that can subsequently cause death (Derraik, 2002), and disease, respectively.

Plastic ingestion is a particular immediate concern, as this is an increasing problem for marine mammals worldwide. In some cases, such as the northern fur seal, interaction with debris and plastics is the principal cause of population decline (Laist, 1987). The few known published accounts of debris and plastics affecting river dolphins are from the boto, *Inia geoffrensis* of South America (Iriarte and Marmontel, 2012; de Sá Alves *et al.*, 2012; Aliaga-Rossel and Quevedo, 2011).

It will therefore be essential that all waste and garbage is appropriately removed from site, or processed according to current day best-practice protocols. A 'nil-to-water' policy should also be employed so it is standard protocol that no construction waste or garbage should enter the Mekong River.

**Summary:**
For the impact of **construction waste and increased domestic garbage and sewage**, there are no apparent differences in the level of impact between the three dam options.

### *Seismic mapping*

All Dam Options:

It is unclear from any available documents whether seismic mapping has been conducted, or is planned, at the project site for any of the dam options. Dolphins use well-developed echolocation to communicate and forage, and as such their hearing system is sensitive to damage and sound masking from high-energy noise.

Since dolphins are known to regularly inhabit the project site (during both dry and wet seasons), any seismic mapping should include stringent mitigation for dolphins following standard international guidelines (i.e. EPBC Act and JNCC), although mitigation zones may be larger for river dolphins than oceanic dolphins because of the potentially increased sound attenuation in a river system.

The risk to dolphins associated with seismic mapping is less than other impacts, however appropriate mitigation protocols (i.e. soft starts, ramp ups, mitigation zones) need to be implemented in order to reduce the possibility for auditory damage, or death, of a single dolphin. Short-term behavioral and habitat use changes may be unavoidable despite mitigation protocols.

**Summary:**
For the impact of **seismic mapping**, there are no apparent differences in the level of impact between the three options.

*Excavation and construction*

All Dam Options:

A major impact during the construction phase will be excavation and construction of cofferdams and the dam infrastructure.

There is minimal literature available regarding the potential impact of dry excavations on marine mammals, and no previous studies for river dolphins are known to exist. However, there are recent anecdotal reports that dry explosions for the Don Sahong Dam on the Lao-Cambodian border may be impacting the remaining dolphins in the Mekong trans-boundary pool and causing movements away from the pool (RFP, 2016). Construction noise and associated activities are can impact marine mammals over large distances (e.g. David, 2006; Bailey *et al.*, 2010; Thompson *et al*., 2013). There is no reason these impacts would not translate to riverine environments, and although anecdotal evidence suggests Mekong dolphins are affected by construction noise at the Don Sahong dam site (RFA, 2016), we know of no studies that have documented the effects on river dolphins. However, it is known that toothed whales (i.e. including dolphins) have extremely sensitive hearing, and a complex sonar system used for foraging, navigating and communicating (Richardson *et al.*, 2013; Au and Fay, 2012). The impact of human-made sounds (i.e. associated with construction activities) may therefore result in physical and/or behavioural changes for these animals. The nature and degree of any acoustic disturbance will vary with the animal's distance from the source, and propagation qualities of the source, where received levels and characteristics of sound is a result of a complex interaction of many factors. Some of the known impacts associated with sound are summarised in (Finneran *et al.*, 2002; Southall *et al.*, 2007; Kujawa and Liberman, 2009), and include:

- at very close range to an extremely intense sound source, death and physical damage to body tissue is possible.
- as the noise attenuates with distance from the sound source, the character of its potential impact changes, grading downward through:
  - permanent hearing loss;
  - temporary hearing loss;
  - avoidance of the sound;
  - masking of biologically relevant sounds;
  - interruption of feeding, breeding, nursing;
  - behavioural changes including interruption of feeding, breeding, nursing.

Ketten, 1995 analysed the physical parameters of two underwater detonations of Class A explosives (1200 lbs and 10000 lbs, 544 kg and 4535 kg respectively: TNT derivatives with fast rise-time waveforms), for their potential to induce blast injury and acoustic trauma in marine mammals. 100%

lethal impact zones for a 1200Ib source were between 40-300m, and for a 10000Ib source between 70-800m. The level of impact from blasts depends on both an animal's location and, at outer zones, on the individual's sensitivity to the residual noise. Important factors for trauma from explosive sources are:

- topography
- proximity of ear to the source
- anatomy and health of ear
- charge weight and type
- rise time
- overpressure
- pressure and duration of positive pressure phase

A concept widely used in regulation and management of noise is that of zones of influence, within which different types of impacts would be expected to occur. If a uniform field of propagation and attenuation is assumed (and ignoring the third dimension of depth), these can be represented as a series of concentric circles around a noise source, whose radii are the ranges at which the level of the sound might be expected to have fallen to a certain threshold level. Four zones suggested by Richardson et al. (1995) are:

1. the zone of audibility (the area within which the sound is both above the animal's hearing threshold and detectable above background noise);
2. the zone of responsiveness (the region within which behavioural reactions in response to the sound occur);
3. the zone of masking (the zone within which the sound may mask biologically significant sounds);
4. the zone of hearing loss, discomfort, or injury (the area within which the sound level is sufficient to cause threshold shifts or hearing damage).

The radius of the circle defining each zone will depend on the characteristics of the sound itself, the susceptibility of the animals being considered, and the acoustic propagation characteristics in the survey area. In devising management guidelines and regulations that are appropriate for a particular development, managers will often use threshold sound levels for certain effects (based perhaps on research in a different area) and calculate the ranges at which the sound level from the particular source being used will fall to this threshold in the area being considered. In these situations, the nature of propagation conditions in the local area becomes critical. Propagation conditions can vary widely from location to location and depend on a variety of factors (Urick, 1983). Differing propagation conditions will have a magnified effect (squared if considering area, cubed if volume) on zones of influence since these represent areas, which rapidly increase or decrease with even small changes in radius. For example, the radius of a zone of behavioural influence for an air gun array with a threshold of 140dB could vary by 4000 times between different likely propagation conditions, in which case the area and number of individuals affected would vary by a factor of 16 million. This highlights the importance of making empirical measurements of propagation loss and applying appropriate models informed by up-to-date oceanographic/water flow data when management involving a zones of influence model is used (Madsen et al., 2006).

As an example of the above precautionary zones, standard procedures adopted internationally for seismic and other sound-based construction activities (such as piling), require precautionary zones, where construction work will not commence if a marine mammal is sighted within the zone (Australian Government, 2008). As an example, for seismic surveys in Australia, standard precaution zones are:

- observation zones – 3+ km radius from the sound source
- low power zone – 2 km radius from the sound source
- shut-down zone – 500m radius from the sound source

It is often assumed that temporary displacement from important areas may occur as a result of increased sound in the environment, where precaution zones provide an opportunity for animals to move out of the area. Temporary displacement is often unlikely to result in any real biological cost to the animals unless the interaction occurs during critical behaviours (e.g. breeding, feeding and resting), or in important areas such a narrow migratory corridors and/or areas that animals cannot move away from. As stated by the Australian Government (2008): '*In these biologically important habitats, where the displacement of marine mammals may have a more significant or biologically relevant effect, the proponent is encouraged to conduct surveys at a different time of year, or not proceed if mitigation cannot be guaranteed'*.

Temporary displacement of animals may be occurring during the construction of the Don Sahong Dam, near the upstream-most population at Cheuteal (RFA, 2016).

Dolphins have been recorded consistently within the immediate proposed dam structure areas (**Error! Reference source not found.**, Figure 9-6, & Figure 9-7). Additionally, the next closest deep water pools are only 5.6 and 13.9 km from the proposed Sambor CSP site and Sambor Alt_7 respectively, and many pools fall within ranges noise could feasible *travel (Table 9-2).* Therefore, it is certain that noise from excavation and construction will be a primary threat to the dolphins in the vicinity. The noise levels and propagation of sound from construction activities is unknown, but impacts to dolphins may range from lethal (i.e. direct death) to short-term behavioural changes (Richardson and Würsig, 1995; Richardson *et al.*, 2013). There has been no evidence provided otherwise by any of the related documents.

*Table 9-2. Distance in kilometres of important dolphin pools away from the dam alternatives (distance taken from the middle of each pool except where pools overlap dams).*

| | Sambor CSP | Upstream /Downstream | Sambor Alt_7 Alternatives | Upstream/ Downstream | Subpopulation |
|---|---|---|---|---|---|
| Kampi | 21.1 | downstream | 38 | downstream | Kratie |
| Sambor | 0.0 | *within* | 20 | downstream | Kratie |
| Koh Pdao | 5.6 | upstream | 13.9 | downstream | Kratie |
| Khasach Makak | 17.2 | upstream | 0.0 | *within* | Kratie |
| Koh Dambong | 43.2 | upstream | 25.4 | upstream | Siembok |
| Tbong Klar | 51.4 | upstream | 34. | upstream | Siembok |
| Koh Konsat | 59.7 | upstream | 42.4 | upstream | Siembok |
| Koh Santuak | 66.9 | upstream | 49.6 | upstream | Siembok |
| Cheuteal | 126.5 | upstream | 109 | upstream | Cheuteal: est. 3 individuals remain |

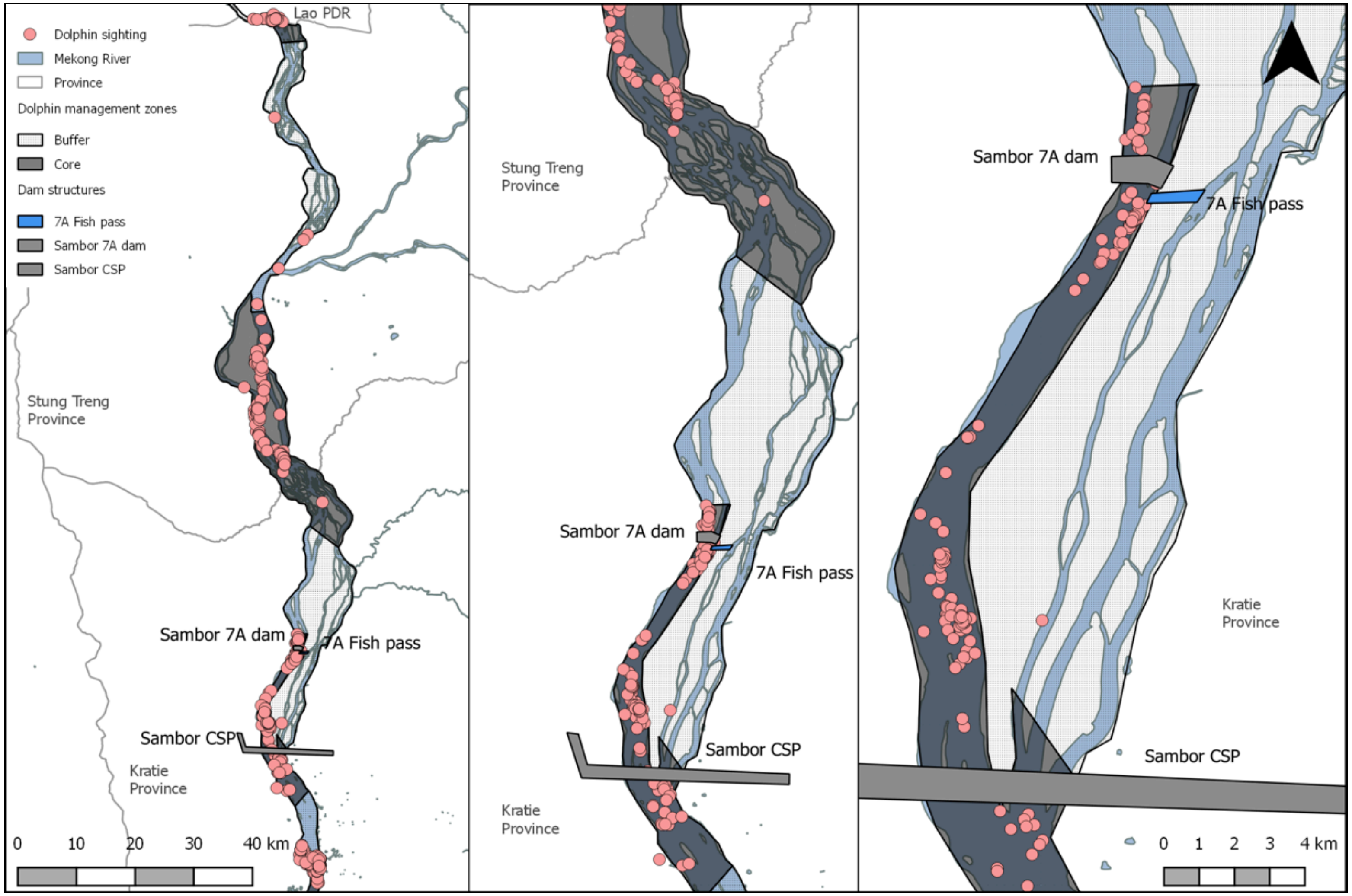



Figure 9-5.*Dolphin sightings and management zones (RGC 2012) in relation to the proposed Sambor CSP and Sambor Alt_7 dam. Left panel shows the full extent of dolphin distribution in the Mekong River, with closer views of study area mid & R. Sightings based on Beasley and colleagues (2013), Ryan and colleagues (2010), and Beasley unpublished data. Dam structures indicative only.*

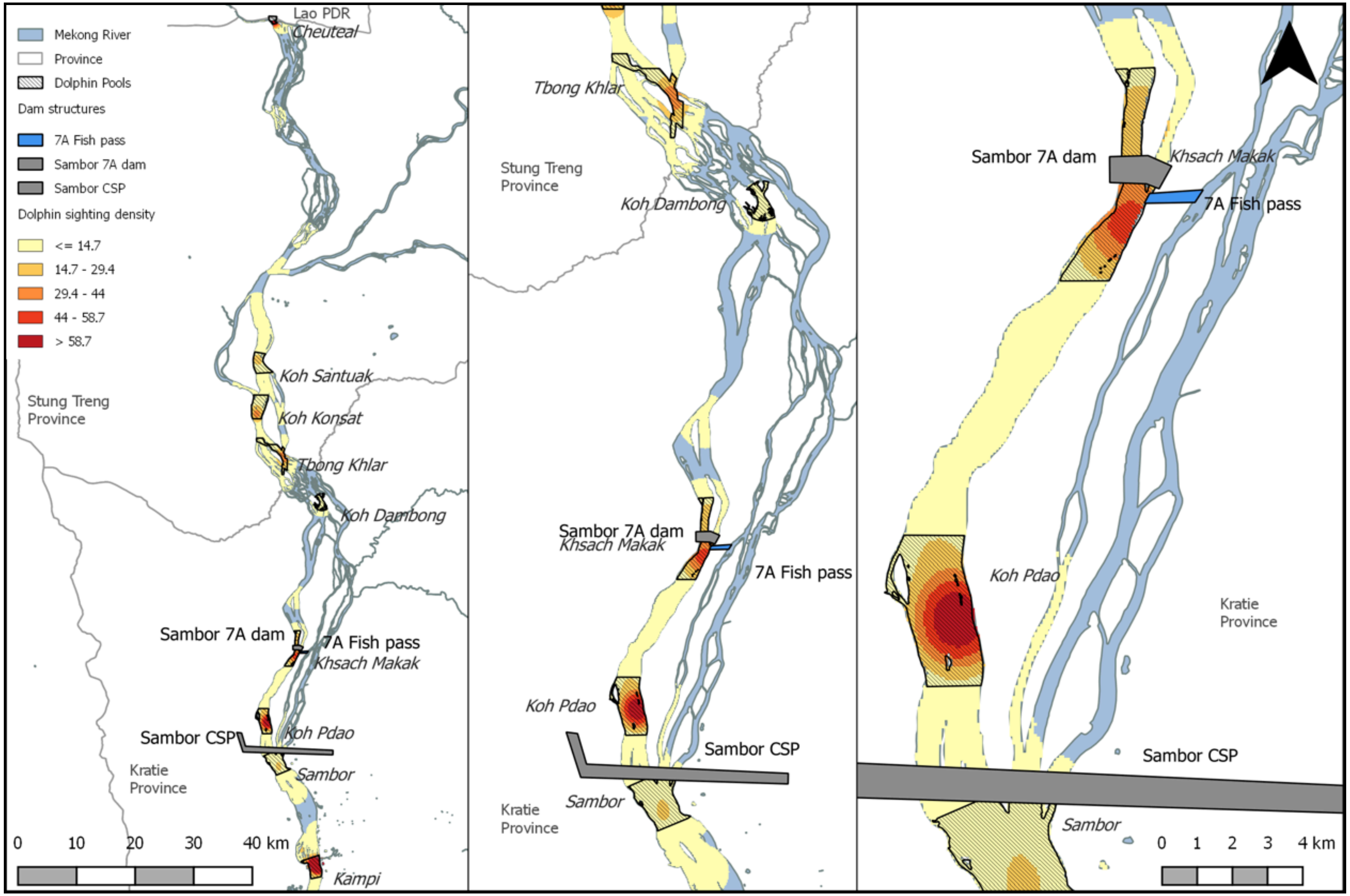



*Figure 9-6. Dolphin sighting density and key deep pool areas. Density in relative sighting units with layout following Figure 9-1.*

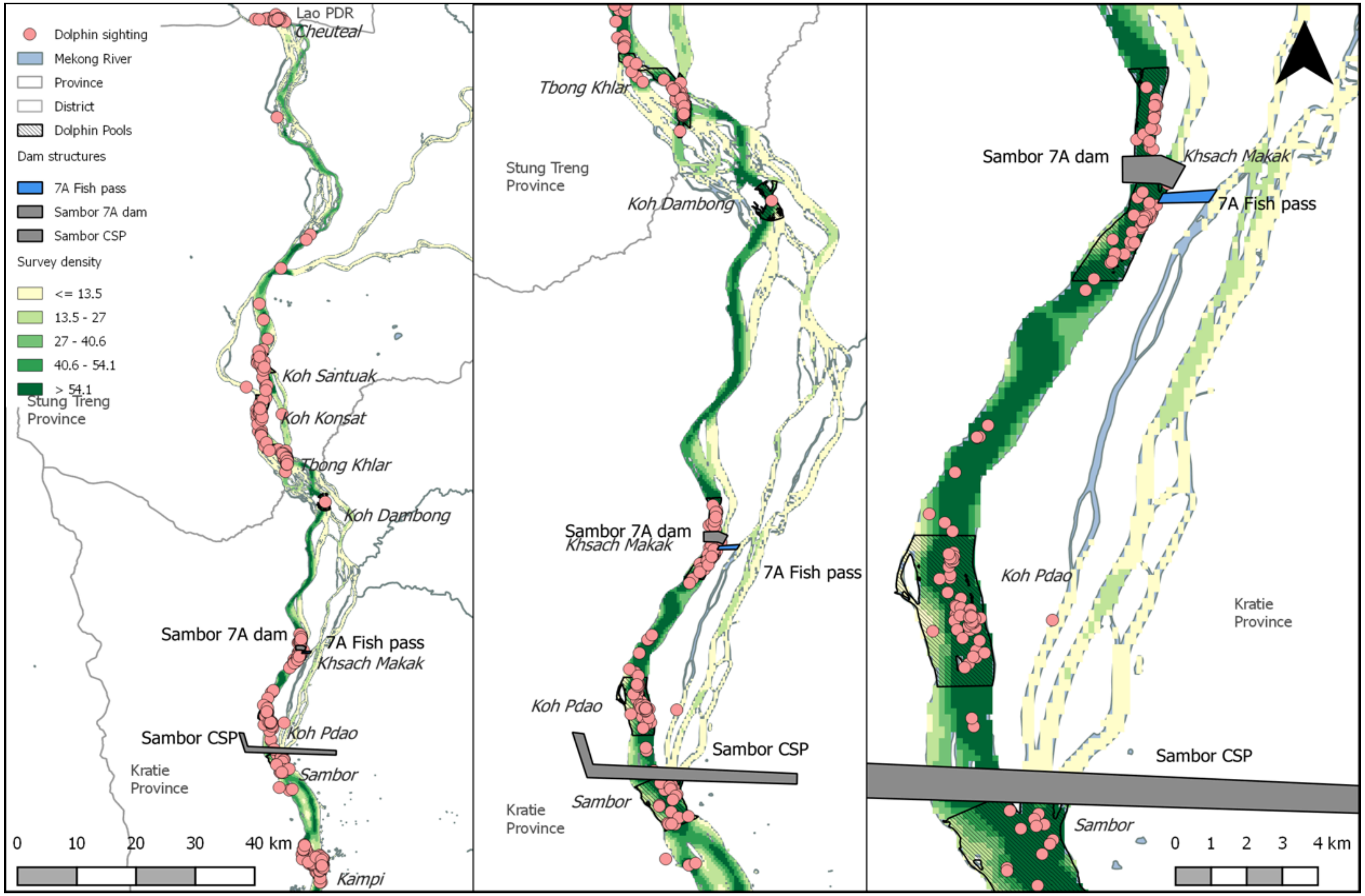



*Figure 9-7. Extent and relative density of dolphins surveyed by Beasley (2001-2005), Beasley unpublished data. Darker green corresponds to greater survey effort.*

During the construction phase, it is possible that dolphins may leave the nearby dolphin pools if conditions become unsuitable (i.e. excessive noise) and travel to pools further south and north. It is unknown what impact this would have on the group undertaking the movement, or to the resident dolphins in other areas.

Prior to construction, peer-reviewed sound modelling studies are required to adequately assess the potential impacts of excavation and construction activities on the dolphin population and determine whether appropriate mitigation is possible. Modelling opportunities are currently presented by construction and operation of the Don Sahong Dam on the Lao PDR-Cambodia border (Beasley, 2014b; Ryan, 2014). Based on similar dams in river dolphin habitat, proposed measures to minimise the effects of excavation and construction include:

Excavation

- disposing of excavated materials as part of permanent works;
- all excavation at the downstream end to be carried out in the dry behind a cofferdam;
- no underwater blasting, all blasting to be on the dry.

Construction

- planning construction works when animals are known to not inhabit the project area, or when important behaviours such as breeding, calving and foraging are not occurring;
- mitigation zones in the vicinity of construction works, particularly piling, when soft start, ramp up and shut down protocols are established (JNCC, 2010).

**Summary:**
For the impact of **excavation and construction**, Sambor Alt_7 (screen or unscreened) would cause comparatively less impact to the Mekong dolphin population because of the smaller size of the infrastructure required.

### *Increased boat traffic*

All Dam Options:

A possible phenomenon with infrastructure development is an increase in boat traffic. This increase results from vessels associated with construction and delivery of materials, traders moving into the area, and increased fishing activity to feed workers and an increasing transient population. The increased water depth in a reservoir may also make the route more attractive to commercial shipping. Any increase in boat traffic, particularly the very fast boats that transverse the river from Cambodia to Lao PDR, would have a major impact on the Mekong dolphin population through increased noise, reduced time for important behaviours such as resting, feeding and socialising, and the potential for direct deaths due to collision.

Based on mitigation measures used for other heavy boat traffic regions, proposed measures to minimise the effects of increased boat traffic are ‘go-slow zones’ in important dolphin habitats, though as these may not mitigate all impacts of boat traffic on dolphins (Steckenreuter *et al.,* 2012), they should be used in conjunction with conservation areas where vessels are prohibited.

**Summary:**
For the impact of **increased boat traffic**, there are no apparent differences in the level of impact between the three options.

*Toxic substance spill*

All Dam Options:

There are no known examples in the existing literature where dolphins have been exposed to a toxic substance spill during construction of a water development. However, recent anecdotal reports suggest that pollutants may now be entering the Mekong River during construction of the Don Sahong Dam (RFP, 2016).

Toxic substance spills are a possibility during construction of water development projects. Therefore, at a minimum, the construction company should have a toxic/oil spill management plan, with appropriate equipment and regular drills, to ensure such an event can be appropriately dealt with to mitigate impacts.

**Summary:**
For the impact of toxic substance spill, there are no apparent differences in the level of impact between the three options.

*Operational noise from turbines*

All Dam Options:

Once operational, the dam turbines will contribute to additional noise-levels in the local water-ways. Although not as significant as the construction noise in the short-term, continual noise from dam turbines can cause behavioural changes, mask biologically relevant sounds, and cause avoidance of the sound (Richardson et al., 1995). Few studies have been conducted on the effects of marine mammals and turbines. One study examined the reactions of harbour porpoises and harbour seals to a 2MW wind turbine, where responses occurred within a 60 to 200m perimeter around the sound source. This study concluded that the impact zone for 2 MW turbine noise is potentially small for marine mammals (Koschinski *et al.,* 2003). Other similar studies have documented negative effects to terrestrial and marine animals from chronic exposure to noise (Richardson and Würsig, 1997). No studies are known to have yet been conducted on the noise levels emitted from hydro-electric dam turbines, or the potential impact of marine mammals.

As with construction activities, peer-reviewed sound modelling studies are required prior to construction. These modelling studies would assess underwater noise levels (compared to baseline current levels) to assess the potential impacts of noise and determine whether mitigation is possible, or required. Modelling studies during operation of the 260 MW Don Sahong Dam would have provided sufficient comparison from which to establish potential impacts (Beasley, 2014a; Beasley, 2014b), however, these recommended studies were apparently never conducted.

Original Sambor CSP Dam:

The powerhouse contains forty 60.33 MW turbines with 2600 MW of installed capacity. Each turbine will rotate at approximately 138 rpm.

<u>Sambor Alt_7 Options:</u>

The powerhouse contains twelve 103 MW turbines with 1230 MW of installed capacity. Each turbine will rotate at approximately 55rpm. Both Kaplan and Alden turbines are assessed.

Once operational, there is no mitigation possible to reduce the effects of turbine noise. Based on other studies, it is possible that given dolphins reliance on biosonar to communicate, forage and navigate, the continual noise may displace dolphins from habitat near the dam, perhaps up to 4km or more away from the dam structure.

**Summary:**
For the impact of **operational noise from turbines**, the Sambor Alt_7 options are preferred because of less installed capacity and theoretically less operational noise from the turbines.

## Changes to Habitat Availability and Quality

As outlined in the introduction, Mekong dolphins are known to utilize deep water pools (10-20m deep) during the dry season. These deep pools are critical to the dolphins' survival, providing abundant prey and suitable counter-current habitat. Although 30-80m deep water pools do exist along the upper Cambodian Mekong River, dolphins are not known to frequent pools of these depths (Beasley, 2007).

Their habitat requirements during the wet season are less well-known, but appear to be related to providing shelter from the strong downstream currents.

Any change in Mekong River water depth or hydrology (i.e. within the reservoir) to depths greater than 20m, or less than 10m, will therefore likely reduce habitat available to the Mekong dolphin population. Similarly, any alteration of wet season flows may disrupt the dolphins foraging, breeding or calving behaviors. Given that the remaining Mekong dolphin population only inhabits a 190 km stretch of Mekong River during the dry season, any loss of habitat will be significant. Additionally, the habitat utilized by the population will be reduced to only 100 km if the trans-boundary dolphin population at the Cambodian-Lao PDR border becomes extirpated, magnifying the importance of remaining habitat.

Mekong dolphins show strong site fidelity during the dry season and strong social bonds (Beasley, 2007). Although Mekong dolphin behavior is not well understood, intraspecific aggression has been observed (GER pers. obs), and may be the source of calf mortality (Nao *et al.*, 2014). Given the known small home-range of dolphins throughout the Mekong River during the dry season (i.e. 1-2 $km^2$ for individuals within the trans-boundary subpopulation up to 32 km from the Sambor population), it is unclear if individuals would be able to relocate to other habitat already occupied by dolphins, or if they may be driven away by resident animals. The loss of home-ranges may therefore cause indirect mortality if this is the case. During the wet season dolphins are believed to move throughout the river in response to fish migrations. These movements would also be an opportunity for genetic exchange with other subpopulations.

The primary concerns regarding habitat degradation are described further below, consisting of:

- direct loss of habitat due to the infrastructure and change to hydrological conditions immediately below it;

- formation of the dam-created reservoir altering water depth, temperature and hydrology behind the dam;
- water temperature changes below dam;
- increasing and/or decreasing sediment flows, including sedimentation of deep pools;
- potentially altered water flow and river morphology; and
- fragmentation

### *Direct habitat loss*

Both dam sites are directly over core habitat that would be fundamentally changed by the presence of the infrastructure, and the changed hydrology immediately downstream. Mekong dolphins show strong site fidelity, have a particular preference for a few specific areas within the river (Beasley, 2007 and Chapter 2, section 2.8.5 of this document). For behavioral reasons outlined above, individuals are unlikely to be able to simply move into new habitat, and may not be able to move directly into occupied areas either. The direct loss of core habitat, in this case a *large portion of the remaining available habitat*, is likely to strongly affect the population's chances of survival. Both dam sites would result in the loss or contraction of individual home ranges, and potentially restrict wet season movements.

Original Sambor CSP Dam:

It is known that habitat downstream of the Sambor CSP is important to dolphins commonly in the Sambor group (see section 5.6: Beasley, 2007), and may be important to the majority of the population during the wet season. If dolphins can longer pass downstream of the Sambor CSP, this dam would therefore reduce some Koh Pdao/Khasak-Makak individuals home range from ~20 linear km to ~12 linear km (assuming an exclusion zone of 4km around the powerhouse because of underwater noise from turbines). Similarly, some dolphins from Kampi pool are known to utilise habitat north to at least Koh Pdao during the dry season. The Sambor CSP would therefore reduce the home range of some Kampi individuals from > 30 linear km to < 20 linear km.

Sambor Alt_7 (Screened and Unscreened) options:

The infrastructure for the Sambor Alt_7 would likely exclude dolphins from utilizing Khasak-Makak and Sampan Pools because of dam infrastructure and turbine operation noise. In the worst-case scenario where dolphins do not use the anabranch channel, Sambor Alt_7 would therefore reduce the home range of some Koh Pdao/Khasak-Makak individuals from 20 linear km to ~12 linear km (assuming an exclusion zone of 4km around the powerhouse because of underwater noise, and dolphins preferring to use the deep pool at Koh Pdao). However, Sambor Alt_7 would not theoretically affect the Kampi subpopulation home range because the proposed dam structure is outside their known home range (at least during the dry season).

Fragmentation caused by both the original Sambor SCP and Sambor Alt_7 options would turn one already very small population of around eighty individuals into two even smaller populations of ~ 30 (above the dams) and ~50 (below the dams). Small populations are highly vulnerable to chance processes. Once fragmented, any of the smaller sub-populations are more liable to be wiped out by chance catastrophes such as e.g., pollution or disease outbreaks, and would be unable to be replenished. Small populations are also vulnerable to stochastic processes such as the birth of only males into the population, or the chance death of many individuals in a short period. Such vulnerabilities greatly increase the likelihood of extirpation of each population (Lande, 1993; Mangel and Tier, 1993; Caughley and Gunn, 1996).

The risk of fragmentation and reduced subpopulation sizes is however lower with Sambor Alt_7 than the original Sambor CSP project due to the potential for dolphin movement through the anabranch (see also section 9.6.3.5: Fragmentation).

**Summary:**
For the impact of the **direct habitat loss** direct habitat loss will be potentially minimised by the Sambor Alt_7 alternative because of the smaller footprint, and reduced impact to dolphin home range.

*Dam-created reservoir*

The dam-created reservoir may alter important deep water pools and habitat currently utilized by the Mekong dolphin population. The effects of reservoirs on river dolphin populations are irreversible. In addition to habitat changes, reservoirs may also interfere with natural behaviors. For example, it has been suggested that stratification of the reservoir above the Three Gorges Dam would cause temperature changes in the dam discharge, which could affect mating cues and the survival of newborn baiji calves (Hua *et al.*, 1989).

Original Sambor CSP Design:

For the original Sambor design, the dam would create a reservoir approximately 82 km long (during mean operating flow conditions), with a total volume of 5,206 million cubic meters and span from 30-10m deep from the riverbed (closest to furthest point from the dam wall respectively) (***Figure 9-8***). Based on known Mekong dolphin habitat preferences, it appears that the original Sambor CSP design would inundate at least three important dolphin deep pool areas (i.e. Koh Pdao, Khasak Makak-Sampan and Tbong Klar).

Sambor Alt_7 (Screened and Unscreened) options:

For Sambor Alt_7 option, the dam would create a reservoir approximately 37 km long (during mean operating flow conditions), with a total volume of 1,4000 million cubic meters and span from 10-5m deep from the closest to furthest point from the dam wall respectively (***Figure 9-8***). Based on ***Figure 9-9***, the Sambor Alt_7 reservoir may only result in one important deep water pool (Khasak-Sampan) being uninhabitable to Mekong dolphins.

**Summary:**
For the impact of the **dam-created reservoir**, the Sambor Alt_7 option is undoubtedly preferred due to the smaller reservoir and reduced habitat loss.

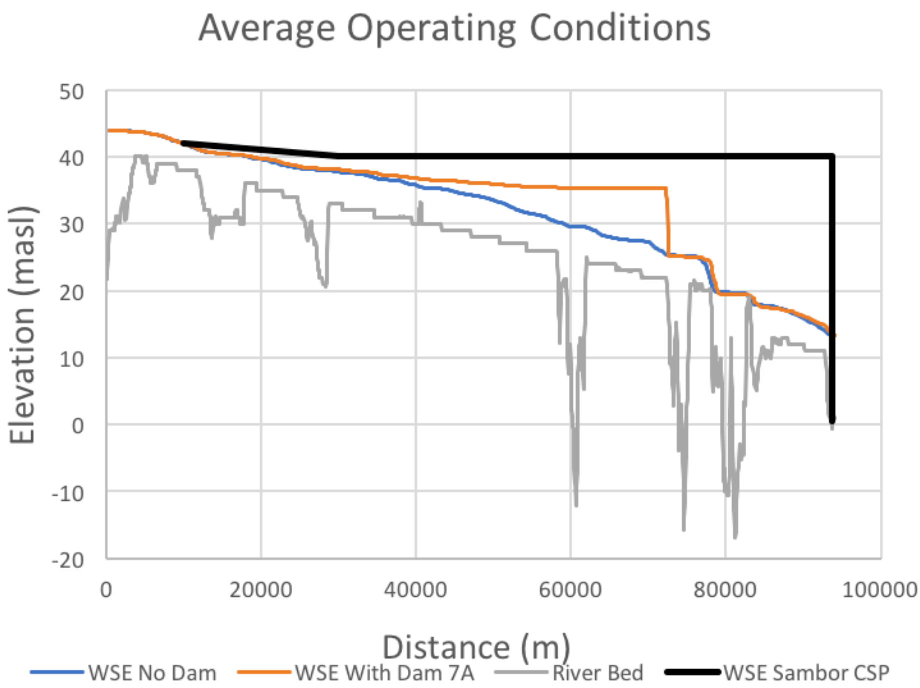



*Figure 9-8. Proposed reservoir created by the alternative dam options. These estimations were developed by Dr. George Annandale, where the Sambor CSP estimates are modeled using a best guess scenario. Provided by GA/NHI.*

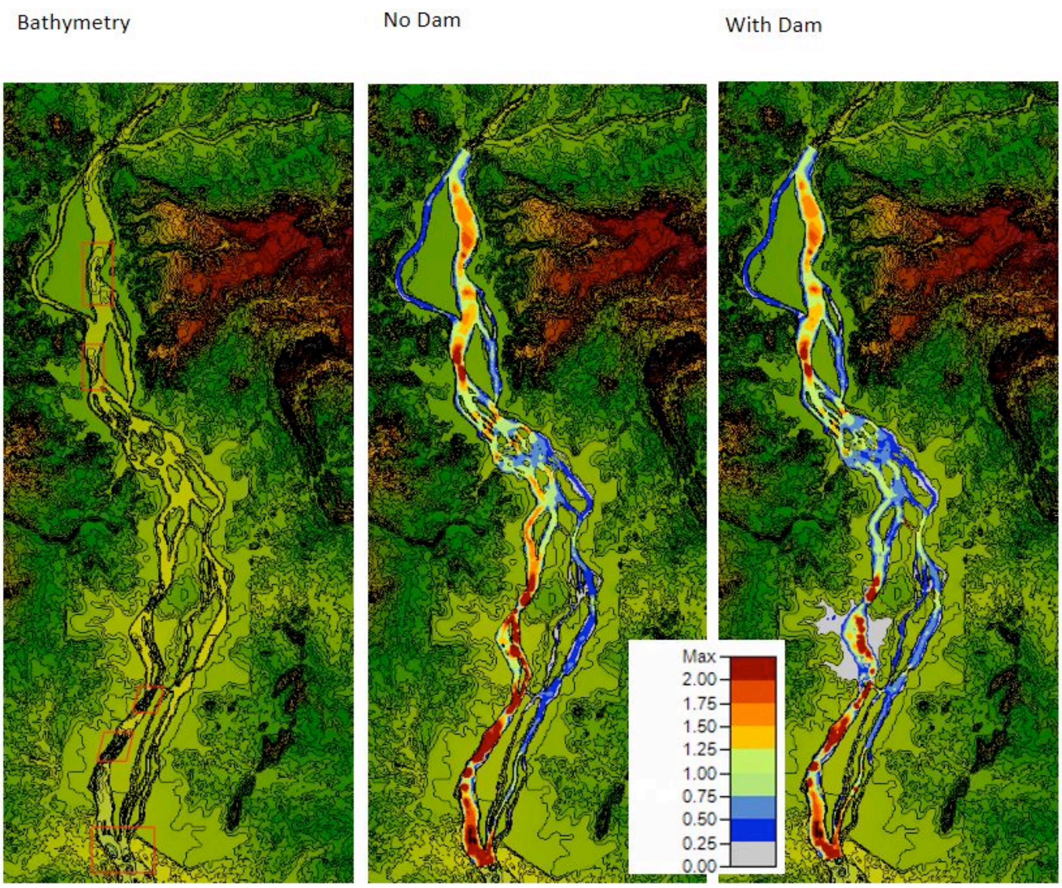



*Figure 9-9. Dolphin deep pool areas (red rectangles) and flow velocities with and without Sambor Alt_7 for average flow conditions (13,400m$^3$/s). Figure from NHI.*

### *Increased sediment, altered water flow and altered river morphology*

Regardless of their purpose, all dams trap sediment to some degree and most alter the flood peaks and seasonal distribution of flows, thereby profoundly changing the character and functioning of rivers (Kondolf, 1997). By changing flow regime and sediment load, dams can:

- produce adjustments in alluvial channels, the nature of which depends upon the characteristics of the original and altered flow regimes and sediment loads;
- disrupt the longitudinal continuity of the river system and interrupt sediment transport.
- Alter phenological cues to biodiversity such as fish migration triggers.

Upstream of the dam bedload sediment and part of the suspended load (depending upon the reservoir capacity relative to inflow) is deposited in the quiet water of the reservoir, which reduces reservoir capacity upstream of the reservoir in reaches influenced by backwater (Kondolf, 1997).

Downstream, water released from the dam possesses the energy to move sediment, but has little or no sediment load. This clear water released from the dam is often referred to as '*hungry water*', because the excess energy is typically expended on erosion of the channel bed and banks for some years following dam construction, resulting in incision (down-cutting of the bed) and coarsening of the bed material until equilibrium is reached and the material cannot be moved by the flows. The riverbed in this reach of the Mekong River consists mainly of bed rock rather than alluvial deposits, so while bottom scouring is unlikely increased bank erosion may result.

Reservoirs also may reduce flood peaks downstream, potentially reducing the effects of hungry water, inducing channel shrinking, or allowing fine sediments to accumulate in the bed (Kondolf, 1997). Variation in water level is one of the most important factors for triggering fish migration in the Mekong River (Baran, 2006), and changes to flow regime may impact fish migrations, and therefore dolphin prey. This is discussed further below in section 9.6.3.4. Sediment transport, altered water flow regimes, and altered river morphology are all major considerations regarding the proposed dams impact on the Mekong dolphin population. Decreased sediment, declines in water flows and changes to the flood-pulse systems of rivers are a major concern for river dolphins throughout Asia, and may have significantly contributed to river dolphin population declines elsewhere (Smith and Reeves, 2000; Smith and Reeves, 2012; Smith et al., 2000; Braulik *et al.*, 2014; Pavanato *et al*., 2016).

Original Sambor CSP Option:

CSP (2008) believed there would be little sediment accumulation in the Sambor CSP reservoir because:

- the reservoirs back water storage is relatively small,
- crest of discharge sluice and elevation of flushing sluice has little difference with that of the natural river bed,
- the capacity of sediment discharging is great; in addition,
- the inflowing sediment mainly concentrates in flood season,
- sediment grading in suspension is small and it is easy to recover to natural state;

However, it has been estimated by that the Sambor CSP would have only allowed 38% of sediment to pass.

Sambor Alt_7 (Screened and Unscreened) options:

Sediment modeling was undertaken by NHI as part of the Sambor Alt_7 options assessment (Appendix 9.1). In order to assess whether flow in the Mekong River will be able to evacuate sediment from the deep pools simulations were executed using HECRAS 2D with, and without, the dam for average flow conditions, and with the dam for monsoon conditions.

The figures indicate that the dam does affect flow velocities in the river, but that the flow velocities in the deep pools are largely maintained for average flow conditions, and that it increases under monsoon conditions.

The areal extent of high flow velocities in the second to last pool with the dam in place under average flow conditions reduces because less water is discharged down the main stem due to the presence of the dam (the increased water level in the reservoir upstream of the dam forces more water into the anabranch). However, when comparing the length of that pool with the locations of high flow velocities it appears that the high flow velocities are maintained in the pool, thereby evacuating sediment from the pool.

Under average flow conditions, the flow velocity in the dolphin deep pool conservation area immediately downstream of the dam (Khasak-Makak) reduces in extent, while flow velocities in excess of 2 m/s still prevails in parts of the pool. Under monsoon flow conditions the flow velocities in this river reach is predominantly larger than 2 m/s.

Based on the results described in Appendix 9.1, Sambor Alt_7 is expected to have minimal noticeable effect on sedimentation in the deep pools. The only pool that might be affected is the pool immediately downstream of the dam (Khasak-Makak) although, based on the fact that the flow velocity in this area during monsoon flows remains high, the dam likely does not have a significant impact even on this pool.

**Summary:**
For the impact of **increased sediment, altered water flow and altered river morphology**, the Sambor Alt_7 alternative is certainly preferred due to the potential for minimal effects to sedimentation, a subsequently reduced probability of altered water flow and altered river morphology.

*Reduced prey abundance and diversity*

Reduced prey availability is a primary concern for the long-term survival of the Mekong dolphin population. The upper Cambodian Mekong River is a well-known major pathway for important fish species throughout the year (Roberts and Baird, 1995; Poulsen *et al.*, 2004; Valbo-Jørgensen *et al.*, 2009), most of which are known dolphin prey (Baird *et al.*, 1994). Dams can are a barrier to fish migration, and there are numerous published works regarding the potential, and actual, effects of water development projects on fisheries in the Mekong River (Ziv *et al*., 2012; Orr *et al*., 2012), where fisheries decline is a primary concern for other riverine fauna that rely on fish for prey, as well as local subsistence communities (Van Zalinge *et al.*, 2000; Baird and Flaherty, 2005). Mekong dolphins rely on known fish migrations and established hydrological cycles to forage effectively. The majority of fish in the Mekong River are believed to be migratory, and water flow regimes are known to be the an important trigger of migration (Baran, 2006; Schmutz and Mielach, 2015). Changes to the hydrology of the river may have negative effects on timing fish migrations, and therefore further reduce prey.

Fish mortality also occurs due to downstream passage of fish through turbines (Schmutz and Mielach, 2015). The fish screen in Sambor Alt_7-C and D should prevent this source of mortality.

<u>All Dam Options:</u>

Other technical experts will provide comment on this specific topic for both Sambor CSP and Sambor Alt_7 conceptual designs (Mallen-Cooper *et al.*, 2016). While this information suggests the alternative 7 design should have a high success rate for fish passage, the actual outcome remains uncertain, and thus remains a risk for the Mekong dolphin population. It is important to highlight that dolphins must consume 4-9% of their body weight each day, which translates to 10-22.5 kg of fish each day per dolphin. For a population of 80 individuals, this equates to 800-1800 kg of fish a day. A reduction in fish abundance that results in more time dolphins are required to forage (thus reducing time for other necessary behaviours), or dolphins not being able to meet their daily calorie requirements, with impact the remaining Mekong dolphin population. The decline in fish populations necessary to effect dolphin foraging is unknown.

**Summary:**
For the impact of the **reduced prey abundance and diversity**, the Sambor Alt_7 option is undoubtedly preferred due to the careful consideration of fish passes to theoretically allow up- and down-stream fish migration. Sambor Alt_7 screened options are preferred over Sambor Alt_7 unscreened options due to the additional protection of fish mortality in turbines.

### *Potential Impacts from Fragmentation of the Mekong dolphin population*

Fragmentation of the remaining Mekong dolphin population into separate, distinct subpopulations, with no gene-flow is a primary concern.

The effects of fragmentation of populations, leading to higher species extinction risk, is described extensively in the literature for terrestrial (Young *et al.*, 1996, Andren, 1994) and marine examples (Harwood, 2001, Bell *et al.*, 2001), and generally for biodiversity (Saunders *et al.*, 1991, Fahrig, 2003). Saunders *et al.* (1991) warn that conservation agencies have not realized the important biological consequences of ecosystem fragmentation, and therefore have not developed adequate policies to maintain their conservation values. Some of the primary biological consequences associated with fragmentation of the Mekong dolphin population are listed below.

- Changes in microclimate of the fragmented regions (i.e. alterations of various components of the hydrological cycle, water levels, and particulate and nutrient fluxes) (Dudgeon *et al.*, 2006);
- Changes in prey distribution and use of the fragmented regions (Strayer and Dudgeon, 2010, Dudgeon *et al.*, 2006);
- Isolation causing a reduction in the total area of habitat available (possible increased densities of dolphins), and the habitat that is left is broke up into remnants that are isolated

to varying degrees (Lovejoy and Oren, 1981, Haila and Hanski, 1984);

- Reduced gene-flow and subsequent inbreeding depression, causing reduced health, increased disease and increased newborn mortality (Pavanato *et al.*, 2016).

Although the dolphin population consists of stable groups with high site fidelity, it is the infrequent genetic exchange that maintains connectivity and is essential for survival of the population. Such infrequent genetic exchange can be due to either dispersing sub-adult animals, or infrequent encounters of normally separate groups during wet season movements. The barrier to any movement between groups that a dam wall would cause is the primary source of concern.

Fragmentation of river dolphin populations caused by water developments is well-documented in the literature from the Yangtze River of China (Zhang et al., 2003, Turvey, 2009, Smith et al., 2008, Reeves et al., 2000b), Ganges River of Nepal, India and Bangladesh (Baruah *et al.*, 2012), Indus River of Pakistan (Braulik *et al*., 2014, Braulik, 2006) and Amazon River of South America (Pavanato *et al.*, 2016, Aliaga-Rossel and Quevedo, 2011). The historical range of the Indus dolphin was approximately 3400 linear km, consisting of the entire lower Indus River system from the delta with the Indian Ocean to the foothills of the Himalayas (Anderson, 1878). By the early 1990s, Indus dolphins had undergone an 80% reduction in range. The remaining population has been fragmented into 17 river sections by diversion dams, ten sections of which they have now been extirpated from (Braulik *et al.*, 2014). Braulik *et al.* (2014) determined that Indus dolphins were significantly more likely to be extirpated in smaller river fragments, which underlies the importance of maintaining large sections of intact river habitat to sustain dolphin populations.

The baiji is now considered functionally extinct (Smith *et al*., 2008, Turvey, 2009), where it has been reported that dam and waterway construction were principal stressors on the population, causing range declines and fragmentation of subpopulations. Baiji were historically distributed throughout 1700 km of the middle and lower reaches of the Yangtze River, from Yichang to the estuary near Shanghai and in appended Dongting and Poyang Lakes (Wang *et al.*, 2006a). As of 2006, the baiji was limited to several short sections of the river (Zhang *et al.*, 2003). Although a number of threatening processes were impacting the baiji, construction of the Three Gorges dam (which began in 1994) and subsequent operation (dam completed in 2012) are believed to have contributed significantly to the baiji's decline through construction disturbance, fragmentation, altered hydrological regimes and increased fishing pressure downstream of the dam (Turvey, 2009, Wang *et al.*, 2006a, Wang *et al.*, 2006b, Yang *et al.*, 2006).

The effects of water developments and fragmentation on South American river dolphins boto (genus *Inia*) and tucuxi, *Sotalia fluviatilis* are described by Pavanato et al., 2016 where population declines and isolation have resulted after project's have become operational. Precautionary measures were highlighted as important, ideally being taken before the construction of any hydroelectric dams (Pavanato *et al.*, 2016).

In situations where dam barrages exist on mainstream rivers and gates are left open for parts of the year (Braulik *et al.*, 2014, Smith, 1993), downstream migration attrition of upstream river dolphin populations is a reported phenomenon. Due to the high water velocity and turbulence often found within barrage gates and fish passes, it may be more likely for dolphins to move downstream than upstream (Braulik *et al.,* 2014, Pavanato *et al.*, 2016). If this situation occurred for the Mekong dolphin population when using the anabranch channel in the wet season, the majority of the Mekong dolphin population may be restricted to below the Sambor Alt_7 dam after the first few wet seasons, if they were not able to return up the anabranch channel before water levels lowered at the start of the dry season.

Original Sambor CSP Design:

There is no doubt that the original Sambor CSP design would fragment the remaining Mekong dolphin population. Based on its design with no access to anabranch channel, there is no possible way that dolphins could move up-, or down-stream from the dam. This would result in up to two subpopulations; around 25 dolphins in Kratie Province downstream of the dam, and the remaining animals upstream in three groups: in Kratie Province upstream of the dam, Stung Treng Province, and the Cheuteal Pool on the Cambodia- Lao PDF border. While genetic exchange could continue among the upstream groups, the downstream subpopulation would be isolated.

Sambor Alt_7 (Screened and Unscreened) options:

The Sambor Alt_7 is a superior design to that of the Sambor CSP because of the anabranch channel, designed in an attempt to facilitate water flow and fish movement up- and down-stream. The open channel has potential to allow dolphins to pass through and thus maintain connectivity of the population. However, despite numerous surveys, dolphins have previously been sighted in the anabranch channel only once, very near the southern end of the channel where a resident group occurs. There is no evidence of dolphins travelling through the anabranch, or using areas within. The lack of movement is likely because of a lack of deep water pools and shallow regions that are often impassable in the dry season even by small vessels (Figure 9-3). We conclude that dolphins are probably unable to use the anabranch in the dry season. Whether dolphins do use the anabranch in the wet season, or if dolphins would use it for dispersal if the mainstem was blocked is unlikely but uncertain. The Alt_7 option would probably also fragment the remaining population, however, there still remains a small chance that dolphins could begin to use the anabranch channel, particularly if fish are using this channel via the constructed fish pass.

**Summary:**
For the impact of **fragmentation**, the Sambor Alt_7 option is undoubtedly preferred due to the potential for dolphin movement up- and down the anabranch channel.

### *Mortality from impingement on the debris barrier*

Fish are often entrained and pass through the turbines at generating facilities (Schilt, 2007, Taft, 2000, Turnpenny, 1988, Coutant and Whitney, 2000). One solution to prevent this involves stopping them physically at water intakes using screens that must have a sufficiently small grid size to physically prevent fish from passing through (Taft, 2000). These screens have to guide fish towards a bypass, which is done most effectively by placing them diagonally to the flow, with the bypass in the downstream part of the screen (Larinier and Marmulla, 2004). Despite extensive literature reviewed for this study, there are no known accounts of dolphins being impinged on the debris barrier or within the turbines. It is however unlikely that dolphins may be impaled on trash racks, since the approach and through flow velocities are estimated to be 1m/s, which is currently the average flow velocity in the river.

Original Sambor CSP Design:

There are no plans for a fish screen on the Sambor SCP, therefore, there is a high probability that fish, and possibly dolphins, would become impinged on the debris barrier or within the turbines for this dam option.

Alt_7-A and B Options (Unscreened):

These alternatives do not have a fish screen. Instead, there would be a trash screen to protect the turbines from large logs. These would be vertical bars with 120-250mm spacing with water velocity of 1.0 m/s. Large fish would certainly be impinged on these trash screens.

Alt_7-C and D Options (Screened):

These alternatives would have a coarse horizontal screen. Water, fish and likely dolphins would then be diverted around the turbines. With a fish screen in place, no dolphin could possibly enter the turbines from upstream.

**Summary:**
For the impact of **mortality from impingement on the debris barrier**, the Alt_7 screened option is undoubtedly preferred due to the fish screen reducing fish and dolphin impingement.

### *Mortality in lock gates*

A further potential for mortality is within the ship locks. Although the probability of this occurring is slim, there are previous cases of river dolphins being found dead within lock gates. For example, in February 1979, a baiji was found dead at the bottom of one of the lock gates within the Madian Ship Lock in the Guganhe River, a tributary of the Yangtze River in China (Liu and Wang, 2000).

**Summary:**
For the impact of **mortality in lock gates**, there are no apparent differences in the level of impact between the three options.

## Consideration of Cumulative Impacts

The assessment of impacts of a water development project requires consideration of 'cumulative impacts': for example, when new potential impacts are added to existing threats.

Contraction of geographic range is one of the principal characteristics exhibited by declining or threatened species (Braulik *et al.*, 2014). At the periphery of a species geographic range, populations occupy less favourable habitat, and persist in core habitat until the final stages of decline (Lomolino and Channell, 1995; Braulik *et al.*, 2014). This contraction of range has been confirmed for the Mekong dolphin population, where the species previously occurred along 1000 km of the Mekong River from the Lao PDR-Cambodia border south to the Vietnamese Delta and into Tonle Sap Great Lake, including major river tributaries (Beasley, 2007). No one stressor can be blamed for this contraction of range. Rather a multitude of factors have impacted the population in the past 30 years, such as direct catch/persecution and illegal fishing, accidental catch in subsistence fisheries, habitat degradation, river development, disease, increased contaminant loads, waterway development and high newborn mortality from unknown causes (Beasley, 2007; Dove, 2009; Gilbert and Beasley, 2006; Baird and Mounsouphom, 1997; Baird *et al.*, 1994; Beasley *et al*., 2009; Ryan *et al.*, 2011).

Stressors can accumulate and interact in unforeseen ways. Synergies among stressors magnifying impacts further are often a concern. While this can be overstated (Côté *et al.*, 2016), in the usual case, the synergies are largely or completely unknown, and conclusions should be drawn with caution. The Mekong dolphin population is very small and declining, with ongoing and uncertain threats (Gilbert and Beasley, 2006; Dove, 2009). At present the major known threats are the widespread use of gill nets, and the construction of large infrastructure immediately within and around core habitat, for example, the Don Sahong Dam on the Lao PDR-Cambodian border. Uncertainty remains about mortality from other illegal fishing methods like the use of dynamite and electricity, and inbreeding difficulties. We may however draw some conclusions from the cumulative effects of the proposed Sambor dam options, as described further below.

### Vulnerability to Catastrophe and Stochasticity

Fragmentation caused by both the original Sambor SCP and Sambor Alt_7 options would turn one already very small population of around eighty individuals into two even smaller populations of ~ 30 and ~50 individuals. Small populations are highly vulnerable to chance processes. Once fragmented, any of the smaller sub-populations are more liable to be wiped out by chance catastrophes such as e.g., pollution or disease outbreaks, and would be unable to be replenished from other sources. Small populations are also vulnerable to stochastic processes such as the birth of only males into the population, or the chance death of many individuals in a short period. Such vulnerabilities greatly increase the likelihood of extirpation of each population (Lande, 1993; Mangel and Tier, 1993; Caughley and Gunn, 1996).

The risk of fragmentation and reduced subpopulation sizes is lower with Sambor Alt_7 than the original Sambor CSP project due to the potential for dolphin movement through the anabranch (see also section 9.6.3.5: Fragmentation).

**Summary:**
For the **cumulative effect of vulnerability to catastrophe** the Sambor Alt_7 options are preferential due to the improved potential for maintaining connectivity within the population.

### Genetic Vulnerability

While the genetic diversity among a small population is inherently low, it is uncertain whether this is currently causing inbreeding depression in the Mekong dolphin population (Kratie Declaration, 2012; Dove, 2009; Krutzen *et al.*, in review). There are numerous studies that have indicated that inbreeding causes reduced reproductive success (i.e. reducing individual fitness and loss of genetic variability) and increases extinction rates (Lynch, 1991; Frankham and Ralls, 1998; Lande, 1988). Although it has also been argued that random demographic (i.e. reduced fecundity, juvenile survival and lifespan) and environmental (i.e. annual variation in climate variables and catastrophes such as disease epidemics) events will drive small wild populations to extinction before genetic factors come into play (Lande, 1988). Genetic inbreeding becomes an ‘extinction vortex’ (Fagan and Holmes, 2006; Gilpin, 1986), whereas a population declines, a mutual reinforcement loop among processes such as environmental stochasticity, demographic stochasticity, inbreeding, and behavioural failures makes the effect progressively larger and drives the species towards extinction (Fagan and Holmes, 2006; Gilpin, 1986). This effect would be greatly exacerbated by population fragmentation and gene flow reduction.

Any strategy to promote connectivity between fragmented subpopulations is essential for conservation genetics and promotion of gene-flow (Frankham *et al.*, 2002; Caughley, 1994). The Sambor Alt_7 alternative(s) provides a potential opportunity for dolphins to move up-and downstream through the anabranch channel, therefore is most certainly the preferred option.

**Summary:**
For the **cumulative effect of genetic vulnerability,** the Sambor Alt_7 option is preferential due to the improved potential for maintaining connectivity within the population.

### Cumulative Effect of Hydropower Dams

The Don Sahong Hydropower Dam upstream on the Mekong River is currently under construction immediately beside core habitat at Cheuteal Pool on the Lao PDF-Cambodia border. This dolphin population is this area is now very small (only three individuals, WWF, 2016), and is likely to be extirpated in the near future (Ryan, 2012; WWF, 2016). The loss of this population, regardless of cause, will cause a drastic reduction in the extent of occurrence of dolphins in the Mekong River. Further upstream and on tributaries are a large number of hydropower dams. Although many aim to have minimal effect on hydrology downstream, the Mekong's flow is becoming increasingly regulated, and the cumulative effect of multiple dams operating independently is uncertain. Flow changes can have a wide range of environmental effects such as changes to phenology of plants and fishes, changes to bathymetry and sediment flow (Kummu and Varis, 2007; Li and He, 2008; Lu and Siew, 2006; Dugan *et al.*, 2010). The cumulative effect of such operations is likely to have negative impacts on dolphins, rendered primarily through impacts on their habitat and prey. However, specifying the extent of such impacts is uncertain.

**Summary:**
For the **cumulative effect of hydropower dams**, the Sambor Alt_7 alternative is preferential given the reduced footprint and maintenance of open channels.

### Additional Fisheries and Bycatch

The construction of a large infrastructure project in a remote area may increase fishing activity and therefore associated bycatch of dolphins in the area. There are two reasons for this: improved access to the site through improved infrastructure, and the addition of demand for food by workers during construction. Bycatch is the major known threat to the Mekong dolphin population (Gilbert and Beasley, 2006; Dove, 2009; De La Fuente Marquez, 2012), any additional bycatch is an extreme risk to the population.

Improved access to remote sites via infrastructure such as roads is well known to increase the hunting and fishing occurring there (Gunn and Sein, 2000; Laurance *et al.*, 2009). The Sambor Alt_7 site is currently inaccessible and would require access road construction, and possible bridges. The Sambor site is near the town Sambor and would require less new access construction. However, the Sambor original proposal is a much larger project and would likely require more staff and a longer production schedule. Both projects are liable to increase demand for fish products to feed workers, however the Sambor Alt_7 proposal is likely to open the area to additional access and therefore more long-term additional fishing pressure.

**Summary:**
For the **cumulative effect of fisheries and bycatch**, the Sambor CSP project may be preferable as it may result in less disturbance from road infrastructure, and subsequently less potential for increased bycatch risk.

## Summary of Impacts

The above threats are discussed further in Table 9-4, based on IUCN assessment criteria (Reeves et al., 2000b), with consideration of the Sambor CSP and Sambor Alt_7 alternatives.

The risks to dolphins from potential impacts of the Sambor Dam alternatives are assessed based on international standard methods for risk assessment, where risk is the product of likelihood and consequence (Burgman 2005, Table 1). Here consequence is measured as the chance of increasing the risk of extinction of dolphins from the Mekong River, and assessments are based on Table 9-3.

The results indicate that it will difficult to mitigate for the majority (if not all) of the threats the proposed dam will have on the remaining Mekong dolphin population.

*Table 9-3. Risk assessment matrix used to rank impacts the proposed Sambor dam on the Mekong's dolphins based on Burgman, 2005, p. 150.*

| | | **Consequence** | | | | |
|---|---|---|---|---|---|---|
| **Likelihood** | | **Very high**<br>75–100% | **High**<br>50-74% | **Moderate**<br>25-49% | **Low**<br>1–24% | **Very low**<br>0–1 % |
| **Highly likely** | >85% | Very high | Very high | High | Moderate | Moderate |
| **Likely** | 50–85% | Very high | Very high | High | Moderate | Moderate |
| **Fairly likely** | 21–49% | Very high | High | High | Moderate | Low |
| **Unlikely** | 1–20% | Very high | High | Moderate | Moderate | Low |
| **Very unlikely** | <1% | Very high | High | Moderate | Low | Low |
| **Extremely unlikely** | <0.01% | Very high | High | Moderate | Low | Low |

*Table 9-4. Summary of potential impacts from Sambor dam options to Mekong dolphins, risks, mitigation, and examples of impacts.*

| Threat | Potential impact from Sambor CSP | Potential Impact from Sambor Alt_7 (unscreened) | Potential Impact from Sambor Alt_7 (screened) | Mitigation Potential | Example and Reference |
|---|---|---|---|---|---|
| **1. Dolphins isolated above/below dam** (fragmentation into genetically-isolated subpopulations) | **Certain fragmentation**<br>The original Sambor dam would certainly fragment the remaining Mekong dolphin population. | **Very high Risk**<br>Based on knowledge from other river dolphin popula-tions, there is a small chance that dolphins may move up-and downstream of the Sambor dam using the anabranch channel in the Sambor Alt_7 design (screen and unscreened).<br><br>Probable fragmentation into two subpopulations. | **Very high Risk**<br>Same as un-screened | **Sambor Alt_7 Potential Mitigation**<br>Dolphins may use the anabranch channel during the wet season. However, there have not been dolphins sighted in the anabranch channel despite numerous surveys (dry season the channel is often un-navigable by small boat). | As of 2000, baiji no longer occurred in waters above the Gezhouba Dam in the Yangtze River (Liu and Wang, 2000).<br>Barrages have subdivided the meta-population of Ganges River dolphins. Some sub-populations have become extinct and other are threatened with extirpation, especially in Nepal (Sinha, 2000, Smith et al., 1998, Smith, 1993) |
| **2. Loss/alteration of critical habitats** | **Very High Risk**<br>Loss of critical micro-habitats for dolphins and their prey fish (resting, shelter, breeding) in and near dolphin pool | **High Risk**<br>As a result of the anabranch channel, there is some possibility that sedimentation and hydrology would not be significantly affected with the Sambor Alt_7 design (screened and unscreened). | **High Risk**<br>Same as un-screened | **Sambor Alt_7 Potential Mitigation**<br>Disturbance to the hydro-logy and sediment flow is almost non-existent (although the pool immediately down-stream of the Sambor Alt_7 may be affected). | Construction of numerous dams along the Yangtze River has eliminated important habitat for the Baiji and Yangtze River finless porpoise (*Neophocaena phocaenoides asiaorientalis*) (Liu and Wang, 2000)<br>River dolphins are considered vulnerable specialists at a river basin scale, and therefore vulnerable to habitat changes (Smith and Reeves, 2012) |
| **3. Reduced prey** | **Reduced prey certain**<br>There is a high risk of reduced prey due to dam | **High risk**<br>It is estimated that the Sambor Alt_7 design will | **High risk**<br>It is estimated that the Sambor Alt_7 | **Possible with well-designed fish passages** | The migratory Chinese anchovy (*Colia ectenes*) declined by |

| Threat | Potential impact from Sambor CSP | Potential Impact from Sambor Alt_7 (unscreened) | Potential Impact from Sambor Alt_7 (screened) | Mitigation Potential | Example and Reference |
|---|---|---|---|---|---|
| | construction (see associated fish passage documents for a more comprehensive assessment. | allow 95% of the fish to pass | design will allow 95% of the fish to pass | | more than 99% between 1970s and 1980s, primarily because no fish ladder or passage facilities were incorporated into the dam construction (Liu and Wang, 2000).<br><br>Lentic fish species upstream and lotic species downstream of the Farakka Barrage, India, indicating a local decline in suitable dolphin prey.<br><br>Effects of damming on river biota include decimation of migratory fauna, lost fisheries and imperilment of obligate riverine taxa (Freeman et al., 2003) |
| **4. Short-term construction impacts** | **Very high risk**<br><br>Increased stress to dolphins from blasting, construction and operation from increased under-water noise disrupting social, foraging, navigation and breeding behavior | **Very high risk**<br><br>Increased stress to dolphins from blasting, construction and operation from increased underwater noise disrupting social, foraging, navigation and breeding behavior | **Very high risk**<br><br>Increased stress to dolphins from blasting, construction and operation from increased under-water noise disrupting social, foraging, navigation and breeding behavior | **Minimal**<br><br>Because for all options the dam will be built near to/within, important dolphin habitats there are minimal mitigation options available. | Short-term construction impacts have been shown to impact marine mammal populations because of increased noise and disturbance (Richardson et al., 2013).<br><br>There are anecdotal reports that construction of the Don Sahong Dam (i.e. construction and blasting) is already have a negative effect on the remaining trans-boundary dolphin population (RFA, 2016) |

| Threat | Potential impact from Sambor CSP | Potential Impact from Sambor Alt_7 (unscreened) | Potential Impact from Sambor Alt_7 (screened) | Mitigation Potential | Example and Reference |
|---|---|---|---|---|---|
| | | | | | because recommended mitigation measures were not conducted (Beasley, 2014b) |
| **5. Direct death** | **Very high risk**<br><br>If any blasting occurs during construction, direct death is possible. | **Very high risk**<br><br>If any blasting occurs during construction, direct death is possible.<br><br>Dolphins may become trapped on/in the dam turbines/ infrastructure without a screen | **Very high risk**<br><br>If any blasting occurs during construction, direct death is possible. | | A baiji was found dead at the bottom of one of the lock gates at the Madian Ship Lock in the Yangtze River (Liu and Wang, 2000) |
| **Cumulative impacts** | **Certain**<br><br>It is certain that Sambor dam will contribute to local extinction of the Mekong dolphin population because of population fragmentation of a small, declining population. | **Very High Risk**<br><br>A very high risk that even with mitigation, the Sambor Alt_7 will contribute to local extinction of the Mekong dolphin population | **Very High Risk**<br><br>A very high risk that even with mitigation the Sambor Alt_7 will contribute to local extinction of the Mekong dolphin population | **Minimal** | The baiji is the first mega-faunal vertebrate to become extinct in 50 years.<br><br>Although fishery interactions were probably the primary cause of the baiji's decline, the construction of extensive flood control, hydropower, and irrigation projects in the Yangtze River and its tributaries, resulting in extensive habitat loss, was almost certainly a contributing factor (Turvey, 2009; Huang *et al*., 2012; Smith and Reeves, 2012) |

## Recommendations and Potential Mitigation Guidelines

### Guidelines to Reduce Effects of Water Development Projects

It is undeniable that water development projects, including dams, embankments, barrages and ship locks have had extensive deleterious effects on river dolphin species. The functionally extinct baiji provides a solid case study of the effect of dams, where the species became locally extirpated from rivers and lakes previously utilized once a dam was created (i.e. Xinan and Qiantang Rivers, upstream of Jingzhou, Dongting and Poyang Lakes, Yangtze River: Liu and Wang 2002). Yantze River finless porpoise *Neophocaena phocaenoides asiaorientalis*) have faced a similar situation, where in addition to the Xinan and Qiantang Rivers these species have been extirpated from waters upstream of the Wanan Dam after it was built in 1981 (Zhou *et al.*, 1993). The Indus River dolphin is also extirpated from sections between barrages in the Indus (Braulik *et al*. 2014).

The IUCN Cetacean Specialist Group identified the following potential guidelines to reduce the effects of water infrastructure development on river dolphins (Smith and Reeves, 2012):

1. **Ecosystem integrity**. Natural attributes of a river should be maintained, with four basic principles being considered:
    a. No 'surplus' water, or large-scale withdrawal
    b. Floodplains should be maintained
    c. An alluvial river must be allowed to migrate
    d. Rivers need to maintain their natural temporal and spatial variability
2. **Required habitat conditions.** River cetaceans need suitable alluvial habitat to survive and reproduce:
    a. River flows must allow free movement between deep pools
    b. Freshwater of adequate depth, current, speed and temperature is essential
3. **Dam siting and management**. Dams can drastically affect downstream habitat, where key considerations are:
    a. If built, dams should be located in tributaries to ensure sediment supplies and fish spawning habitat downstream
    b. Large fluctuations in flow should be avoided
    c. Equilibrium between sediment erosion and deposition necessary to maintain essential habitat features
4. **Barrier effects**. The siting and operation of dams or barrages must recognize risks associated with barrier effects and acknowledge the subsequent conservation implications for river dolphin populations:
    a. Dams completely and permanently divide populations
    b. Barrages interrupt free movement, at least during much of the year, and probably restrict gene flow
    c. Such effects increase a populations vulnerability to extinction
5. **Fish migrations.** The availability of sufficient prey is essential for maintaining healthy populations of dolphins.
    a. Water development projects often block migratory pathways within the river channel and onto the floodplain
    b. Fishways should accommodate the specific needs of their new modified environment

   c. Fishways should be designed so they can be modified in light of experimentation and monitoring

6. **Migration corridors.** No technical solution has previously been available to mitigate the barrier effects of dams or barrages on riverine cetaceans. If successful, the anabranch channel described for the Sambor Alt_7 option would be the first of its kind to facilitate dolphin movement around a dam, though this remains highly uncertain.
7. **Interventionist Approaches**. Approaches such as translocation should be avoided as they are unlikely to be effective:
   a. More needs to be learned about the animals' movements, behavior and habitat requirements
   b. There is a high probability of death during capture and movement, so translocation is a high-risk option
8. **Captive propagation.** Maintaining a self-sustaining captive population of river dolphins would be an extremely expensive and controversial proposition – if it could be done at all.
   a. There is no basis for adopting captive propagation as mitigation for water development
   b. Wild animals should be conserved as integral parts of the natural ecosystem.
9. **Assessing environmental impacts.** Aquatic biodiversity must be considered when assessing the impacts of planned water developments.
   a. Adequate information on the pre-development ecological conditions of the river is essential
   b. Cumulative and synergistic impacts of multiple developments should be considered.
   c. Methods for assessing potential impacts should be standardized
   d. If impacts are judges to be severe (by an independent panel of experts), then the option of not constructing the project should be considered
10. **Research and monitoring.** Post-development empirical studies are needed to monitor the operational aspects of water development projects, as well as the effects on upstream and downstream populations of cetaceans and their habitat.

Given the 'Critically Endangered' status of the Mekong dolphin population (Smith and Beasley, 2004), it is reasonable to define 'effective mitigation' for any water infrastructure development project as 'no change in the current status of dolphins' (Bezuijen *et al.*, 2007). In this context, the possibility for effective mitigation of the proposed Sambor Dam, with screened or unscreened Sambor Alt_7 options, appears low.

Through an assessment of the dam options: Sambor CSP, Sambor Alt_7 options (screened and unscreened) (Table 9-4), all options would impact the Mekong dolphin population to some extent, and are assessed as likely to lead to extirpation of the remaining population. Acknowledging this inevitability, the Sambor Alt_7-A (screened) option is the preferred option in relation to the original project objectives, because the 7-A option:

- minimizes sediment retention and reduced the probability of hydrological changes;
- minimizes the chances of dolphin direct deaths through infrastructure interactions;
- provides a chance (although very slim) dolphins as well as fish to pass upstream and downstream through the anabranch channel;
- will not cause as much habitat displacement or behavioral change as the Sambor CSP

proposed dam;

- proposes a strategy to facilitate fish movement upstream and downstream through the anabranch channels.

Sambor Alt_7-C and D (screened) options are preferred over Sambor Alt_7-A and B (unscreened) options because they will reduce mortality of fish, which dolphins rely on for food.

### Minimum Population Size Considerations

The minimum viable population (MVP) size (i.e., the smallest size required for a population of a species to have a predetermined probability of persistence for a given length of time (Shaffer, 1981; Caughley and Gunn, 1996), is not known for small cetaceans, or any other species, although many have attempted to answer this question (Franklin and Frankham, 1998; Lande and Barrowclough, 1987; Soulé, 1987; Reed *et al*., 2003). Importantly, a MVP is not one that can simply maintain itself under average conditions but one that is of sufficient size to endure the calamities of various perturbations and do so within its particular biogeographic context (Shaffer, 1987; Thomas, 1990). As Caughley and Gunn (1996) state, '*common-sense tells us that there is no single number that tips a species into the small, or minimum viable population categories'*. There are various examples of small populations, such as the black footed ferret (*Mustela nigripes*) (May, 1986; Seal, 1989; Russell *et al.*, 1994), Californian condor (*Gymnogyps californianus*) (Sarrazin and Barbault, 1996) and northern elephant seal (*Mirounga angustirostris*) (Hoelzel *et al.*, 2002; Weber *et al.*, 2004) that have been brought back successfully from the brink of extinction. Irrespective of population size, when populations become small the survival of each individual is critical (Caughley and Gunn, 1996).

Given the current estimated Mekong dolphin population size (80 individuals), continual births (although calf mortality remains high), and significant local community support (in Laos and Cambodia) for conservation efforts, it is too early to assume that the Mekong dolphin population has reached its MVP. Effective conservation initiatives are now needed that are radically different from previous unsuccessful efforts to ensure the populations' long-term survival. Recent collaborations between the IUCN Cetacean Specialist Group, WWF-Cambodia and the Commission for Conservation and Development of the Mekong River Dolphin EcoTourism Zone have been a positive step forward, with new conservation initiatives being proposed at a recent national workshop (Kratie Declaration, 2012). Early signs suggest the decline might be stabilising, and give hope that conservation efforts are succeeding (Phan *et al*., 2015). The current population is potentially salvable, and there is no case to proceed with development on the assumption that the population will be lost either way.

### Legal Considerations

This section is intended as an indication of relevant laws regarding dolphins and the prosed Sambor dam development, but not intended to constitute legal advice. The full legal implications of this process should be explored by an appropriate specialist legal advisor.

In Cambodia law, killing Irrawaddy dolphins is illegal. This law may cover direct mortality due to construction activities (i.e. mortality resulting from damage to hearing structures due to construction noise, or being trapped within in a hydroelectric turbine). In addition, the 'Sub Decree on the Creation of the Mekong River Dolphin's Managerial Protection Zones' (Royal Government of

Cambodia, 2012), prohibits large-scale infrastructure development within the locations of both dam sites. The Sambor CSP and Sambor Alt_7 hydropower proposals are sited within a core area under this Sub Decree, and the fish pass for Sambor Alt_7 is within a buffer zone.

Some dolphin habitat is also protected under the Proclamation on the Creation of Fisheries Biodiversity Management Area (MAFF 2013) that envelops the Sambor Alt_7 sites. Further, article 25 of Fishery Law (Royal Government of Cambodia, 2007) requires that the building of dams and other structures that could damage fishery resources, which include Mekong dolphins, must be evaluated by the Ministry of Agriculture, Forestry and Fisheries (MAFF).

## Summary of Mitigation Options

The potential mitigation options for Sambor CSP and Sambor Alt_7 dams are summarised in Table 9-5, with the attendant risk matrix used to calculate risk *presented in Table 9-3.*

*Table 9-5. Summary of mitigation options for Sambor original and Sambor Alt_7, and risk from impact (or mitigation).*

| **Potential Impact** | **Sambor CSP Mitigation** | **Risk Level** | **Sambor Alt_7 Dam Mitigation** | **Risk Level** |
|---|---|---|---|---|
| **Construction and Operational Phase Impacts** | | | | |
| Construction waste and increased domestic garbage and sewage | Essential that all waste is appropriately removed, or processed according to current day best-practice protocols | Low | See Sambor Dam | Low |
| Seismic mapping | If seismic mapping is conducted, appropriate mitigation protocols (i.e. soft starts, ramp ups, mitigation zones) need to be implemented in order to reduce the possibility for auditory damage, or death, of a single dolphin. Short-term behavioral changes may be unavoidable despite mitigation protocols. | Medium | See Sambor Dam | Medium |
| Excavation and construction | | High | | High |
| Increased boat traffic | 'go-slow zones' in important dolphin habitats and creating conservation areas where vessels are prohibited | Low | See Sambor Dam | Low |
| Operational noise from turbines | peer-reviewed sound model-ling studies are required prior to construction to adequately assess the potential impacts of noise from the dam turbines on the Mekong dolphin population and determine whether mitigation is possible, or | High | See Sambor Dam | High |

| Potential Impact | Sambor CSP Mitigation | Risk Level | Sambor Alt_7 Dam Mitigation | Risk Level |
|---|---|---|---|---|
| | required. | | | |
| **Changes to Habitat Availability and Quality** | | | | |
| Direct habitat loss | No mitigation possible | Very High | See Sambor Dam | Very High |
| Dam-created reservoir | No mitigation possible | Very High | See Sambor Dam | Very High |
| Increased sediment | No mitigation possible | *Medium -Extreme | See Sambor Dam | Low |
| Altered water flow and river morphology | No mitigation possible | *Medium -Extreme | See Sambor Dam | Low |
| Reduced prey abundance and diversity | No mitigation possible | *Medium -Extreme | Ensure that fish passages down anabranch channel are effective | *Medium-High |
| **Impacts From Barrier and Passage Effects** | | | | |
| Fragmentation of the population | No mitigation possible | Certain | Possible movement through the ana-branch channel | Very High |
| Mortality from impingement on the debris barrier | No mitigation possible | High | -- | -- |
| Mortality from lock gates | | Medium | | Medium |
| Mortality from impingement on the fish screen | -- | -- | No mitigation possible | Medium |
| **Cumulative impacts** | | | | |
| Vulnerability to catastrophe | No mitigation possible | Very High | Possible movement through the ana-branch channel | High |
| Genetic inbreeding | No mitigation possible | Very High | Possible movement through the ana-branch channel | High |
| Cumulative effect of hydropower dams | No mitigation possible | *Medium -Extreme | No mitigation possible | *Medium-Extreme |
| Additional fisheries and bycatch | Improve fishery management in the area to prevent bycatch, e.g. through support to Fisheries Administration and River Guards | Very High | See Sambor Dam | Very High |

## Key Knowledge Gaps

### Dolphin Use of Eastern Anabranches

A major distinction between the original Sambor dam design, and the Sambor Alt_7 design is the free-flowing anabranch channels east of Koh Rongeav (e.g. see **Error! Reference source not found.** & Figure 9-6). The ability of this design to mitigate the barrier effect of the dam by allowing a passage for dolphin movement is entirely dependent on whether dolphins will use these channels. This is an uncertainty which further research may help to resolve. While current available evidence suggests that dolphins do not use these areas, the fine-scale use of habitats is not well understood, particularly habitat use during the wet season. It is highly unlikely that dolphins use the anabranch in the dry season because of the very shallow water Figure 9-3, where even small boats are not able to pass some of the rapid regions. If there is no evidence of use, it is impossible to predict with certainty whether dolphins would disperse through the anabranch if the main-stem was blocked. However, better understanding of the fine-scale use of habitats, and the fine-scale hydrology of the anabranch channels may provide information supporting or contesting the issue. Resolving this gap in knowledge by detailed study of the movement of animals in this area, especially during wet season, and better understanding of the hydrology of the anabranch would be a significant contribution towards resolving uncertainty about the fragmentation effect caused by the Sambor Alt_7 option.

Based on the extensive literature examined for this study, there are no known examples of waterway development projects in mainstream rivers that have provided an opportunity for dolphins/fish to move up- and down-stream around the dam structure through anabranch channels. Dolphins rely on prey for their survival, and often follow prey movements within a river system. Therefore, if fish regularly use the anabranch channel there is a high probability that dolphins may also begin to use this channel during the wet season, if they do not already. Based on survey data from 2001, the channel is likely to be too shallow for dolphins to use during the dry season.

### Sound Emissions

Sound emission from the project (both above- and under-water) is a significant potential risk to dolphins. The expected noise from this project not a well understood, but has possibilities for mitigation. Potentially harmful sound emissions may come from such sources as excavation with dry explosives, seismic mapping, or turbine operation. Modeling of potential sources of harmful sound emission from all possible sources, and exploring mitigation would be recommended prior to any construction commencing.

### Impacts of the Don Sahong Dam on Irrawaddy Dolphins in the Mekong River

Although there are many relevant cases for examples of the impact of infrastructure development on cetaceans, there are few no specific case studies for this species. The under-construction Don Sahong Dam, cited above the Cheuteal Pool in Lao PDR is the first example of a hydropower dam development within the range of Mekong dolphins. Although a significant threat to the population (Ryan 2014; Beasley, 2014a; Beasley 2014b), it also presents an opportunity to better understand the impacts of hydropower developments on this population of dolphins in both construction and operational phases. Research on the effects of this development would provide valuable information to better-determine the impacts and potential mitigation measures from construction and operational activities on the Mekong dolphin population.

## Conclusions

The Mekong River dolphin population is very small, and already at great risk of extinction. Any additional impacts to the population from construction activities decrease the population's chance of survival. The alteration and loss of a large section of habitat around either dam is certain, and what this means for future dolphin use of it is unknown but likely negative. Mekong dolphins rely heavily on a few specific, deep-water pools of the river during the dry season (Figure 9-2). Both dam sites would cause the loss of some of these deep-water pools. Fragmentation of the remaining population is certain for the Sambor CSP alternative, and possible for the Sambor Alt_7 (screened and unscreened) alternatives. Although the anabranch channel remains open there is currently no evidence of movement of dolphins, or fish, through these channels. The question of whether dolphins would begin to use the anabranch channel with a blocked main channel cannot be answered with certainty. Fragmentation would split the population into at least two smaller groups, and result in a disproportionately higher risk of extinction than the current population is facing.

The close proximity of the proposed dam site to important dolphin pools suggests that disruption from construction and operation activities, altered flows, changes in dolphin habitat use, and reduced prey supplies, would be difficult to avoid. Additionally, fish passes for dams are often ineffective, especially in the Mekong Basin (Baran and Ratner, 2007). Although modelling for Sambor Alt_7 suggests a high rate of successful fish passage (Mallen-Cooper et al., 2016) this remains uncertain and therefore a risk.

Many details of the construction and operation of the proposed dam options are not yet available, particularly regarding the intensity of sound emissions. We consider that this assessment should be revisited in light of new information. However, the risk from key potential impacts like fragmentation and habitat loss is unlikely to change.

**The key knowledge gaps that need to be filled prior to construction, to effectively mitigate some potential impacts are:**

- Better understanding of fine-scale distribution, abundance and movements of the dolphin populations within, and near, the proposed project site, and specifically whether dolphins use the anabranch channel;
- Modeling potential sound emissions and propagation of various construction and operation activities, including dry explosives, turbine operation, and seismic operations, to determine appropriate mitigation zones, and/or determine if mitigation is possible;
- Evaluating the impact of construction and operation of the Don Sahong Dam in Lao PDR on dolphins in the Cheuteal Pool. Such studies could help inform understanding of impacts and potential mitigation options of proposed hydropower developments.

**At this stage, we conclude:**

- The Mekong's dolphin population is threatened with extinction. Recovery efforts currently underway may prevent the extinction of the population, in the absence of additional threats. All proposed Sambor Dam options are likely to substantially increase the risk of extinction of Irrawaddy dolphins in the Mekong River.

- A major difference in the Sambor CSP and NHI's Sambor Alt_7 site options is the open anabranch channel. There is no current evidence that dolphins use this channel, and whether dolphins would disperse through it if the main-stem was blocked is uncertain. However, the Sambor Alt_7 site retains some possibility for the population to remain connected after the dam is built.
- The original Sambor CSP option will certainly fragment the Mekong dolphin population into two disconnected smaller populations, greatly increasing the risk of extinction in each sub-group.
- Of the dam options considered, the proposed Sambor Alt_7 with fish screens is the preferred option, as this option retains the possibility for allows up-stream and downstream movement of dolphins, and the screen would prevent impalement of prey species.
- The construction of dams at either the Sambor SCP or Sambor Alt_7 sites will cause unalterable change in core Mekong dolphin habitat that will no doubt increase the population's risk of extinction.

The no-dam alternative has no additional threat to dolphins, and is the preferred option to minimize potential impacts on dolphins.

## References


Aliaga-Rossel, E. & Quevedo, S. 2011. The Bolivian River Dolphin in the Tijamuchi and Ibare rivers (upper Madeira basin) during rainy season in a "La Niña" event. *Mastozoología Neotropical,* 18**,** 293-299.

Anderson, J. 1878. *Anatomical and zoological researches: comprising an account of the zoological results of the two expeditions to Western Yunnan in 1868 and 1875 and a monograph of the two cetacean genera, platanista and orcella*, Quaritch.

Andren, H. 1994. Effects of habitat fragmentation on birds and mammals in landscapes with different proportions of suitable habitat: a review. *Oikos***,** 355-366.

Araújo, C. C. & Wang, J. Y. 2015. The dammed river dolphins of Brazil: impacts and conservation. *Oryx,* 49**,** 17-24.

Au, W. W. & Fay, R. R. 2012. *Hearing by whales and dolphins*, Springer Science & Business Media.

Australian Government. 2008. EPBC Act Policy Statement 2.1 – Interaction between offshore seismic exploration and whales. Department of the Environment, Water, Heritage and the Arts, Australian Government, 2008.

Bahl, R., Ura, T., Sugimatsu, H., Inoue, T., Sakamaki, T., Kojima, J., Akamatsu, T., Takahashi, H., Behera, S. & Pattnaik, A. Acoustic survey of Irrawaddy dolphin populations in Chilika Lagoon: first test of a compact high-resolution device. OCEANS 2006-Asia Pacific, 2007. IEEE, 1-6.

Baird, I. G. & Beasley, I. 2005. Irrawaddy dolphin Orcaella brevirostris in the Cambodian Mekong River: an initial survey. *Oryx,* 39**,** 301-310.

Baird, I. G. & Flaherty, M. S. 2005. Mekong River fish conservation zones in southern Laos: assessing effectiveness using local ecological knowledge. *Environmental Management,* 36**,** 439-454.

Baird, I. G. & Mounsouphom, B. 1997. Distribution, mortality, diet and conservation of Irrawaddy dolphins (Orcaella brevirostris Gray) in Lao PDR. *Asian Marine Biology,* 14**,** 41-48.

Baird, I. G., Mounsouphom, B. & Stacey, P. J. 1994. Preliminary surveys of Irrawaddy dolphins (Orcaella brevirostris) in Lao PDR and northeastern Cambodia. *Report of the International Whaling Commission,* 44**,** 367-369.

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

Baran, E. and Ratner. 2007. The Don Sahong Dam and Mekong Fisheries. Science Brief. WorldFish Center. p. 3.

Baruah, D., Hazarika, L. P., Bakalial, B., Borah, S., Dutta, R. & Biswas, S. 2012. A grave danger for the Ganges dolphin (Platanista gangetica Roxburgh) in the Subansiri River due to a large hydroelectric project. *The Environmentalist,* 32**,** 85-90.

Beasley, I. 2002. Trapped high and try. *Wildlife Conservation Society-Cambodia Program*.

Beasley, I. 2014a. Review of the Mekong Dolphin Population Status and Potential Impacts of the Proposed Don Sahong Hydropower Project In support of the Prior Consultation process. Mekong River Commission - Annex D.

Beasley, I. 2014b. Review of the Mekong Dolphin Population Status and Potential Impacts of the Proposed Don Sahong Hydropower Project In support of the Prior Consultation process.

Beasley, I., Bejder, L. & Marsh, H. 2010. Dolphin-watching tourism in the Mekong River, Cambodia: a case study of economic interests influencing conservation. *Report to the International Whaling Commission SC/62/WW4*.

Beasley, I., Marsh, H., Jefferson, T. A. & Arnold, P. 2009. Conserving dolphins in the Mekong River: the complex challenge of competing interests. *The Mekong: biophysical environment of an international river basin. Academic Press, London***,** 365-389.

Beasley, I., Pollock, K., Jefferson, T., Arnold, P., Morse, L., Yim, S., Lor Kim, S. & Marsh, H. 2013. Likely future extirpation of another Asian river dolphin: The critically endangered population of the Irrawaddy dolphin in the Mekong River is small and declining. *Marine Mammal Science,* 29**,** E226-E252.

Beasley, I., Robertson, K. M. & Arnold, P. 2005. Description of a new dolphin, the Australian snubfin dolphin Orcaella heinsohni sp. n.(Cetacea, Delphinidae). *Marine Mammal Science,* 21**,** 365-400.

Beasley, I.L. 2007. *Conservation of the Irrawaddy dolphin, Orcaella brevirostris (Owen in Gray, 1866) in the Mekong River: biological and social considerations influencing management.* James Cook University.

Bell, S. S., Brooks, R. A., Robbins, B. D., Fonseca, M. S. & Hall, M. O. 2001. Faunal response to fragmentation in seagrass habitats: implications for seagrass conservation. *Biological Conservation,* 100**,** 115-123.

Bezuijen, M., Zanre, R. & Goichot, M. 2007. The Don Sahong dam and the Irrawaddy dolphin. *WWF, Vientiane*.

Braulik, G.T. 2006. Status assessment of the Indus River dolphin, Platanista gangetica minor, March–April 2001. *Biological Conservation,* 129**,** 579-590.

Braulik, G. T., Arshad, M., Noureen, U. & Northridge, S. P. 2014. Habitat fragmentation and species extirpation in freshwater ecosystems; causes of range decline of the indus river dolphin (Platanista gangetica minor). *PloS one,* 9**,** e101657.

Braulik, G. T., Reichert, A. P., Ehsan, T., Khan, S., Northridge, S. P., Alexander, J. S. & Garstang, R. 2012. Habitat use by a freshwater dolphin in the low-water season. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 22**,** 533-546.

Burgman, M., 2005. Risks and decisions for conservation and environmental management. Cambridge University Press.

Caughley, G. 1994. Directions in conservation biology. *Journal of animal ecology***,** 215-244.

Caughley, G. & Gunn, A. 1996. *Conservation biology in theory and practice*.
[61] CBD. 2016. *Convention on Biological Diversity* [Online]. https://www.cbd.int. [Accessed].

Chheng. 2016. Mother and baby Irrawaddy dolphins found dead in Kratie. *Phnom Penh Post* 1/08/2016

CITES 2016. Convention on International Trade in Endangered Species of Wild Fauna and Flora, Appendices I, II and III. Valid from 21 November 2016.

COP10 2010. Conference of the Parties to the Convention on Biological Diversity. Decision X/2, Strategic Plan for Biodiversity 2011-2020. Convention On Biological Diversity.

Côté, I. M., Darling, E. S. & Brown, C. J. Interactions among ecosystem stressors and their importance in conservation. Proc. R. Soc. B, 2016. The Royal Society, 20152592.

Coutant, C. C. & Whitney, R. R. 2000. Fish behavior in relation to passage through hydropower turbines: a review. *Transactions of the American Fisheries Society,* 129**,** 351-380.

CSP 2008. The Kingdom of Cambodia Feasibility Study of Sambor Hydropower Station. China Southern Power Grid Co. Ltd.

De La Fuente Marquez, J. 2012. Review of pathological data collected (2001–2012). WWF-Cambodia, unpublished report.

De Sá Alves, L. C. P., Andriolo, A., Orams, M. B. & De Freitas Azevedo, a. 2012. The growth of 'botos feeding tourism', a new tourism industry based on the boto (Amazon river dolphin) Inia geoffrensis in the Amazonas State, Brazil. *Sitientibus Série Ciências Biológicas,* 11**,** 8-15.

Derraik, J. G. 2002. The pollution of the marine environment by plastic debris: a review. *Marine pollution bulletin,* 44**,** 842-852.

Dove, V. 2009. Mortality investigation of the Mekong Irrawaddy River dolphin (Orcaella brevirostris) in Cambodia based on necropsy sample analysis. *World Wildl. Fund Tech. Rep*, 1-72.

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

Dugan, P. J., Barlow, C., Agostinho, A. A., Baran, E., Cada, G. F., Chen, D., Cowx, I. G., Ferguson, J. W., Jutagate, T. & Mallen-Cooper, M. 2010. Fish migration, dams, and loss of ecosystem services in the Mekong basin. *Ambio,* 39**,** 344-348.

Fagan, W. F. & Holmes, E. 2006. Quantifying the extinction vortex. *Ecology Letters,* 9**,** 51-60.

Fahrig, L. 2003. Effects of habitat fragmentation on biodiversity. *Annual review of ecology, evolution, and systematics***,** 487-515.

Finneran, J. J., Schlundt, C. E., Dear, R., Carder, D. A. & Ridgway, S. H. 2002. Temporary shift in masked hearing thresholds in odontocetes after exposure to single underwater impulses from a seismic watergun. *The Journal of the Acoustical Society of America,* 111**,** 2929-2940.

Frankham, R., Briscoe, D. A. & Ballou, J. D. 2002. *Introduction to conservation genetics*, Cambridge University Press.

Frankham, R. & Ralls, K. 1998. Conservation biology: inbreeding leads to extinction. *Nature,* 392**,** 441-442.

Franklin, I. & Frankham, R. 1998. How large must populations be to retain evolutionary potential? *Animal Conservation,* 1**,** 69-70.

Freeman, M. C., Pringle, C. M., Greathouse, E. A. & Freeman, B. J. Ecosystem-level consequences of migratory faunal depletion caused by dams. American Fisheries Society Symposium, 2003. 255-266.

Gilbert, M. & Beasley, I. 2006. Mekong River Irrawaddy Dolphin Stranding and Mortality Summary, January 2001–December 2005. *Wildlife Conservation Society-Cambodia Program, Phnom Penh. 39pp*.

Gilpin, M. E. 1986. Minimum viable populations: processes of species extinction. *Conservation biology: the science of scarcity and diversity***,** 19-34.

Gomez-Salazar, C., Trujillo, F. & Whitehead, H. 2012. Ecological factors influencing group sizes of river dolphins (Inia geoffrensis and Sotalia fluviatilis). *Marine Mammal Science,* 28**,** E124-E142.

Gray, T. N., Phan, C., Pin, C. & Prum, S. 2012. Establishing a monitoring baseline for threatened large ungulates in eastern Cambodia. *Wildlife Biology,* 18**,** 406-413.

Gunn, J. M. & Sein, R. 2000. Effects of forestry roads on reproductive habitat and exploitation of lake trout (Salvelinus namaycush) in three experimental lakes. *Canadian Journal of Fisheries and Aquatic Sciences,* 57**,** 97-104.

Haila, Y. & Hanski, I. K. Methodology for studying the effect of habitat fragmentation on land birds. Annales Zoologici Fennici, 1984. JSTOR, 393-397.

Halls, A., Conlan, I., Wisesjindawat, W., Phouthavongs, K., Viravong, S., Chan, S. & Vu, V. 2013. Atlas of deep pools in the Lower Mekong River and some of its tributaries. *MRC Technical Paper No,* 31.

Hamilton, H., Caballero, S., Collins, A. G. & Brownell, R. L. 2001. Evolution of river dolphins. *Proceedings of the Royal Society of London B: Biological Sciences,* 268**,** 549-556.

Hardwood, J. 2001. Marine mammals and their environment in the twenty-first century. *Journal of Mammalogy,* 82**,** 630-640.

Hoelzel, A. R., Fleischer, R., Campagna, C., Le Boeuf, B. & Alvord, G. 2002. Impact of a population bottleneck on symmetry and genetic diversity in the northern elephant seal. *Journal of Evolutionary Biology,* 15**,** 567-575.

Hua, Y., Zhao, Q. & Zhang, G. 1989. The habitat and behavior of Lipotes vexillifer. *Perrin et al***,** 92-98.

Huang, S.-L., Hao, Y., Mei, Z., Turvey, S. T. & Wang, D. 2012. Common pattern of population decline for freshwater cetacean species in deteriorating habitats. *Freshwater Biology,* 57**,** 1266-1276.

Iriarte, V. & Marmontel, M. 2012. Report of an Encounter with a Human-Intentionally-Entangled Amazon River Dolphin (inia geoffrensis) Calf and its Release in Tefé river, Amazonas state, Brazil.

Jefferson, T., Karczmarski, L., Kreb, D., Laidre, K., O'corry-Crowe, G., Reeves, R. R., Rojas-Bracho, L., Secchi, E., Slooten, E., Smith, B., Wang, D. & Zhou, K. 2016. Orcaella brevirostris (Mahakam River subpopulation). . *The IUCN Red List of Threatened Species 2016: e.T39428A98842174. Downloaded on 05 December 2016*.

Jensen, F. H., Rocco, A., Mansur, R. M., Smith, B. D., Janik, V. M. & Madsen, P. T. 2013. Clicking in shallow rivers: short-range echolocation of Irrawaddy and Ganges river dolphins in a shallow, acoustically complex habitat. *PloS one,* 8**,** e59284.

JNCC, 2010. JNCC guidelines for minimising the risk of injury and disturbance to marine mammals from seismic surveys. Joint Nature Conservation Committee, Inverdee House, Aberdeen, UK. Nature Conservation Committee

Keith, D. A., McCarthy, M. A., Regan, H., Regan, T., Bowles, C., Drill, C., Craig, C., Pellow, B., Burgman, M. A. & master, L. L. 2004. Protocols for listing threatened species can forecast extinction. *Ecology Letters,* 7**,** 1101-1108.

Ketten, D. R. 1995. Estimates of blast injury and acoustic trauma zones for marine mammals from underwater explosions. *Sensory systems of aquatic mammals***,** 391-407.

Kondolf, G. M. 1997. PROFILE: hungry water: effects of dams and gravel mining on river channels. *Environmental management,* 21**,** 533-551.

Koschinski, S., Culik, B.M., Henriksen, O.D., Tregenza, N., Ellis, G., Jansen, C. and Kathe, G., 2003. Behavioural reactions of free-ranging porpoises and seals to the noise of a simulated 2 MW windpower generator. *Marine Ecology Progress Series*, *265*, pp.263-273.

Kratie Declaration 2012. Kratie Declaration on the Conservation of the Mekong River Irrawaddy Dolphins. Fisheries Administration of the Ministry of Agriculture, Forestry and Fisheries. Available from: http://www.iucn-csg.org/wp-content/uploads/2010/03/Kratie-Declaration-signed-with-appendices-1.pdf

Krutzen, M., Beasley, I., Ackermann, C., Liekfeldt, D., Ludwig, A., Ryan, G. E., Bejder, L., Parra, G. J. & Wolfensberger, R. *In review.* Low genetic diversity and demographic collapse of the Irrawaddy dolphin population inhabiting the Mekong River. *Conservation Genetics*.

Kujawa, S. G. & Liberman, M. C. 2009. Adding insult to injury: cochlear nerve degeneration after "temporary" noise-induced hearing loss. *The Journal of Neuroscience,* 29**,** 14077-14085.

Kummu, M. & Varis, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology,* 85**,** 275-293.

Laist, D. W. 1987. Overview of the biological effects of lost and discarded plastic debris in the marine environment. *Marine pollution bulletin,* 18**,** 319-326.

Lande, R. 1988. Genetics and demography in biological conservation. *Science(Washington),* 241**,** 1455-1460.

Lande, R. 1993. Risks of population extinction from demographic and environmental stochasticity and random catastrophes. *American Naturalist***,** 911-927.

Lande, R. & Barrowclough, G. F. 1987. Effective population size, genetic variation, and their use in population management. *Viable populations for conservation***,** 87-123.

Larinier, M. & Marmulla, G. Fish passes: types, principles and geographical distribution–an overview. Proceedings of the second international symposium on the management of large rivers for fisheries, 2004. RAP Publication, 183-206.

Laurance, W. F., Goosem, M. & Laurance, S. G. 2009. Impacts of roads and linear clearings on tropical forests. *Trends in Ecology & Evolution,* 24**,** 659-669.

Leatherwood, S. & Reeves, R. R. 1994. River dolphins: a review of activities and plans of the Cetacean Specialist Group. *Aquatic Mammals,* 20**,** 137-154.

Li, S. & He, D. 2008. Water level response to hydropower development in the Upper Mekong River. *AMBIO: A Journal of the Human Environment,* 37**,** 170-176.

Liu, R. & wang, D. 2000. Effects of water development on river cetaceans in China. *Occas. Pap. IUCN Species Survival Comm.,* 23**,** 40-42.

Lomolino, M. V. & Channell, R. 1995. Splendid isolation: patterns of geographic range collapse in endangered mammals. *Journal of Mammalogy,* 76**,** 335-347.

Lovejoy, T. E. & Oren, D. C. 1981. Minimum critical size of ecosystems. *Ecological studies; analysis and synthesis*.

Lu, x. & Siew, R. 2006. Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. *Hydrology and Earth System Sciences Discussions,* 10**,** 181-195.

Lynch, M. 1991. The genetic interpretation of inbreeding depression and outbreeding depression. *Evolution***,** 622-629.

Madsen, P. T., Wahlberg, M., Tougaard, J., Lucke, K. & Tyack, P. L. 2006. Wind turbine underwater noise and marine mammals: implications of current knowledge and data needs. *Marine Ecology Progress Series*.

Ministry of Agriculture, Forestry and Fisheries (MAFF), 2013. Prakas n.126 Proko. Proclamation on the Creation of Fisheries Biodiversity Management Area. 23 April 2013.

Mallen-cooper, M., Jensen, M. & Annandale, G. 2016. Sambor Alt_7A Hydropower project, Conceptual Design for Preliminary Assessment: Fish Passage.

Mangel, M. & Tier, C. 1993. Dynamics of metapopulations with demographic stochasticity and environmental catastrophes. *Theoretical Population Biology,* 44**,** 1-31.

May, R. M. 1986. Species conservation: The cautionary tale of the black-footed ferret. *Nature,* 320**,** 13-14.

Mustika, P., Welters, R., Ryan, G. E., D'lima, C.-Y., P, Jutapruet, S. & Peter, C. 2016. A rapid assessment of wildlife tourism risk posed to cetaceans in Asia. . *Journal of Sustainable Tourism,* http://dx.doi.org/10.1080/09669582.2016.1257012.

Nao, T., Chhith, S. & Reeves, R. R. 2014. Conclusions, recommendations, and working group reports from the workshop on the conservation of Irrawaddy dolphins in the Mekong River.

NHI 2016. Sambor Alt_7A Hydroelectric Project: Conceptual Design for Preliminary Assessment.

O'Connor, S., Campbell, R., Cortez, H. & Knowles, T. 2009. Whale Watching Worldwide: tourism numbers, expenditures and expanding economic benefits, a special report from the International Fund for Animal Welfare. *Yarmouth MA, USA, prepared by Economists at Large,* 228.

Orr, S., Pittock, J., Chapagain, A. & Dumaresq, D. 2012. Dams on the Mekong River: Lost fish protein and the implications for land and water resources. *Global Environmental Change,* 22**,** 925-932.

Pavanato, H. J., Melo-Santos, G., Lima, D. S., Portocarrero-Aya, M., Paschoalini, M., Mosquera, F., Trujillo, F., Meneses, R., Marmontel, M. & Maretti, C. 2016. Risks of dam construction for South American river dolphins: a case study of the Tapajós River. *Endangered Species Research,* 31**,** 47-60.

Phan, C., Hang, S., Tan, S. & Lor, K. 2015. Population Monitoring of the Critically Endangered Mekong Dolphin Based on Mark-Resight Models. WWF-Cambodia Technical Report.

Poulsen, A., Poeu, O., Viravong, S., Suntornratana, U. & Tung, N. T. 2002. Deep pools as dry season fish habitats in the Mekong River basin. *MRC Technical Paper***,** 24.

Poulsen, A. F., Hortle, K., Valbo-Jorgensen, J., Chan, S., Chhuon, C., Viravong, s., Bouakhamvongsa, K., Suntornratana, U., Yoorong, N. & Nguyen, T. 2004. Distribution and ecology of some important riverine fish species of the Mekong River Basin. *MRC technical paper,* 10**,** 116.

Read, A. J., Drinker, P. & Northridge, S. 2006. Bycatch of marine mammals in US and global fisheries. *Conservation biology,* 20**,** 163-169.

Reed, D. H., O'grady, J. J., Brook, B. W., Ballou, J. D. & Frankham, R. 2003. Estimates of minimum viable population sizes for vertebrates and factors influencing those estimates. *Biological Conservation,* 113**,** 23-34.

Reeves, R., Smith, B. & Kasuya, T. 2000a. Biology and Conservation of Freshwater Cetaceans in Asia. IUCN Species Survival Commission Paper No. 23, viii. IUCN-The World Conservation Union, Gland, Cambridge.

Reeves, R. R., Jefferson, T., Karczmarski, L., Laidre, K., O'Corry-Crowe, G., Rojas-Bracho, l., Secchi, E., Slooten, E., Smith, B., Wang, D. & Zhou, K. 2008. Orcaella brevirostris. *The IUCN Red List of Threatened Species 2008: e.T15419A4579987.* http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T15419A4579987.en.

Reeves, R. R., Smith, B. D. & Kasuya, T. 2000b. *Biology and conservation of freshwater cetaceans in Asia*, IUCN.

RFA 2016. Cambodian Villagers Say Dam Construction Is Forcing Endangered Dolphins Upstream. Radio Free Asia, 2016-12-08. Available from:

http://www.rfa.org/english/news/cambodia/cambodia-villagers-say-dam-construction-is-forcing-endangered-dolphins-upstream-12082016162753.html.

Richardson, W. & Würsig, B. 1995. Significance of responses and noise impacts. *Marine Mammals and Noise. Academic Press, San Diego, CA*, 387-424.

Richardson, W. J., Greene Jr, C. R., Malme, C. I. & Thomson, D. H. 2013. *Marine mammals and noise*, Academic press.

Richardson, W. J. & Würsig, B. 1997. Influences of man-made noise and other human actions on cetacean behaviour. *Marine & Freshwater Behaviour & Phy,* 29**,** 183-209.

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

Royal Government of Cambodia 2007. Law on Fisheries.

Royal Government of Cambodia 2009. Sub-Decree 123 អនក្រ. បក On The Determination of Types of Fisheries and Engendered Fisheries Products.

Royal Government of Cambodia, 2012. Sub-decree on the Creation of the Mekong River Dolphin's Managerial Protection Zones, 25th September, 2012.

Russell, W. C., Thorne, E. T., Oakleaf, R. & Ballou, J. D. 1994. The genetic basis of black-footed ferret reintroduction. *Conservation Biology,* 8**,** 263-266.

Ryan, G. E. 2012. Last chance for dolphins in Laos. *In:* a Technical Report from WWF-Greater Mekong Programme, H., Vietnam (ed.).

Ryan, G. E. 2014. The Don Sahong dam and the Mekong dolphin: an updated review of the potential impacts of the Don Sahong Hydropower Project on the Mekong River's critically endangered Irrawaddy dolphins (Orcaella brevirostris). Report prepared for WWF-Greater Mekong.

Ryan, G. E., Dove, V., Trujillo, F. & Doherty, P. F. 2011. Irrawaddy dolphin demography in the Mekong River: an application of mark–resight models. *Ecosphere,* 2**,** 1-15.

Sarrazin, F. & Barbault, R. 1996. Reintroduction: challenges and lessons for basic ecology. *Trends in Ecology & Evolution,* 11**,** 474-478.

Saunders, D. A., Hobbs, R. J. & Margules, C. R. 1991. Biological consequences of ecosystem fragmentation: a review. *Conservation biology,* 5**,** 18-32.

Schiemer, F., Keckeis, H., Winkler, G. & Flore, L. 2000. Large rivers: the relevance of ecotonal structure and hydrological properties for the fish fauna. *ARCHIV FUR HYDROBIOLOGIE-SUPPLEMENT-,* 135**,** 487-508.

Schilt, C. R. 2007. Developing fish passage and protection at hydropower dams. *Applied Animal Behaviour Science,* 104**,** 295-325.

Schmutz, S. & Mielach, C. 2015. Review of Existing Research on Fish Passage through Large Dams and its Applicability to Mekong Mainstream Dams. *MRC Technical Paper No. 48. Mekong River Commission, Phnom Penh, Cambodia. 149 pp. ISSN: 1683-1489*.

Seal, U. S. 1989. *Conservation biology and the black-footed ferret*, Yale University Press.

Shaffer, M. 1987. Minimum viable populations: coping with uncertainty. *Viable populations for conservation,* 69**,** 86.

Shaffer, M. L. 1981. Minimum population sizes for species conservation. *BioScience,* 31**,** 131-134.

Sinha, R. 2000. Status of the Ganges river dolphin(Platanista gangetica) in the vicinity of Farakka barrage, India. *Occas. Pap. IUCN Species Survival Comm.,* 23**,** 42-48.

Smith, B. 2004. Orcaella brevirostris (Ayeyarwady River subpopulation). *The IUCN Red List of Threatened Species 2004: e.T44556A10919593.* Available from: http://dx.doi.org/10.2305/IUCN.UK.2004.RLTS.T44556A10919593.en. (Accessed on 05 December 2016).

Smith, B. & Beasley, I. 2004. Orcaella brevirostris (Mekong River subpopulation). *The IUCN Red List of Threatened Species 2004: e.T44555A10919444.* http://dx.doi.org/10.2305/IUCN.UK.2004.RLTS.T44555A10919444.en.

Smith, B. & Braulik, G. T. 2012. Platanista gangetica. *The IUCN Red List of Threatened Species 2012: e.T41758A17355810.* Available from: http://dx.doi.org/10.2305/IUCN.UK.2012.RLTS.T41758A17355810.en.

Smith, B. & Reeves, R. 2000. Survey methods for population assessment of Asian river dolphins. *Biology and conservation of freshwater cetaceans in Asia***,** 97-115.

Smith, B., Thant, H., Lwin, M. & Cindy, S. 1997. Investigation of cetaceans of the Ayeyarwady River and northern coastal waters of Myanmar. *Asian Marine Biology* 14**,** 173-194.

Smith, B., Zhou, K., Wang, D., Reeves, R., Barlow, J., Taylor, B. & Pitman, R. 2008. Lipotes vexillifer. *The IUCN Red List of Threatened Species 2008: e.T12119A3322533.* Available from: http://dx.doi.org/10.2305/IUCN.UK.2008.RLTS.T12119A3322533.en.

Smith, B. D. 1993. 1990 Status and conservation of the Ganges River dolphin Platanista gangetica in the Karnali River, Nepal. *Biological Conservation,* 66**,** 159-169.

Smith, B. D., Haque, A. A., Hossain, M. S. & Khan, A. 1998. River dolphins in Bangladesh: conservation and the effects of water development. *Environmental management,* 22**,** 323-335.

Smith, B. D. & Reeves, R. R. 2012. River Cetaceans and Habitat Change: Generalist Resilience or Specialist Vulnerability? *Journal of Marine Biology,* 2012.

Smith, B. D., Sinha, R. K., Kaiya, Z., Chaudhry, A. A., Renjun, l., Ding, W., Ahmed, B., Haque, A. A., Mohan, R. & Sapkota, K. 2000. Register of water development projects affecting river cetaceans in Asia. *Occ. Papers IUCN SSC,* 23**,** 22-39.

Sok, K., Claassen, A.H., Wright, H.L., Ryan, G.E. 2012. Waterbird nest protection on the Mekong River: a preliminary evaluation with notes on the recovery and release of white-shouldered ibis *Pseudibis davisoni* chicks. Cambodian Journal of Natural History 2012(1): 29–41

Soto, A. B., Marsh, H., Everingham, Y., Smith, J. N., Parra, G. J. & Noad, M. 2014. Discriminating between the vocalizations of Indo-Pacific humpback and Australian snubfin dolphins in Queensland, Australia. *The Journal of the Acoustical Society of America,* 136**,** 930-938.

Soulé, M. E. 1987. *Viable populations for conservation*, Cambridge university press.

Southall, B. L., Bowles, A. E., Ellison, W. T., Finneran, J. J., Gentry, R. l., Greene Jr, C. R., Kastak, D., Ketten, D. R., Miller, J. H. & Nachtigall, P. E. 2007. Overview. *Aquatic mammals,* 33**,** 411.

Stacey, P. J. & Hvenegaard, G. T. 2002. Habitat use and behaviour of Irrawaddy dolphins (Orcaella brevirostris) in the Mekong River of Laos. *Aquatic Mammals,* 28**,** 1-13.

Steckenreuter, A., Harcourt, R. and Möller, L., 2012. Are Speed Restriction Zones an effective management tool for minimising impacts of boats on dolphins in an Australian marine park? *Marine Policy*, *36*(1), pp.258-264.

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

Taft, E. 2000. Fish protection technologies: a status report. *Environmental Science & Policy,* 3**,** 349-359.

Thomas, C. 1990. What do real population dynamics tell us about minimum viable population sizes? *Conservation Biology,* 4**,** 324-327.

Timmins, R. 2006. An assessment of the biodiversity conservation significance of the Mekong Ramsar site, Stung Treng, Cambodia. *Mekong Wetlands Biodiversity Conservation and Sustainable Use Programme, Stung Treng, Cambodia*.

Turnpenny, A. 1988. Fish impingement at estuarine power stations and its significance to commercial fishing. *Journal of Fish Biology,* 33**,** 103-110.

Turvey, S. 2009. *Witness to extinction: how we failed to save the Yangtze River dolphin*, Oxford University Press, USA.

Tyack, P. L. 2008. Implications for marine mammals of large-scale changes in the marine acoustic environment. *Journal of Mammalogy,* 89**,** 549-558.

Urick, R. J. 1983. The noise background of the sea: ambient noise level. *Principles of Underwater Sound. Peninsula Publishing, Los Altos, California***,** 202-236.

Valbo-Jørgensen, J., Coates, D. & Hortle, K. 2009. Fish diversity in the Mekong River basin. *The Mekong: Biophysical Environment of an International River Basin. Amsterdam, Elsevier Publishers***,** 161-196.

Van Parijs, S. M., Parra, G. J. & Corkeron, P. J. 2000. Sounds produced by Australian Irrawaddy dolphins, Orcaella brevirostris. *The Journal of the Acoustical Society of America,* 108**,** 1938-1940.

Van Zalinge, N., Nao, S., Touch, S. & Deap, L. 2000. Where there is water, there is fish? Cambodian fisheries issues in a Mekong River basin perspective. *ICLARM Studies and Reviews-Int. Center for Living Aquatic Resources Management (Philippines)***,** 37-48.

Vörösmarty, C. J., McIntyre, P. B., Gessner, M. O., Dudgeon, D., Prusevich, A., Green, P., Glidden, S., Bunn, S. E., Sullivan, C. A. & Liermann, C. R. 2010. Global threats to human water security and river biodiversity. *Nature,* 467**,** 555-561.

Wade, P. R. 1998. Calculating limits to the allowable human-caused mortality of cetaceans and pinnipeds. *Marine Mammal Science,* 14**,** 1-37.

Wang, D., Zhang, X., Wang, K., Wei, Z., Wursig, B., Braulik, G. T. & Ellis, S. 2006a. Conservation of the baiji: no simple solution. *Conservation biology,* 20**,** 623-625.

Wang, K., Wang, D., Zhang, X., Pfluger, A. & Barrett, L. 2006b. Range-wide Yangtze freshwater dolphin expedition: The last chance to see Baiji? *Environmental Science and Pollution Research,* 13**,** 418-424.

Weber, D. S., Stewart, B. S., Schienman, J. & Lehman, N. 2004. Major histocompatibility complex variation at three class II loci in the northern elephant seal. *Molecular Ecology,* 13**,** 711-718.

WWF. 2016. *Irrawaddy dolphins functionally extinct in Laos.* http://wwf.panda.org/wwf_news/?282590/Irrawaddy-dolphins-functionally-extinct-in-Laos*, posted 26th October, 2016.* [Online]. [Accessed].

Yang, G., Bruford, M. W., Wei, F. & Zhou, K. 2006. Conservation options for the baiji: time for realism? *Conservation biology,* 20**,** 620-622.

Young, A., Boyle, T. & Brown, T. 1996. The population genetic consequences of habitat fragmentation for plants. *Trends in Ecology & Evolution,* 11**,** 413-418.

Zhang, X., Wang, D., Liu, R., Wei, Z., Hua, Y., Wang, Y., Chen, Z. & Wang, L. 2003. The Yangtze River dolphin or baiji (Lipotes vexillifer): population status and conservation issues in the Yangtze River, China. *Aquatic Conservation: Marine and Freshwater Ecosystems,* 13**,** 51-64.

Zhou, K., Gao, A. & Sun, J. 1993. Notes on the biology of the finless porpoise in Chinese waters. *IBI Reports,* 4**,** 69-74.

Ziv, G., Baran, E., Nam, S., Rodríguez-Iturbe, I. & Levin, S. A. 2012. Trading-off fish biodiversity, food security, and hydropower in the Mekong River Basin. *Proceedings of the National Academy of Sciences,* 109**,** 5609-5614.