VOLUME 4
Technical
Appendices

Sambor Hydropower Dam Alternatives Assessment

Final Report

[Includes Comparison Of Dam And “No-Dam” Alternatives]

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

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Royal Government of Cambodia

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Sambor Hydropower Dam Alternatives Assessment

Final Report

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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.

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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
$m\ s\text{-}^1$	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

VOLUME 4 – TECHNCIAL APPENDICES

Appendix 1.1

NHI Team of Technical Experts

NHI Team of Technical Experts

1) Gregory Thomas, Project Manager/Chief of Party

   Mr. Thomas has over 35 years of experience as an environmental advocate, professor, and project manager. In addition to practicing natural resources law and planning, for the past 26 years Mr. Thomas has served as the founder and president of NHI. In this capacity, he has spearheaded many international projects focused on improving the management of developed river systems to protect biodiversity and restore natural values and environmental services, which have aggregated to several million USD in scale. His areas of expertise include water resources management and planning, hydropower reoperation, energy policy, international environmental law and conservation, and building negotiations and consensus processes for natural resources management projects.

2) Dr. George Annandale, Dam Engineering and Sediment Management Expert

   Dr. Annandale has more than 40 years of experience as a civil engineer specializing in water resources engineering. He offers services in the field of fluvial hydraulics, design and engineering; reservoir and water supply management; and hydrology and hydraulics. As a recognized expert in reservoir sedimentation management he has published numerous peer-reviewed papers and is author, co-author and contributing author to eight books on sedimentation and scour. He was named by International Water Power and Dam Construction as one of 20 engineers who globally made a significant contribution to dam engineering.

3) Thomas B. Wild, Hydrologic and Sediment Modeling

   Dr. Wild is a Postdoctoral Fellow at the School of Civil and Environmental Engineering, Atkinson Center for a Sustainable Future at Cornell University. His specialty is developing and applying new modeling tools for solving water resources and environmental problems, especially in the areas of storm water management, fluvial water quality, and reservoir sediment management.

4) Mr. Erland Jensen, Informatics

   Mr. Jensen has worked in a variety of positions in the Mekong River basin, including as a Chief Technical Advisor for the Mekong River Commission Secretariat and DANIDA. His expertise spans environmental impact analysis related to hydropower development, climate change, hydrology, sediment dynamics, nutrient processes and carbon balance to primary production and to fisheries productivity.

5) Dr. Peter Meier, Hydropower Economist

   Dr. Meier is a hydropower economist and consultant to the World Bank with extensive experience in risk assessment, and economic and financial analysis of hydro projects (in Asia including Trung Son (Vietnam), Dasu and Tarbela (Pakistan), Rampur and the Upper Krishna power projects (India), Nam Theun 2 (Laos)). He was formerly Chief Economist of Asia Power (a New Zealand based IPP), and has also advised ADB, KfW, UNDP, JBIC and many Governments (India, Philippines, and Vietnam) on tariff and power sector reforms, PPAs, environmental economics and investment appraisal.

6) Dr. Martin Mallen-Cooper, Fishery Science and Fishway Biologist

   Dr. Mallen-Cooper has been a fishway biologist for 30 years and has designed over 200 fishways in Australia and overseas, from fish locks and fish lifts on large dams to low-level pool-type and nature-like fishways. He works closely with engineers, managers and diverse interest groups, to develop solutions that are not only site-based but integrate ecological objectives over different spatial scales.

7) Dr. Ashley Halls, Fisheries Scientist

   Dr. Ashley Halls is a leading expert in inland fisheries management and assessment, particularly on interactions between fisheries and hydropower projects. He has worked in the Mekong region for more than a decade as a senior fisheries advisor to the MRC where he designed and led quantitative studies on the ecology of Mekong fish and their fisheries, and led the development of models to predict the cumulative impacts of dams on the Mekong's fisheries. As a consultant, he has also led projects to assess the vulnerability of Cambodia's fisheries and food security to mainstream and tributary dam development, as well as the vulnerability of Vietnam's catfish farming sector to upstream development. He has also advised clients on the impacts of hydropower projects on fish and fisheries in Lao PDR and Bhutan.

8) Dr. Lee Baumgartner, Freshwater Fish Ecologist

   Dr. Baumgartner is a Freshwater Fish Ecologist based at the Institute for Land, Water and Society at Charles Sturt University in Australia. His research has been in several broad areas, including fish passage and fish migration, dietary interactions among native fish species, the effectiveness of native fish stocking, and more recently, understanding mechanisms to help fisheries recover from human disturbance and quantifying the value of fish in a food security context in the Lower Mekong Basin.

9) Dr. Wayne Robinson, Wildlife Ecologist

   Dr. Robinson is a wildlife ecologist who has worked as a teaching and research academic at the University of Canberra, Charles Sturt University and the University of the Sunshine Coast – all in Australia - for 17 years. His experience spans data analysis and natural resource management themes and he aims to develop management and research techniques that can be employed in an environmentally, economically and socially sustainable manner.

10) William Bryan/Farmers Conservation Alliance, Fish Screen Technology

    FCA is a nonprofit social enterprise whose mission is to develop resource solutions for rural communities. The leader in the marketing and installation of the Farmers Screen™, a horizontal, flat-plate fish and debris screen, FCA is comprised of industry experts in fish screening and passage who conduct fish passage assessments; develop site specific recommendations for fish screens; and create fish passage and screening strategy for meeting state and federal requirements, reducing operational costs, and improving fish habitat.

11) Dr. Ian Cowx, Fishery Ecologist and Fisheries Resource Management Expert
Dr. Cowx is a Professor of Applied Fisheries Science & the Director of Hull International Fisheries Institute (HIFI), at the University of Hull in the UK. He has extensive experience in rehabilitation techniques for freshwater fisheries, integrated aquatic resource management planning, environmental impact assessment, particularly associated with water resources development schemes, and aquaculture extension in developing (Africa and Asia) and developed countries (UK, Europe and Australia).

12) Dr. Daniel Peter Loucks, Hydrology and Environmental Engineering
Dr. Loucks is an NHI Director and an experienced educator, researcher, and consultant with expertise in the fields of systems analysis, economic theory, ecology and environmental engineering to solve problems in regional water resources development and environmental quality management. He is a professor at Cornell University's School of Civil and Environmental Engineering and a visiting professor in Hydroinformatics and Systems Analysis at UNESCO-IHE Institute for Water Education in Delft, The Netherlands.

13) Dr. Mathias Kondolf, Fluvial Geomorphologist
Dr. Kondolf is a fluvial geomorphologist, environmental planner and Professor of hydrology, river restoration and environmental planning at the University of California, Berkeley. His current research includes the Lower Colorado, Sacramento, Trinity, and Klamath Rivers of California/Oregon; the Apalachicola River, Florida; and the Lower Mekong River.

14) Mr. Zan Rubin, Fluvial Geomorphologist
Mr. Rubin is a PhD student at the University of California, Berkeley, specializing in fluvial geomorphology and environmental restoration. His contribution to the project included modeling reservoir sediment trapping in Mekong River watershed under different dam construction scenarios.

15) John R. Irving, Power & Energy Engineering Expert
Mr. Irving is an electrical and power engineer with extensive experience in Project Financial & Economic Appraisal & Technical Due Diligence Assessments; Macro/Microeconomics, Risk Analysis, Project Management, Procurement, Environmental and Social Issues. He has worked for and with power companies and several International Finance Institutions (e.g. World Bank, Asian Development Bank and European Bank for Reconstruction and Development) on projects around the world. Currently, Mr. Irving works as an independent consultant providing technical advice on energy sector projects in South East Asia, Pacific Islands and Africa under various short term contracts. He holds a Bachelors and Masters Degree in Electrical & Communications Engineering from the Auckland University, New Zealand.

16) Solar Energy Institute of Singapore (SERIS)
A unit of the National University of Singapore, SERIS (www.seris.nus.edu.sg) is Singapore's national institute for applied solar energy research. SERIS conducts research, development, testing and consulting on solar energy technologies and their integration into power systems and buildings. The Institute's R&D spectrum covers materials, components, processes, systems and services, with an emphasis on solar photovoltaic cells, modules and systems. SERIS is

globally active but focuses on technologies and services for tropical regions, in particular for Singapore and South-East Asia. Led by Professor Armin Aberle (CEO) and Dr. Thomas Reindl (Deputy CEO), SERIS is comprised of a multi-disciplinary team of 150 scientists, engineers, technicians and PhD students. SERIS was retained by NHI to provide technical expertise on Assessing a Solar Power Alternative to Sambor Hydropower Dam. Members of the SERIS team that contributed to the Solar PV option in this final report include:

- Thomas Reindl, PhD.
- Monika Bieri, PhD.
- Yanqin Zhan, PhD.
- Lu Zhao, PhD.

17) Dr. Isabel Beasley, Dolphin Conservation Expert

Dr. Isabel Beasley has been involved with marine mammal research and conservation since 1996. She researched the Mekong River Irrawaddy dolphin population from 2001-2007, as part of her PhD with James Cook University, Australia. From 2012-2016, Isabel conducted a postdoctoral research fellowship, which collaborated with Traditional Owners and Indigenous Rangers to assess the status of inshore dolphins in the coastal waters of northern Australia. Isabel's primary research interests include coastal and riverine dolphin population dynamics and conservation biology, methodological considerations associated with marine mammal monitoring, evaluation of the effects of coastal and riverine developments on marine megafauna, and indigenous marine resource management.

18) Mr. Gerry Ryan, Dolphin Conservation Expert

Mr. Ryan is a conservation scientist focused on dolphin research in Southeast Asia. Currently, he is a Ph.D. candidate in Conservation Biology at the University of Melbourne, Australia, and he also serves as an advisor to World Wildlife Fund's River Dolphin Programme and he is a member of IUCN's SSC Cetacean Specialist Group. He has authored or co-authored several research articles and reports on Mekong dolphins.

19) Ly Nguyen Degai, Project Administration

Mrs. Degai holds a B.A. in Business Operation from Lake Forest College and M.S. in Risk Management from University of San Francisco. Ly has worked at NHI since 2011, working under various capacities, including project administration for NHI's domestic and international projects, as well as managing the organization's operations and development. She currently handles all financial and budgetary aspects for NHI's projects.

20) Jessica Peyla Nagtalon, Project Administration

Mrs. Peyla-Nagtalon helps coordinate NHI's international projects. She holds an M.S. in Environmental Management from the University of San Francisco, an M.S. in International Development Studies, and a B.A. in Biology and Environmental Studies from the University of California at Santa Cruz. She has over 15-years of experience working with non-profit organizations and has been at NHI since 2006. She also leads her own charitable project that helps young women in Kenya achieve their educational goals.

Appendix 6:

Identification of Sambor Alternative 7 Reservoir Operating Policies and their Multi-Objective Tradeoffs

Identification of Sambor Alternative 7 Reservoir Operating Policies and their Multi-Objective Tradeoffs

Prepared by Thomas B. Wild

1. Introduction

Chapter 6 proposes a single reservoir operating policy for Sambor Alternative 7 (Alt_7) that is intended to maximize energy production. This approach to specifying a single policy is based on the assumption that no significant tradeoffs among objectives such as hydropower production, larvae passage, and fish passage exist at the dam. Indeed, results from *HEC-RAS* modeling of the reservoir suggest that significant year-round larvae passage may be possible without much sacrifice in energy production. However, more conservative hydraulic modeling conducted using the *Tuflow* model suggest a circumstance in which high velocities (to improve the likelihood of larvae passage) are much more difficult to create in the reservoir throughout the year, so tradeoffs do exist between energy and fishery objectives. The results highlighted in this appendix demonstrate the complex array of potential conflicts among multiple objectives that could result at Sambor Alt_7 depending upon the ultimate nature of hydraulics at the upstream end of the reservoir and within the reservoir itself. The existence of these strong tradeoffs suggests that data to illuminate this complex hydraulic behavior (e.g., bathymetric data) will be critical to collect in future studies of Sambor Alt_7.

Given the complexity of the Sambor Alt_7 reservoir, with respect to reservoir hydraulics and site hydrology, as well as multiple potential conflicting hydropower and ecological objectives, the approach taken here was to identify, rather than specify, multiple alternative reservoir operation strategies. This appendix presents the development of a novel modeling framework, *PySedSim*, and its application to identifying and evaluating a suite of alternative reservoir operating policies for Sambor Alt_7. *PySedSim* is a daily time step stochastic river basin simulation model for flow, sediment and hydropower in networks of reservoirs and river channels. *PySedSim* was coupled with an evolutionary optimization model to create a simulation-optimization framework capable of identifying candidate Sambor Alt_7 operating policies and their resulting tradeoffs among ecological and energy production objectives. While the results presented below pertain to Sambor Alt_7, the modeling framework is generic, offering the flexibility to be used for any dam (or cascade of dams).

Taking an approach to searching for operating policies, rather than pre-specifying them, bears more discussion. This approach was taken because (1) site hydraulics and hydrology are exceedingly complex at Sambor Alt_7; and (2) multiple conflicting ecological and hydropower objectives exist, making it difficult to pre-specify an operating that performs well, especially under an uncertain hydrologic future.

Regarding site hydraulics, Chapter 6 demonstrates clearly the complexity of the Sambor Alt_7 reservoir. Specifically, the reservoir would have three completely unregulated upstream spillways into the main anabranch channel. 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 fractions of the main stem flow entering the reservoir. Additionally, the reservoir's water levels are not fully controllable. At lower main stem flow rates, it is not possible to achieve a full reservoir supply level, as the reservoir naturally equilibrates by emptying into the anabranch. Again, the nature of this hydraulic behavior was identified through hydraulic modeling with both a *HEC-RAS* model and a *Tuflow* model.

Due to this complexity, energy is not maximized by maintaining full storage levels in the reservoir, as maintaining full storage levels will result in excessive spilling. It is difficult to pre-specify an operating policy that maximizes energy production without doing some form of optimization, as this requires seasonally varying water levels so as to avoid excess spillage while still maintaining high hydraulic head. This is a unique result, because the Sambor Alt_7 reservoir is hydrologically very small. For example, if the reservoir maintained full storage throughout the year, it would have an average annual residence time of less than one week. Typically, reservoir operations are not considered to be particularly complex for a reservoir this small, so pre-feasibility studies specify a single rule curve operating policy (e.g., an energy maximizing run-of-river policy), much as if it is a design feature. This appendix demonstrates the danger of such an approach, even at a hydrologically small dam.

The remaining sections of this appendix describe

(1) the *PySedSim* simulation model used to stochastically evaluate the performance of candidate reservoir operating policies with respect to multiple objectives, and *PySedSim*'s input data requirements;

(2) the formulation of the multiple ecological and energy production objectives used to define performance of candidate reservoir operating policies;

(3) the approach taken to multi-objective optimization, including the definition of operating policy functions whose parameters are to be optimized; and

(4) application of the modeling framework to identifying tradeoffs composed of alternative reservoir operating policies at Sambor Alt_7.

2. Simulation Model and Basic Input Data Requirements

2.1. Simulation Model

PySedSim is an open-source, object-oriented river basin simulation model for flow, sediment and hydropower in networks of reservoirs and river channels. The model was developed in the Python programming language. *PySedSim* implements all of the functionality originally available *SedSim* (originally developed in Visual Basic for Applications), the user manual for which (Wild and Loucks, 2012) is freely available upon request. Additional details regarding *SedSim*'s approach to modeling suspended sediment production, transport, and reservoir trapping and management are detailed in Wild and Loucks (2015a). *SedSim* has been applied in other studies in the Mekong basin to evaluate reservoir sediment trapping potential (Wild and Loucks, 2014) and reservoir sediment management strategies such as flushing (Wild and Loucks, 2015b, 2015c). *PySedSim* also offers new features not available in *SedSim*, including stochastic (Monte Carlo) simulation, with capacity to handle stochastic hydrology, and stochastic sampling of sediment-related model parameters; and reservoir operating policy optimization. *PySedSim* will be available as an open-source simulation package on Github in 2017.

PySedSim was used to simulate three processes important to the ecological and energy production performance of Sambor Alt_7: (1) upstream and downstream fish passage, (2) maintenance of a natural sediment regime, and (3) hydropower production. *PySedSim* can simulate multiple reservoir sediment management techniques, including flushing, sluicing, bypassing, density current venting and dredging. At Sambor both the sediment flushing and sediment sluicing features in *PySedSim* are used. While developed for and applied in the Mekong River basin, *PySedSim* is a generic, data-driven model that can be applied in any river basin, and is particularly well suited for data-scarce regions.

In the study results presented in section 5, 100-year long simulations were run at a daily time step. A simulation duration of 100 years was selected because the effectiveness of various reservoir sediment management processes, evolves over long time periods.

The basic input data requirements for running the *PySedSim* model of Sambor Alt_7 and Sambor CSP are reviewed below. The primary input data are daily water and sediment load inflows. Significant inter-annual and intra-annual uncertainty exists in the historical sediment and hydrological records, so Monte Carlo simulations were run to expose operating policies to this uncertainty. About 500 different 100-year sequences of daily flows were generated, from which multiple random sequences were drawn to conduct each Monte Carlo simulation. As will be discussed, performance measures (defined in section 3 below) used in the optimization represent quantiles of the probability distribution of outputs resulting from the combined results of the multiple 100-year long simulations.

2.2. Basic Input Data Requirements

Basic input data requirements to run a *PySedSim* simulation include (1) hydroclimatic data, (2) sediment-related data (including sediment production, reservoir trapping, and reservoir management), and (3) reservoir and dam specifications data. Reservoir and dam specifications data are provided in the chapters of the main report (e.g., Chapter 6 on Sambor Alt_7). Note that specific data requirements and modeling approach for larvae passage and survival through and around the reservoir are addressed in the performance measure section.

2.2.1. Hydroclimatic Data

2.2.1.1. Daily reservoir water inflows

The 107-year long daily hydrologic record at Stung Treng gage, which is located just upstream of the Sambor Dam site, was used to synthetically generate 500 different 100-year long stochastic sequences of daily hydrologic inflows. Figure 6.2.1 shows the historical flows in blue and the synthetically generated flows in gray. The approach taken was identical to that described in Quinn *et al.* (in review), wherein auto-correlated sequences of monthly flows were generated using the method of *Kirsch et al.* (2013), disaggregating monthly flows into daily flows using the bootstrapping approach described in Nowak *et al*. (2010). To generate monthly flows, only the historical statistics (autocorrelation, mean, and variance) from the Stung Treng gage record were used. Multiple random sequences from this pool were drawn for a given Monte Carlo embedded in the optimization. Table 6.2.1 summarizes the key assumptions discussed above.

Table 6.2.1. Key simulation assumptions used to generate results in Section 5 of this appendix.

Duration of daily time step simulations (years)	100
Number of simulations embedded in a stochastic (Monte Carlo) simulation	5
Size of pool of 100-year long hydrologic sequences generated	100

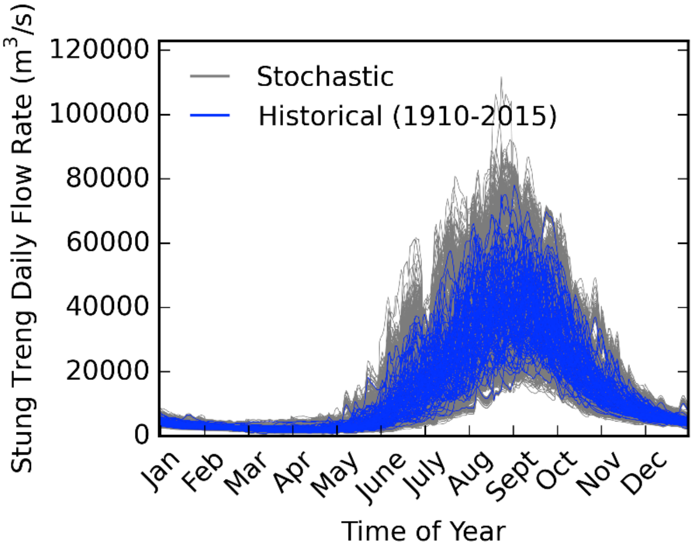

Figure 6.2.1. *Annual traces of daily flows for 105 years of historical daily flows (blue lines) at Stung Treng gage station near the Sambor Dam site. Synthetically generated flows are appear as gray lines.*

2.2.2. Sediment Data

2.2.2.1. Daily sediment loads

Daily sediment loads are also sampled in the Monte Carlo simulation. Each 100-year long sequence of daily sediment load inflows is generated using a rating curve that specifies sediment load as a function of discharge (see Eq. 1 below). The approach implemented in generating separate 100-year sequences of daily sediment loads is described in detail in Wild and Loucks (2012, 2015b). A rating curve relationship, based on the power regression of suspended sediment concentration, Cs (kg/m3), on discharge, Q (m3/s), is given by Eq. A1 as follows:

$$C_s=aQ^b \qquad (1)$$

Prior to dam development, the Mekong's watershed delivered approximately 160 million metric tons (Mt) of suspended sediment per year to the South China Sea (Milliman and Meade, 1983). Reservoir sediment trapping has reduced the sediment load transported past the dam site to 72.5 Mt/yr on average, as recorded at the Stung Treng gage from 2009-2013 (Koehnken, 2014). Data from Koehnken (2014) were used to parameterize Eq. 1. These parameters are the same in every simulation, so the mean annual sediment load is 72.5 Mt/yr, but varies across years as hydrology varies.

2.2.2.2. Daily sediment trapping at Sambor Alt_7

Input assumptions related to sediment trapping are summarized in Table 6.2.2. During simulated days when reservoir sediment management operations (sluicing and flushing) are not taking place, the fraction of inflowing sediment mass trapped during each time period, or trapping efficiency, is determined using the Brune (1953) curve method. Using this method, trapping efficiency is a function of sediment size and residence time of water in the reservoir. The Brune method has been shown to provide adequate long-term reservoir trapping efficiency estimates for ponded reservoirs throughout the world. Numerous Mekong Basin studies of sediment trapping have applied the Brune method (Fu and He, 2007; Kummu and Varis, 2007; Kummu *et al.,* 2010;

Kondolf *et al*., 2014; Wild and Loucks, 2014). In this study, the median sediment coarseness curve from Brune (1953) was used.

Within the reservoir's storage capacity, the volume occupied by settled sediment mass depends on its bulk density, which is determined in part by the sediment composition, the extent to which the sediment is submerged in water, and sediment compaction processes, none of which were considered in this study. Instead, the bulk density of sediment was assumed to be 1100 kg/m^3, selected to represent the density of sediment in the Vietnam Delta (Xue *et al*., 2010). Based on a study by Lara and Pemberton (1963) of over 100 reservoir sites, 1100–1500 kg/m^3 is a reasonable range for the density of reservoir sediment deposits, so the use of 1100 kg/m^3 is conservative.

Table 6.2.2. Summary of important assumptions related to reservoir sediment trapping.

Brune curve (Brune 1953)	Median
Bulk density of deposited sediment (1100 kg/m^3)	1100

2.2.2.3. Daily reservoir sediment management

Sluicing and flushing are both feasible techniques to implement at Sambor Alt_7, as is discussed in previous chapters of the report. The sluicing and flushing techniques to sediment pass-through and removal are reviewed by Annandale (2013). Sediment sluicing involves annually opening sluice gates at Sambor Alt_7 during the monsoon season to release all reservoir inflow, and associated sediment suspended, in excess of powerhouse discharge capacity. For this reason, sluicing does not reduce power production, as it is only performed with flow that would otherwise be spilled.

Some sediment trapping will occur at times of year when sluicing is not taking place. Reservoir sediment flushing is conducted infrequently to remove these accumulated sediments. Sediment flushing requires full drawdown of the reservoir, such that free flow conditions are achieved and scour of deposited sediments can occur. Flushing is conducted by opening the sluice gates, just as is done with sluicing. More frequent flushing, and extended periods of drawdown, result in more significant flushing impacts on energy production. The theoretical basis of the approaches taken to simulating sluicing and flushing in *PySedSim* are reviewed in Wild and Loucks (2012).

2.2.2.3.1. Sediment Sluicing

PySedSim implements the Churchill (1948) approach to compute daily reservoir sediment trapping efficiency during sluicing. This approach is mainly a function of reservoir length. These assumptions are summarized in Table 6.2.3.

Table 6.2.3. Sediment sluicing input data and assumptions for Sambor Alt_7.

Reservoir inflow above which sluicing occurs (m^3/s)	14000
Reservoir length (m)	30000

2.2.2.3.2. Sediment Flushing

The approach in *PySedSim* to simulating flushing, based on Atkinson (1996), is detailed in Wild and Loucks (2012). The flushing process includes drawing the reservoir down to achieve free-flow conditions, maintaining drawdown for some specified duration to remove sediment, and refilling of the reservoir. This process occurs at any user-specified integer frequency (e.g., at regular intervals of 1 year, 5 years, 20 years, etc.). The amount of sediment removed during a given event depends on the amount of sediment deposited in the reservoir, and the shape of the incised flushing channel.

The majority of these flushing factors are pre-specified, remaining the same across the pareto approximate suite of policies that emerge from the simulation-optimization framework. However, some factors are decision variables in the optimization experiment, including: flushing frequency (constrained to a range of every 1-15 years), *g*; flushing start date in a given year (constrained to a range of days 120-225), *d*; and the reservoir inflow triggering drawdown (constrained to a range of 6000-10000 m^3/s), *h*. Table 6.2.4 below summarizes flushing assumptions for the results presented in this appendix.

Table 6.2.4. Sediment flushing input data and assumptions for Sambor Alt_7. Where ranges are specified, these factors were included as optimization decision variables in all simulation-optimization experiments.

	Value	**Decision variable in optimization?**
Date in a given year after which drawdown can be initiated	120-225	Yes
Reservoir inflow triggering drawdown, after start date (m^3/s)	6000-10000	Yes
Frequency (years)	1-15	Yes
Flushing duration (days)	5	No
Target free-flow water surface elevation during flushing (masl)	22	No
Target flushing discharge, i.e. reservoir inflow during drawdown (m^3/s)	8000	No
Maximum drawdown rate (m/day)	2	No
Reservoir bottom width at dam	1000	No
Reservoir representative side slope (m/m)	0.1	No

2.2.3. Reservoir and Dam Specifications

The Sambor Alt_7 dam and reservoir specifications are provided in Chapter 6. Some additional details bear additional discussion here.

2.2.3.1. Site Hydraulics Controlling Reservoir Inflows

Fig. 2.2 is an image from Google Earth of the upstream end of the Sambor Alt_7 reservoir. The reservoir would have three completely unregulated natural spillways into the anabranch channel. These are marked by three blue arrows in Figure 6.2.2. The result, as revealed by hydraulic modeling, is that the reservoir's inflow is nonlinearly controlled by both the reservoir's water level and the main stem Mekong flow rate. This creates an exceptionally complex reservoir, wherein higher water levels result in lower reservoir inflows, and vice versa for lower reservoir water levels.

Figure 6.2.2. *Satellite image of the upstream end of the Sambor Alt_7 reservoir site, with blue arrows indicating natural spillways into the anabranch channel.*

To simulate daily reservoir inflows, two-dimensional hydraulic modeling (in Tuflow) was conducted to develop a relationship between reservoir inflow and the combination of reservoir water level and main stem flow rate. Figure 6.2.3 shows a sample of hydraulic modeling outputs from Tuflow for three example main stem flow rates (m3/s) and a range of reservoir water surface elevations.

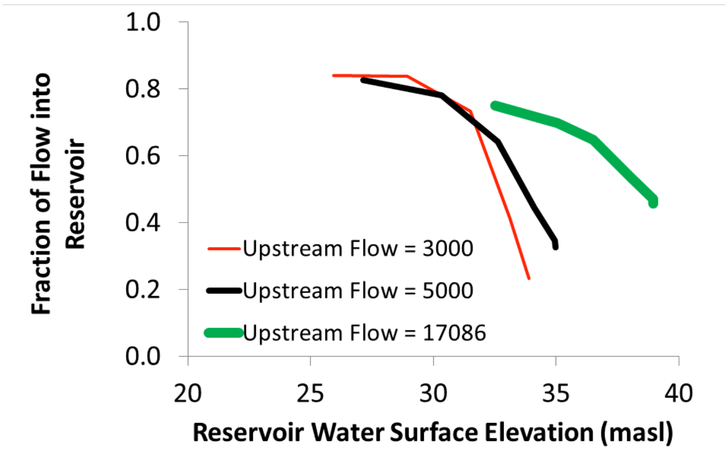

Figure 6.2.3. *Modeled rate of spillage into the anabranch channel as a function of water surface elevation and reservoir inflow using model Tuflow. Reservoir inflows are lower at higher water levels, and vice versa at lower water levels.*

It is important to note that the reservoir's water levels are not fully controllable. At lower main stem flow rates, it is not possible to achieve a full reservoir level, as the reservoir naturally equilibrates by emptying into the anabranch. These results are critical in shaping the multi-objective tradeoffs among the objectives defined in section 3 below. These hydraulic modeling outputs represent a source of significant uncertainty in the analysis to follow, as the results are highly dependent on the poorly understood bathymetry of the river.

2.2.3.3. Sambor Alt_7 partitioning of flow between the anabranch channel and the fish pass

Referring to the Sambor Alt_7 aerial schematic in Figure 6.2.2, the fish bypass channel (indicated by the number 4 in the figure) connects the anabranch channel to the tailwater of the dam's powerhouse. As fish are attracted to flow, this siting/design feature accounts for the likelihood that during upstream migration many fish will migrate to just downstream of the powerhouse, failing to locate the downstream-most entrance to the anabranch channel. The distribution of flow westward into this fish pass, versus continuing southward into the anabranch channel, is important not only for fish passage, but also because it affects the dam's tailwater elevation and resulting hydropower production. Table 6.2.5 summarizes the results of hydraulic modeling to identify the fractional partitioning of flow at different flow rates.

Table 6.2.5. Corresponding to Sambor Alt_7, this specifies the modeled fraction of flow rate in the anabranch channel that is distributed to the west through the fish pass to the main stem of the river (at the dam's tailwater) versus southward into the anabranch channel that eventually reaches the main stem.

Anabranch flow rate before partition (m3/s)	Fraction distributed through fish pass to main stem	Fraction distributed down anabranch channel
682	0.22	0.78
1862	0.29	0.71
2467	0.32	0.68
2674	0.31	0.69
3251	0.32	0.68
2617	0.34	0.66
4423	0.35	0.65
4571	0.36	0.64
7021	0.38	0.62
9864	0.42	0.58
13417	0.43	0.57
16761	0.44	0.56
18113	0.43	0.57
19749	0.41	0.59
21384	0.40	0.60
23020	0.39	0.61
50000	0.39	0.61

3. Objectives and Performance Measures

The performance of policies at Sambor Alt_7 was evaluated with respect to six objectives that fall into three categories: (1) upstream and downstream fish passage, (2) maintenance of a natural sediment regime, and (3) hydropower production.

The results presented in section 5 of this appendix are just an example of results emerging after iterating through multiple competing problem formulations, wherein different combinations of objectives were explored (and the objectives' temporal and statistical definition). Some measures were excluded from the final formulation in section 5 because they did not produce strong tradeoffs with other objectives, such as long-term sediment passage and wet season anabranch flow rate. Those removed objectives are not defined below.

All of these objectives below are simply surrogate measures for extremely complex ecological processes. They are intended to serve as an entry point for a discussion about diverse stakeholder preferences.

3.1. Comments on the Temporal and Statistical Composition of Performance Measures

Each of the six performance measures included in this study is a temporal and statistical manipulation of one of the following four daily time series state variables in *PySedSim*: anabranch attraction flow rate (m^3/s), daily larvae flow fraction of (fraction, 0-1), energy production (Gigawatt-hours/day, GWh/day), and sediment load released from the dam during flushing events (kg/day). Each of these four time series variables is discussed in more detail below, after which their manipulation to define six seasonal and probabilistic measures is discussed.

For each year in a given 100-year simulation, representative wet season and dry season values for each of these previous four time series variables was computed by averaging values across the days contained in each season within the year. The dry season is demarcated by main stem flow rates below 8000 m^3/s, whereas the wet season occurs for values above 8000 m^3/s. Thus, each 100-year simulation results in 100 values for each seasonal performance measure. As each Monte Carlo simulation consists of five of these 100-year simulations, each measure has a probability distribution comprised of 500 values. Performance is maximized or minimized with respect to the 1st percentile of the empirical cumulative distribution function (CDF) for those 500 values. Each Monte Carlo is comprised of five simulations because, across policies, this resulted in convergence of all performance measures across all quantiles in the CDF. This approach is intended to identify policies that are robust, in that they are expected to perform well in an approximation of worst-case conditions. Performance was maximized in all objectives except for the sediment-related objective, is minimized.

Dry and wet season values are demarcated using a flow rate (see Figure 6.3.1) because the peak periods of larvae drift past the Sambor Dam site occurs at approximately 8,000 m^3/s on average (Cowx *et al.,* 2015). This does not align exactly with rigorous definitions of Mekong hydrologic seasons. The performance measures used here are simply rough approximations of seasonality defined to effectively capture the tradeoffs among ecological and energy objectives.

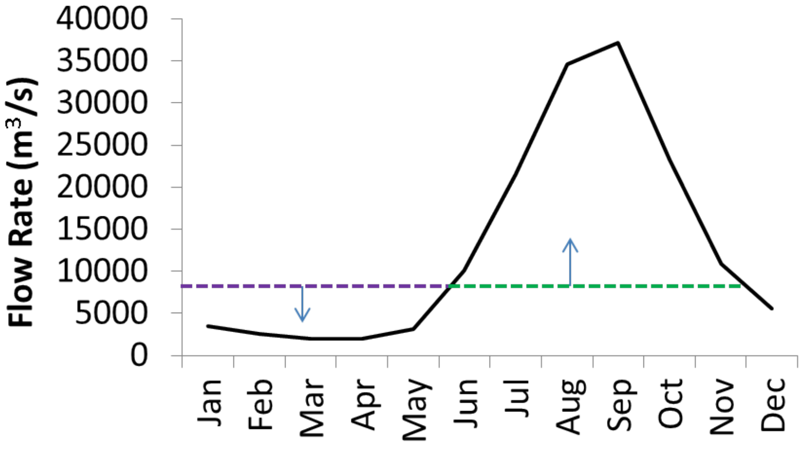

Figure 6.3.1. *Mean daily flow rates on main stem of Mekong River at Stung Treng gage station different months of the year. The dashed line indicates a main stem flow rate of 8,000 m^3/s, which was used in this study to demarcate wet season from dry season performance measures values. Values below the dashed line (purple) occur during the dry season, whereas values above the dashed line (green) indicate wet season.*

Below, each of the four categories of objectives (energy production, larvae passage, fish attraction flow, and sediment flushing load) are introduced, including providing a rationale for the modeling approach and mathematical definition of the measure.

3.2. Hydropower Energy Production

3.2.1. Modeling Approach and Rationale

The *PySedSim* state variable for daily energy production (GWh), E_t, **i**s computed as follows:

$$E_t = f(x) = \begin{cases} eg\bar{h}_t q_t^{tur}(10^{-6}), & \bar{h}_t \geq h_{min} \\ 0, & \bar{h}_t < h_{min} \end{cases}$$

where:
e = turbine efficiency
g = gravitational constant
$\bar{h}_t$ = average net hydraulic head during time period *t*, which varies given the discharge vs. tailwater elevation curve provided
q_t^{tur} = turbine flow during time period *t*
h_{min} = minimum allowable net hydraulic head for power production to occur

3.2.2. Mathematical Definition of Performance Measure

Included in this study are two energy-related performance measures: (1) Annual energy production, J_{Hydro}^{ann}, and (2) Dry season energy production, J_{Hydro}^{dry}. Both are defined separately below.

1. Annual Energy Production (Gigawatt-hours, GWh), 1st percentile of annual values

The 1st percentile effectively represents an approximation of the "worst case" annual energy production value. One would expect a value of energy production equal to or less than this value to occur only once every 100 years.

Annual energy production is given by:

$x_A = \sum_{t=1}^{365} E_t^{m,n}$ for each year *n* in [1, N_S] and each stochastic realization *m* in [1, M]
where:
t = day of a year *n* [1, 365]
n = year of simulation
m = stochastic realization number in ensemble of stochastic realizations φ
N_S = number of years in a simulation = 100
M = number of Monte Carlo simulations in each "function evaluation" of stochastic optimization = 5

The first energy-related performance measure is defined by inverting the cumulative distribution function (CDF) for annual energy production, F_{x_a}, at the 1st percentile of annual energy production:

$$J_{Hydro}^{ann} = F_{x_A}^{-1}(p)$$

where:

F^{-1} =Inverse empirical CDF of x_A
p = selected quantile = 0.01

2. Dry season energy production (Gigawatt-hours, GWh) , 1st percentile of annual values

This represents the portion of annual energy production that takes place when strong competition for a limited water supply exists among energy and ecosystem objectives. The 1st percentile effectively represents an approximation of "worst case" dry season energy production. One would expect a value of dry season energy production equal to or less than this value to occur only once every 100 years.

Dry season energy production in a given year is given by:

$x_d = \sum_{t=1}^{365} E_t^{m,n}$ for each year *n* in [1, N_S] and each stochastic realization m in [1, M], for any t ∈ Y

where:
t = day of a year *n* [1, 365]
n = year of simulation
$Qs_t^{m,n}$ is the daily flow rate (m^3/s) just upstream of the reservoir, before distribution to the reservoir or anabranch
q_l= 0 m^3/s, lower threshold of main stem flow rate at Stung Treng gage
q_u= 8,000 m^3/s, upper threshold of main stem flow rate at Stung Treng gage for dry season
Y = any *t* where $q_l \leq Qst_t^{m,n} \leq q_u$
m = stochastic realization number in ensemble of stochastic realizations φ
N_S = number of years in a simulation = 100
M = number of Monte Carlo simulations in each function evaluation of stochastic optimization = 5

The second performance measure is defined by inverting the empirical cumulative distribution function (CDF) for dry season total energy production, F_{x_d}, at the 1st percentile:

$$J_{Hydro}^{dry} = F_{x_d}^{-1}(p)$$

where:
F^{-1} =Inverse empirical CDF of x_d
p = selected quantile = 0.01

3.3. Migratory Fish Passage

3.3.2. Modeling Approach and Rationale

Especially during downstream passage, fish can either enter the anabranch to circumnavigate the dam or swim through the reservoir to the dam. Effectiveness of passage through the dam, either through the turbines or the sluice gates, is difficult to assess at this time because it will depend on the ultimate turbine and sluice gate designs. It is also difficult to quantitatively assess how effectively dam design features such as the fish locks and the right bank fish pass will be given they have not ever been implemented in this combination at a tropical dam. Thus, this assessment focused on the effectiveness of fish passage in the anabranch channel, as the anabranch channel is intended to serve as the primary means for fish to circumnavigate the dam.

Unfortunately, given the sheer biomass and diversity of Mekong fish migrating past the dam site, it is not possible to establish credible ecohydrologic and ecohydraulic criteria for safe fish attraction and passage in the anabranch channel. Rivers with small fish and biomass can have small fishways, but in large tropical rivers like the Mekong, fishways must be sized to accommodate large fish, large biomass and high flows. In the absence of other criteria, flow rate in the anabranch is used as a surrogate for fish pass effectiveness. The fundamental assumption made here is that more fish are attracted to flow, so more flow in general will attract more fish, and will provide more cross-sectional space for the large biomass of migrating fish. While flow may represent one aspect of the effectiveness of the fishway, is it still just one surrogate measures, and does not of course represent effectiveness of fish passage through the anabranch channel, nor does it represent the effectiveness of downstream fish passage though the dam's hydraulic infrastructure. Directly assessing fish survival would require integrating into the *PySedSim* modeling approach an accounting of mortality factors associated with factors such as barotrauma and blade strike.

The total daily anabranch channel inflow rate (m^3/s), Q_t, is the *PySedSim* time series variable used as one measure to evaluate the effectiveness of fish attraction into the anabranch. The location of measurement for this time series value is explained in Figure 6.3.2. Time series of values for this variable are given by the relationships between reservoir inflow and the combination of reservoir water surface elevation and main stem flow rate. These relationships were determined through hydraulic modeling in Tuflow, as described below.

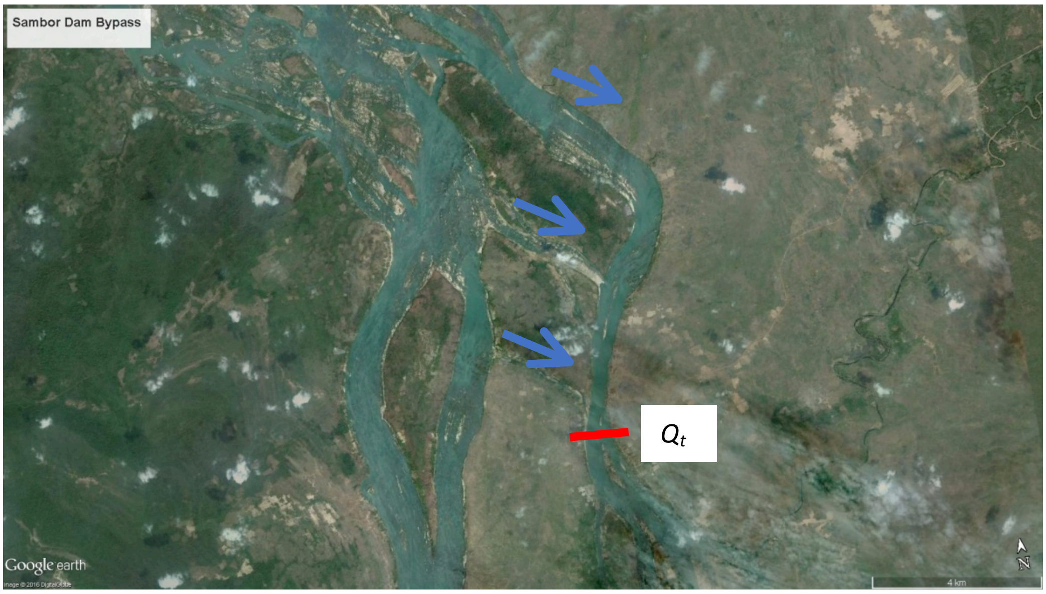

Figure 6.3.2. *A Google Earth image of the Mekong River at the Sambor Dam site. A red line on the anabranch channel indicates the location to which the time series state variable Q_t pertains.*

3.3.3. Mathematical Definition of Performance Measures

Included in this study is one fish migration-related performance measure: (1) Dry season bypass flow, J_{Fish}^{dry}. Wet season fish pass flow rate, J_{Fish}^{wet}, was removed from the simulation-optimization formulations for which results are presented in section 5 because enough water is available on an annual basis in the wet season to fill the anabranch channel to capacity. Thus, J_{Fish}^{wet} was not in strong conflict with other objectives.

1. Dry season mean daily bypass flow rate, 1st percentile of annual values.

The flow rate during the dry season is important to maintain because some fish migrate upstream and downstream during the dry season. The 1st percentile effectively represents an approximation of the "worst case" year's dry season average anabranch flow rate. One would expect an average dry season flow rate equal to or less than this value to occur only once every 100 years.

Dry season mean daily bypass flow rate in a given year is given by:

$x_d = \frac{1}{365}\sum_{t=1}^{365}(Q_t^{Ana})^{m,n}$ for each year *n* in [1, N_S] and each stochastic realization m in [1, M] , for any t $\in Y$

where:
t = day of a year *n* [1, 365]

n = year of simulation
Q_t^{Ana} = daily flow rate in the anabranch channel at the location indicated in Fig. 3.2.
$Qst_t^{m,n}$ is the daily flow rate (m^3/s) just upstream of the reservoir, before distribution into the reservoir or anabranch
q_l= 0 m^3/s, lower threshold of main stem flow rate at Stung Treng gage defining the dry season
q_u= 8,000 m^3/s, upper threshold of main stem flow rate at Stung Treng gage defining the dry season
Y = any t where $q_l \leq Qst_t^{m,n} \leq q_u$
m = stochastic realization number in ensemble of stochastic realizations φ
N_S = number of years in a simulation = 100
M = number of Monte Carlo simulations in each function evaluation of stochastic optimization = 5

The performance measure is defined by inverting the empirical cumulative distribution function (CDF) for dry season daily anabranch flow rate in each year, F_{x_d}, at the 1st percentile:

$$J_{Fish}^{dry} = F_{x_d}^{-1}(p)$$

F^{-1} =Inverse empirical CDF of x_d
p = selected quantile = 0.01

3.4. Fish Larvae Passage

3.4.1. Background and Motivation

Many of the Mekong's migratory fish species annually migrate upstream past the Sambor Dam site to spawning grounds on the main stem and tributaries. After spawning, these adult fish swim back downstream to the floodplains to feed and grow. At the spawning grounds, fish eggs eventually become larvae. Once suspended in the water column, these larvae passively drift back downstream, through the Sambor Dam site, to the Mekong's lower floodplains to feed and grow. Larvae that drift in the wet season typically drift at higher concentrations and represent species that exist in the largest numbers, thus contributing the most to overall fishery productivity. While potentially less important to Mekong's total fishery productivity, species spawning in the dry season still contribute to biodiversity, and are thus critical to sustaining the complex Mekong food web's productivity. Larvae are vulnerable to death, through predation and starvation, if trapped in a reservoir impoundment while drifting downstream. This impact has been observed most extensively in South America (Agostinho *et al.*, 2007; Pelicice and Agostinho, 2008; Pelicice *et al.*, 2015; Pompeu *et al.*, 2011), with impacts on pelagic fish species in some river basins observed as well (Dudley and Platania, 2007; Wilde and Urbanczyk, 2013; Pelicice *et al.,* 2015). No tropical dam project has considered drifting larvae in its design or operation. This is likely the main reason large riverine species have disappeared from large tropical dams, notably in South America.

3.4.2. Available Data

Larvae data available to inform our modeling approach are discussed in Chapter 7. Knowledge was drawn from two fish larvae studies conducted in the Mekong basin: 1) the Cowx et al. (2015) regional study conducted for one year at 11 sites along the entire lower Mekong River, and 2) the Inland Fisheries Research and Development Institute (IFReDI) long-term study, which has collected 13 million samples of larvae from 76 species (annually, over a span of 14 years) in the Mekong River near Phnom Penh and in Tonle Sap Lake. The two data collection efforts suggest two key points: (1) different species of fish spawn at different flows and different times of year, including the dry season; and (2) peak spawning for many species occur during the rising limb of the hydrograph, declining again after the peak flow of the monsoon season.

Using the data from Cowx et al. (2015), peak periods of downstream larvae drift for several representative carp and catfish species were identified to occur for main stem flows exceeding approximately 8,000 m^3/s at Stung Treng gage. This flow threshold was used as a rough means of demarcating dry and wet season performance across all fish- and energy-related objectives.

3.4.3. Modeling Approach and Rationale

Larvae drifting downstream can enter either the reservoir or the anabranch channel. Larvae entering the anabranch channel are likely to safely circumnavigate the dam. However, the reservoir poses an array of more serious threats to larvae survival. First, larvae entering the reservoir's slowly moving water can sink to the reservoir's bottom, where they are prone to starvation. Second, the reservoir's relatively slow-moving and clear water pose an increased predation risk to larvae. Third, larvae that do safely navigate through the reservoir to the dam face a variety of risks when passing through either the dam's sluice gates, fishways (e.g., fish lock and right bank pass), or turbines. Comprehensively modeling fish mortality at Sambor Alt_7 would require carefully quantifying each of these mortality risks associated with larvae passing through the dam. Those risks are not considered here.

The modeling approach presented here focuses on evaluating the suitability of reservoir hydraulic conditions (i.e., velocities throughout the reservoir) to prevent larvae from sinking. The rationale for this approach is that the closer the reservoir gets to flowing like a natural river (i.e., high velocities and low residence times), the less likely larvae are to sink, starve, or be eaten by predators. Without specific data on the behavior and transport characteristics of multiple larvae species on the main stem of the Mekong River, a "top down" methodology is implemented here, seeking to create lotic hydrodynamics that encourage survival of riverine pelagic larvae, rather than a "bottom up" methodology, which would quantify and examine the multiple mechanisms of larval survival (e.g., sustenance and predation).

To better understand natural hydraulic conditions, Acoustic Doppler Current Profiler (ADCP) measurements of mean channel velocities at different main stem flow rates near Kratie gage station (just downstream of the Sambor Dam site) were reviewed. The results appear in Figure 6.3.3. Mean channel velocity can exceed 1.5 m/s during the wet season, but are as low as 0.3 m/s during the dry season. As a starting point, in this study this 0.3 m/s threshold was used to define reservoir hydraulic conditions conducive to larvae passage. While a very coarse criterion, the credibility of such a threshold appears to be supported by observations from other tropical river basins. For example, field measurements for pelagic drifting temperate and tropical fish larvae are often in the range of 0.6 to 1.0 m/s and occasionally are as low as 0.3-0.4 m/s (Bialetzki *et al.,* 1999; Braaten *et al.,* 2012). In Australia, similar threshold velocities of 0.3-0.4 m/s maintain fish larvae in suspension during downstream drift. It is certainly possible that certain fish species with peak drift in the wet season (e.g., at flow rates of 8,000 m^3/s or more) have adapted to being transported at higher reservoir velocity conditions (e.g., 0.8 m/s or more), and will thus require those conditions to sustain recruitment, so future studies could explore setting different target velocity thresholds for different representative species or guilds (Welcomme *et al*., 2006).

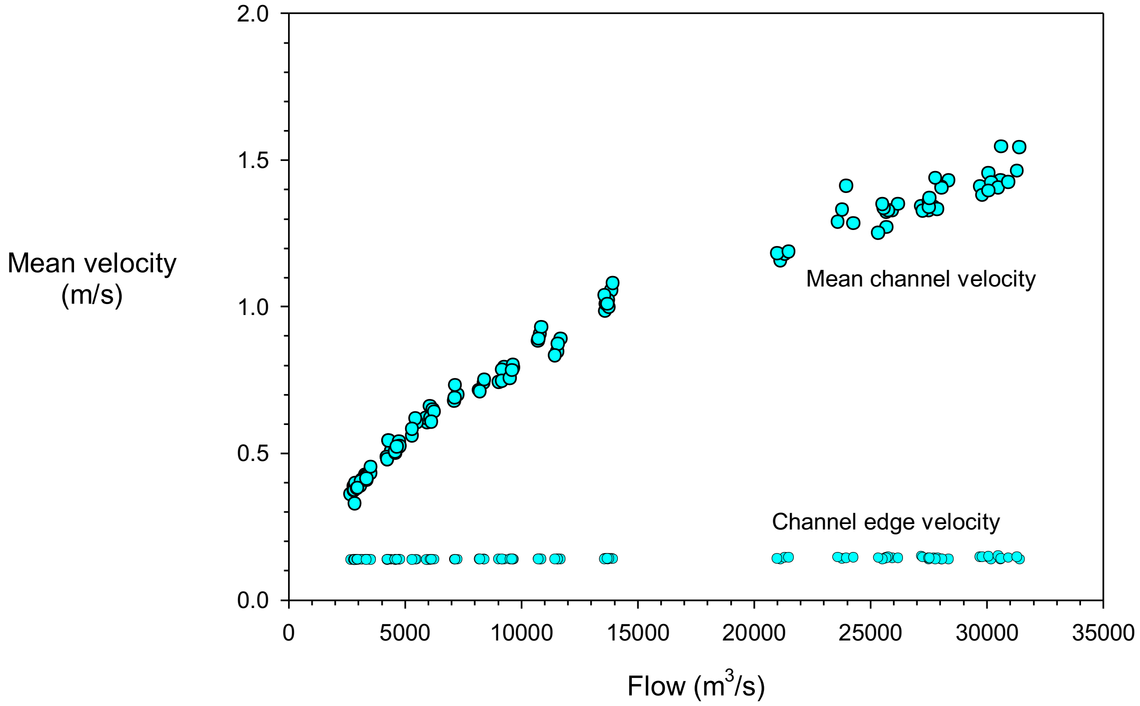

Figure 6.3.3*. Mekong River discharge versus mean channel velocity at Kratie (ADCP data). Red dashed lines show the range of minimum mean velocities to model for larval transport in the impoundment for the wet season (A) and dry season (B).*

The modeling approach presented here evaluates on a daily basis whether or not depth-averaged reservoir velocity conditions in excess of 0.3 m/s are maintained for a significant continuous corridor throughout the reservoir's length. Reservoir conditions that meet this criterion on a given day are capable of safely passing larvae through the reservoir to the dam. Reservoirs not capable of meeting this condition on a given day do not successfully pass larvae on that day. All days are equally weighted, and performance in this measure is tracked in both the wet and dry seasons, to account for the occurrence of larval drift throughout the year, despite the fact that most drift appears to occur during the rising limb of the hydrograph in June and July.

A 2-dimensional Tuflow hydraulic simulation model for the Sambor Alt_7 reservoir and anabranch channel was developed to evaluate suitability of reservoir hydraulic conditions for larvae passage. Specifically, a representative set of 70 different combinations of reservoir water surface elevation and main stem flow rate was simulated. The 70 resulting spatial maps of reservoir velocity (see Figure 6.3.4) were then visually reviewed, identifying those combinations of water surface elevation and main stem flow rate that led to acceptable versus unacceptable conditions. A red line in Figure 6.3.4 demarcates combinations that lead to success versus failure.

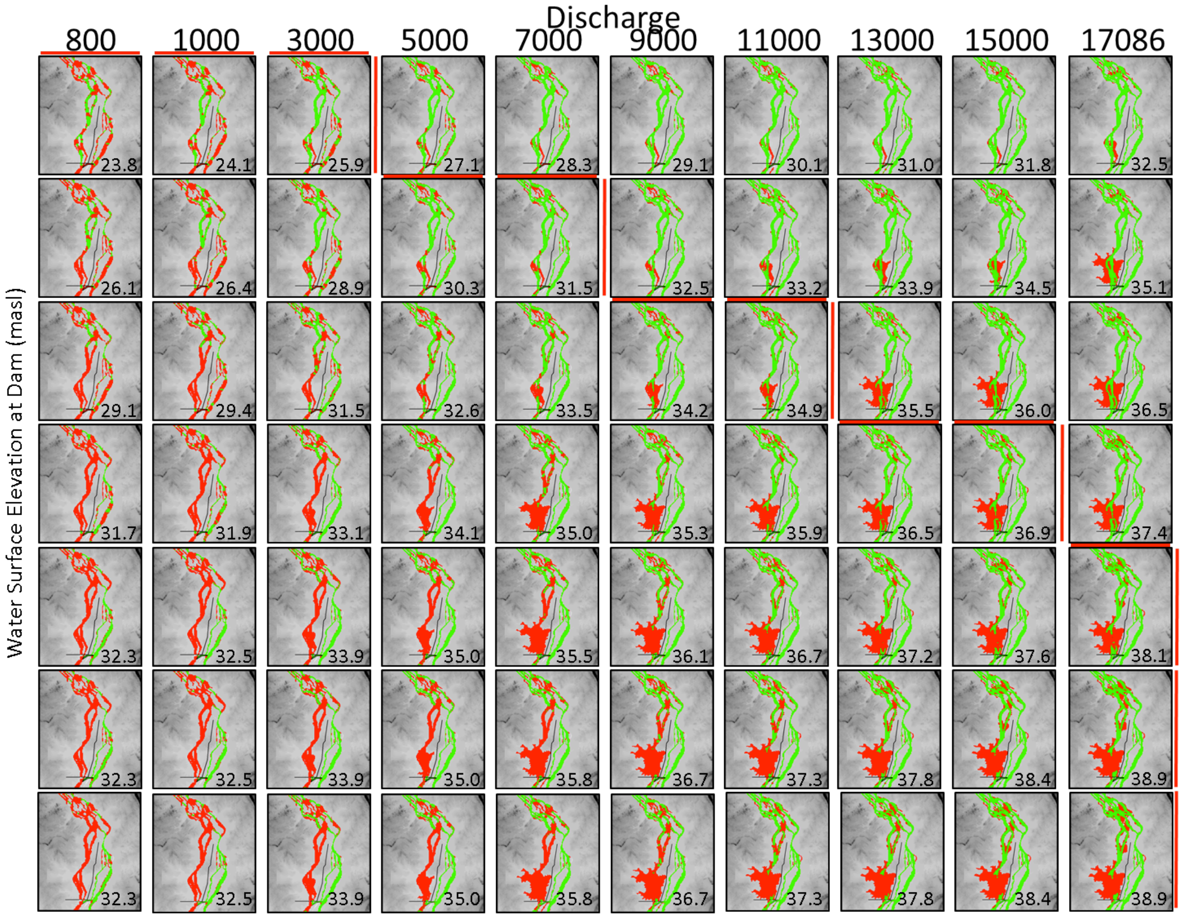

Figure 6.3.4. *Results from 70 2-dimensional hydraulic modeling runs with Tuflow corresponding to different reservoir water surface elevations (masl) and main stem rates (m^3/s). Each image represents results for a different modeling run. Main stem discharge (and corresponding reservoir inflow) is held constant for each column of images. Reservoir water surface elevations (denoted by the number to the bottom right of each image) generally increase from the top of each main stem discharge column to the bottom, but do not remain the same across rows. Water surface elevations at or above the red line drawn diagonally across the figure must be maintained at a minimum for the corresponding inflow rate to ensure there exists a continuous path through the middle of the reservoir that the larvae could theoretically use to drift through the reservoir naturally (i.e., a path with velocity exceeding 0.3 m/s). Within each of the 70 images, red zones indicate velocity < 0.3 m/s, and green indicates velocity >= 0.3 m/s.*

For purposes of understanding how reservoir water level and inflow combine to influence spatial velocity conditions in the reservoir, consider the column from Figure 6.3.4 corresponding to a main stem flow rate of 8,000 m^3/s. As the images in this column proceed from the top to bottom, the reservoir's water level increases. As water level increases, the cross-sectional area through which water flows also increases, which reduces velocity for a given flow rate. This is why red zones of inadequate velocity appear as water levels rise, and are especially problematic at the dam itself, where the deepest section of reservoir with the largest cross-sectional area exists. The red line demarcating combinations of main stem flow rate and reservoir water level that produce conditions suitable to larvae passage is described in Table 6.3.1.

Table 6.3.1. Flow rate and reservoir water level values demarcating reservoir water levels below which hydraulic conditions are conducive to larvae passage for a given flow rate. This corresponds to the red line in Figure 6.3.4.

Main stem flow rate (m3/s)	Reservoir water level (masl)
0	20.0
4137.71	27.1
5637.57	28.3
6490.09	32.5
7768.20	33.2
8350.16	35.5
9825.27	36.0
9995.35	37.4

While larvae entering the reservoir can either successfully pass through the reservoir or sink, depending on the reservoir's hydraulic conditions, it was assumed that larvae entering the anabranch channel always safely circumnavigate the dam. Thus, operating policies with significant spillage increase rates of larvae survival.

The mathematical representation of daily larvae passage at the Sambor Alt_7 site, as represented in *PySedSim*, is described below.

The *PySedSim* state variable for daily larvae passage through (via the reservoir) and/or around the dam site (via the anabranch) is given by V_t below:

$$V_t = f_t^{Res} b_t^{Res} + f_t^{Byp}$$

In the relationship above, f_t^{Res} and f_t^{Byp} represent the daily fraction of main stem flow at Stung Treng that enters the reservoir and bypass, respectively, and are defined by:

$$f_t^{Res} = \frac{Q_t^{Res,in}}{Q_t^{ST}}$$

$$f_t^{Byp} = \frac{Q_t^{Byp,in}}{Q_t^{ST}}$$

The daily deposition of larvae in the reservoir, b_t^{Res}, is given by the conditional relationship below, where all larvae entering the reservoir every day either deposit (=0) or are passed (=1) every day:

$$b_t^{Res} = \begin{cases} 1, & WSE_t \leq T_{WSE}\left(Q_t^{Res,in}\right) \\ 0, & WSE_t > T_{WSE}\left(Q_t^{Res,in}\right) \end{cases}$$

The following is a simple example to clarify the nature of our current approach. Suppose 50% of main stem flow on a given day enters the reservoir (the latter 50% entering the anabranch channel). If the reservoir doesn't successfully pass larvae on that day due to its water level and main stem flow combination falling below the red line in Figure 6.3.4, then the overall passage rate (V_t) for the system on that day is 50%. This reflects the fraction of larvae assumed to enter the anabranch channel. Conversely, if hydraulic conditions are suitable, the passage rate is 100% for that day.

It is important to note that in the approach outlined above, particles of larvae mass are not generated on a daily basis, with a mass balance maintained in the reservoir over the course of a simulation (e.g., as with suspended sediment). This would require data that do not exist, such as relationships defining the generation of daily larval loads across species as a function of multiple factors (e.g., main stem discharge). Instead, the approach implemented here simply tracks the suitability site conditions on a daily basis for larvae passage.

In this particular study, the focus is only on larvae passage, rather than larvae survival. To provide the opportunity for future studies to account for survival, rather than just passage, included in *PySedSim* are the relationships below, which partition mortality risks among reservoir releases on a daily basis. These relationships apply to the current study, because it is assumed that the various survival rates through control structures, as listed below, are 100%. This approach could be refined in the future to represent a more detailed array of mortality factors (e.g., Halls and Kshatriya, 2009).

Daily fraction of larvae survival around the dam site is given by S_t as:

$$S_t = f_t^{Res} b_t^{Res} Z_t^{Res} + f_t^{Byp} Z_t^{Byp}$$

The fraction of larvae surviving in the reservoir (Z_t^{Res}) and bypass (Z_t^{Byp}) every day is defined as:

$$Z_t^{Res} = r_t^P z_t^P + r_t^R z_t^R$$
$$Z_t^{Byp} = 1.0$$

The daily fraction of flow distributed into the powerhouse (r_t^P) and radial gates (r_t^R), respectively, are defined as:

$$r_t^P = \frac{Q_t^P}{Q_t^{Res,out}}$$
$$r_t^R = \frac{Q_t^R}{Q_t^{Res,out}}$$
$$Q_t^R = Q_t^{Res,in} - Q_t^P$$
$$Q_t^P \leq K_P$$

where:
Q_t^{ST} is the daily flow rate (m^3/s) at Stung Treng gage station
$Q_t^{Res,in}$ is the daily reservoir inflow rate (m^3/s), a function of WSE_t and Q_t^{ST}
$Q_t^{Res,out}$ is the total reservoir outflow rate (m^3/s) during time t
Q_t^P is the flow rate (m^3/s) distributed to the turbines during time t
Q_t^R is the flow rate (m^3/s) distributed to the radial gates during time t
f_t^{Res} is the daily fraction of Q_t^{ST} entering the reservoir during time t
f_t^{Byp} is the daily fraction of Q_t^{ST} entering the bypass channel(s) during time t
b_t^{Res} is a binary variable describing whether larvae are deposited (=0) or remain suspended (=1) during time t
r_t^P is the fraction of flow that is distributed to the turbines during time t
r_t^R is the fraction of flow that is distributed to the radial gates during time t
K_P is the maximum powerhouse discharge capacity = 14,000 m^3/s. Daily capacity varies with head.
Z_t^{Res} is the total surviving fraction of larvae that entered the reservoir during time t
Z_t^{Byp} is the total surviving fraction of larvae that entered the bypass during time t
$z_t^P = 1.0$ is the survival rate of larvae passing through the turbines (powerhouse) during time t
$z_t^R = 1.0$ is the survival rate of larvae passing through the radial gates during time t
WSE_t is the daily average reservoir water surface elevation (masl) during time t

T_{WSE} is the target water surface elevation required to prevent deposition for a given level of reservoir inflow, which is a function of reservoir inflow $Q_t^{Res,in}$
t = day of simulation [1, T]

3.4.4. Mathematical Definition of Performance Measures

Downstream larvae drift occurs during both the wet and dry seasons. Larvae sampling data on the Mekong main stem indicate peak periods of drift for several representative carp and catfish species occur for main stem flows exceeding about 8,000 m^3/s at Stung Treng gage (Cowx *et al.*, 2015), so this flow threshold is used as a rough means of demarcating dry and wet season performance across all objectives.

Included in this study are two larvae passage-related performance measures: (1) Wet season larvae passage, J_{Larvae}^{wet}, and (2) Dry season energy production, J_{Larvae}^{dry}. Both are defined separately below.

1. Wet season daily larvae passage (%) through and around the dam site, 1st percentile of annual values.

Species spawning during (or at the onset) of the wet season spawn in the largest numbers, likely contributing the most to overall fishery productivity. The 1st percentile effectively represents an approximation of the "worst case" year's average daily fraction of larvae expected to be exposed to site conditions conducive to passage (through or around the reservoir) on a wet season day. One would expect an average daily larvae flow fraction in the wet season to be equal to or less than this value only once every 100 years.

The fraction of larvae expected to be exposed to site conditions conducive to passage on a wet season day in a given year is given by:

$x_w = \frac{1}{365}\sum_{t=1}^{365} V_t^{m,n}$ for each year *n* in [1, N_S] and each stochastic realization m in [1, M] , for any t $\in Y$

where:
t = day of a year *n* [1, 365]
n = year of simulation
Q_t^{Ana} = daily flow rate in the anabranch channel at the location indicated in Fig. 3.2
$Qst_t^{m,n}$ is the daily flow rate (m^3/s) just upstream of the reservoir, before allocation to the reservoir or anabranch
q_l= 8,000 m^3/s, lower threshold of main stem flow rate at Stung Treng gage defining the wet season
q_u= 100,000 m^3/s, upper threshold of main stem flow rate at Stung Treng gage defining the wet season
Y = any *t* where $q_l \leq Qst_t^{m,n} \leq q_u$
m = stochastic realization number in ensemble of stochastic realizations φ
N_S = number of years in a simulation = 100
M = number of Monte Carlo simulations in each "function evaluation" of stochastic optimization = 5

The performance measure is defined by inverting the empirical cumulative distribution function (CDF) for wet season larvae passage in each year, F_{x_w}, at the 1st percentile:

$J_{Larvae}^{wet} = F_{x_w}^{-1}(p)$

F^{-1} =Inverse empirical CDF of x_w

p = selected quantile = 0.01

2. Dry season daily larvae passage, 1st percentile.

While potentially less important to overall fishery productivity, species spawning in the dry season still contribute to biodiversity and are inextricably embedded in the complex Mekong food web. The 1st percentile effectively represents an approximation of the "worst case" year's average daily fraction of larvae expected to be exposed to site conditions conducive to passage (through or around the reservoir) on a dry season day. One would expect an average daily larvae flow fraction in the dry season to be equal to or less than this value only once every 100 years.

The fraction of larvae expected to be exposed to site conditions conducive to passage (through or around the reservoir) on a dry season day in a given year is given by:

$x_w = \frac{1}{365}\sum_{t=1}^{365} V_t^{m,n}$ for each year n in [1, N_S] and each stochastic realization m in [1, M] , for any t $\in Y$

where:
t = day of a year n [1, 365]
n = year of simulation
Q_t^{Ana} = daily flow rate in the anabranch channel at the location indicated in Fig. 3.2
$Qst_t^{m,n}$ is the daily flow rate (m^3/s) just upstream of the reservoir, before allocation to the reservoir or anabranch
q_l= 0 m^3/s, lower threshold of main stem flow rate at Stung Treng gage demarcating dry season
q_u= 8,000 m^3/s, upper threshold of main stem flow rate at Stung Treng gage demarcating dry season
Y = any t where $q_l \le Qst_t^{m,n} \le q_u$
m = stochastic realization number in ensemble of stochastic realizations φ
N_S = number of years in a simulation = 100
M = number of Monte Carlo simulations in each "function evaluation" of stochastic optimization = 5

The performance measure is defined by inverting the empirical cumulative distribution function (CDF) for average daily dry season larvae passage in each year, F_{x_d}, at the 1st percentile:

$$J_{Larvae}^{dry} = F_{x_d}^{-1}(p)$$

F^{-1} =Inverse empirical CDF of x_d
p = selected quantile = 0.01

3.5. Maintenance of Natural Sediment Regime

3.5.1. Background and Motivation

The Mekong basin's naturally large sediment yield of 160 million metric tons (Mt) per year (Milliman and Meade, 1983), and its associated seasonal sediment regime, is important to maintain because it sustains the river's geomorphology and habitats such as deep pools (Halls *et al.*, 2013); transports nutrients to drive primary productivity (Liljeström *et al.,* 2012); and contributes to slowing the subsidence of the delta landform in Vietnam. Currently, annual sediment loads at the Sambor site are about 72.5 Mt/yr, significantly reduced from 160 Mt/yr as a result of upstream trapping (Koehnken 2014).

3.5.2. Modeling Approach and Rationale

To improve sediment passage through Sambor Alt_7, as previously discussed in section 2, annual sediment sluicing is implemented to pass the bulk of the basin's suspended load, with infrequent sediment flushing removing much of the sediment not released during sluicing. Ultimately, this enabled long-term passage of much of the inflowing 72.5 Mt/yr without significant reduction of hydropower production. However, the more infrequently flushing takes place, the larger the sediment loads released during short-term events become, thus posing downstream ecological risks (Baran and Nasielski, 2012). It is for this reason that performance measures related to sediment focused on limiting the magnitude of loads released during flushing, rather than on long-term passage, which was naturally highly efficient due to sluicing and flushing.

Both the concentration and duration of sediment loads released during flushing have fishery implications. It is not possible to address the implications of flushing events for all of the species that exist downstream of the dam site or that migrate near the dam site. Instead, the focus here is to minimize the magnitude of loads that are released on average during a given flushing day.

The *PySedSim* time series variable used to form the performance measure is suspended sediment discharge from Sambor Alt_7, S_t (kg/day). Only the days during which flushing is occurring are sampled in the performance measure defined below. The magnitude of these values can be reduced by trapping less sediment and by increasing the frequency of flushing events, which is included in the optimal search for reservoir operating policies.

3.5.3. Mathematical Definition of Performance

1. Maximum daily sediment load released during all flushing events

Sediment load released from the reservoir:

$x = S_t^{out}$ for each stochastic realization m in [1, M] , for any t $\in Y$

where:
t = day of a simulation [1, T]
T = simulation duration (days) = 36,500
Y = any t where reservoir sediment flushing is taking place
m = stochastic realization number in ensemble of stochastic realizations φ
M = number of Monte Carlo simulations in each "function evaluation" of stochastic optimization = 5

The performance measure is defined by inverting the empirical cumulative distribution function (CDF) for daily sediment load released during flushing, F_x, at the 1st percentile:

$$J_{Sediment}^{flush} = F_x^{-1}(p)$$

F^{-1} =Inverse empirical CDF of x
p = selected quantile = 0.01

4. Coupling PySedSim with an Optimization Model for Identifying Alternative Reservoir Operation Strategies

4.1. Overview

Given the likely conflicts among the multiple energy production and fish passage objectives relevant at Sambor Alt_7, and the complexity of reservoir hydraulics and site hydrology, *PySedSim* was coupled with a multi-objective evolutionary optimization algorithm (MOEA), *Borg* (Hadka and Reed, 2013), to create a simulation-optimization framework (see Figure 6.4.1) capable of identifying multiple alternative reservoir operating policies designed to perform well across conflicting hydropower and ecological objectives. The schematic in Figure 6.4.1 describes this coupled framework. In this simulation-optimization approach, a multi-objective evolutionary optimization algorithm, Borg (Hadka and Reed, 2013), parameterizes and iteratively refines operating policies, optimizing them in response to their simulated performance with respect to six different objectives (outlined below).

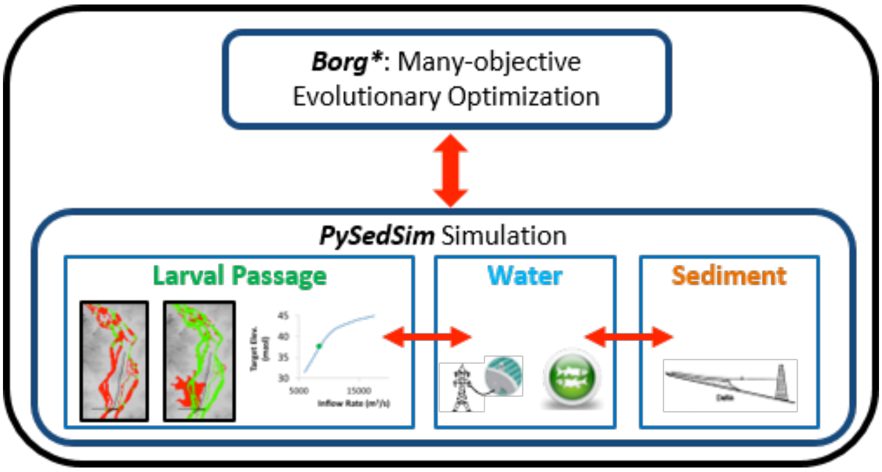

Figure 6.4.1. *Schematic describing the coupled simulation-optimization framework described below, wherein PySedSim is the simulation model, and Borg is the optimization model used to identify alternative reservoir operating policies.*

PySedSim was used to expose a given reservoir operating policy to multiple synthetically generated sequences of stochastic hydrologic and sediment inflows, tracking the long-term movement of water and sediment through the reservoir and Sambor Alt_7 anabranch channel resulting from the given operating policy. Using the evolutionary multi-objective direct policy search (EMODPS) approach (Giuliani *et al.*, 2015), *PySedSim* was coupled with an evolutionary optimization model to identify a Pareto approximate (Pareto, 1896) suite of candidate operating policies. The intent of this multi-objective optimization approach is not to seek a single optimal solution. Instead, the goal is to identify a set of non-dominated solutions, also called the Pareto optimal set (Pareto, 1896). By definition, within this Pareto set, performance in any one objective can only be improved by degrading performance in one or more of the other objectives.

4.2. Definition of Operating Policies

EMODPS is a parameterization-simulation-optimization approach (Koutsoyiannis and Economou, 2003) in which reservoir operating policies are parameterized within a family of functions (e.g., piecewise linear functions, radial basis functions, etc.). The simplest operating policy would be to describe reservoir release as a linear function of inputs such as storage volume and/or inflow rate (Guariso *et al.*, 1986; Hashimoto *et al.*, 1982; Oliveira and Loucks, 1997; Revelle *et al.*, 1969). Recent studies have demonstrated the value of instead using non-linear Gaussian Radial Basis Functions (RBFs) to define operating policies (Giuliani *et al.*, 2015), due to their demonstrated flexibility in solving a wide class of problems (Busoniu *et al.,* 2011). The policies presented below in the results section of the appendix were generated using radial basis functions.

Equation 4.1 below describes the RBF-based operating policies, which prescribe release, u_t, from Sambor Alt_7 in time period *t* as a function of *A* time-varying inputs:

$$u_t = \sum_{i=1}^{B} w_i \, exp \left[- \sum_{j=1}^{A} \frac{\left((x_t)_j - c_{j,i} \right)^2}{b_{j,i}^2} \right]$$

where

t is the day of the simulation (i.e., from 1 to 36,500 in a 100 year simulation with no leap years)
B is the number of RBFs = 4
A is the number of inputs to the RBF = 3 (current main stem flow rate, reservoir water surface elevation, and day of year)
$(x_t)_j$ is the value of the *j*-th input at time *t*
w_i is the weight of the *i*-th RBF, where $\sum_{i=1}^{B} w_i = 1$
$c_{j,i}$ is the center of the *i*-th RBF associated with the *j*-th input, where $c_{j,i} \in [-1, 1]$
$b_{j,i}$ is the radius of the *i*-th RBF associated with the *j*-th input, where $b_{j,i} \in (0, 1]$

The three inputs to each RBF are:

1. WSE_t, the reservoir's water surface elevation during day *t* (which translates to reservoir storage)
2. Q_t, the main stem flow rate during day *t*
3. μ, the day of year (1-365) of simulation day *t*

Therefore, the array of time varying inputs is given by:

$$x_t = \{WSE_t, Q_t, \mu\}$$

These three inputs were selected in particular because they represent information that a reservoir operator could reasonably be expected to have on hand. These inputs also result in operating polices that are highly dynamic, modifying releases quickly in response to changing site conditions.

The centers, radii and weights of the three RBFs represent the decision variables to be optimized by the MOEA. Therefore, there are B*(1+2A) decision variables (function parameters) that describe a given operating policy, or 4*(1+2*3) = 28 decision variables for Sambor SA. Also, in this particular case study, three additional decision variables were included in the optimization: (1) Flushing Frequency (how often reservoir sediment flushing is conducted, constrained from 1-15 years); (2) Day of the year on which to begin considering flushing the reservoir (constrained from days 150-225 to avoid dry season and monsoon conditions); and (3) reservoir inflow rate (m3/s) triggering flushing drawdown to occur, on dates after the flushing initiation date variable from (2).

Note that most of the assumptions listed above (e.g., A=3, B=4, the time series variables used as inputs) are the values selected for Sambor Alt_7, but *PySedSim* users can easily change these assumptions to explore alternative formulations.

The actual reservoir release rate at Sambor SA, r_t, may be different than the prescribed release described above, u_t, due to physical constraints such as total water storage available for release in a given time step, total reservoir storage capacity, and release capacities of a dam's multiple outlets given the current water level. These constraints are handled within *PySedSim* based on the corresponding user-specified data for the dam.

To evaluate the performance of these operating policies (RBF functions), each policy was simulated over M=5 sequences synthetically generated daily streamflows, each of T = 100 years in duration.

The objective function is formulated as a minimization across objectives J. Thus, objectives that should be maximized, such as energy production, are negated, whereas values that should be minimized, such as sediment load during flushing, are not negated. In the results presented in section 5 below, J corresponds to the six objectives defined in section three.

(1) $$\theta^* = \underset{\theta}{\operatorname{argmin}} J(\theta)$$

where

$$J = \begin{bmatrix} -J_{Hydro}^{ann}(\theta) \\ -J_{Hydro}^{dry}(\theta) \\ -J_{Larvae}^{wet}(\theta) \\ -J_{Larvae}^{dry}(\theta) \\ -J_{Fish}^{dry}(\theta) \\ J_{Sediment}^{flush}(\theta) \end{bmatrix}$$

$$\theta = \begin{bmatrix} c_{j,i} \\ b_{j,i} \\ w_i \\ g \\ d \\ h \end{bmatrix}$$, with *i={1,2,3,4}*, *j={1,2,3}*

where:

g is an integer decision variable reflecting the recurring frequency (in years) of sediment flushing operations, where $g \in [1,15]$

d is an integer decision variable reflecting the day of the year on which to begin considering flushing the reservoir, where $d \in [120,225]$ \\

h is a real-valued decision variable reflecting the reservoir inflow rate (m^3/s) triggering flushing drawdown to occur if simulation day $t \geq d$, where h $\in$ [6000,10000] \\

$c_{j,i}$, $b_{j,i}$, w_i are the radial basis function parameters defined earlier in this section.

5. Identifying Alternative Reservoir Operating Policies for Sambor Alt_7

The following results correspond to the same Sambor Alt_7 dam and reservoir presented in Chapter 6, with slight modifications to the assumed powerhouse installed capacity. In these results, the powerhouse installed capacity is assumed to be 1080 MW, with a design flow of 10,580 m^3/s, and a design head of about 15m. As feasibility (or more advanced) studies proceed with Sambor Alt_7, the powerhouse specifications (i.e., design flow) will require more rigorous economic analysis to evaluate the value of more or less installed capacity to turbine wet season discharge.

The results presented below emerge from a simulation-optimization experiment involving 25,000 MOEA “function evaluations” for each of 20 random initial starting populations (i.e. seeds) of the MOEA. Each function evaluation is a stochastic (Monte Carlo) simulation of a given operating policy over five independently drawn 100-year long daily sequences of synthetically generated main stem flow rates. The resulting pareto approximate set was then sorted over the 20 best solutions from each seed to form a reference set representing the best-performing operating policies across all seeds.

As was discussed in previous sections, the intent of this approach is not to identify a single "optimal solution". Instead, the purpose is to explore tradeoffs composed of a large suite of alternative operating policies. This approach offers a forum for exploring diverse stakeholder preferences (e.g., ecological versus hydropower objectives).

The parallel axes plot in Figure 6.5.1 shows the optimal six-objective tradeoffs for the candidate reservoir operating policies discovered using the simulation-optimization framework outlined above. Each vertical axis represents performance for a separate one of the six objectives described in section 3. Performance improves toward the top of each axis. Each line represents a different operating policy. Several thousand policies (i.e. lines) are displayed, though *PySedSim* offers users the ability to easily reduce the size of the set while still representing the shape of the tradeoff space. The ideal (though not attainable) solution would be represented by a single blue horizontal line crossing all six axes at the top of the plot. The color of each line represents the dry season flow rate spilled into the anabranch channel to attract migrating fish, which also appears on the left most axis of the figure. This is highlighted because higher flow rates tend to attract and pass more migrating fish at fish passes (Bunt *et al.,* 2012). Two lines crossing one another between any two of the six axes represent the existence of a tradeoff between two objectives.

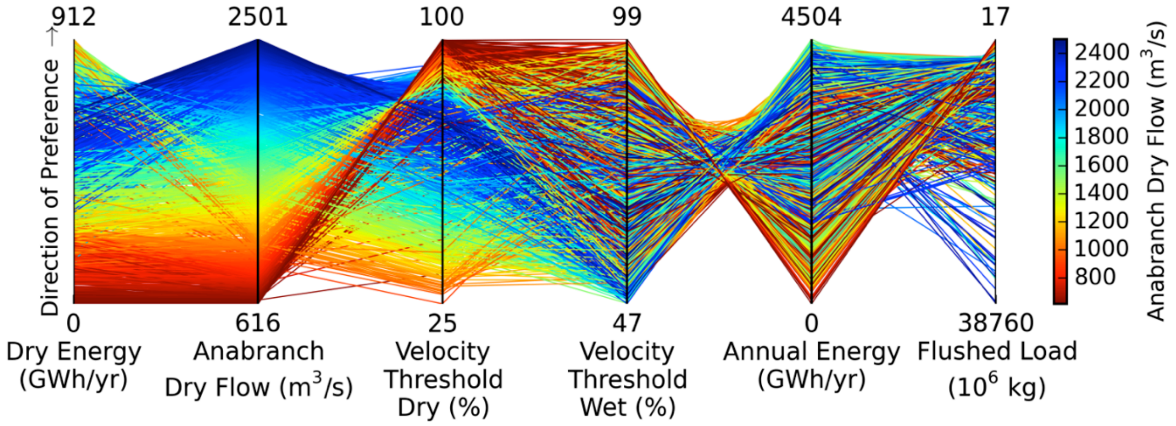

Figure 6.5.1. *Parallel axis plot of Pareto-approximate tradeoffs among the six objectives described earlier in this appendix: dry season energy production, dry season anabranch flow rate, dry season fraction of days with conditions adequate for larvae passage, wets season days with conditions adequate for larvae passage, annual energy production, and sediment load released during flushing. Each y-axis represents a different objective, with better performance toward the top of each axis. Each line represents a different operating policy, with each policy's performance described by where it intersects each vertical axis. When two lines cross one another between two axes, this indicates the existence of a tradeoff. The steepness of the diagonal lines between two axes provides a sense of the sharpness of the tradeoff between two objectives. Several thousand lines appear in Fig. 6.5.1, but PySedSim offers users the potions of reducing the number of policies displayed on a plot.*

Figure 6.5.1 demonstrates clearly that tradeoffs exist among hydropower and ecological objectives. For example, policies maximizing annual energy production, on the fifth axis, tend to produce low fractions of days when conditions are suitable for larvae passage in the wet season, on the fourth axis. Furthermore, complex seasonal tradeoffs exist among hydropower and ecological objectives. For example, policies that perform well with respect to dry season larvae passage perform poorly not only with respect to dry season energy production, but also with respect to dry season anabranch spill rates (i.e., fish attraction flow rates during the dry season). This suggests that tradeoffs exist not only among hydropower and ecological objectives, but among the ecological objectives as well.

Again, these rich tradeoffs in Figure 6.5.1 occur because more conservative TuFlow hydraulic modeling results (as opposed to HEC-RAS modeling results) have been used that reflect greater difficulty in achieving hydraulic conditions suitable for larvae passage. Chapter 6 proposes a single reservoir operating policy for Sambor Alt_7 that maximizes energy production, but that approach is based on the assumption that no tradeoff exists between larvae passage and energy production. (Again, this assumption in Chapter 6 is based on HEC-RAS results, which suggested that for a policy maximizing energy production, significant larvae passage would be possible throughout the year). The more conservative TuFlow hydraulic modeling results suggest a circumstance in which high velocities are much more difficult to create in the reservoir throughout the year, so tradeoffs do exist between energy and fishery objectives. The results above highlight the complex array of possible conflicts among multiple objectives that could result at Sambor dam depending upon the ultimate nature of hydraulics at the upstream end of the reservoir and within the reservoir itself. Additional data need to be collected to better understand the bathymetry of the river at the reservoir site to reduce this uncertainty.

To identify a subset of policies from Figure 6.5.1 that balance ecological and energy objectives requires somehow defining what constitutes acceptable performance across objectives, then applying those criteria to the policies from Figure 6.5.1. It is difficult to accomplish this for fish-related objectives. The large diversity of Mekong fish species, and the scientific community’s incomplete understanding of their life cycle processes, make it difficult to identify generic fish-related performance criteria for Sambor Alt_7. For example, it is not possible to say for each fish species what rates of larvae passage at what times of year would sustain the species population, nor how reduced recruitment would ultimately impact other fish species and the overall productivity of the lower third fishery.

In its mainstream Mekong dam design guidance documentation, the Mekong River Commission defines effective fish passage as “providing safe passage for 95% of the target species under all flow conditions” (MRC, 2009). It is not possible to credibly translate this 95% criterion into a flow rate value for the anabranch fish pass, except to say that higher flow rates may attract more fish. However, it is possible to apply this 95% criterion to seasonal larvae passage objectives, by identifying those policies achieving 95% of days in both seasons with hydraulic conditions conducive to successful larvae passage (policy “L” in Figure 6.5.2).. Policy “L” presents potentially problematic performance with respect to energy production and dry season anabranch flow rate objectives, so a potential compromise policy “C” in Figure 6.5.2 is also included wherein about 80% performance is possible in the larvae objectives for a reduction in annual energy production from about 4500 GWh/yr to 2800 GWh/yr. Additionally, the energy-maximizing policy (Policy “E” in Figure 6.5.2), which produced about 4500 GWh/yr, is included for purposes of comparison. Policies “E”, “C” and “L” are highlighted in Figure 6.5.2, whereas all of the remaining policies that appeared in Figure 6.5.1 are shown in gray in the background.

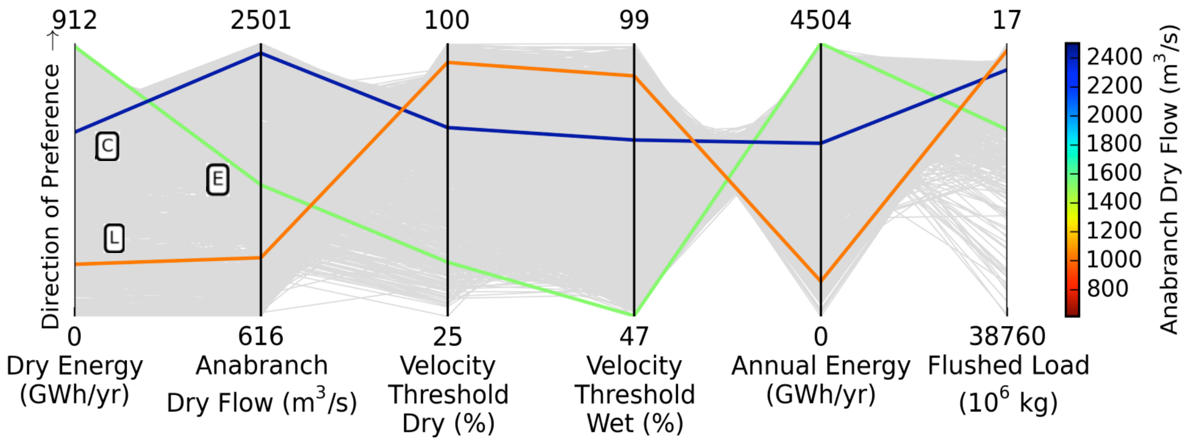

Figure 6.5.2. *Three policies selected from the several thousand policies in Fig. 6.5.1. Policy "E" maximizes energy production (E), policy "L" achieves suitable hydraulic conditions for larvae passage in 95% of days in both seasons (L), and policy "C" represents a potential compromise policy (C) that reduces larvae passage to less than 95% but spills more flow into the anabranch channel and produces more energy than policy "L".*

What is clear from Figure 6.5.2 is that maximizing performance in any one objective (e.g., energy production or larvae passage) could significantly degrade performance in other objectives. It will clearly be a benefit to search the space of alternative operating policies to identify policies that offer some compromise. However, this will require identifying what constitutes an acceptable compromise. For example, would passing only 70-80% of the Mekong's larvae at Sambor Alt_7 instead of 100% irreversibly degrade the Mekong fishery and lead to ecosystem collapse? It is not possible to answer this question definitively. For this reason, in a delicate and dynamic ecosystem like the Mekong, a "compromise" policy similar to what is shown in Figure 6.5.2 would still constitute a significant risk to the Mekong fishery, even if it produces a better ecological outcome than the energy maximizing policy.

While comparing the performance of policies E, C and L is valuable, so too is reviewing the water surface elevation trajectories of those policies. Figure 6.5.3 shows the average monthly water surface elevation for policies "E", "C", and "L" (see Figure 6.5.2.) when stochastically reevaluated with five randomly drawn 100-year long sequences of daily inflows, and average Mekong flow rates at Stung Treng gage. Figure 6.5.3 highlights the complexity of the Sambor Alt_7 reservoir. For example, the policy maximizing annual energy production was not a run-of-river policy maintaining full reservoir water levels throughout the year. Rather, water levels are kept low during low flow conditions to prevent excess spillage, and water levels are filled into the wet season as the monsoonal main stem discharge begins to exceed the powerhouse discharge capacity. Conversely, the compromise policy "C" actually maintains higher average water levels during the dry season. In a normal reservoir, increasing water levels might increase energy production due to higher hydraulic head. However, at this reservoir the increased head actually results increased spillage, which reduces flow throughput to the powerhouse and therefore reduces energy production. The increased spillage also increases overall larvae passage by directing a larger fraction of larvae into the anabranch channel (as larvae are suspended in the spilled flow), where safe passage is assumed to occur at a rate of 100%. The result that higher reservoir water levels could actually result in improved ecological performance is not intuitive, and underscores the importance of carefully conducting an optimal search for flexible operating policies at this hydraulically complex reservoir, rather than pre-specifying inflexible rule curves that may fail to capture this complexity.

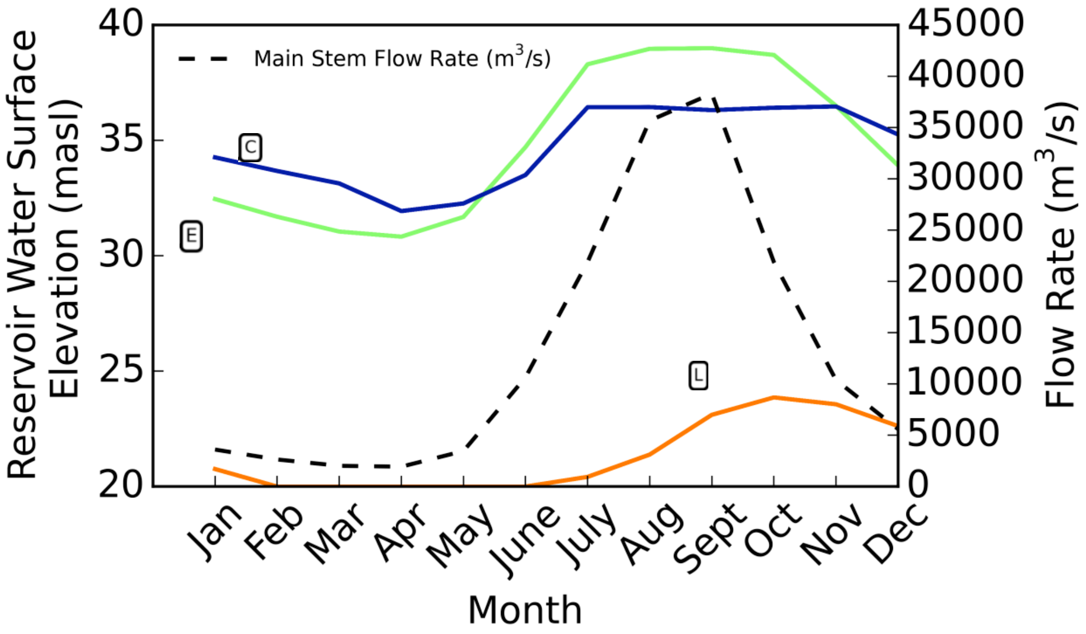

Figure 6.5.3. Average monthly water surface elevation for policies "E", "C", and "L" (see Fig. 6.5.2.) when stochastically reevaluated with five randomly drawn 100-year long sequences of daily inflows, and average Mekong flow rates at Stung Treng gage. The solid lines represent water level trajectories, whereas the dashed line represents main stem flow rates. Note that actual reservoir inflows for the three policies differ due to complex site hydraulics, as detailed in section 3 of this appendix. Also, note that this plot simply represents average monthly water levels for three poliicies, which is different from the actual operating policy functions, which describing release in a given day as a function of inflow, water level and day of year.

Furthermore, it is worth nothing that policy "L" requires maintaining nearly an empty reservoir (i.e., a free-flowing river), which is surely not economically feasible. This result is important, as it highlights the risk associated with separating planning (dam siting and design) from management (operations). If a policy similar to policy "L" is legitimately required to sustain the fishery's productivity, then the Sambor Alt_7 dam is surely excessively over-designed (e.g., storage capacity and powerhouse installed capacity), and is unlikely to be economically feasible if the dam produces only a small fraction of its energy production potential as a result of larvae passage operations. However, this does not necessarily mean an economically viable and fish friendly Sambor alternative does not exist. Including design features such as installed capacity in the optimal search, and measures related to infrastructure cost in the suite of optimization objectives, could potentially identify infrastructure alternatives better suited to the corresponding operational requirements for larvae passage (i.e., reduced water levels).

The results presented above are just intended to serve as a small sample of the *PySedSim*'s flexibility to generate insight into multi-objective tradeoffs composed of flexible alternative operating policies. There are numerous ways to formulate ecological and energy objectives (e.g., their seasonal and probabilistic definitions, as discussed in section 3). Thus, the example results above are not intended to serve as final results. Rather, these results are simply a starting point for an iterative process through which alternative problem formulations of ecological and energy objectives are explored to better understand tradeoffs and vulnerabilities at Sambor Alt_7.

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Appendix 7.1.

Fish Passage in Large Tropical Rivers: Design Principles and Preliminary Concepts

FISH PASSAGE IN LARGE TROPICAL RIVERS: DESIGN PRINCIPLES AND PRELIMINARY CONCEPTS[1]

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EXECUTIVE SUMMARY

Global hydropower is in an intensive growth phase in large tropical rivers in South-East Asia, South America and Africa. Migratory fish in these rivers are a major source of food and livelihoods and large hydropower dams threaten their migrations. Despite the long history of mitigation through fish passage facilities (e.g. fishways, fish screens, turbine design) the experience in large tropical rivers has been consistently poor with no examples of migratory fish populations sustained upstream of large dams.

The objectives of the present paper are to: i) review the status of fish passage at large tropical dams, ii) describe fundamental design principles for fish passage in large tropical rivers and iii) present preliminary concepts for a hydropower dam in these systems that sustains fish populations.

Large tropical rivers carry the highest diversity of freshwater fish species and variation in migration patterns in the world. Despite this there are six common principles in fish passage design which apply to all fish species and river systems:

1. Assess site fish passage objectives in a regional context of habitats, migrations, and existing and proposed dams.
2. Integrate biology, hydrology and hydraulics.
3. Address upstream and downstream migration.
4. Design for fish attraction and passage.
5. Size the fishway to meet the biomass and flows of the river system.
6. Document assumptions and use adaptive management .

Using these principles highlights some special challenges for large tropical rivers that have yet to be addressed effectively, including: larval drift, fish screens, turbine design, high diversity and migratory biomass, and spillway and gate design.

The principles highlight two fundamental flaws of past fish passage attempts in large tropical rivers: i) at the catchment scale, not incorporating a long-term vision of interconnected habitats that includes some level of hydropower development, and ii) at the site scale, underestimating the scope of fish passage.

There are no examples of catchment plans that include strategic hydropower with the specific objective of sustaining a major portion of fish populations; instead, scientists and natural resource managers are often reactive, responding to each dam as it is proposed. The issue can be addressed by incorporating all objectives into catchment planning with engineers, scientists and managers jointly selecting initial dam sites for investigation.

At the site scale of a dam, facilities for upstream migrants are sometimes addressed but at large tropical dams they have: grossly undersized attraction flows; underestimated migratory biomass; not accommodated differing migratory behaviour; and overestimated swimming abilities. These issues are, however, all solvable.

Downstream fish passage is the greater challenge. Maintaining larval drift through reservoirs depends on the dam location and valley geomorphology, combined with dam design and operation. Hence, it needs to be a factor in the initial selection of dam sites. Fish screens have been used for decades at large water diversions passing up to 200 $m^3 s^{-1}$ but full depth screens (for surface and benthic species) have never been used at hydropower dams with high discharge (e.g. 10,000 $m^3 s^{-1}$).

Despite the claims by some manufacturers of “fish friendly turbines” there are no turbine designs with quantitative data to show they would safely pass a diverse range of tropical fish species. Equally, turbine designers are rarely given the opportunity to design for fish passage first and power generation second. Engineers are also often not given design criteria for safe passage of fish through gates and spillways.

For large hydropower dams that have an objective of maintaining biodiversity and a major portion of fish productivity, the design paradigm needs to change from a linear path that starts with dam siting and design, followed by identifying impacts, and then mitigation of impacts (including fish passage) to one that integrates impacts, mitigation, and dam design as parallel themes from the beginning.

Underestimating the scope of fish passage at large tropical dams leads to a larger problem: underestimating the capital and operating cost. This has consistently led to compromised solutions and to a perception that fish passage does not work in tropical rivers. Realistic estimates of fish passage requirements - which are likely to be 10-25% of the total capital cost - need to be part of the initial business case.

Despite the history of poor fish passage in large tropical rivers, applying some simple design principles has the potential to develop innovative dams with fish passage solutions that are effective. It will also enable transparent decisions about the potential effectiveness of fish passage at these dams and impacts on fish populations.

1. Introduction

Global hydropower is in an intensive growth phase in large tropical rivers in South-East Asia, South America and Africa (Winemiller *et al.* 2016). The Mekong River, in particular, is at the cusp of major hydropower development on the main stem and major tributaries. The Mekong River has the most productive freshwater fishery in the world, worth up to US $4 billion per year, providing food and livelihoods for over 60 million people. In Laos PDR and Cambodia, fish provide 48-79% of animal protein intake, while 80% of rural households in the Lower Mekong Basin are involved in capture fisheries. All fish species that occur in the Mekong mainstream migrate at varying spatial scales (Valbo-Jørgensen *et al.* 2009). The long distance migratory fish specifically contribute 39% of the fisheries yield (Baran 2010) and these are also the highest value fish.

Large hydropower dams have numerous environmental impacts but blocking migration of fish is a very visible impact with a high profile in rivers where migratory fish are a major source of food and livelihoods. There is also a long global history of mitigation of this impact through fish passage facilities (e.g. fishways, fish screens, turbine design). Although these have been successful in small to moderate-sized rivers, especially in temperate systems, they have performed poorly in large tropical rivers.

The objectives of the present paper are to: review the status of fish passage at large tropical dams, describe fundamental design principles for fish passage in large tropical rivers and present preliminary concepts for a hydropower dam in these systems that sustains fish populations.

2. Status of Fish Passage on Large Tropical Dams

It is useful to synthesize the status of fish passage on large tropical dams and highlight the problems. Most of the experience has been in South America, which is reasonably well documented, with some in Africa. The status is that fish passage in large tropical rivers has consistently performed very poorly or failed, to the point where they are considered a negative environmental impact – passing fish upstream but not downstream (Agostinho *et al.* 2007).

The reasons for these failures, which have generated the scepticism around fish passage at high tropical dams, include:

- Biology and migratory ecology are poorly understood and there has been little attempt to investigate the key knowledge gaps or:
    - document them,
    - accommodate them by choosing conservative design criteria, or
    - provide flexibility in fish passage design for future modification.
- Biomass volumes have been underestimated (only 2% passed in one case (Oldani and Baigún 2002)).
- Size range has been underestimated (adult fish assumed to be the major group migrating upstream but smaller immature fish, with poorer swimming ability, often make up greater numbers and biomass).
- Diversity of behaviour has been underestimated (some large species use the deepest channel in the river [thalweg] and will not move to the side of the dam where fishways are located (Oldani and Baigún 2002)).

- Despite attempts at upstream passage there are very few attempts at providing downstream passage.
- Poor entrance location.
- No physical modelling to optimise entrance location.
- Very little water provided for fishways, so there is little attraction for fish to enter.
- Design criteria are often selected to reduce cost (e.g. increase gradient for pool-type fishways, or reduce the size of lock chambers or fish lift hoppers) without consideration of impacts on fish passage.
- No adaptive management program with performance standards and identified steps and funds for improving the design and operation.
- Monitoring poorly resourced.
- Monitoring often, but not always, focused on *passage efficiency* through the fishway and not *attraction efficiency* of fish locating the fishway.
- No clear ecological or fish passage objectives.

These issues appear to relate to poor design decisions – which in some case they are - but the deeper flaw is that these designs have been under-resourced. The prefeasibility studies and business cases consistently underestimate the cost of fish passage which leaves designers in later stages of design needing to compromise. It is understandable that data on detailed migratory behaviour of diverse river systems is not available for many tropical rivers but the option of the choosing conservative design criteria for fish passage is rarely, if ever, available because of initial capital estimates used in the business case.

These documented issues also provide the basis for a clear set of design principles to avoid these shortcomings, which are outlined in the next section.

3. Principles of Design

Large tropical rivers carry the highest diversity of freshwater fish species and variation in migration patterns in the world. Despite this there are common approaches and principles in fish passage design which apply to all fish species and river systems.

Principle 1. Assess site fish passage objectives in a regional context of habitats, migrations, and existing and proposed dams.

Fish passage at a site needs to be considered in a regional context because migrations of fish are regional. The objective of fish passage is to provide for migration past a structure to enable life cycles to be completed and for fish populations to be sustained, or impacts minimized. In this context the regional location and preservation of spawning, nursery, feeding and refuge habitats - and the connectivity between these - must be the template upon which a site-based fish passage solution is considered, evaluated and measured.

The regional context needs to include a model of the life cycle of each fish species, or guilds[2] of fish using available data, but knowledge gaps will likely be prevalent and acknowledging these is important. A key regional context for large dams in tropical rivers is:

i) the location in the catchment, as lowlands have higher biodiversity, biomass and more migratory species, than upland areas; and

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

Strategically, developing a river system for hydropower needs to consider the degree of fragmentation of the river and the dam locations relative to the overall fish species distribution, and the modification of habitat and accessibility to key habitats to complete life cycles. If maintaining migratory fishes is a priority, then maintaining minimum lengths (e.g. 300-500 km) of flowing water between dams is essential to allow for migration upstream and larval drift downstream, as well as to complete other aspects of the life cycle. If a cascade of dams is planned that creates a series of contiguous lakes, fish passage for migratory fishes becomes a low priority, as the likelihood of maintaining these populations is severely reduced.

Principle 2. Integrate biology, hydrology and hydraulics.

Developing fish passage solutions is a combination of three disciplines: biology, hydrology and hydraulics. The relationship between these disciplines is shown in Figure 7.1.1, along with some key design parameters.

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

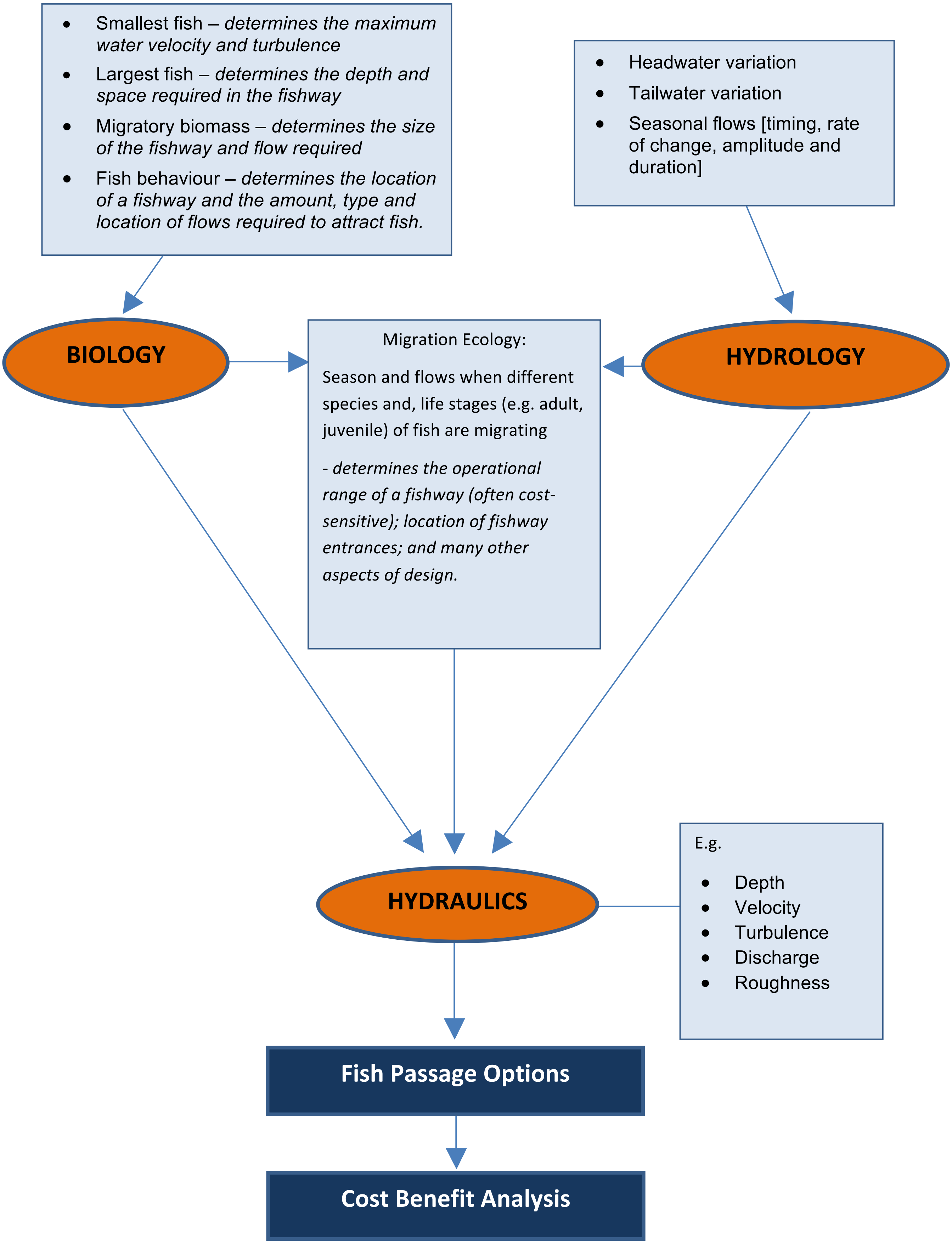

Figure 7.1.1. *Diagram showing the interaction of three disciplines – biology, hydrology and hydraulics – in developing fish passage options. Key parameters are show in light blue boxes.*

In biology it is important to know the:

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

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

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

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

- If fish are migrating downstream at high flows then the gates and spillway need to be designed for safe passage.

All these characteristics, and many more, form a set of hydraulic criteria for fish passage design, which can be directly used to develop fish passage options (Figure 7.1.1). The cost-benefits of each option can then be evaluated. Note that cost is the final filter in this process after all the design parameters and initial options are developed. The final design is then driven by the economic viability of the fish passage solution and the net benefit likely to be achieved in terms of fishery production and conservation of biodiversity.

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

Principle 3. Address Upstream and Downstream Migration.

Fish migration is cyclic, involving upstream and downstream movements or return lateral movements on and off floodplains. It is most commonly seasonal, and this applies in the Mekong and tributaries. In tropical rivers most species make return annual migrations, and there are a few species that migrate upstream to spawn as adults once and die, like salmon.

Fish passage at dams and weirs often concentrates on upstream migration, but without safe downstream passage the life cycle is not completed and the function of upstream passage facilities to maintain or rehabilitate fish populations is severely or completely conceded.

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

At large hydropower dams there are two components of downstream passage to consider:

i) passage through the impoundment or reservoir which can change from a flowing river that enabled larvae to drift passively downstream, to a lake where larvae stop drifting and can die from: settling out on the bottom, or lack of food or predation; and
ii) passage at the dam itself, which will potentially have four paths: turbines, spillway, fishways and sluice gates for sediment.

Principle 4. Design for Fish Attraction and Passage.

There are two components of effective fish passage:

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

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

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

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

Designing for fish attraction is mostly independent of the choice of fishway design; it involves the design of the dam orientation, spillway, gates and abutments to guide fish to one or more fishways. Flows at dams are complex and physical modelling is essential (Figure 7.1.2). Computer modelling (Computational Fluid Dynamics) has been used to model flows for fish passage but the limitation is the outputs are fixed whereas in a physical model flows can be manipulated in real time.

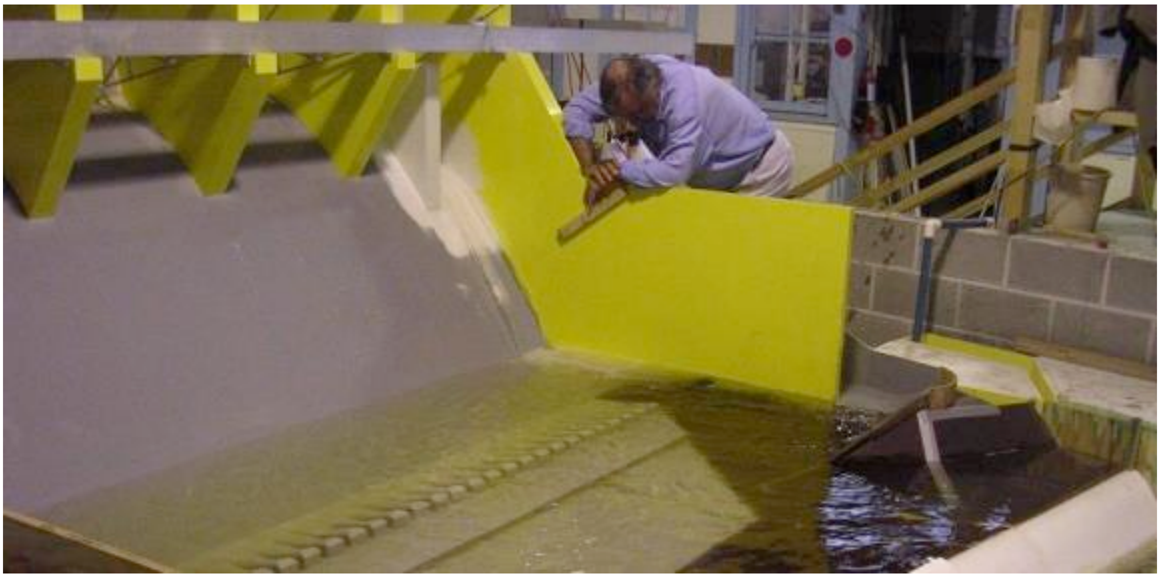

Figure 7.1.2. *Example of a physical model of a 32m high dam and fishway in Australia that was used to determine entrance location and hydraulic conditions for the fishway. Scale is 1:20 but 1:10 is preferred.*

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

i) <u>Fish are attracted to flow</u>.

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

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

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

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

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

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

iii) Avoid recirculating flows.

Migrating fish orient and swim against, or with (for downstream migrants), the direction[3] of the current[4]. At large dams, recirculation flows can occur near spillway abutments (

Figure ***7.1.3***), regulating gates that have asymmetrical operating regimes (Figure 7.1.4), or powerhouses. Recirculating flows cause migrating fish to orient to these circular directions and swim past fishways (Quirós 1989). These recirculating flow patterns need to be minimized and ideally flow direction should not differ by more than 90^{O} from the stream centreline. The main method of predicting these flow patterns and minimising them is physical modelling. Reducing recirculating flows is also a key design objective of dam engineers as it reduces the likelihood of erosion near the abutments.

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

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

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[3] vector

[4] called rheotaxis

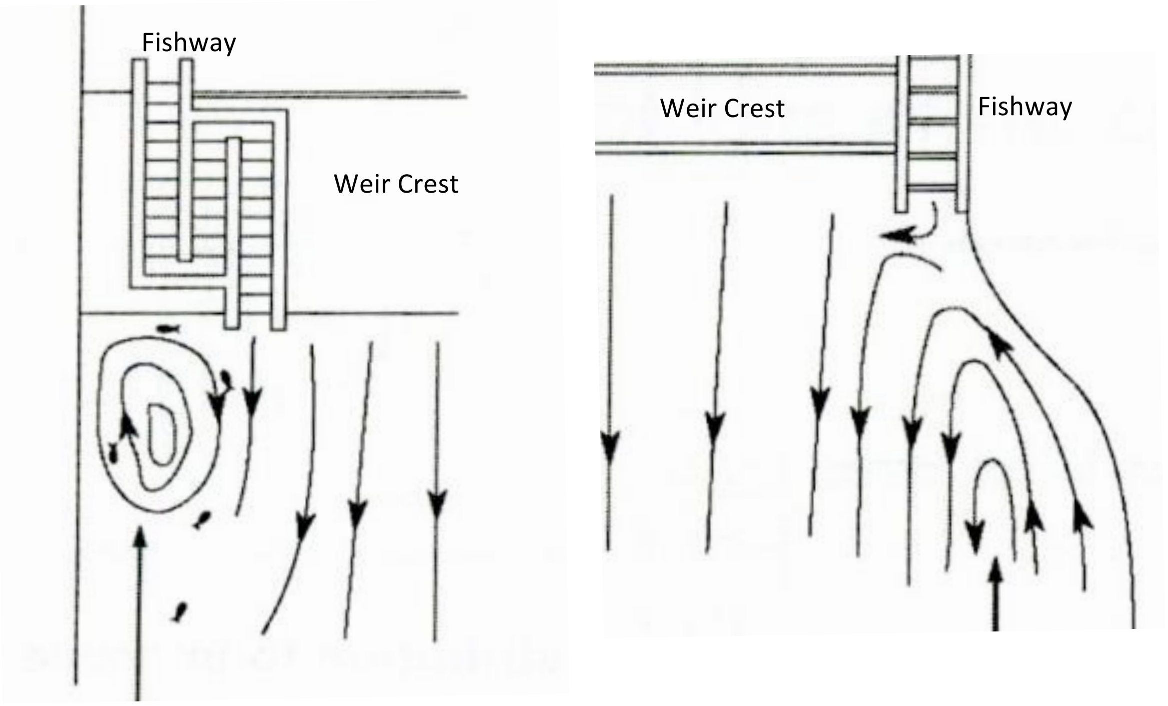

Figure 7.1.3. *Examples of recirculation eddies that mask fishway flow and direct fish away from a fishway (Larinier 2002).*

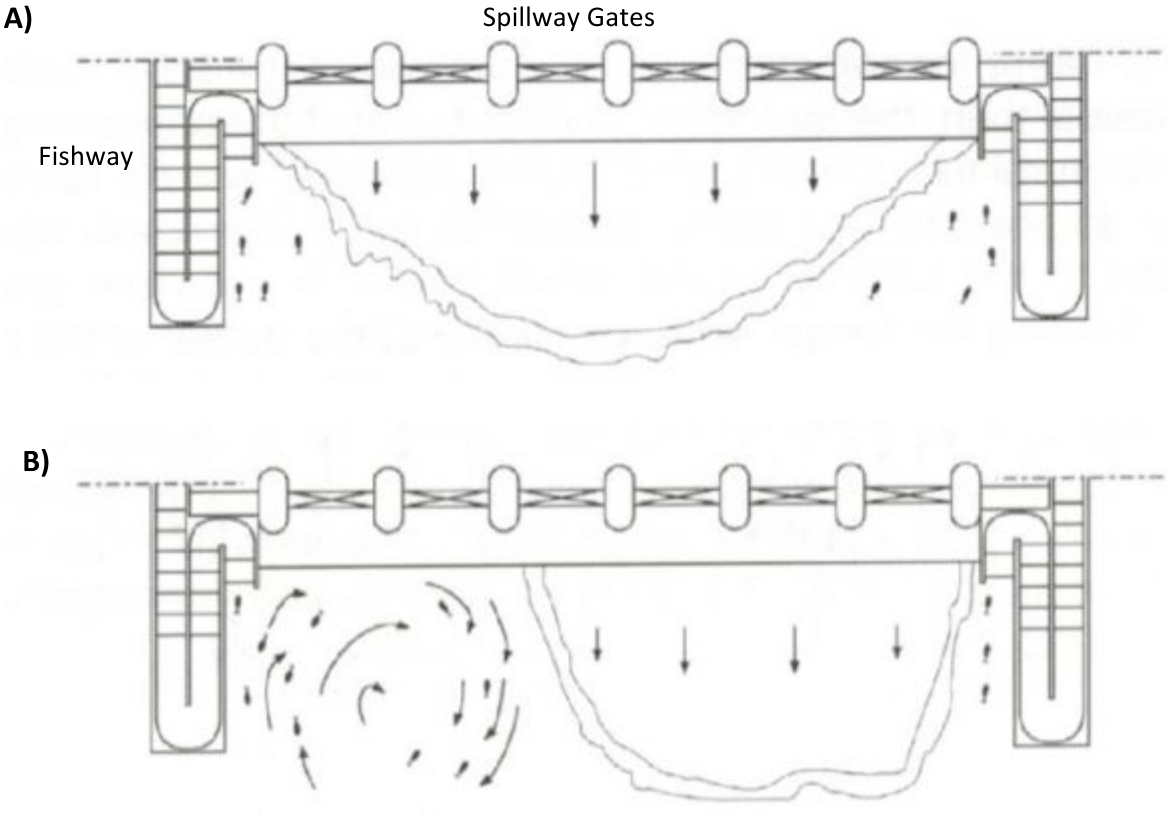

Figure 7.1.4. *Diagram of spillway gates showing a) optimised for fish attraction, and b) a recirculation eddy caused by asymmetric gate operation. (Larinier 2002).*

Principle 5. Size the Fishway to meet the Biomass and Flows of the River System.

Fishways need to be sized to suit the river system. Small rivers can have small fishways if there are small fish and little biomass. In large tropical rivers like the Mekong, fishways need to be suitably sized to accommodate large fish, large biomass and high flows.

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

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

Principle 6. Document Assumptions and use Adaptive Management.

At any dam or weir site it is not possible to have all the specific biological data. The method to overcome this in fishway design is to:

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

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

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

4. Biology, Hydrology and Hydraulics

In this section, we expand on the second principle of design using the Mekong as a case study. Much has been written about fish migration in the lower Mekong Basin (e.g. Poulsen et al. 2002, 2004). Fish migration in the Mekong is often condensed and summarised by the diagram in ***Figure 7.1.5***.

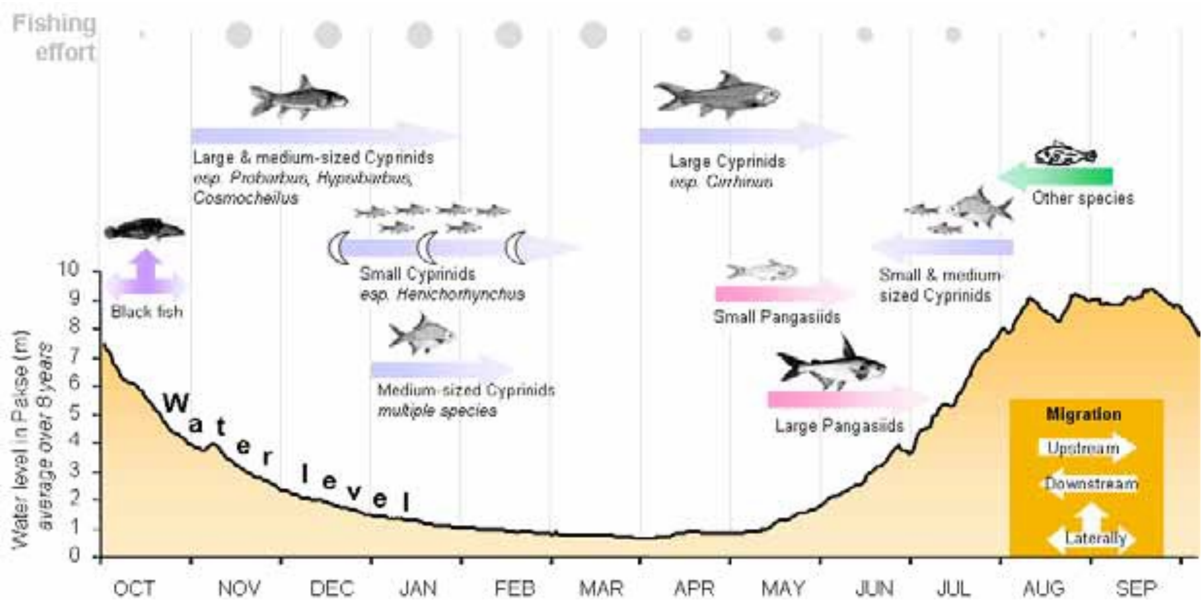

***Figure 7.1.5**. Fish migration patterns at Khone Falls, in the lower Mekong River (Baird 2001).*

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

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

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

The hydrology and seasonality of migration can be summarised to:

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

A more detailed analysis of the seasonal migrations of key migratory species in the large tributary system of the Sekong, Sesan, and Sre Pok rivers (3S system) shows the same patterns (Figure 7.1.6) (migration data are from the Mekong River Commission fish database). Figure 7.1.6 also shows the typical period of spillway operation. Hence, both peak upstream and downstream migration periods coincide with two conditions of dam operation, when there is:

a. only flow from the powerhouse, and
b. flow from the powerhouse and spillway.

4.1. Implications for Fish Passage Design

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

1. Low flows and low tailwater. All fish will be attracted to flow from the powerhouse (Figure 7.1.7).
2. Moderate flows and tailwater level. Occurring in the early wet and late wet season. Typically, a few gates would be used on the spillway and fish would be attracted to both the powerhouse and spillway. Upstream-migrating fish will be able to migrate up relatively close to the spillway because some spillway gates will not be used, which creates areas of low velocity and turbulence on the spillway apron (Figure 7.1. ***8***).
3. High flows and high tailwater level. In the peak of the wet season most gates of the spillway would be used which will pass the major flow and will be a major attraction for migrating fish. In these conditions the spillway area will be very turbulent and the upstream limit of migration is likely to be at the end of the spillway area and abutments (Figure 7.1.9). Note it is fish will be able to negotiate upstream passage through the spillway gates because water velocity greatly exceeds swimming ability.

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

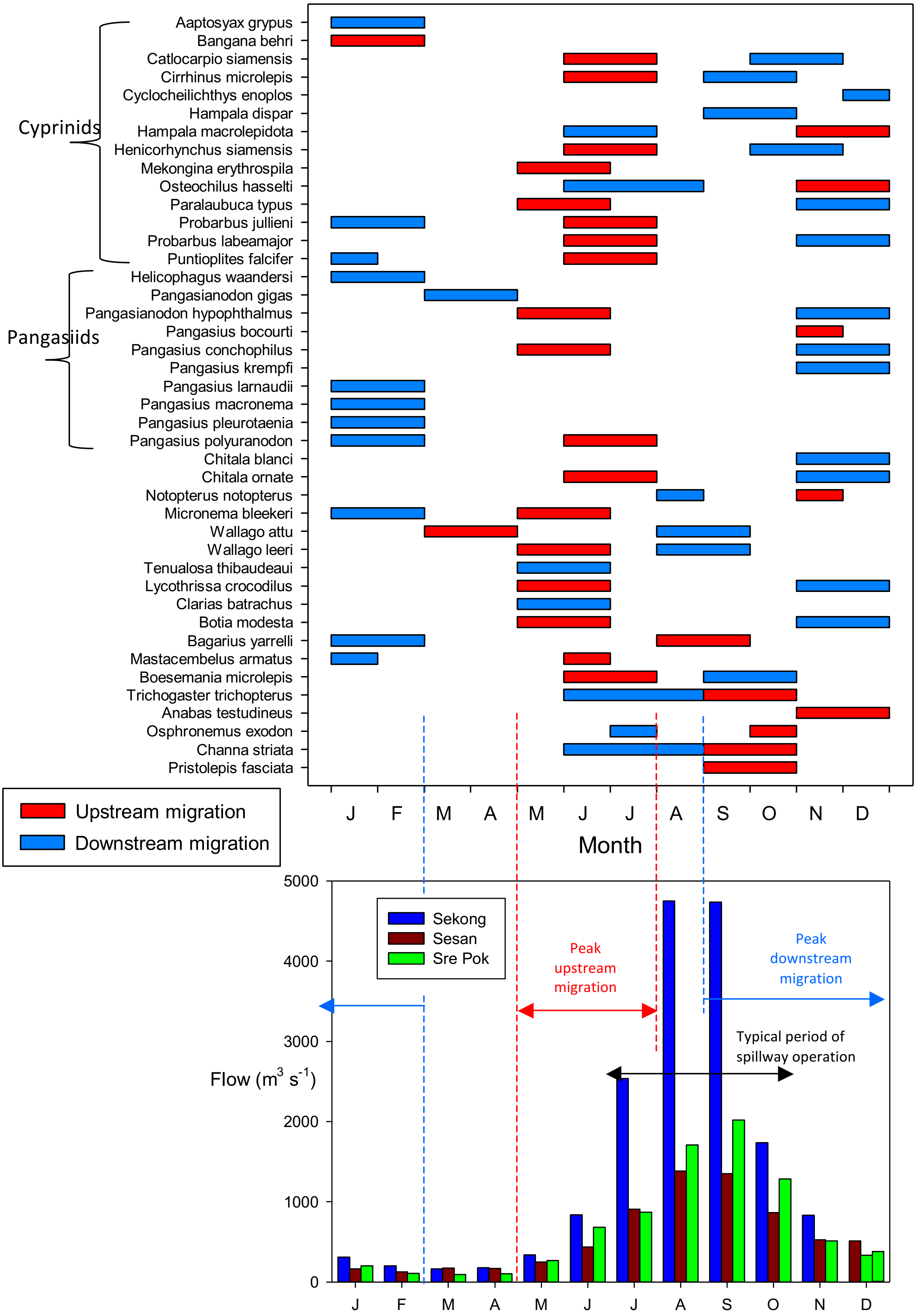

Figure 7.1.6. *Direction and season of migration of key species in the 3S system, shown with the mean monthly flow of each river (Fish data, MRC; flow data CNMC).*

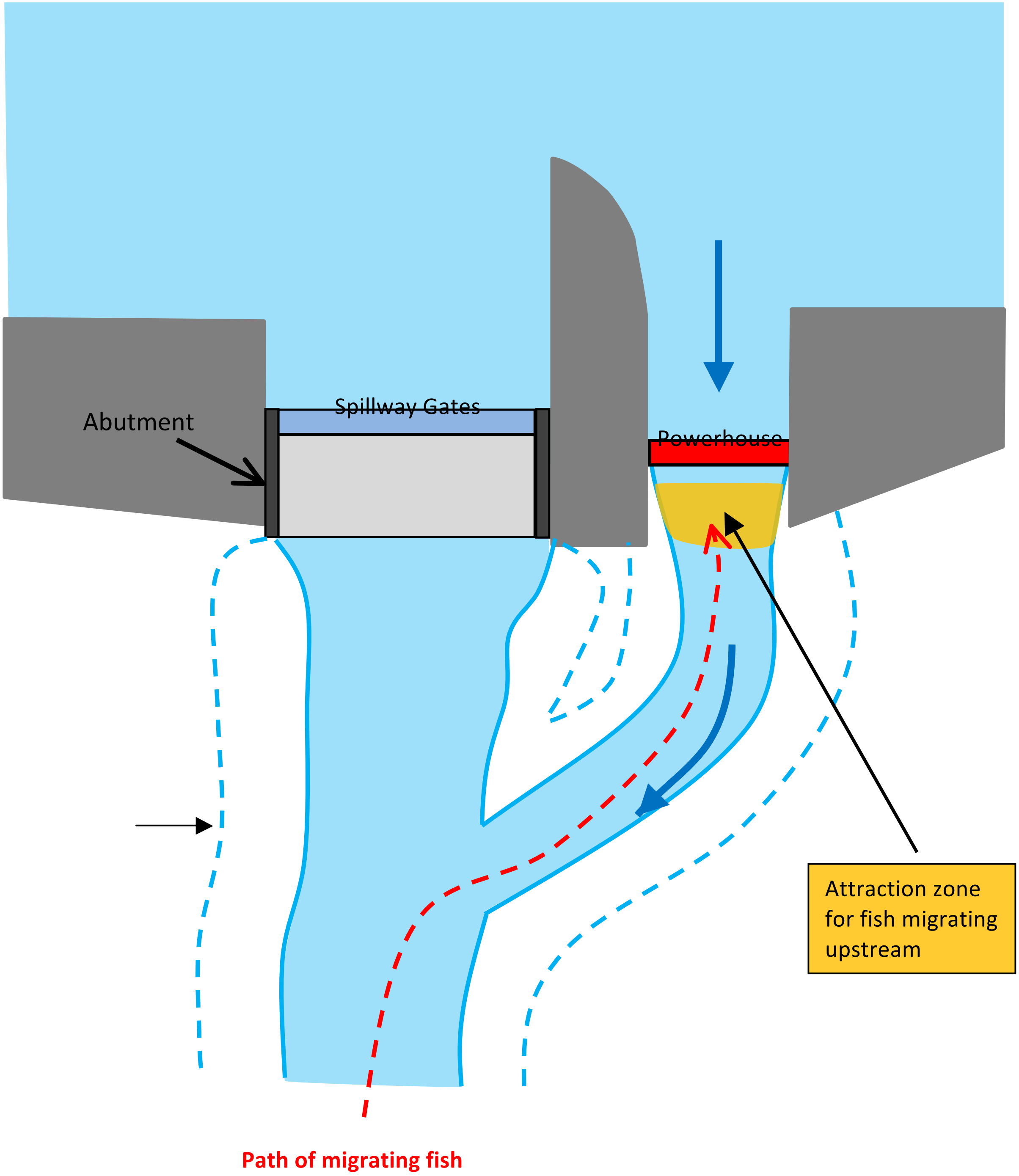

Figure 7.1.7. *Diagram of a typical large hydropower dam passing low flows through the powerhouse and showing the attraction zone for fish migrating upstream.*

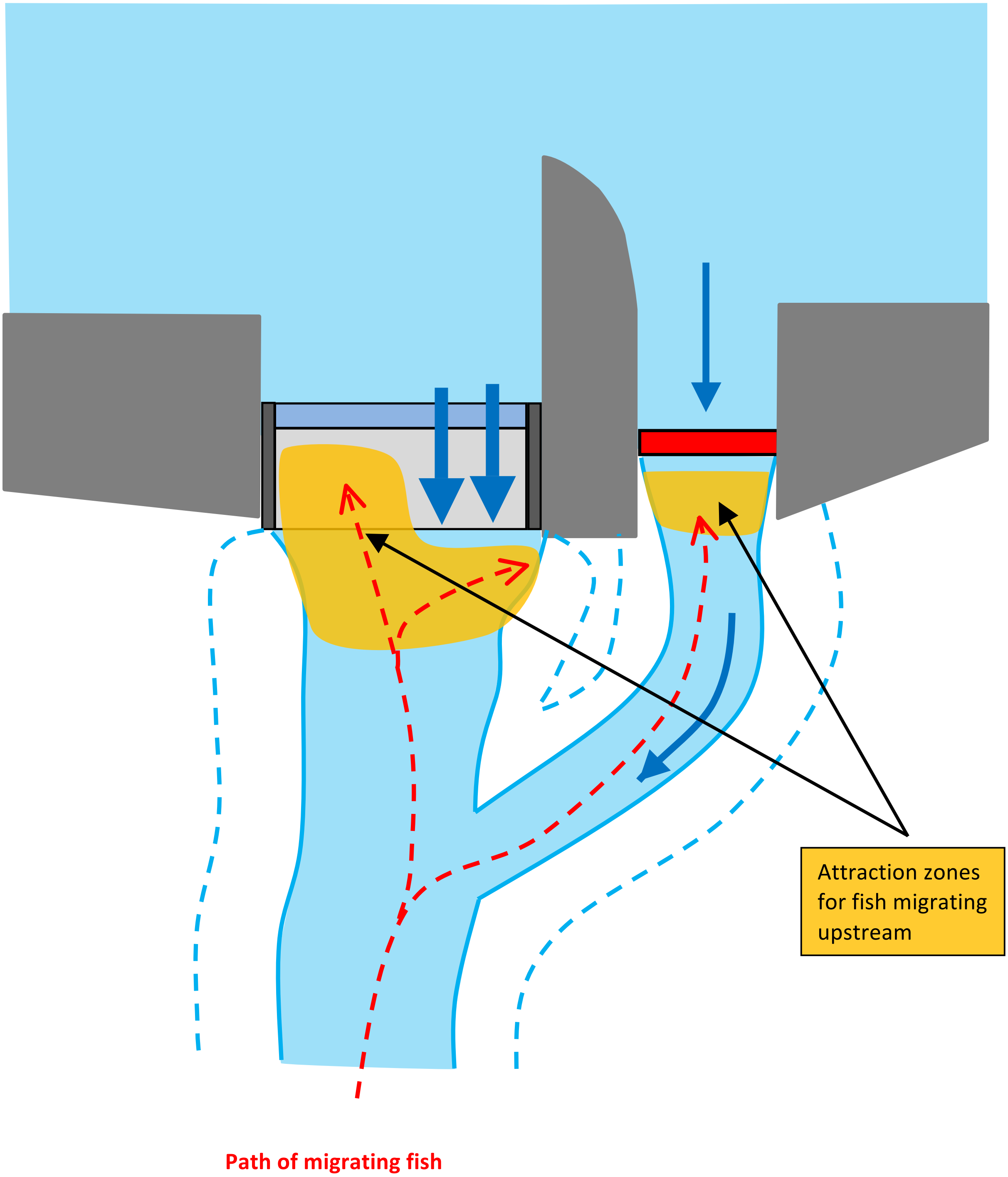

Figure 7.1. 8. *Diagram of a typical large hydropower dam passing moderate flows through the powerhouse and some of the spillway, showing the attraction zones for fish migrating upstream.*

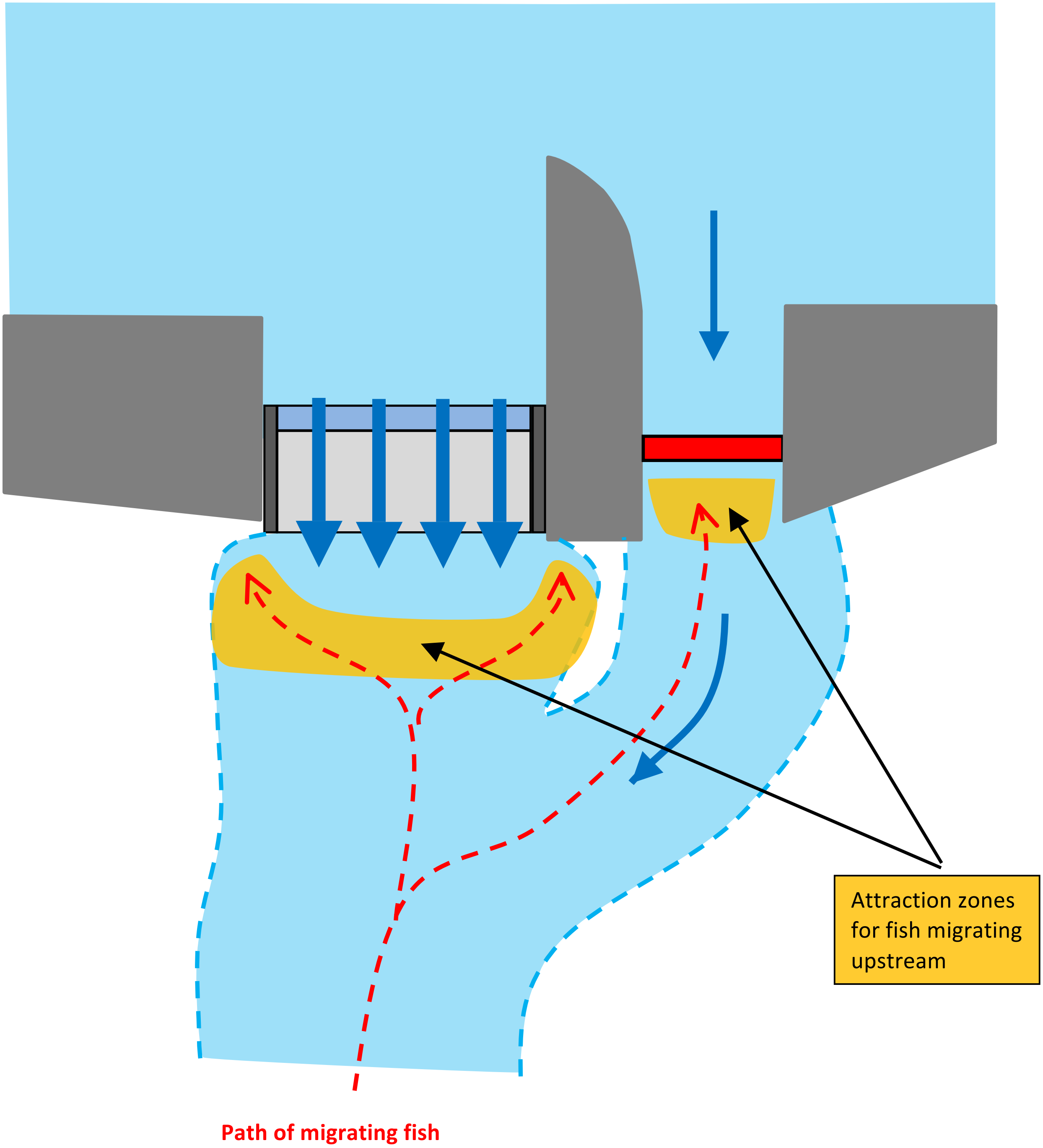

Figure 7.1.9. *Diagram of a typical large hydropower dam passing high flows through the spillway with continued operation of the powerhouse, showing the attraction zones for fish migrating upstream.*

5. Design Philosophy

5.1. Upstream passage

Use conservative assumptions

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

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

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

Use river hydraulics to inform design

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

The Mekong channel itself also provides guidance on depth in a bypass channel. Recent ADCP measurements in the Mekong downstream of Stung Treng show the shallowest reaches that large fish need to negotiate are 3.4 to 5.6 m deep for a maximum length of 4 km. This provides some initial design criteria for the bypass channel. A typical ADCP cross-section of the Mekong is shown in Figure 7.1.10 which also shows low water velocities along the sides of the river and high water velocities in the middle. These characteristics form the basis of a design for a bypass channel.

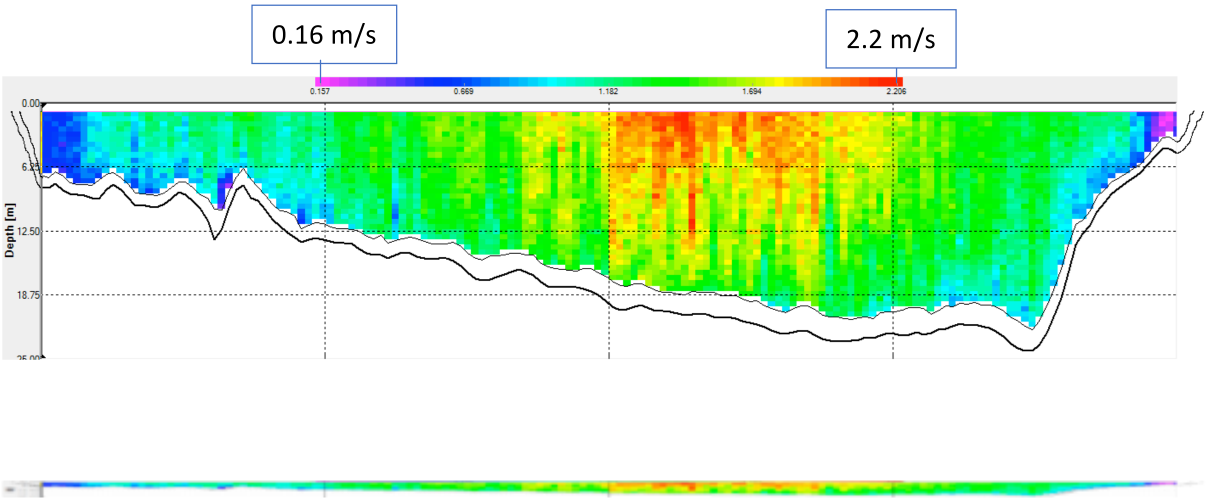

Figure 7.1.10. *A typical ADCP cross-section of the Mekong River.*

Design for Attraction and Passage

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

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

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

5.2. Downstream passage

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

1 passage of fish, particularly drifting larvae, through the impoundment; and

2 passage at the dam itself, via turbines, spillway and the sluice gates for sediment.

Use river hydraulics to inform design

Again, river hydraulics provides a very suitable template for fish passage; in this case the passage of drifting larvae through the impoundment. Firstly, it is noteworthy that despite the strong seasonality of migration in the Mekong there is dry-season and wet-season spawning and year-round drift of fish larvae, as demonstrated by MRC data on larval drift at Stung Treng (Figure 7.1.11).

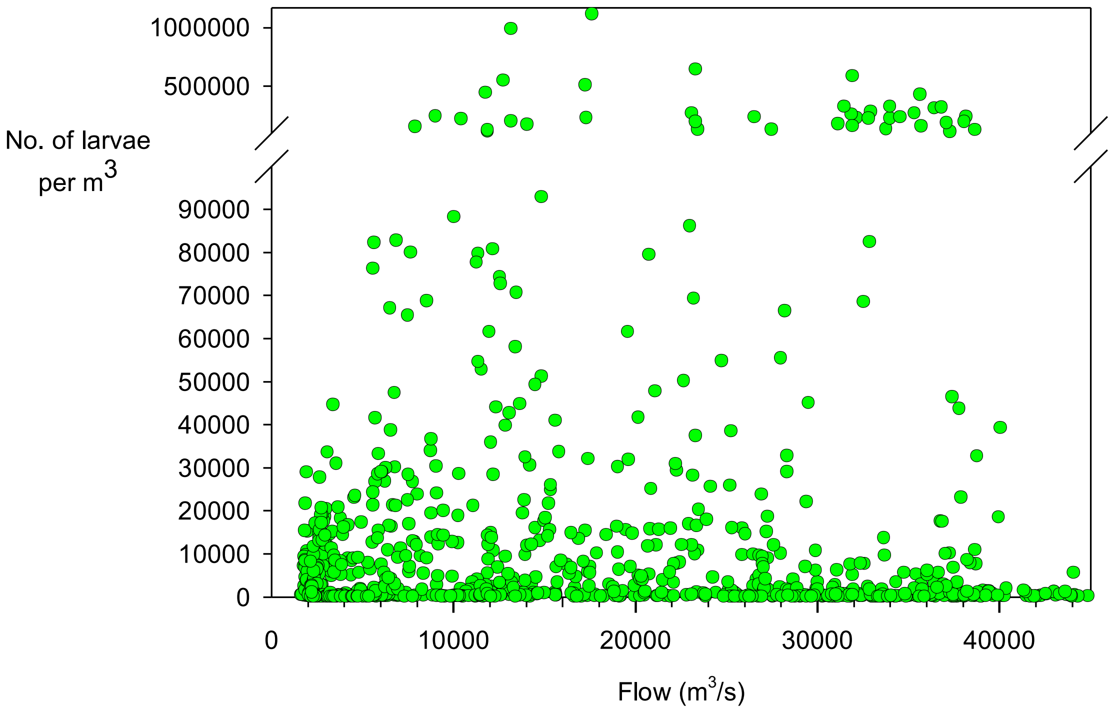

***Figure 7.1.11**. Density of drifting fish larvae in the Mekong River at Stung Treng in 2013. Intensive migration occurs in the dry season and during the start of the wet season.*

Recent ADCP data provides the data on river hydraulics to inform the minimum conditions required for larval drift. Mean channel velocity is plotted against river discharge in **Figure 7.1.12**. Mean water velocity can be over 1.5 m/s, although velocities along the edges are always much lower. In the dry season the mean velocity could be as low as 0.3 m/s. To maintain larval drift in impoundments in the lower Mekong, 0.4 to 0.5 m/s is suggested as a minimum target range of velocities within the impoundment in the dry season and a middle range of 0.8-1.0 m/s is suggested for the wet season, which is likely to have fish larvae that are adapted to higher mean water velocities. These criteria directly affect dam heights and operation and need to be incorporated in the prefeasibility design and power generation models, which are integral to the business case.

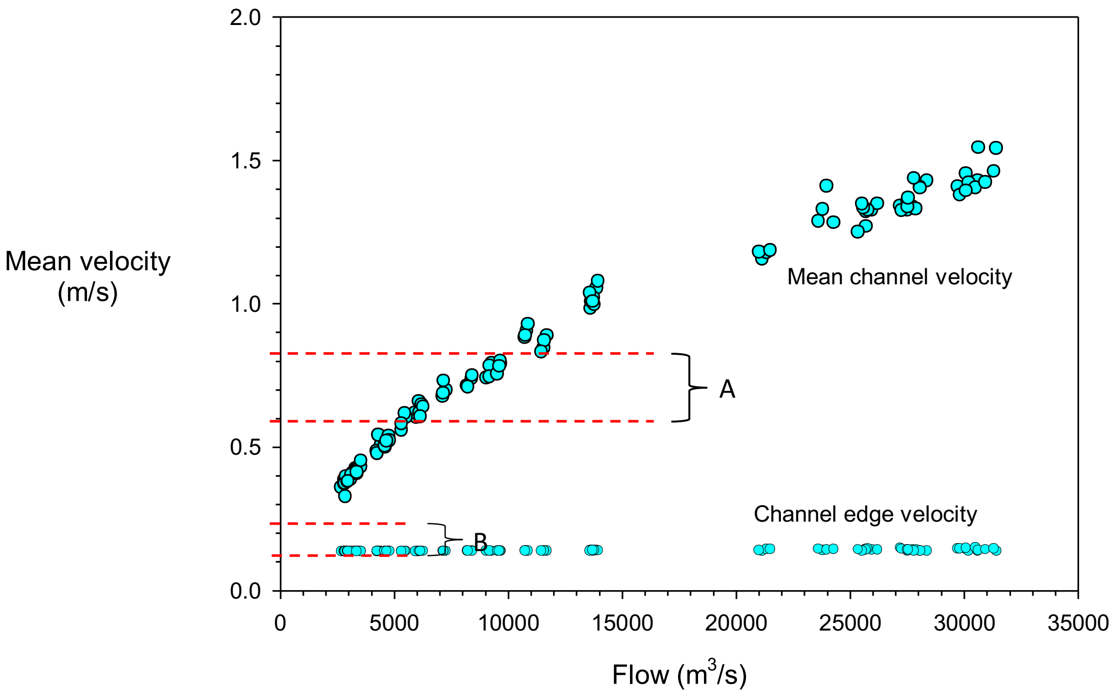

Figure 7.1.12. Mekong River discharge versus mean channel velocity at Kratie (from ADCP data). Red dashed lines show the range of minimum mean velocities to model for larval transport in the impoundment for the wet season (A) and dry season (B).

Use conservative assumptions

Passage at a dam itself is complex due to the range of pathways (turbines, spillway, sluice gates), and the range of fish sizes (larvae to large adult fish). Fish passing through turbines are exposed to pressure changes (barotrauma), shear stress and blade impacts. There is little specific data for tropical fish species that apply to turbine design. Using data from other species we have summarised the latest design criteria that apply to turbines (Lee Baumgartner, Craig Boys and Luiz Silva pers. comm.) which are conservative interpretations of the available data that would provide high expected survival (e.g. 99%) of a range of fish species (Table 7.1.1). These criteria have yet to be incorporated in turbine design but they provide a quantitative approach to this issue for both stakeholders and turbine manufacturers. Interviews with turbine manufacturers indicate that these criteria are achievable, except for impact speed, but there would be a small loss of efficiency.

Some general trends in turbine design that would improve fish passage are worth noting: large diameter, slowly rotating turbines with fewer blades reduces risks for fish and locating the turbine below tailwater (e.g. 10 m) reduces the specific risk of pressure changes (barotrauma). Most importantly, even if all the characteristics in Table 7.1.1 were incorporated into turbine design the risks for larger fish being injured and killed by blade strike are still very high. Hence, fish screens that enable large fish to bypass the turbines need to be an essential feature of large dams in the Mekong if sustaining migratory fish populations is an objective.

The criteria in Table 7.1.1 relating to barotrauma and *ratio of pressure change* show the sensitivity of fish to acclimation pressure; that is, the depth of acclimation before they enter the turbine. For example, if fish are acclimated to 10m depth (200kPa) as they approach the turbine and exit the turbine in the tailwater near the surface (100kPa) the swim bladder will double in size and in some species (e.g. physoclists) it may rupture and cause death. Hence, there are pressure impacts that can be in addition to the turbine design. One solution is to ensure fish volitionally acclimate to surface pressure before they enter the turbine, which could be done with a sloping weir in the intake channel. A second option is to locate the turbine and draft tube deep in the tailwater, at the same relative depth as fish enter from the reservoir; therefore, fish enter and leave the turbine at the same pressure. Locating the turbine deep in the tailwater also enables the nadir of 100 kPa to be achieved.

Table 7.1.1. Turbine design criteria for passage of Mekong fish. These are conservative values to ensure 99% survival (including drifting eggs, larvae and adults diverse in size, shape, and swim bladder morphology).

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

6. Preliminary Fish Passage Concepts

6.1. Catchment Strategy

Hydropower planners often have a catchment vision which involves all the potential dam sites with an analysis of discharge, river gradient and suitability of sites for construction. If minimizing biodiversity loss and retaining a substantial proportion of fish production is an objective as well as hydropower development then the vision also needs to include:

- A model of fish habitats (e.g. spawning, nursery, refuge) and migrations between them.
- Retaining flowing water (lotic) habitats of sufficient spatial scale for riverine fish species; for many species that migrate this is likely to be > 200km of continuous flowing river habitat.
- Avoid mainstem and lowland dam sites and utilise headwater and tributary sites, whilst leaving a mosaic of headwater habitats for biodiversity.
- Hydrological modelling and dam design to minimise impact of changes to flow regimes, including seasonal changes and daily/hourly changes due to hydropeaking.

If a cascade of dams is planned that creates a series of connected lake habitats, or highly fragmented short reaches of flowing water between the reservoirs, the utility of providing fish passage would need to be reviewed and alternative mitigations considered, such as offsets.

6.2. Upstream Passage

6.2.1. Concept

Upstream-migrating fish are attracted to flow and at tropical hydropower dams are attracted to the powerhouse in the dry season and to both the powerhouse and spillway in the wet season. These define the locations that require fish passage. Figure 7.1.13 shows a concept for upstream and downstream passage for a large hydropower dam. There are three upstream fishways:

i) a large bypass channel on the left bank;

ii) a large pool-type fishway between the powerhouse and spillway, which connects with both a collection gallery above the draft tubes of the turbines and to the side of the spillway; and

iii) large twin locks that enable navigation but are primarily designed for fish passage. This is relevant for the mainstem of the Mekong where navigation locks are required. At dam sites where navigation locks are not required, a fishway would replace it.

The axis of the dam and powerhouse is tilted to guide fish to the bypass channel. To ensure large benthic (bottom-dwelling) species will approach the dam and enter the fishways the downstream channel profile would be modified during construction to ensure the deepest channels (thalweg) lead directly to the fishways. The existing deep channel of the river is aligned with the left abutment of the spillway, which provides a suitable location for the sluice gates for sediment.

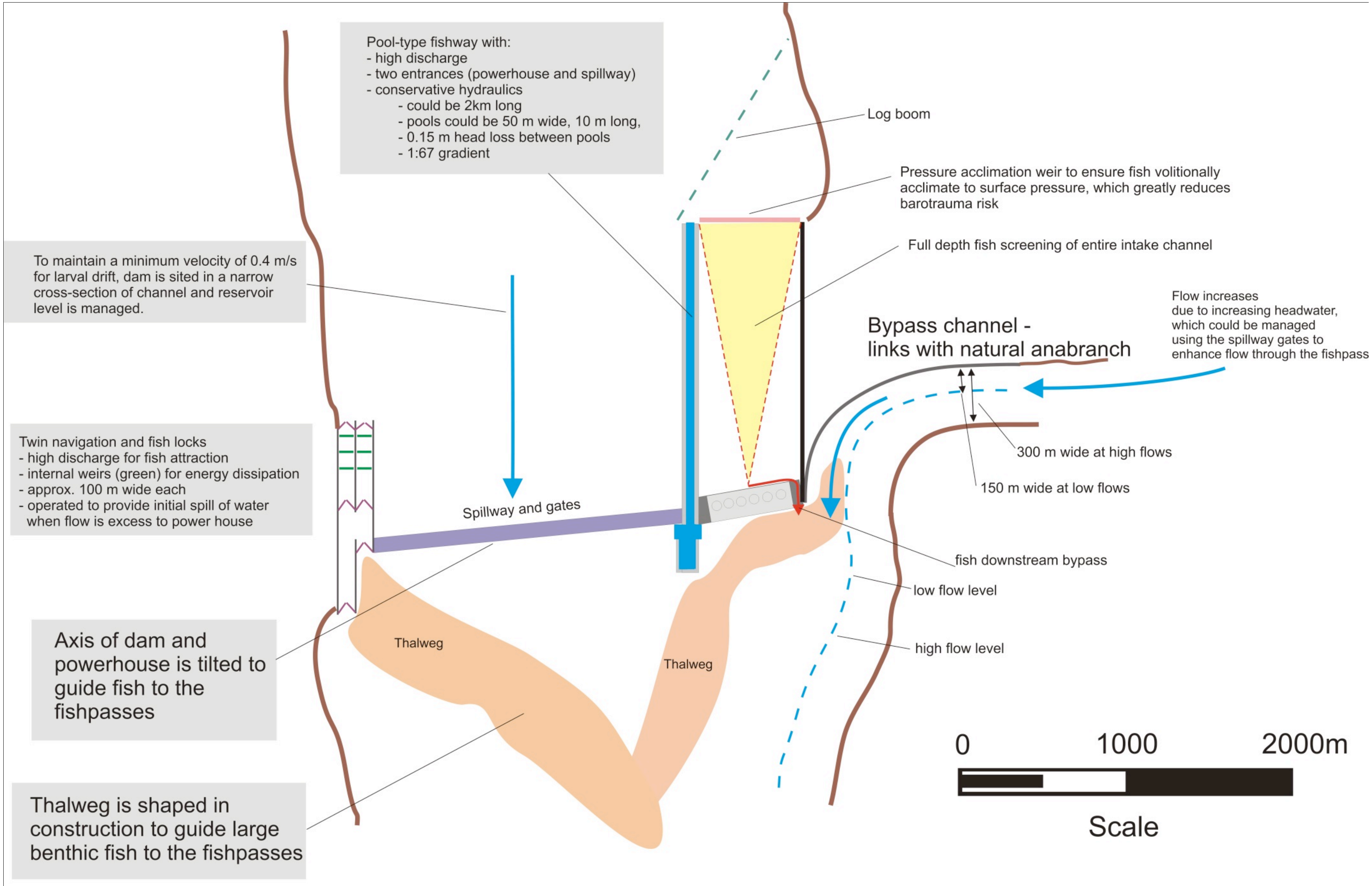

Figure 7.1.13. *Fish passage concepts for a large hydropower dam.*

Martin Mallen-Cooper

A bypass channel is shown in ***Figure 7.1.13***. Although the suitability of this option would be site-specific it can also influence the dam location if a suitable topography or channel already exists. If this option was used in the lower Mekong the gradient and profile of the channel should be modelled on the Hou Sahong channel at Khone Falls, with a 1:100 to 1:250 gradient.

The channel is shown with a minimum width of 100-150 m wide but would be profiled and benched to be 300 m wide or more, to pass much higher flows in the wet season. Importantly, where the bypass channel meets the powerhouse it would be oriented to direct the flow parallel to the river to ensure it is at the upstream limit of migration and to avoid recirculating eddies (***Figure 7.1.13***). The same principles apply to other types of fishways.

The hydraulic design criteria of a bypass channel would be based on mean channel velocities in the Mekong River of 0.4 to 0.6 m/s. It would have a trapezoidal cross-section and may be benched for low and high flows. It would likely have a minimum depth of 5 m in a central section that is 25 m wide.

6.2.2. Pool-type fishway

In the concept a large pool-type fishway is located between the powerhouse and spillway to pass fish attracted to each location (Figure 7.1.13). It would connect with both using collection gallery above the draft tubes of the turbines and an entrance pool with multiple entrances to the side of the spillway.

Large pool-type fishways for high dams have been used in North and South America (Figure 7.1.14). These have been successful for salmon but much less so for tropical species in South America. Pool-type fishways have predictable hydraulics and their effectiveness is largely due to selecting the appropriate design parameters rather than inherent features of this type of fishway. Often a high gradient is selected because it results in a shorter fishway and saves cost, but this creates turbulent hydraulics and results in reduced fish passage.

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

Alongside water velocity, turbulence is a primary design criterion of many types of fishways and is particularly applicable to pool-type fishways. Turbulence is the energy of water entering a pool and the pool volume available to dissipate it, and is measured in Watts per cubic metre (W/m^3). Salmonid fishways use 200 W/m^3, whereas fishways for non-salmonid fishes that are over 150 mm in length use 100 W/m^3 (Mallen-Cooper 1999) and fishways for smaller fish use 30 or 40 W/m^3 (Mallen-

Cooper pers. comm.). Initial pool-type fishways for Mekong fishes should use no higher than 100 W/m^3.

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

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

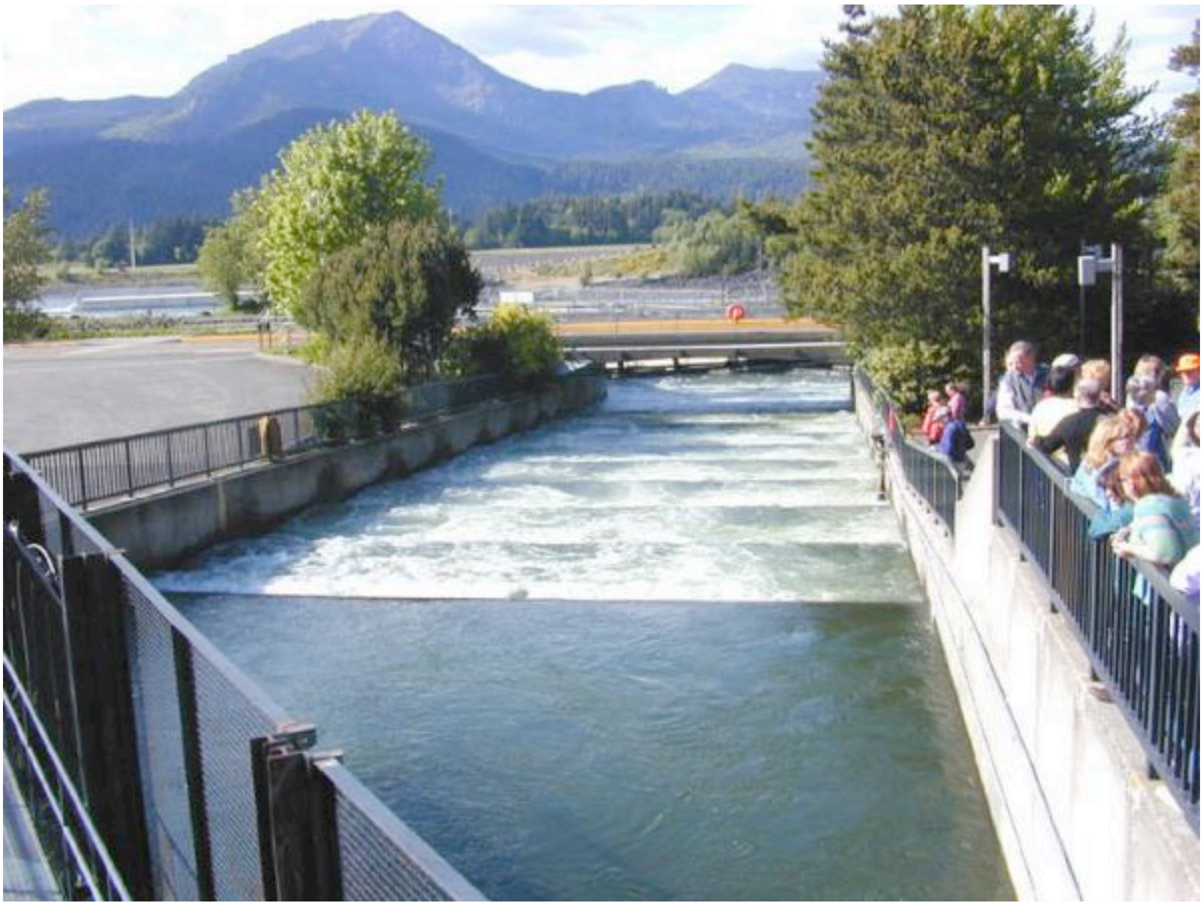

Figure 7.1.14. *Example of large pool-type fishway on the 27m high Bonneville Dam, Columbia River, USA. A suitable fishway for the lower Mekong, which would have a high migratory biomass, would be five times wider.*

6.2.3. Twin fish locks

Where a navigation lock is required these can be designed specifically for fish passage. In the concept in Figure 7.1.13 twin fish/navigation locks are shown on the right bank, where fish would aggregate when the spillway is in operation. A weakness of a single fish lock is that it is not attracting fish when it is in the filling, exit or draining phase; having two fish locks operating sequentially reduces this inefficiency. The MRC Preliminary Design Guidance for main-stem hydropower dams recommends navigation locks. To pass a high biomass of fish the size would need to be extended and additional valves and possibly gates would be required to specifically attract and pass fish.

Potentially each fish lock could be 100 m wide and 300 m long and have two entrances; one next to the spillway for moderate flows and one at the end of the abutment, possibly 100m downstream of the spillway, for high flows. Each fish lock may have three internal weirs to dissipate the energy of the water entering the lock and allow a very high discharge. The upper weir in each lock would act like a 100m wide fixed crest weir and could be adjustable (recess or tilt) to:

i) enable higher discharges at high river flows to ensure sufficient attraction for fish, and

ii) lower and provide the minimum required depth of 4m for navigation.

An advantage of this lock design is that it would be adaptable, with discharge and turbulence settings responsive to fish monitoring, as well as providing another route for safe downstream fish passage.

6.2.4. Operation of fishways

The operation of the three fishways needs to be integrated with the powerhouse and spillway to optimise function, with preference given to providing flow to the fishways before the spillway. Hence, the sequence of operation with increasing flow is:

1. Bypass channel.
2. Powerhouse, with bypass channel (or other fishway) passing a minimum of 10% of flow, and operate turbines next to fishway first.
3. Central pool-type fishway, increasing flow with increasing availability.
4. Twin fish locks.
5. Spillway, starting with gates adjacent to fishways and then minimising turbulence next to fishway entrances at high flows through gate operation.

6.3. Downstream Passage

6.3.1. Concept

Downstream passage would be provided by:

i) Managing water velocity through the impoundment,

ii) Applying screens and a bypass at the powerhouse,

iii) Design of the turbines,

iv) Design and operation of the spillway gates,

v) Design of the sluice gates, and

vi) Design of the spillway and apron,

vii) Passage through fishways for upstream migrants.

6.3.2. Managing water velocity through the impoundment

As discussed earlier a key aspect of downstream passage is drifting larvae. Managing water velocity through the impoundment is a major component of maintaining larval passage, along with turbine and gate design. A minimum of 0.4 to 0.5 m/s mean channel velocity is the suggested minimum in the dry season and 0.8 to 1.0 m/s is the suggested minimum in the wet season, as interpreted from the ADCP data in the lower Mekong River (**Figure 7.1.12**).

6.3.3. Screens and a bypass at the powerhouse

Screens are required at the powerhouse because larger fish have a very high risk of injury in turbines, regardless of the design. Screens for fish have been applied at numerous irrigation channels in North America. Large flat screens, either vertical or horizontal (Farmers Screens™), can be used, as well as rotating drum screens. Significantly, screens for fish passage presently between pass flows of 20 to 250 m^3/s. The maximum discharges for large dams in the lower Mekong is up to 10 to 50 times larger, which represents a major design challenge. Recommended approach velocities of fish screens are between 0.3 and 0.4 m/s, although the horizontal flat plate screens are higher. Initial estimates of screening for a large Mekong project of 10,000 $m^3 s^{-1}$ suggest that the area of screen required could be 1.0 sq. km. The screens would direct fish to a channel that would bypass the turbines and release fish downstream.

6.3.4. Turbine design

The turbines would be located approximately 10m below tailwater to minimize barotrauma. This would be combined with a *pressure acclimation weir* in the intake channel which ensures fish volitionally acclimate to surface pressure, which also minimises barotrauma.

All larvae and small fish will pass through the fish screens and through the turbines. Table 7.1.1 outlines some preliminary criteria for the design of turbines for Mekong fish species. These are conservative criteria with the objective of 99% survival. However, due to the lack of data on Mekong fish and turbine passage, field assessment would be required.

6.3.5. Design and operation of the spillway gates

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

6.3.6. Design and Operation of the Sluice Gates

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

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

6.3.7. Design of the spillway

Spillways can be specifically designed and operated to enhance passage of fish. Spillways need to be smooth and not stepped, with no dissipators or vertical endsills. Deceleration needs to as gradual as possible with a long spillway and apron.

6.3.8. Passage through fishways for upstream migrants

Although the fishways discussed in Section 6.2 are primarily for upstream migrants, downstream migrants will also use them. The extent that fish use them will largely depend on the discharge they use, although adult fish will tend to follow known migration paths. Hence, the bypass channel could pass 10% of downstream migrants in low flows and probably a lower proportion in high flows. The fish lock could pass a significant flow and could be useful for downstream passage, while the pool-type fishway will pass less flow and have an upstream entrance that is located in the middle of the river with little cue to enter from upstream.

7. Summary

The fish passage concepts presented in this paper are preliminary but identify the scope of fish passage required. In summary, they are:

Upstream Fish Passage

- Downstream bathymetry modified to ensure the deepest channel (thalweg) lead to the fishway.
- Axis of dam tilted to guide fish to the fishways.
- Bypass channel on the left bank,
    - that uses a natural anabranch,
    - has a 4 km connecting channel to the dam, 150 to 300 m wide,
    - with potentially three low-level weirs in the anabranch to divert low flows and three low-level weirs at the inlets to regulate low flows,
    - with a minimum discharge between 150 and 225 m^3/s,
- A large pool-type fishway between the powerhouse and spillway,
    - utilising a collection gallery on the draft tubes of the turbines,
    - having a second entrance next to the spillway,
    - with preliminary design criteria of 50 m wide, 10 m long pools on a 1:67 gradient, creating a 1.1 km long channel.
    - passing 12 to 120 m^3/s.
- Large twin fish locks on the right abutment that pass high discharge.
    - Each lock is 100 m wide and 300 m long.
    - There are two entrances: one next to the spillway for moderate flows and one at the end of the abutment for high flows and boat passage.
    - Each fish lock would have at least three internal weirs to dissipate the energy of the water entering the lock
    - The upper weir in each lock would be adjustable to enable higher discharges at high river flows to ensure sufficient attraction for fish and provide the minimum required depth of 4 m for navigation.

Downstream Fish Passage

- Managing water velocity through the impoundment, using
    - 0.4 to 0.5 m/s mean channel velocity in the dry season, and

  - 0.8 to 1.0 m/s in the wet season.
- Applying screens and a bypass at the powerhouse,
  - Screen approach velocity would be 0.3 to 0.4 m/s,
  - Screens would be automatically cleaned,
  - Screens would likely be in a "V" formation and may be 1.3 to 1.8 km long.
- Design of the turbines and associated infrastructure,
  - Pressure acclimation weir in intake channel for fish approaching turbines
  - Turbines located significantly below tailwater (e.g. 10 m)
  - Large diameter (e.g. > 10 m)
  - Slow rotation
  - Few blades
  - Thick leading edge
  - Nadir pressure close to atmospheric (100kPa)
  - Pressure ratio of 1.0
- Design and operation of the spillway gates,
  - Overshot gates used, or
  - Radial gates used fully open,
  - One or more overshot gates may be required if small increments of flow are discharged.
- Design of the sluice gates
  - Further investigation required but decompression chamber possible.
- Design of the spillway,
  - Smooth, not stepped,
  - No vertical dissipators.
  - Long apron, providing gradual deceleration
- Passage through fishways for upstream migrants.
  - Dependent on proportion of flow passing through.

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Appendix 7.2.

Conceptual Basis for Fish Passage Design at Sambor

Conceptual Basis for Fish Passage Design at Sambor

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Executive Summary

The conceptual basis for fish passage at Sambor is the fish ecology, fish behaviour and hydrology of the lower Mekong River. The major points are:

- To design a hydropower dam that minimises impacts on fish populations, and hence food security and livelihoods, it is essential to understand the ecology and life cycles of fish.
- Fish migration is an essential part of the life cycle of many fish species, especially key commercial species in the lower Mekong.
- A common life cycle in the Lower Mekong River is 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 downstream to refuge areas, including deep pools.
- The implications for hydropower in the lower Mekong and specifically at Sambor are:
    - There is a wide size range (e.g. 30-3000 mm) and high biomass of fish migrating upstream, with varying swimming ability and behaviour, that need to be accommodated in fish passage facilities.
    - Upstream fish passage is required at the powerhouse and spillway for varying flows; hence multiple fishways and multiple entrances would be required passing > 10% of flow to ensure fish attraction.
    - Downstream migration includes larvae that require flowing water to maintain drift; otherwise they are trapped by the stillwater of reservoirs. From ADCP data it is likely that a mean channel water velocity of 0.4 to 0.5 m/s is required in the dry and early wet season and 0.8 to 1.0 m/s may be required in the dry season.
    - Maintaining survival of fish approaching the turbines is required, either through turbine design and/or screens to divert fish.

1. Introduction

To design a hydropower dam that minimises impacts on fish it is essential to understand the ecology of fish, specifically:

- The species, size and biomass of fish that migrate upstream and downstream.
- The seasonality of migration and response of fish to specific flow cues.
- The spatial scale of migration – i.e. whether they migrating a short distance or 100s km of kilometres.
- The use of habitats within the inundated reservoir area
- The hydrodynamics of habitats. That is, the use of habitats in flowing water
- The use of habitats downstream of the dam that may be affected by changes in daily, and seasonal flow patterns

2. Fish Ecology in the Lower Mekong

Much has been written on the life cycles of Mekong fish (e.g. (Poulsen *et al.* 2002; Poulsen *et al.* 2004; Baran *et al.* 2005)), including migration cues (Baran 2006), so only a brief summary is presented here with the key points that influence hydropower development.

2.1. Groupings of Fish

Mekong fish, and tropical floodplain fishes in general, are can be grouped into three broad categories:

White fish

> These are riverine species that use the main channel of the Mekong and large tributaries and most species migrate long distances. These species frequently require flowing water for spawning and other habitats and do not survive in reservoirs.

Grey fish

> These fish are also riverine species but migrate shorter distances and often use floodplain habitats in the rainy season.

Black fish

> These fish are specifically adapted to floodplains and wetlands. They are dark in colour and can tolerate very low dissolved oxygen in stagnant water.

For hydropower development, the groups that are directly impacted are the ones that migrate, which are *white fish* and *grey fish*. The Mekong River Commission has further divided these groups into 10 migratory guilds (i.e. species with similar characteristics) to refine the impacts of hydropower on Mekong fishes (Halls and Kshatriya 2009). Table 7.2.1 shows guilds such as floodplain species (blackfish) which will not be impacted by hydropower, and four migratory guilds that are specifically impacted. The migratory fish in these guilds make up the well-documented, productive fisheries in the Tonle Sap River (e.g. Siamese mud carp makes up 40% of the Dai fishery), Khone Falls, and in the Cambodian section of the Mekong and 3S system.

Table 7.2.1. Migratory guilds for the Mekong River system (Halls and Kshatriya 2009). Guilds that are highly vulnerable to impacts from hydropower are shaded in blue.

	Migratory Guild	Habitats
1.	Headwaters (rithron) resident	Headwaters
2.	Migratory main channel and tributaries, resident	River channel, from marine to upper reaches
3.	Migratory main channel spawner	River channel to upper reaches, & floodplains
4.	Migratory main channel refuge seeker	River channel & floodplains
5.	Generalist	River channel & floodplains
6.	Floodplain resident	Floodplains
7.	Estuarine resident	Estuary
8.	Semi-anadromous	Estuary and lower river channel
9.	Catadromous	Marine and river channel to upper reaches
10.	Marine	Estuary

2.2. Life Cycles

There are some similar aspects of the life cycles of the migratory guilds that are at risk from main stem hydropower developments in the Mekong. A common migration pattern in these guilds is for adult fish and sub-adult fish to migrate upstream, often at the beginning of the rainy season. These fish feed and the adults spawn. Importantly, larvae and juveniles drift downstream. Most species have sticky eggs so these don’t drift and whether yolk-sac larvae drift is unknown. The relevance of this life history is that, to meet fish passage objectives:

- upstream passage needs to consider adult and sub-adults fish (of varying sizes), and
- downstream passage needs to consider returning adults, and drifting larvae and juveniles.

The ecology of upstream migrations is relatively well understood and prudent design decisions with flexibility in design can accommodate most eventualities. However, no dam project has ever considered drifting larvae, which is probably a large reason these large riverine species have disappeared from large tropical dams, notably in South America. We have also found in this project that accommodating larval drift has a major influence on design, operation and energy production. Therefore, the following sections examine the ecology of Mekong larvae to refine the design and operation.

2.3. Larval Ecology

2.3.1. Seasonality

There are two key fish larval studies for the region: i) the MRC regional study (Cowx *et al.* 2015) which was over 12 months and covered 11 sites along the entire lower Mekong, ii) the IFReDi long-term study, which has collected larvae in the Mekong River near Phnom Penh and in the Tonle Sap, annually since 2002. Cowx *et al*. (2015) show that there is larval drift all year while the IFReDI study is more intensive, almost daily from the onset of the rainy season till after the peak flow, and shows more patterns among species in relation to season and flow. IFReDI have collected and identified over 13 million larvae fish of 76 species over 14 years.

The IFReDI data is dominated by Siamese mud carp (*Cirrhinus siamensis/lobatus*)[5] (Figure 7.2.1), representing 82% of drifting larvae in the Mekong at Phnom Penh. To examine monthly trends this species is separated from other species and plotted in Figure 7.2.2 as mean monthly number of larvae per cubic metre, while other species are grouped together.

Figure 7.2.1. *Siamese mud carp, Cirrhinus spp, the most important commercial species of the Tonle Sap Dai fishery, which also dominates the larval drift (Photograph by Terry Warren).*

Cirrhinus species have peak spawning in June and July while other species have a broader peak from April to July. Despite the numerous samples in peak flows in August and September, larval drift is less at this time; although this may reflect the difficulty of sampling and the dilution of larvae density at very high flows.

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[5] An important commercial species: >40% of Dai fishery; >40% of fence-filter traps at Khone Falls.

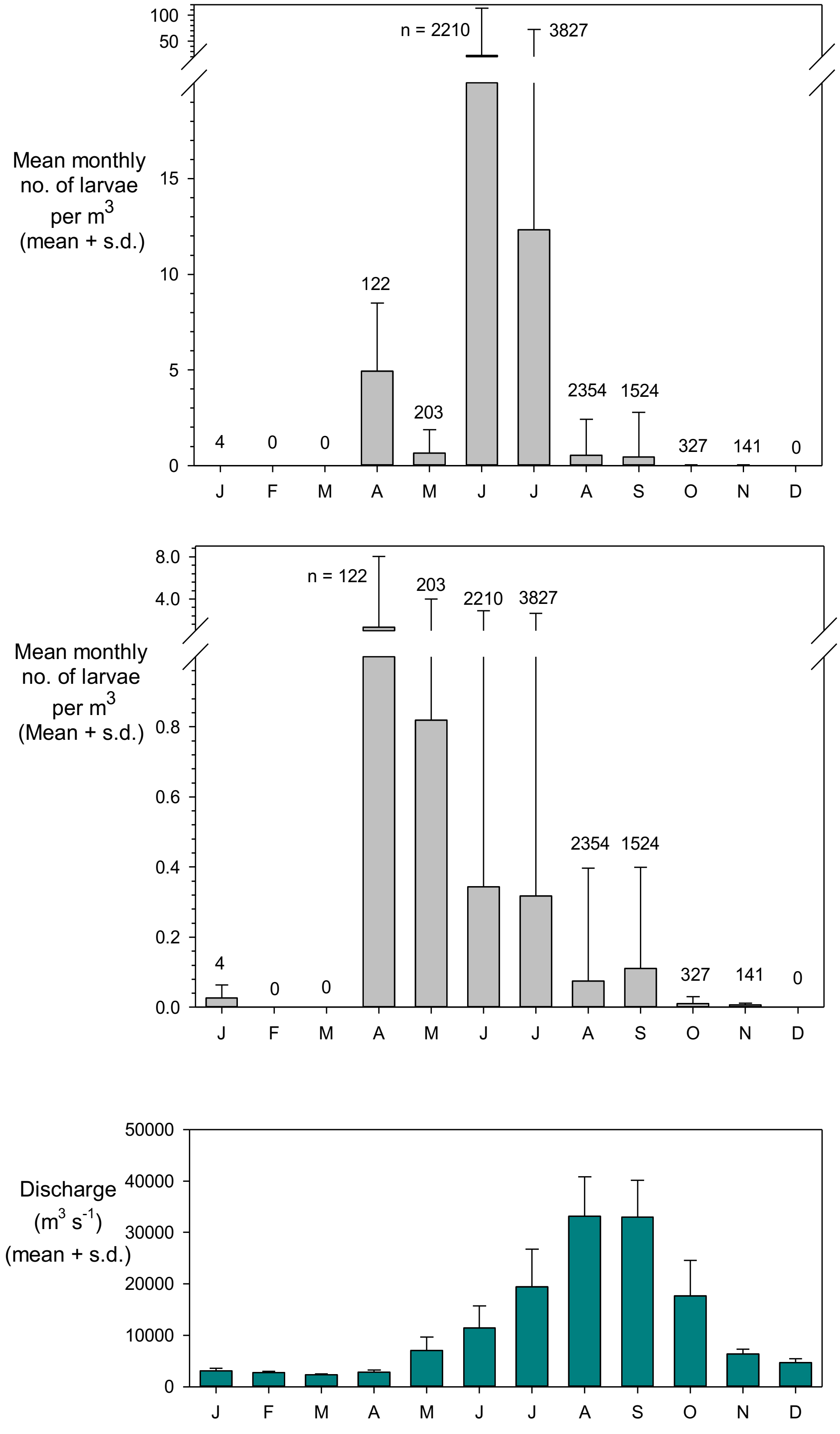

Figure 7.2.2. *Drifting larvae of Henicorhynchus spp. (top) and other species (middle) in the Mekong at Phnom Penh, 2002-2013, shown with monthly flow (bottom). The total number of larval samples for each month over the 11 years is shown at the top of each bar.*

The first implication for hydropower is that it is important to maintain larval drift through the reservoir from April to July inclusive. The second implication is that there will be a higher proportion of flow passing through the turbines, with potentially higher mortality in the earlier months when there is less flow.

To illustrate some other key points for hydropower development in the Mekong main stem, three species in two years (2008 & 2013) are examined in detail in Figure 7.2.3. The figure shows that spawning is highly variable within and among species between years, to the extent that some species are absent from the samples in some years (e.g. Figure 7.2.3: in 2013, Species B & C were not collected). Other key points to note are numbered in the figure and include:

1. Different species are spawning at different flows and times. In 2008 Species B is mainly spawning in low flows, just before the increase in flow, while the more common strategy is for species to spawn after the onset of the rainy season.
2. Peak spawning of many species is associated with a pulse of flow during the rising river of the rainy season.
3. In general, spawning intensity appears to decline after the peak flow of the rainy season.
4. In 2013, the onset of the rainy season was delayed and spawning was initiated, with high intensity, at lower flows than other years. Although this is only one year, it may mean that for hydropower development at Sambor more larvae would pass through the turbines – with potentially greater mortality - than over the spillway. It is also noteworthy that a delayed onset of the rainy season is a predicted impact up upper catchment dams which store water at this time.

The key implications for hydropower are:

i) There is larval drift all year but a high priority is to maintain larval drift through a hydropower reservoir is the early wet season, from April to July.
ii) If further hydropower development continues in the Mekong Basin and delays the onset of the rainy season, spawning may occur at higher intensity at lower flows, which means more fish (adults and larvae) will pass through the turbines and less will pass through the spillway, which will likely result in higher mortalities.

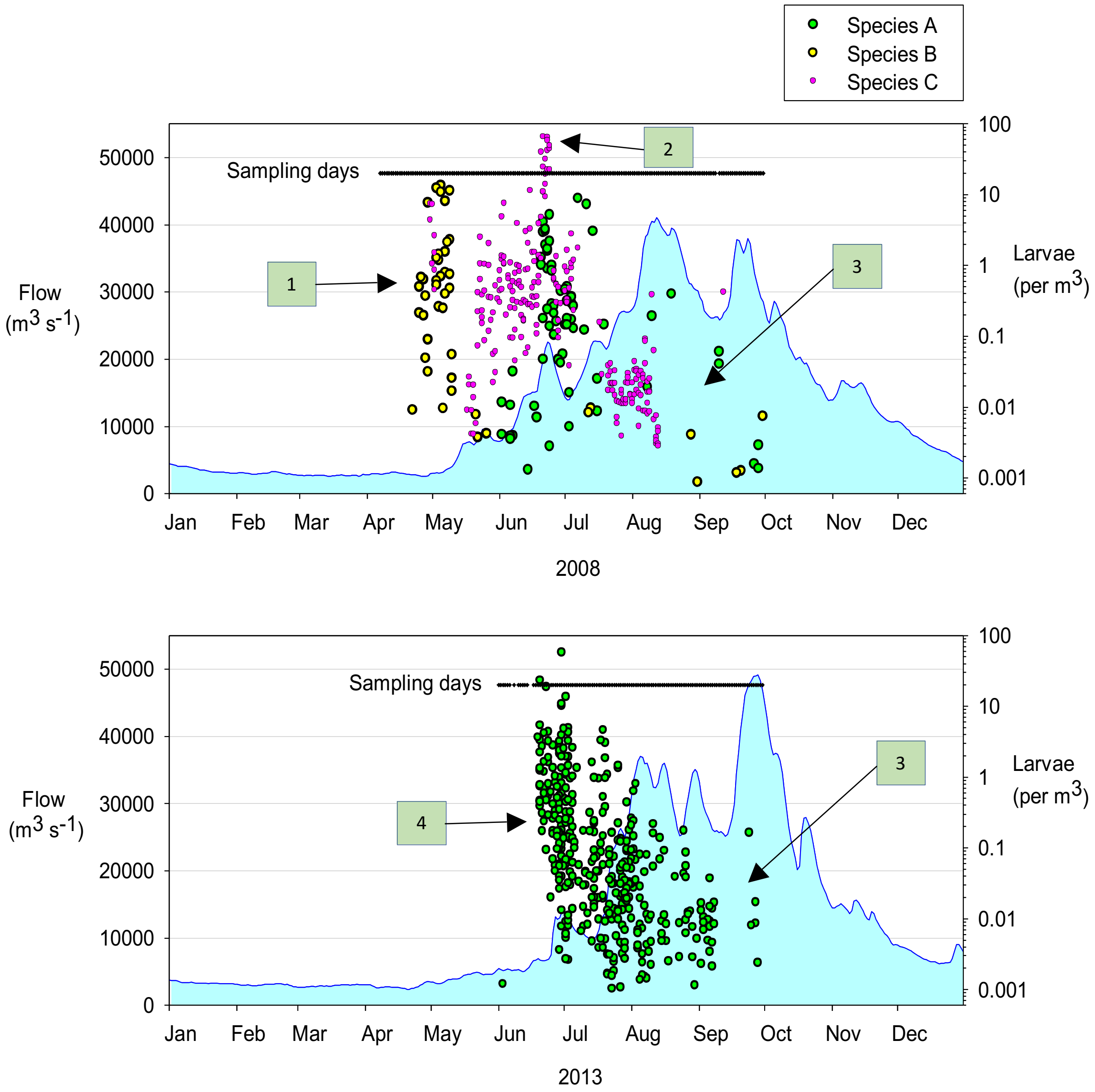

Figure 7.2.3. *Drifting larvae of three species in 2008 and 2013 (IFReDI data), shown with daily Mekong flow. Note that larval numbers are on a log scale and sampling days are shown as a horizontal symbols. (Species names are uncertain at this stage due to database incompatibility).*

2.3.2. Larval behavior in reservoirs

To assess the impact of reservoirs on drifting larvae in the Mekong the most useful comparisons are in other large rivers that have long-distance migratory species with larval drift. The South American rivers are good examples, as are some North American rivers and the Murray-Darling river system in Australia. Existing dams in tributaries of the Mekong and other large rivers also provide an insight into what types of species will survive.

South American fish scientists have been very active assessing the impacts of hydropower dams in South America. The key messages from their publications are that: i) upstream passage has been done very poorly, ii) migratory fish in dammed rivers require extensive flowing water (lotic) habitats upstream to sustain populations, as well as connections to floodplains; and that iii) reservoirs prevent larval drift and these larvae die - it is considered one of the highest impacts (Agostinho *et al.* 2007; Pelicice and Agostinho 2008; Pompeu *et al.* 2011; Pelicice *et al.* 2015).

For riverine (lotic) fish species the specific gravity of larvae with an oil droplet is a fraction greater than water (e.g. (Dudley and Platania 1999; Coleman 2015)), so a constant current is needed to keep them in suspension. Once larvae inflate the swim bladder they are potentially control buoyancy but these riverine larvae still appear to need flowing water to survive; this may relate to suspended food in the water or to transport to productive downstream floodplains.

The loss of riverine species with pelagic larvae is well documented in other impounded rivers with reservoirs (Dudley and Platania 2007; Wilde and Urbanczyk 2013; Pelicice *et al.* 2015) and the loss of species in the Mekong tributary dams provides an indication of which species are sensitive to this and which are not.

A key issue for the Sambor project is the minimum water velocity required to maintain larval drift through the reservoir. A lower velocity in the reservoir generally, but not always, means that a higher head differential can be achieved with greater power production.

The literature has records of larval drift and water velocity in the field but no experimental data that might vary this parameter. Field measurements for pelagic drifting temperate and tropical fish larvae are often in the range of 0.6 to 1.0 m/s and occasionally down to 0.3-0.4 m/s (Bialetzki *et al.* 1999; Braaten *et al.* 2012). In Australia, similar threshold velocities of 0.3-0.4 m/s maintain fish larvae in the drift.

For the Sambor project we used the ADCP data and mean channel velocity as a first of the hydrodynamic data. Under present conditions high numbers of larvae are drifting at flows greater than 10,000 m^3/s so mean channel velocities greater than 0.8 m/s maintain larval drift (Figure 7.2.4. However, it is likely that lower water velocities can maintain drift and based on present conditions and data from other studies, 0.4 to 0.5 m/s should be sufficient. We are presently using 0.3 m/s which can be considered the minimum. Further work on the sensitivity of these data is required if the project proceeds.

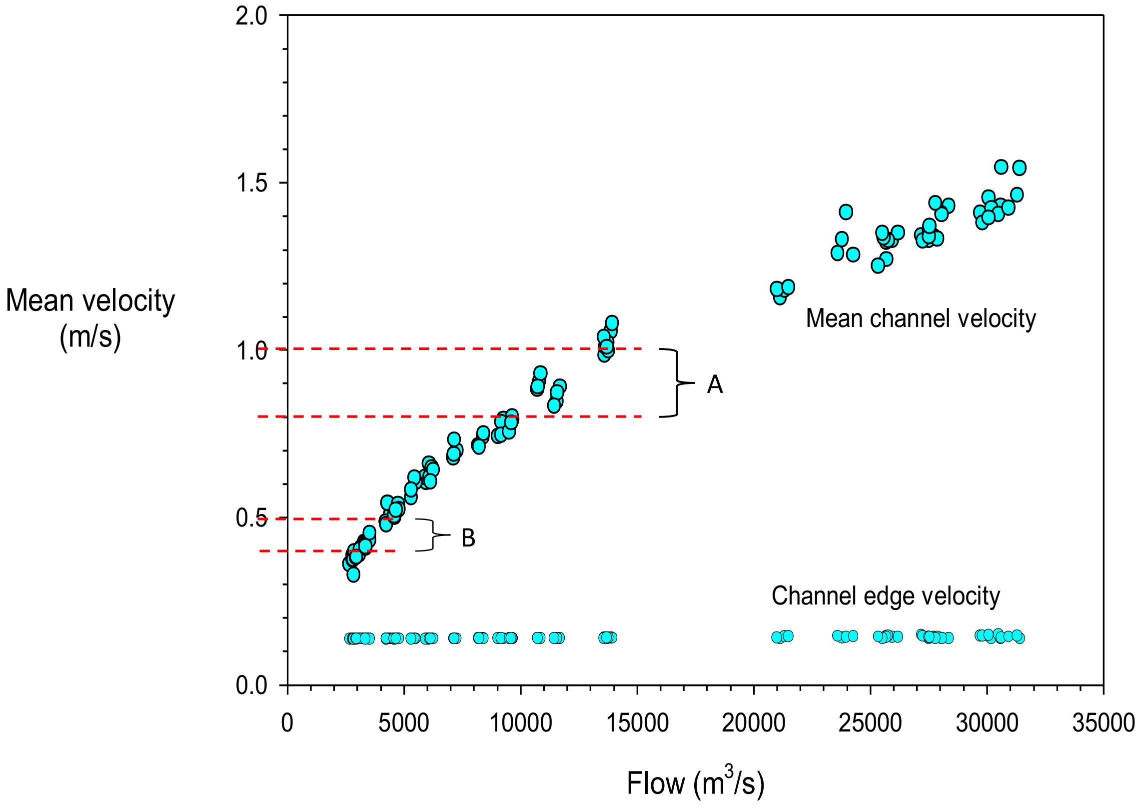

Figure 7.2.4. *ADCP water velocity data of the main channel of the Mekong River.*

2.3.3. Application at Sambor

From the analysis of larval ecology, the underlying design principle for the Sambor project is to maintain a flowing water (lotic) habitat in the impounded area; maintaining the hydrodynamics of a slow-moving river and many of the river processes. This is a very different approach from any existing hydropower dam.

That approach changes many of the assumptions that are normally make about larval survival in reservoirs, including food availability, susceptibility to predation, and water quality.

In a typical reservoir, the residence time of larvae would be important because it is a standing water (lentic) habitat. In these conditions food for larvae (zooplankton assemblage and availability) can change, larvae may sink, and turbidity is reduced as fine sediments drop out which can add to predation of larvae.

In the present approach at Sambor the objective is to not only maintain fish larvae in the drift but also zooplankton and fine sediment; as well as maintaining a high turnover of water which greatly reduces water quality risks. Hence, food availability, predation risk and water quality risk for these larvae are very likely to be similar to the river where it flows slowly, but not a still reservoir. In these conditions residence time and starvation of larvae are unlikely to be significant issues.

Without specific data on the behaviour on larvae in the Mekong main stem channel, we are using a "top down" methodology, where maintaining flowing water (lotic) hydrodynamics has a high likelihood of optimising survival of riverine pelagic larvae, rather than a “bottom up” methodology which examines the mechanisms of larval survival and tries to quantify them.

There is little data on fish species that spawn in the dry season months of January to March. It is possible their larvae do not drift very far, or they have larvae that survive in more stillwater habitats typical of low flows. For the present, April to July should be considered the key months for larval drift. Dam operating policies should prioritise continuity of drift (i.e. 100%) in these months. Outside of that period drift could arguably be 90% or less, although, as mentioned above there is larval drift all year (Cowx *et al.* 2015).

3. Conclusion

Much has been written on the life cycles of Mekong fish and upstream migration so this report has focused on larval biology as maintaining larval drift has a major influence on the design and operation of the dam. Significantly, spawning and larval drift occurs all year with pulses in the early- and mid- wet season. ADCP data suggests that a mean channel velocity of 0.4 to 0.5 m/s is required to maintain larval drift in the dry and early wet season and 0.8 to 1.0 m/s is required on the wet season. Safe downstream passage is required for at the spillway and at the turbines, either through turbine design and /or screens to divert fish.

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Appendix 7.3.

Hydraulics of Pool-Type Fishways

Hydraulics of Pool-type Fishways

Estimating the maximum water velocity

The maximum water velocity of water passing through a pool-type fishway such as a vertical-slot occurs just downstream of the slot where the jet of water narrows to form a *vena contracta* (Figure 7.3.1). This velocity is estimated by the following formula (Vennard and Street, 1982) which uses the difference in water levels upstream and downstream of the slot (called head loss or head difference – see Figure 7.3.2):

$$V = Cd \sqrt{(2g\ \Delta h)}$$

where	V	is velocity (m s^{-1})
	Cd	is coefficient of discharge
	g	is acceleration due to gravity (9.8 m s^{-1} s^{-1})
	Δh	is head loss (m)

A ‘coefficient of discharge’ of 1.0 provides a good estimate of the maximum water velocity in the *vena contracta*. This is also the convention used for designing fishways.

To estimate the water velocity across the upstream face of the vertical-slot (orange dotted line in Fig. 1), and not at the *vena contracta*, a coefficient of discharge (Cd) needs to be applied; in vertical-slot fishways 0.7 is commonly used. The coefficient of discharge is the ratio of the width of the jet at the *vena contracta* to the width of the upstream part of the jet, which is the width of the slot – a high Cd (e.g. 0.95) represents very little contraction and a low Cd (e.g. 0.5) represents very significant contraction of the jet.

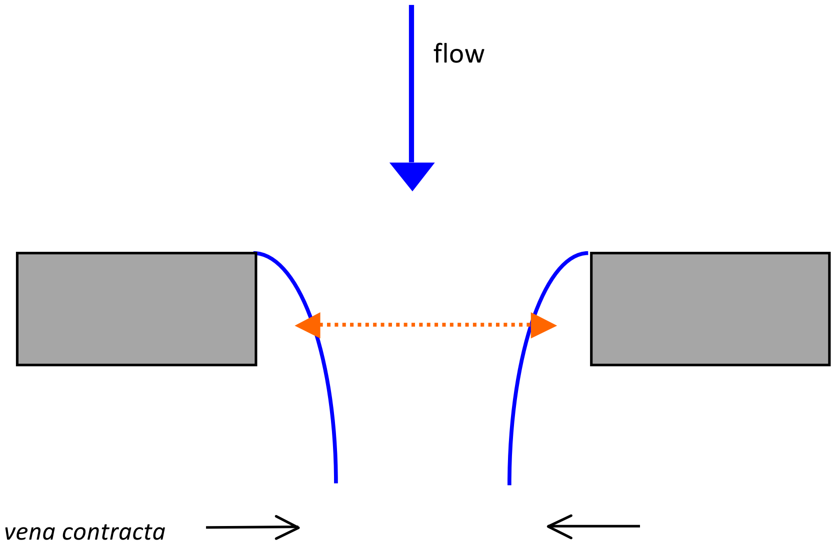

Figure 7.3.1. *Plan view of a jet through a slot or orifice showing the vena contracta.*

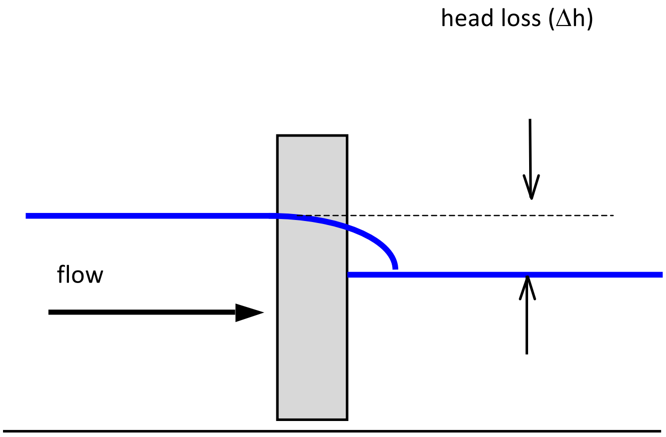

Figure 7.3-2. *Elevation of vertical-slot fishway showing the head loss.*

Estimating discharge through a vertical-slot

To estimate discharge through a vertical-slot the following formula is used:

$$Q = Cd\ V\ A$$

where Q is discharge in cubic metres per second

Cd is coefficient of discharge

V is water velocity through the vertical-slot (not at the *vena contracta*)

A is cross sectional area of water passing through the slot

To use this formula, V is first calculated from the head loss across a fishway baffle and a Cd of 0.7 is often used for the most common type of vertical-slot baffle. However, Cds can vary from 0.55 to 0.95 in different baffles. Vertical-slot baffles with sills can also produce a vertical contraction that often results in a slightly lower Cd than normal.

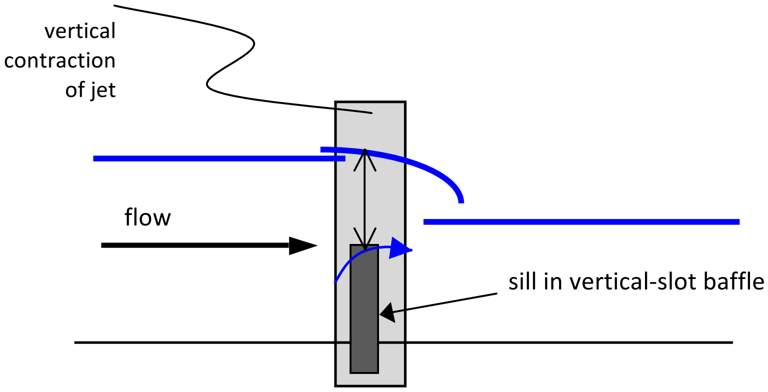

Fig. 7.3.3. *Vertical-slot fishway baffle showing the vertical contraction that occurs when using a sill.*

Estimating turbulence in a vertical-slot fishway

Turbulence within a fishway is determined by the discharge and velocity of the water entering a fishway pool, and the pool volume that is available to dissipate the energy of that water. It is measured in watts per cubic metre, which are units of power. Turbulence was described in general terms by Bell (1973) and further quantified by White and Peninno (1980), and Katopodis (1981) in the following equation:

$$P = (Q\ \Delta h\ \gamma) / V_p$$

where P is power, watts/m^3 (W/m^3)

(or energy / pool volume)

Q is discharge (m^3/s)

Δh is head loss (m)

γ is weight density of water (9777 Newtons/m^3 at $25^{O}C$)

v is pool volume (m^3)

It is also referred to Energy Dissipation Factor (EDF).

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Appendix 7.4.

Sambor Dam Fish Screen Inlet Facility Concepts: A pre-feasibility assessment of two alternatives

Sambor Dam Fish Screen Inlet Facility Concepts: a pre-feasibility assessment of two alternatives

By William Bryan, Les Perkins and Dan Kaler
Farmers Conservation Alliance

ABSTRACT

The Mekong River system is the second largest fishery in the world, providing a sustainable source of protein for the Cambodian population. Fish protection and survival is therefore important when considering the Sambor Dam hydroelectric facility. Both a horizontal flat plate fish screen, the Farmers screen, and a more conventional vertical traveling belt fish screen, the Hydrolox screen, are considered with a goal to protect at least 95 percent of all species and all life stages at the Sambor Dam site. The screening of fish from turbine intakes is explored based upon two flow discharge scenarios: 1) passing up to 12,000 m^3/s (the main stem site) and 2) passing 1,200 m^3/s (the anabranch site). The study is unconstrained with regard to fish screening inlet facility footprint and cost. With qualified language, it is tentatively concluded that screening at the Sambor Dam to protect 95% of the fish species is feasible. One screen alternative, the Farmers screen, is a passive, self-cleaning system with no moving parts, relying on open channel hydraulic energy to gently ease water through the screen material while safely bypassing fish and debris. Substantial additional computer modeling and prototypical testing would be required, however, so as to ensure scalability to the size proposed for the Sambor Dam project. The more conventional vertically oriented traveling belt screening system, the Hydrolox screen, on the other hand, would function without additional computer modeling but would likely require mechanical spray bars, pump systems, tension arms, fish handling buckets, mechanical torque override systems, debris conveyor belts, and electricity costs to operate the screens and associated support mechanisms. Comparing the total footprint of the Farmers screen and the Hydrolox screen, the horizontally oriented Farmers screen requires more total surface area (~$9.2\text{x}10^{-5}$ $km^2/m^3/s$), whereas the vertically oriented Hydrolox screen requires less total surface area (~$6.25\text{x}10^{-6}$ $km^2/m^3/s$). Since the Hydrolox screen units are generally vertical in orientation, their associated horizontal footprint is relatively small. For illustrative purposes, assuming a basic 5.7 m^3/s Hydrolox screen unit, a 1,200 m^3/s system would require 212 screen units a total of ~1.5 km long; a 12,000 m^3/s system would require 2,118 screen units a total of ~15 km long. For comparison, assuming a basic 300 m^3/s Farmers screen unit, a 1,200 m^3/s system would require 4 screen units a total of ~0.125 km^2; a 12,000 m^3/s system would require 40 screen units a total of ~1.25 km^2. The Farmers screen requires a water depth of ~1.5 metres, whereas the Hydrolox screen requires a minimum water depth of ~11 metres. Levelized pricing developed by fish agency and business development experts in the US suggests an in-place estimated pre-feasibility cost of USD~175,000/m^3/s for the Farmers screen facility and USD~529,000/m^3/s for the Hydrolox screen facility. This pricing assumes US NMFS criteria for both screen alternatives with a goal to meet the targeted 95% fish species survival standard for the Sambor Dam project. This pre-feasibility assessment provides an opportunity to re-think large-scale hydropower schemes and associated fish protection strategies, potentially providing a model for future fish screen embodiments on large dams.

INTRODUCTION

The Mekong River system is the second largest fishery in the world, providing a sustainable source of protein for the Cambodian population, and, as such, fish protection and survival is important when considering the Sambor Dam hydroelectric facility. With a goal to protect at least 95 percent of all species at all life stages in the Mekong River in the Sambor Dam reach, this pre-feasibility assessment considers a horizontal flat plate fish screen, the Farmers screen, and a more conventional traveling belt fish screen technology, the Hydrolox screen. The feasibility of screening fish from the Sambor Dam turbine intakes for each screen embodiment is explored under two flow scenarios, developing suitable fish screen alternatives for the following two discharges:

i) passing up to 12,000 m^3/s (i.e., the main stem dam site) and
ii) passing 1,200 m^3/s (i.e., the anabranch dam site)

For the purposes of this assessment, it is assumed that the screen facility footprint is largely unconstrained, and no economic limitations are imposed at this pre-feasibility level.

With regard to the overarching goal to protect at least 95% of all species at all lifestages, the practicality of screening to protect drifting larvae and juvenile fish less than 100 mm is explored.

In addition to developing the screen systems per se, the assessment includes considerations for managing debris and sediment, noting that the Sambor Dam power house will operate during flood flows and that trees up to 10 tons or more are part of the floating debris.

While no unequivocal representations regarding fish screening for the Sambor Dam can be made at this pre-feasibility assessment level, if properly qualified and understood, the findings as presented herein might offer a feasible solution for protecting the fish of the Cambodian Mekong from entrainment into the Sambor Dam hydroelectric turbines. Here again, these findings are entirely dependent upon the two previously stated primary assumptions that allow for this conclusion:

1. The footprint for the fish screening inlet facility is unconstrained, and
2. Economic limitations are not to be considered.

Because of its simplicity and lack of moving parts, the Farmers screen is attractive but lacks sufficient testing at the large scale of the Sambor Dam flows to move forward without further computer and prototypical modeling; alternatively, while the Hydrolox screen has many moving parts, it is easy to design and characterize. The Farmers screen, despite its operational simplicity, resists traditional basic fluid mechanical analyses, and, as such, would require extensive dynamic 3-dimensional modeling and the installation and testing of a prototypical field embodiment if the project were to move forward with this scheme. Overall, whether a Farmers screen or a traditional Hydrolox screen, given the large amount of land available for a fish screen inlet facility, this assessment discerns no immediately self-evident insurmountable fatal flaws with either option.

Introductory background for those unfamiliar with the form and function of the Farmers screen can be viewed at farmerscreen.org. For the Hydrolox screen, see Hydrolox.com. Sheets 1 through 5 provided in Attachment 1 at the end of this document, are the preliminary conceptual design drawings for the Farmers screen concepts. Standard drawings for the conventional Hydrolox screen are also provided at the end of this document in Attachment 2.

While much additional work would need to be completed if these concepts were to be developed beyond this very basic preliminary feasibility assessment, this study concludes that there is enough land to accommodate either facility and protect at least 95 percent of the fish species in the project reach. Accordingly, economic considerations might prove to be the primary driver as to whether or not to pursue high-level fish protection screening on the inlet facility of this large-scale hydroelectric diversion.

GENERAL PRE-FEASIBILTY ASSESSMENT LIMITATIONS

This preliminary feasibility assessment is constrained to the following assumptions, limitations, and qualifications.

- There is a big knowledge gap between what has actually been done to screen for fish at large dam facilities and what this preliminary feasibility assessment seeks to do.

- For the purposes of this preliminary design, as mentioned elsewhere in this chapter, it is assumed that a uniform water surface elevation will be available at the invert of the Farmers screen inlet headgates and flumes or on the face of the Hydrolox screen.

- Upstream passage is not considered in this preliminary design; instead, the focus is on safe downstream passage of all fish species, all life stages, striving to avoid all injury and mortality.

- For the purposes of this preliminary feasibility analysis, whether for the Farmers screen or the Hydrolox screen, given the understanding that the turbines will operate during flood flow conditions, it is assumed that flows exceeding turbine hydraulic capacity would pass through a separate spillway or pipe bypass system detached from the screen inlets.

- Considerable effort has been dedicated to developing properly comparative pricing for both the Farmers screen and Hydrolox screen.

- Price estimates for each fish screening embodiment have been derived from fish screen business development and fish agency experts working in the US, utilizing an all-inclusive, in-place price estimate methodology.

- This pre-feasibility pricing holds both screen embodiments to NMFS criteria developed for the Western Pacific States for the protection of salmonids. In light of the targeted 95% survival standard for the Sambor Dam project, these criteria appear reasonable.

- It has been noted that new turbine blade technology might reliably solve issues of barotrauma, blade strike, and shear stress such that fish <150mm might safely pass through the turbines without injury or mortality. If fish <150mm will safely pass through the turbines, screen material hole diameter or slot dimensions could increase with a corresponding increase in net open screen area, which in turn would reduce the screen footprint without increasing the screen approach velocity. Accordingly, as a function of the reduced total screen size, it is appropriate to expect a corresponding reduction in total screen cost.

- This pre-feasibility assessment process included a brief consideration of other alternative screen technologies such as traditional rotary drums, V-screens, inclined horizontal screens (both low- and high-velocity embodiments), and tapered vertical panel screens. At this pre-feasibility level, based on substantial direct operational experience and costs, these alternatives were rejected. The requirements for cleaning devices in vertical embodiments, the risk of exposed dry screen sections in traditional inclined quasi-horizontal embodiments, and the ongoing operation and maintenance expenses associated with these traditional fish screens in a system as large as the envisioned Sambor Dam are of concern. Furthermore, FCA's experience pricing the Farmers screen and the Hydrolox screen, including the benefit of its ongoing relationship with Hydrolox, allowed for more timely preliminary pricing information.

HORIZONTAL FLAT PLATE (FARMERS SCREEN) FISH SCREENING OPTION

The Farmers screen is a horizontal flat plate screen that functions naturally and passively according to Newtonian laws governing incompressible fluid flow. The screen material itself is typically perforated stainless steel plate but can also be wedgewire bars. Water flows through the screen material at very low velocities and sweeps across the screen material at relatively high velocities. Sweeping velocities can range from 20 to 40 times greater than velocities through the screen. High sweeping velocities provide passive cleaning, eliminating the need for any mechanical components. Proper screen function is ensured by balancing systemic mass flow with taper walls and downstream weirs. Fish and debris are passed over the screen and out the bypass throat into the fish bypass return channel to the river.

FARMERS SCREEN PRE-FEASIBILTY ASSESSMENT LIMITATIONS

- The largest Farmers screen embodiment in operation to date only accommodates approximately 5 m^3/s. This is especially small-scale by comparison to the Sambor Dam 300 m^3/s Farmers screen units anticipated in this pre-feasibility study.

- Within the confines of present knowledge and understanding, the largest Farmers screen embodiment that could be designed and constructed without further modeling and testing is 15 m^3/s.

- Research and scaling studies are presently ongoing, utilizing the basic concepts of conventional dimensional analysis and dynamic similitude. Because time is of the essence at this stage in the development of this Sambor Dam preliminary fish screening feasibility study, initial similitude studies tentatively suggest that a basic 300 m^3/s Farmers screen unit (made up of two 150 m^3/s embodiments hybridized into one) would be feasible. Should the Sambor Dam team wish to move forward with further consideration of the Farmers screen for this large-scale project, a more sophisticated dimensional analysis would need to be completed so as to uncover additional insights as to how large the Farmers screen might be scaled.

- CFD (FEA) modeling is ongoing with an eye to ultimately scaling the Farmers screen by two or three orders of magnitude above the present applied-side design limits. This three-dimensional dynamic modeling research, conducted by the Gilkes Hydropower R&D group, is already well underway. Should this screening project move forward, emphasis to support this Sambor Dam project via the Gilkes CFD research group would focus specifically on the 300 m^3/s fish screening unit building blocks envisioned in this preliminary feasibility study.

- Confidence in ultimately proposing a Farmers screen system for the Sambor Dam site beyond this preliminary feasibility assessment would be greatly enhanced with additional data from a demonstration prototype with a hydraulic capacity of approximately 30 m^3/s. A prospective prototypical 30 m^3/s site is presently being discussed at an Australian site. If this scheme were to move forward, this prototypical data would be utilized to help validate the Gilkes CFD modeling.

- Preliminary PNNL sensor fish studies have been completed on a relatively very small Farmers screen (~0.5 m^3/s) embodiment with favorable results. More intensive sensor fish studies on larger Farmers screens, directed by Dr. Zhiqun (Daniel) Deng, are anticipated. As with the prospective CFD work cited above, if this Farmers screen concept for the Sambor Dam were to move forward, then sensor fish studies on a larger (~30 m^3/s) Farmers screen embodiment would also be advantageous.

- For preliminary design plan and profile purposes, eight 300 m^3/s screens are envisioned in parallel to each other for a total assumed Q=2,400 m^3/s (see Drawing Sheet 1 and Drawing Sheet 2 for a plan view of a single screen and eight screens in parallel, respectively). It is assumed that the eight screens in parallel would share a common inlet pool with an associated constant water surface elevation of 1.5 meters above the screen inlet flume inverts.

- For practical purposes, a basic 300 m^3/s screen unit is proposed with the provision to site these individual units in parallel to one another as required to meet the desired hydraulic capacity, whether the inlet facility requires four 300 m^3/s for the 1,200 m^3/s anabranch scenario or forty 300 m^3/s for the 12,000 m^3/s mainstem scenario.

- The Farmers screen is highly sensitive to initial hydraulic conditions at the screen inlet proper and, therefore, the entry flume must be carefully configured to establish these initial conditions. Care has been taken even at this preliminary stage to address this need. Here again, a lack of experience at these levels of flow negates the ability to make absolute assurances regarding performance at this time, but, based on initial static model runs and exercises in theoretical similitude, the dimensions indicated on the plan and profile view drawings in Attachment 1 reflect reasonable first estimates of the required dimensions to establish a uniform, steady state flow at the screen inlet.

- The drawings in Attachment 1 presently anticipate a headgate system at the upstream (upper) end of the screen entry flumes so as to control the inlet of flow as a function of the upstream pool elevation. Specific headgate design details have not been developed at this pre-feasibility stage.

- Algae, when present, could negatively impact Farmers screen function. Should this concept move to its next stage, a thorough understanding of the aquatic plant species associated with the Mekong River at the proposed Sambor Dam site would be required.

- The preliminary design drawings in Attachment 1 assume that fish bypass flow will generally be approximately five to ten percent of the total diverted flow.

TURBINE INTAKE FARMERS FISH SCREENING SCENARIO

The basic initial design assumptions and consequent concepts are informed as follows:

- Irrespective of total system flow, whether 1,200 m^3/s, 12,000 m^3/s, or otherwise, a basic screen building block of 300 m^3/s is proposed (see Drawing Sheet 1, Attachment 1).

- Standard Farmers screen uniform water surface control weirs are incorporated into the basic 300 m^3/s unit design on both sides (right and left) of the screen plate with no walls or other impediments to flow immediately outside (downstream) of the weirs. Water that passes through the plane of the screen material would cascade over the weir walls into the underlying attenuation bay. Structural support elements for these individual screens have not been considered at this preliminary feasibility stage (see Drawing Sheets 1 through 3, Attachment 1).

- Each of these 300 m^3/s screen units would be suspended over a very large, common attenuation bay, and this attenuation bay would serve as the inlet facility for the powerhouse penstocks (see Drawing Sheets 2 and 5, Attachment 1). The penstocks (size and quantity) depicted on the drawings are for illustrative purposes only.

A single 300 m^3/s unit is anticipated to require a footprint of ~0.03 km^2.

The preliminary design results for the 300 m^3/s screen embodiment are informed by the standard hydraulic parameters presently established for all Farmers screen systems. These standard hydraulic parameters require a minimum sweeping velocity parallel to the horizontally oriented perforated flat plate screen surface ranging between 1.5 to 2.5 m/s; the through-screen velocity (the velocity of water flowing nominally perpendicular to the plane of the screen) is set at a net value of approximately 0.1 m/s after including an allowance for screen open area and the screen's structural framework.

A minimum water depth of 1.5 meters at the invert of the screen inlet flume is presently assumed. A very rough conceptual sketch of the water surface elevation at the inlet flume and over the plane of the screen surface can be seen in Drawing Sheet 3, Attachment 1.

Theoretically, it is possible to accommodate any targeted fish screening facility hydraulic capacity, no matter how large or small, utilizing the basic building block of 300 m^3/s. Any total system flow, therefore, whether 1,200 m^3/s or 12,000 m^3/s, more or less, might be accommodated by simply adding or subtracting the individual 300 m^3/s screen units determined necessary to meet the comprehensive Sambor Dam site objectives. For example, see Drawing Sheet 2, Attachment 1, for a proposed array of eight 300 m^3/s Farmers screens for a theoretical capacity of 2,400 m^3/s. For perspective, then, at the outside limits of this pre-feasibility study, an array of forty parallel 300 m^3/s Farmers screen units with a total estimated footprint of approximately 1.25 km^2 would be required to provide the 12,000 m^3/s of flow anticipated for the mainstem alternative.

If fish protection standards are relaxed such that the screen area per unit of flow could be decreased, then the total footprint would decrease. With regard to the Farmers screen, larger screen hole openings might (or might not) have an effect on screen cleaning dynamics. Here again, further studies would be required if this screen alternative were to be further considered.

FLOOD FLOW, DEBRIS, WAVE FORCES, AND SEDIMENT MANAGEMENT

Maintaining awareness that the Sambor Dam power house is expected to continue to operate during flood flows and that massive volumes of floating debris, including trees up to 10 tons or more, are to be expected, large debris grates positioned above the Farmers screen inlet bay headgates (as shown on Drawing Sheet 2, Attachment 1) are assumed. The need for a floating debris mitigation boom positioned in the pool well upstream of the fish screening inlet facility is also anticipated.

For the purposes of this preliminary feasibility assessment, it is assumed that the dam design engineers will make structural provisions for bypassing flood flow, and flood flow management through the Farmers screen facility is thus not anticipated. More specifically, this pre-feasibility Farmers screen inlet facility has not been designed to pass flood flows but rather has been restricted in hydraulic capacity to accommodate only the desired turbine flow and the fish and debris bypass flow necessary to facilitate the passive cleaning dynamic of the screen units.

As for the screen material proper, while final specifications have not been developed at this preliminary stage, a heavy-gauge perforated stainless steel plate or wedgewire is anticipated such that the screens are better able to withstand the heavy debris that will inevitably make its way past the debris boom and large debris grates. Heavy gauge screen plate material is also believed to be necessary so that the screen plates are able to withstand the momentum forces which are the probable consequence of large volumes of relatively deep water pulsing over the screens in oscillating wave forms. If this project were to move forward, screen material selection would be informed by the same unifying vision as with the balance of the system design criteria with an eye to protecting all species and all life stages from larval stages up to fish species as large as 1.5 meters long, weighing up to 50 kg. As a first suggestion for appropriate screen material, and further to the previously discussed concerns regarding oscillating wave forms, debris management, and sediment load, a thick-gauge plate of high-grade stainless steel perforated with circular holes approximately 2.24 mm in diameter in a pattern that results in a screen with ~50% open area is anticipated. Wedgewire screen material with comparable openings would also be considered.

Preliminary considerations of a sediment management system associated with the fish screen inlet facility suggest that the existing small-scale sediment management systems, as presently utilized on existing (albeit much smaller) embodiments of the Farmers screen, might well be developed and adapted to the Sambor Dam system. It is imagined that the sediment management system would be incorporated into the floor of the fish screening facility attenuation bay. Here again, however, the existing Farmers screen systems are extremely small-scale by comparison, and the design team members for this preliminary Sambor Dam fish screening assessment are gravely ignorant with regard to the magnitude of flood flows, debris load, suspended sediment, and bed load that are omnipresent in the Mekong River system.

PRACTICALITY OF FISH PROTECTION

As with every project historically developed throughout the world, cost will likely be the limiting agent in assessing the practicality of this Farmers screen alternative. At this preliminary stage, while it appears probable that the reservations and qualifications regarding a functional design would ultimately be overcome, as discussed in further detail in the following section, despite the fact that cost is ignored in developing this fish screening concept, the real world of short-term economics might well render this proposed option impractical.

While this study scope does not necessarily require the protection of drifting larvae and juvenile fish less than 100 mm in length, based upon direct experience with salmonids in the Pacific Northwest, these salmonids being particularly strong swimmers, reliable screen performance and the ultimate protection of all species and all life stages in the Mekong River would likely be greatly enhanced by adhering to these extreme fish screen criteria from the Pacific Northwest States. It should once again be noted here, nevertheless, that this preliminary screen feasibility design team is ignorant to specific Mekong River attributes including the swim capabilities and habits of fish species in the Mekong.

PRELIMINARY COST ESTIMATE

Fully appreciating that this study is pre-feasibility, a first cut cost estimate of USD 175,000/m^3/s is anticipated for the in-place cost of the Farmers screen at the Sambor Dam site. This estimated pricing, which is corroborated by fish screening agency experts and business development directors with extensive experience in the US, is based on actual installed screen costs in the US. The price includes costs for steel, placed concrete, labor, fabrication, proximity to materials and labor sources, among other factors. It is assumed, however, that the Sambor Dam project economist might properly index this unit price to local conditions.

So as to target at least 95 percent survival of all species and all life stages for this preliminary fish screening concept, assuming a perforated plate screen hole diameter of 2.4 mm (NMFS criteria for hole size), then, theoretically, anything smaller than 2.4 mm could be entrained. However, experience also demonstrates that only a portion of any eggs or larvae under this 2.4 mm size threshold would be entrained due to the high sweeping velocity and very low screen approach velocity associated with the Farmers screen. The depth at which the eggs and larvae travel in the water column would also play a large influential role in governing percent entrainment.

As discussed previously, if fish protection standards were relaxed as a function of enhanced fish protection attributes in turbines, then the screen material hole diameter or slot dimensions could possibly be increased, thus resulting in a corresponding increase in net open screen area. This would allow for a reduced total footprint without increasing the approach velocity and, accordingly, as a function of reduced total screen area, a corresponding reduction in total screen cost would likely be realized. With regard to Farmers screen function and cleaning reliability, larger openings might or might not have an effect on the cleaning dynamics. If this project were to move forward with this alternative, as with the other additionally required computer modeling and prototypical research, cleaning dynamics associated with larger screen openings would also require further study.

TRAVELING BELT (HYDROLOX) FISH SCREENING OPTION

The Hydrolox screen is an inclined, essentially vertical, traveling belt screen that relies on spray bars and drive motors, among other attributes, to keep the screens clean and protect fish. The Hydrolox screen potentially offers a feasible solution for protecting the fish of the Cambodian Mekong from entrainment into the Sambor Dam hydroelectric turbines. See Attachment 2 for the standard Hydrolox screen drawings and details.

HYDROLOX PRE-FEASIBILTY ASSESSMENT LIMITATIONS

- The largest screen embodiment Hydrolox normally offers has a hydraulic capacity of approximately 5.7 m^3/s. This pre-feasibility assessment assumes utilization of this Hydrolox screen unit with a maximum flow of 5.7 m^3/s (sized for NMFS screen criteria approach velocities). An approach velocity of 0.12 m/s (NMFS Criteria in the US for salmonid protection) at the screen face is assumed, and the Hydrolox system and screen surface area are sized accordingly.

- Larger single Hydrolox screen systems could be designed for specific sites such as the proposed Sambor Dam site, but site specific design information regarding dam location and intake requirements would be required to design a larger, site-specific Hydrolox screen unit.

- Hydrolox screens will not provide upstream or downstream passage; upstream and downstream passage must be provided through a separate, unrelated bypass channel.

- Hydrolox has developed a debris management system that carries debris over the top of the screen system from where the debris then drops into a debris handling system on the backside of the screen structure, typically utilizing a conveyor belt to move the debris out to a location where it can be removed and disposed. This debris handling system has not been fully tested for fish protection but has been installed in several locations. This system appears to be highly effective at handling filamentous algae and aquatic vegetation.

- In order to manage a wide range of fish species with varying swimming abilities, Hydrolox has developed a Ristroph-style fish collection bucket system. This system requires additional infrastructure to safely move aquatic species back into the river system. As with the Hydrolox debris handling system, this fish collection bucket system has not been fully tested for fish protection but has been installed at operating sites. The need for this bucket system has not been fully assessed at this pre-feasibility stage, but, assuming some of the Mekong species are weaker swimmers, if this project were to move forward with this alternative, then the need for these buckets would require further research.

- Hydrolox screens have been developed to minimize moving parts under the water surface. This allows for easier ongoing maintenance as well as decreased system wear.

- Hydrolox screens are sensitive to high levels of sediment and gravel. A spray bar system has been developed to keep the screens clear of sediment buildup and to decrease wear on the screen system.

- A minimum water depth of 11 metres (optimally at 12.5 metres) at the screen face would be required to meet the Sambor Dam site fish protection specifications assumed for this pre-feasibility study.

- Extensive research regarding debris and sediment management and fish protection would need to be conducted if one were to more confidently move forward with this Hydrolox fish screening concept.

- Flushing flows, using a guided, high sweeping velocity flow stream parallel to the screen face, are advisable so as to keep sediment and debris from accumulating in front of the screens. Given the minimum 11 meter depth requirement at the face of the screens, should this conventional alternative be further considered, particular attention should be given to developing a design that would reliably induce and maintain this sweeping flow across the screen face.

- For the purposes of this preliminary feasibility analysis for the Hydrolox screen, it is assumed that flood flows would pass through a separate spillway system detached from the Hydrolox screen bays.

TURBINE INTAKE HYDROLOX FISH SCREENING SCENARIO

The basic initial Hydrolox design assumptions and consequent concepts are informed by the following two assumptions:

- Irrespective of total system flow, whether 1,200 m^3/s or 12,000 m^3/s, the largest single standard Hydrolox screen unit has a hydraulic capacity of ~5.7 m^3/s.

- The minimum water depth required on the face of the screens is 11 meters.

To address the request for a traditional fish screening concept at 1,200 m^3/s (the anabranch site) and the second scenario at 12,000 m^3/s (the mainstem site), Hydrolox has specified its largest standard traveling belt screen unit, which is ~4.25m wide by ~12.5m long with a hydraulic capacity of ~5.7 m^3/s/unit. This unit is sized to comply with NMFS fish screen protection criteria so as to at least meet the 95 percent survival target for fish species in the Mekong River at the Sambor Dam site. Accordingly, 212 screen units would theoretically be required for the 1,200 m^3/s anabranch scheme; 2,118 screen units would theoretically be required for the 12,000 m^3/s mainstem scheme. Spacing between each screen unit is typically suggested to be approximately 1m. Since the Hydrolox screen units are generally vertical in orientation, their associated horizontal footprint is relatively small (~6.25×10^{-6} km^2/m^3/s.), but, for illustrative purposes, a system consisting of 212 screen units would be approximately1.5 km long; a system consisting of 2,118 screens would be about 15 km long.

As for theoretically accommodating any targeted fish screening hydraulic capacity – no matter how large or small – any range of flow capacity, whether 1,200 m^3/s or 12,000 m^3/s, more or less, would be accommodated by simply adding or subtracting the number of individual 5.7 m^3/s screen units determined necessary to meet the comprehensive Sambor Dam site objectives.

If fish protection standards are relaxed such that the screen area per unit of flow could be decreased, then the total footprint (essentially the length of the Hydrolox facility) would decrease proportionately to the allowable increase in slot opening dimensions in the Hydrolox screen material. In the instance of the Hydrolox screen system, larger screen openings and consequent reduced screen surface area would be expected to have no appreciable impact (for better or worse) on cleaning dynamics, but the reduction in total footprint would be expected to have an associated reduction in total cost.

FLOOD FLOW, DEBRIS, AND SEDIMENT MANAGEMENT

As with the Farmers screen discussion, maintaining awareness that the Sambor Dam power house is expected to continue to operate during flood flows and that massive volumes of floating debris, including trees up to 10 tonnes or more, are to be expected, heavy bar grates would be required to protect the Hydrolox screen system. A floating debris mitigation boom positioned in the pool well upstream of the fish screening inlet facility would also be anticipated.

Hydrolox has developed a debris management system for its screens that carries debris over the top of the screen system from where the debris then drops into a debris handling system on the backside of the screen structure, typically utilizing a conveyor belt to transport the debris out to a location where it can be conveniently removed and disposed. This debris handling system has not been fully tested for fish protection but has been installed in several locations. This system has been shown to be highly effective at handling filamentous algae and aquatic vegetation.

As for a sediment management system associated with the Hydrolox fish screening inlet facility, flushing flows across the face of the Hydrolox screen belts must be well established so as to ensure that sediment does not accumulate in front of the screens. Sediment accumulation would compromise performance and cause excessive wear and tear on the Hydrolox screens, thus potentially disrupting operations and adding to operation and maintenance expenses.

PRACTICALITY OF FISH PROTECTION

Parallel to the discussion of the practicality of fish protection via the Farmers screen, similar preliminary conclusions appear to apply to the Hydrolox system. As with every project historically developed, cost will likely be the limiting agent in assessing the practicality of this Hydrolox screen alternative. At this preliminary stage, as discussed in further detail in the following section, despite the fact that cost is ignored in developing this fish screening concept, the real world of short-term economics might well render this proposed option impractical.

The Hydrolox screen's robust design is corrosion free, UV-resistant, and resilient to abrasive conditions. The Hydrolox screen is crafted from polymer modules assembled in an interlocked, "bricklayed" pattern. If the Hydrolox screen becomes compromised due to impact or damage, the bricklayed pattern offers a quick and simple replacement of the damaged section. The Hydrolox screen material has slots rather than round holes, and the minimum slot dimensions for the Hydrolox screen are 1.73 mm x 7.6 mm.

While the protection of drifting larvae and juvenile fish less than 100 mm in length are not absolutely required at this pre-feasibility level, based upon direct experience with salmonids in the Pacific Northwest, these salmonids being particularly strong swimmers, yet here again acknowledging ignorance with respect to the Mekong River system and species, both screen alternatives are held to the same standard with an eye to the possibility of protecting all species at all lifestages. Reliable screen performance and the ultimate protection of all species and all life stages would likely be greatly enhanced by adhering to these extreme fish screen criteria from the Pacific Northwest States.

For the Hydrolox screen alternative, this requires an approach velocity of 0.12 m/s (NMFS Criteria in the US for salmonid protection), and the Hydrolox screen system is sized accordingly. Hydrolox screens do not provide upstream or downstream passage; upstream and downstream passage must be provided through a separate, unrelated bypass channel. In order to manage a wide range of fish species with varying swimming abilities, however, Hydrolox has developed a Ristroph-style fish collection bucket system. This system requires additional infrastructure to safely move aquatic species back into the river system, and, while this system has been installed at an operating site, this fish collection bucket system has not been fully tested for fish protection. If this Hydrolox alternative were to move forward as an option for the Sambor Dam fish screening facility, further research related to these fish buckets would be required in order to fully prove the practicality of this Hydrolox alternative.

PRELIMINARY COST ESTIMATE

Fully appreciating that this study is pre-feasibility, a first cut, in-place cost estimate of USD 529,000/m^3/s is anticipated for the Hydrolox screen alternative. This estimated pricing, which is corroborated by fish screening agency experts and business development directors with extensive experience in the US, is based on actual installed screen costs in the US. As with the Farmers screen pricing, this Hydrolox price attempts to include all costs for the Hydrolox system, but it is assumed that the Sambor Dam project economist might properly index this unit price to local conditions.

So as to target at least 95 percent survival of all species and all life stages for this preliminary fish screening concept, assuming minimum slot dimensions for the Hydrolox screen are 1.73 mm x 7.6 mm, then, theoretically, anything smaller than these dimensions could be entrained, but experience also demonstrates that only some of the eggs, larvae, or fish species smaller than these dimensions would be entrained due to object orientation and position in the water column.

As discussed in other sections of this chapter, if fish protection standards were relaxed as a function of enhanced fish protection attributes in turbines, then the screen material slot dimensions and screen approach velocity could possibly be allowed to increase, thus resulting in a corresponding increase in net open screen area, which in turn would allow for a reduced total screen system length and, accordingly, as a function of reduced total screen area, a corresponding reduction in total screen cost would likely be realized. Unlike the uncertainty associated with Farmers screen performance and cleaning reliability as a function of increased hole or slot dimensions, the cleaning system for the Hydrolox screens would be expected to be equally reliable whether with smaller or larger slot dimensions. In the instance of the Hydrolox system, in other words, a reduction in screen size would likely have no appreciable impact (one way or the other) on cleaning dynamics.

OVERALL DISCUSSION AND CONCLUSIONS

At this pre-feasibility level of analysis, assuming the footprint is unconstrained and economic limitations are not considered, there appear to be no immediately discernable fatal flaws to the Farmers horizontal screen being a viable and scalable option to adequately screen and protect up to 95% of all species at all life stages. Based on current working knowledge of screening for salmonid species in the Pacific Northwest states, the Farmers screen might actually exceed the targeted 95% goal for fish protection. Despite the operational simplicity and other attractive attributes of the

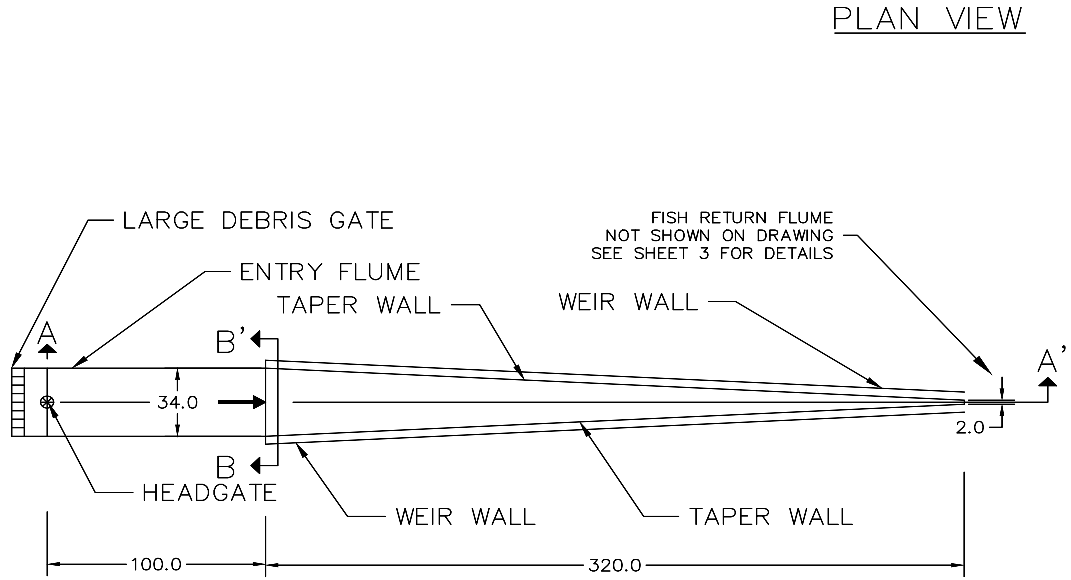
Farmers screen, however, the Farmers screen system resists traditional basic fluid mechanical analyses and, as such, would require extensive further dynamic 3-dimensional modeling and testing of a prototypical field embodiment if the project were to move forward with this prospective Farmers Screen solution.

Using the same unconstrained assumptions as for the Farmers screen, at this pre-feasibility level of analysis, there appear to be no immediately discernable fatal flaws to the Hydrolox vertical fish screen being a viable and scalable option to adequately screen and protect up to 95% of all species at all life stages. Based on current working knowledge of screening for salmonid species in the Pacific Northwest states, the Hydrolox screen might actually exceed the targeted 95% goal for fish protection. No further modeling of the Hydrolox screen would be required at this time, but, given the demanding environment of the Mekong River, so as to ensure adequate cleaning and fish passage by means of mechanical spray bars, pump systems, tension arms, fish handling buckets, mechanical torque override systems, debris conveyor belts, and electricity costs to operate the screens and associated support mechanisms, further in depth study and analyses seem prudent if this alternative were to move forward.

Developing the proper system to fully protect the fish species of the Mekong River at the proposed Sambor Dam is complex in multivariable ways. The issues of scaling to very large flows, flood flow management, large debris management, sediment management, and protection of all the diverse aquatic species of all life stages in this reach of the Mekong River all provide multidimensional challenges. Nevertheless, subject to all the assumptions, disclosures, limitations, and qualifications repeated throughout this chapter, it appears reasonable to move forward with a more detailed analysis of the proposed alternatives to develop a solution for the Sambor Dam project should the Sambor Dam team so choose. This project provides an opportunity to re-think large-scale hydropower schemes and associated fish protection strategies, potentially providing a model for future fish screen embodiments on large dams.

APPENDIX 7.4, ATTACHMENT 1: SHEETS 1-5

PRELIMINARY SAMBOR DAM FISH SCREEN - 300 M³/S



ALL UNITS IN METERS
NOT TO SCALE

NOTE: PRELIMINARY FEASIBILITY DESIGN
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SHEET 1 - SAMBOR DAM - SINGLE FARMERS SCREEN

PRELIMINARY SAMBOR DAM FISH SCREEN - 2400 M^3/S

AT THE CURRENT PRELIMINARY STAGE OF THIS PROCESS, FCA FEELS OPTIMISTIC SCALING A SINGLE FARMERS SCREEN TO 150 m^3/S. PLACING TWO IN A DUAL CONFIGURATION (SIDE BY SIDE), AS SHOWN IN THESE DOCUMENTS, PROVIDES A MAXIMUM CAPACITY OF ONE UNIT AT 300 m^3/S. AS CAN BE DISCERNED FROM THE DRAWING, (8) DUAL SIDE BY SIDE SCREENS COULD ACCOMMODATE 2400 m^3/S. AS PART OF THE DESIGN PROCESS, FURTHER ANALYSIS, FIELD TESTING, CFD MODELING, STUDIES IN DYNAMIC SIMILITUDE, AND FISH SAFETY (VIA SENSOR FISH) WOULD BE REQUIRED TO CONFIRM OUR ASSUMPTIONS IN SCALABILITY.

THIS ANALYSIS COULD ALSO BE SCALED LINEARLY, ADDING ADDITIONAL 300 m^3/S SCREEN SECTIONS UNTIL THE ARRAY PROVIDES ENOUGH CAPACITY TO MEET THE COMPREHENSIVE SAMBOR SITE OBJECTIVES. WITHOUT BIAS TO SOCIO–ECONOMIC OR ECOLOGICAL PARAMETERS, FCA ELECTED TO SHOW AN ARRAY OF 8 INDIVIDUAL SCREENS. AS DIRECTED WE DID NOT CONSTRAIN OUR THINKING WITH REGARDS TO THE TOTAL FOOTPRINT THAT WOULD CONCEPTUALLY BE REQUIRED TO ACCOMMODATE 12000 m^3/S. A 40 UNIT ARRAY UNDER THIS SCENARIO WOULD REQUIRE AN ESTIMATED FOOTPRINT OF 1.25 km^2.

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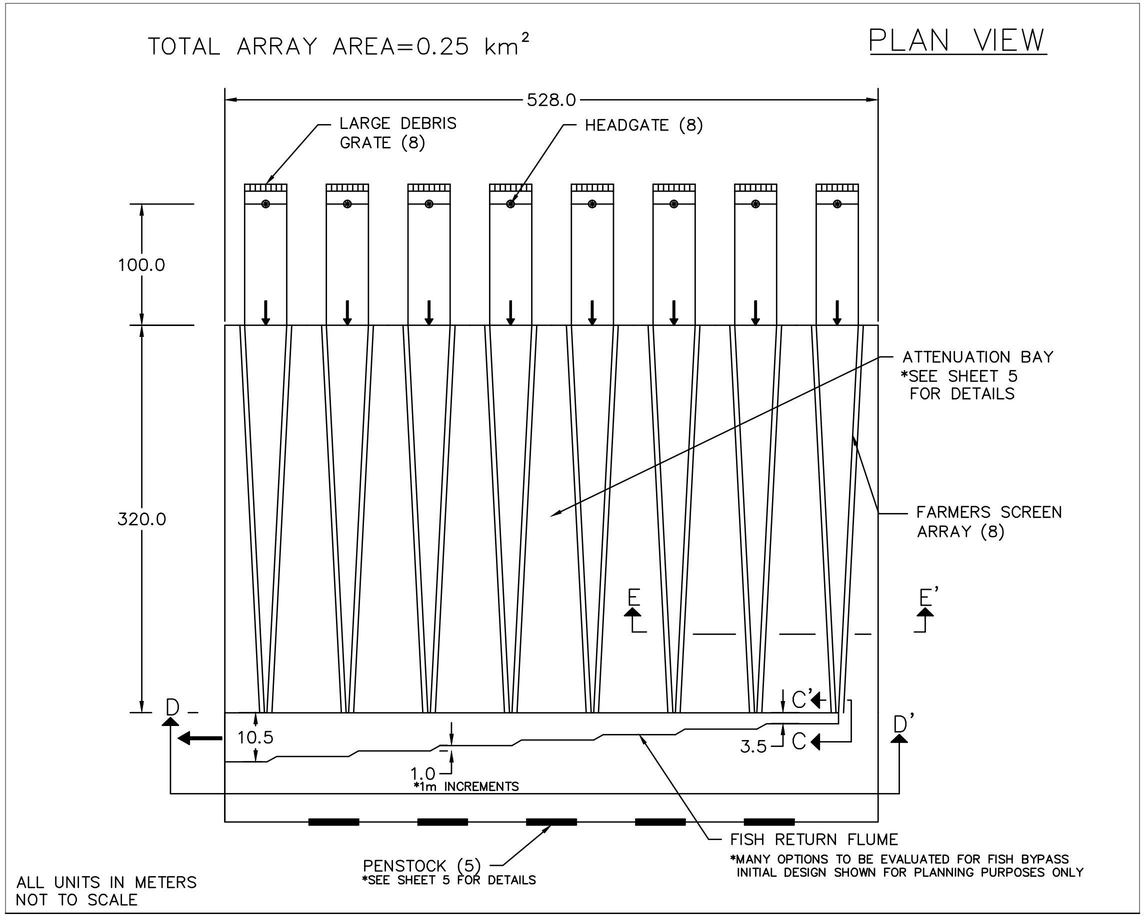
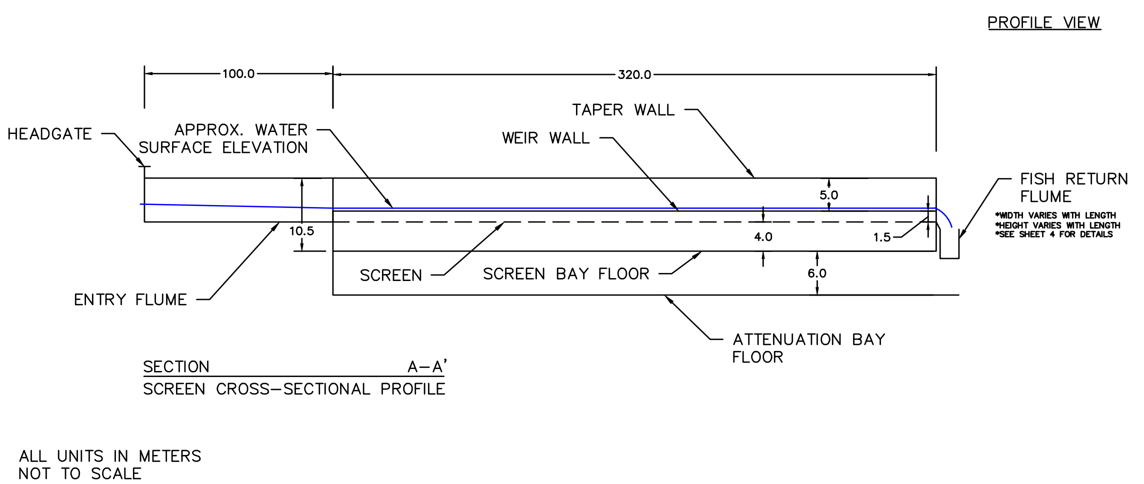


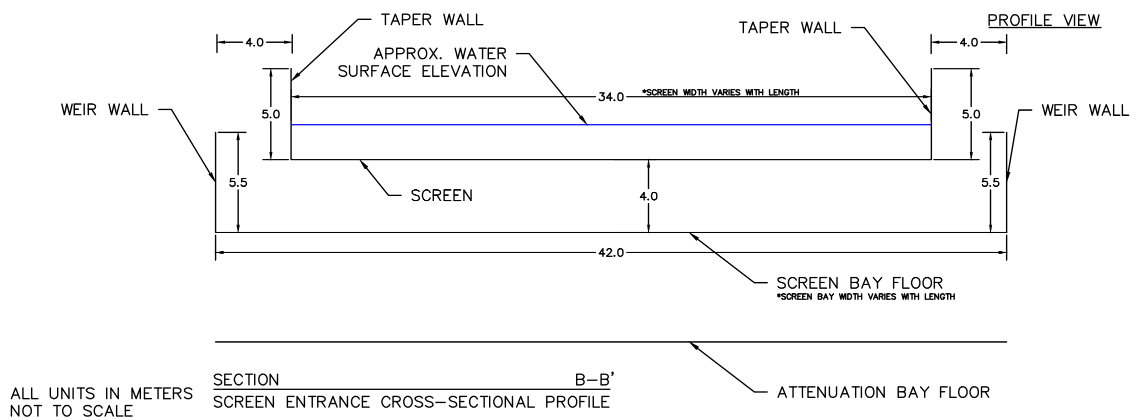
SHEET 2 - SAMBOR DAM - (8) FARMERS SCREEN ARRAY

PRELIMINARY SAMBOR DAM FISH SCREEN - 300 M^3/S



SECTION A–A'
SCREEN CROSS–SECTIONAL PROFILE

ALL UNITS IN METERS
NOT TO SCALE



SECTION B–B'
SCREEN ENTRANCE CROSS–SECTIONAL PROFILE

ALL UNITS IN METERS
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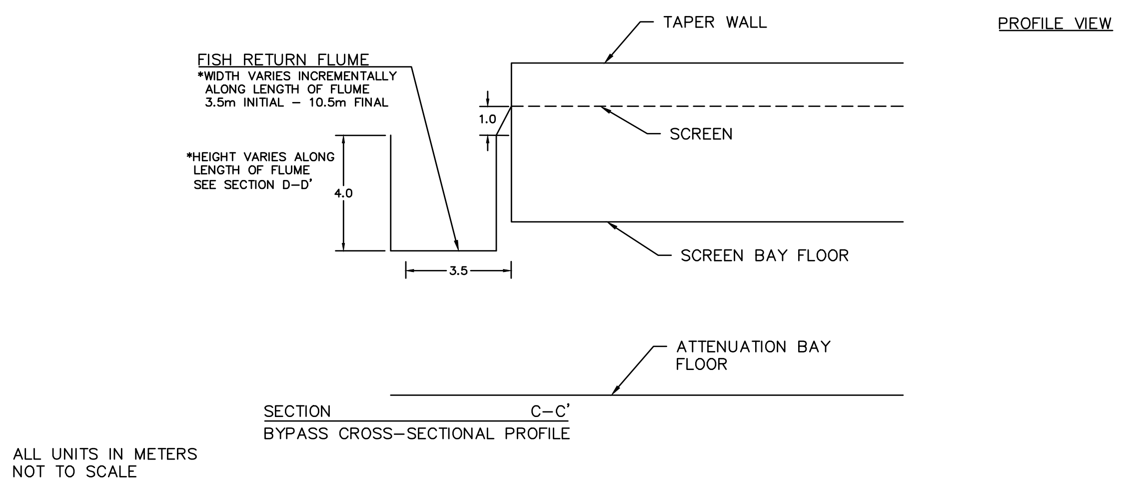
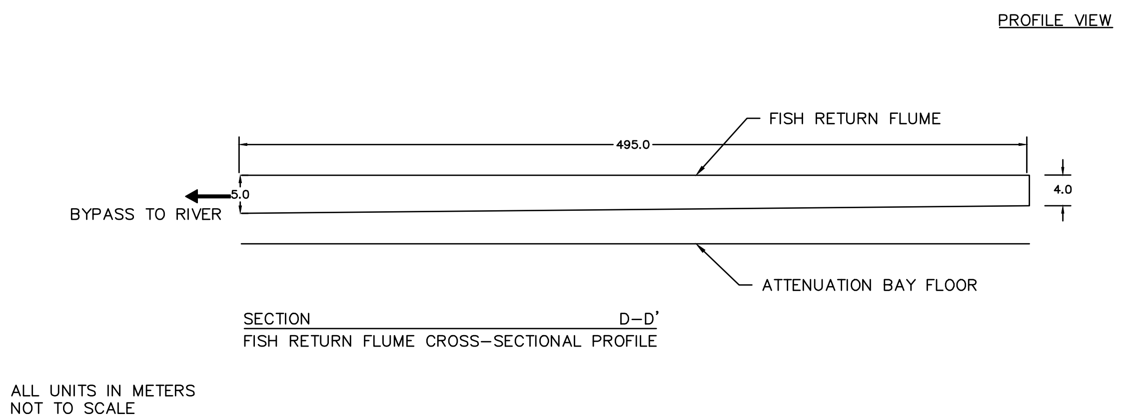
SHEET 3 - SAMBOR DAM - FARMERS SCREEN SECTIONS

PRELIMINARY SAMBOR DAM FISH SCREEN - 2400 M^3/S



SECTION C–C'
BYPASS CROSS–SECTIONAL PROFILE

ALL UNITS IN METERS
NOT TO SCALE



SECTION D–D'
FISH RETURN FLUME CROSS–SECTIONAL PROFILE

ALL UNITS IN METERS
NOT TO SCALE

NOTE: PRELIMINARY FEASIBILITY DESIGN
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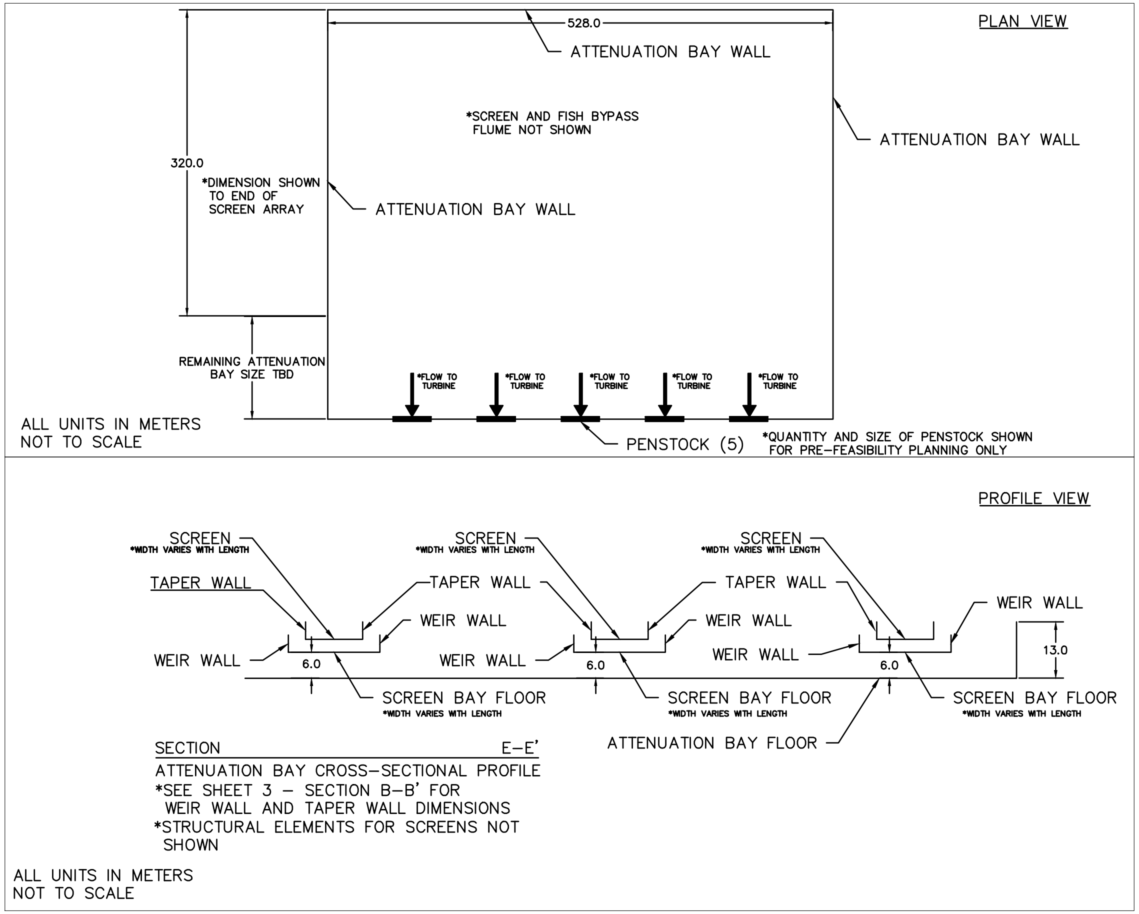
SHEET 4 - SAMBOR DAM - FISH RETURN FLUME

PRELIMINARY SAMBOR DAM FISH SCREEN - 2400 M^3/S



NOTE: PRELIMINARY FEASIBILITY DESIGN
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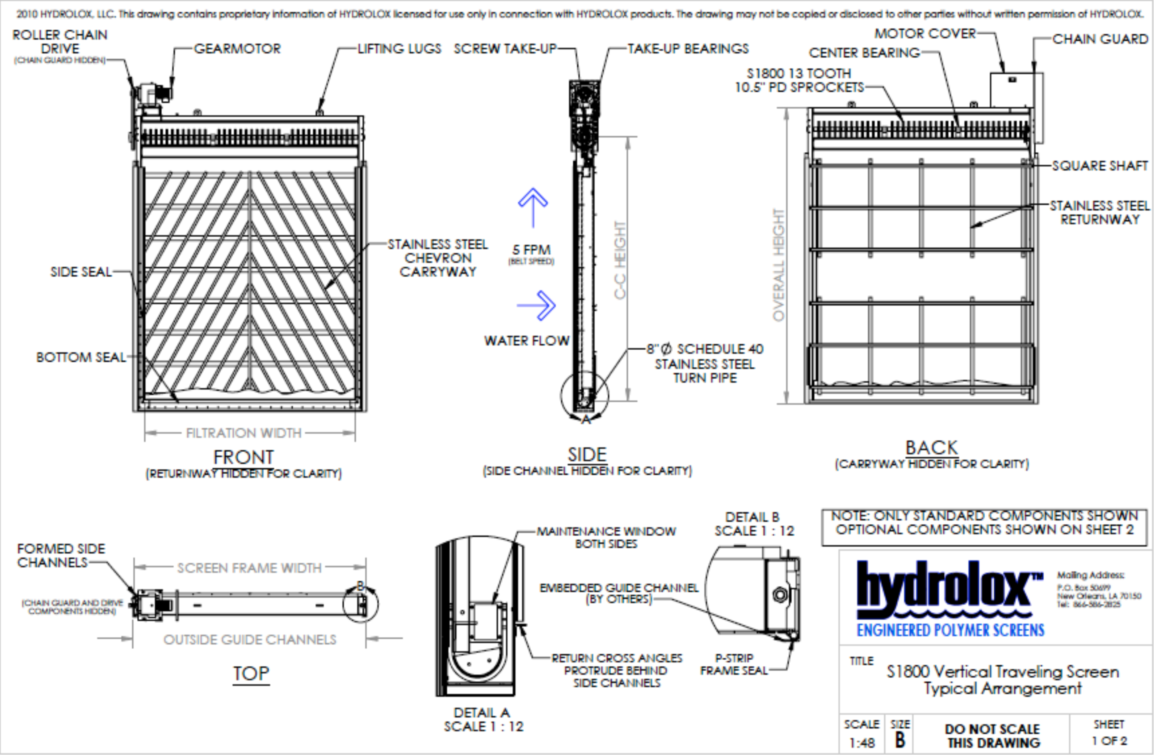
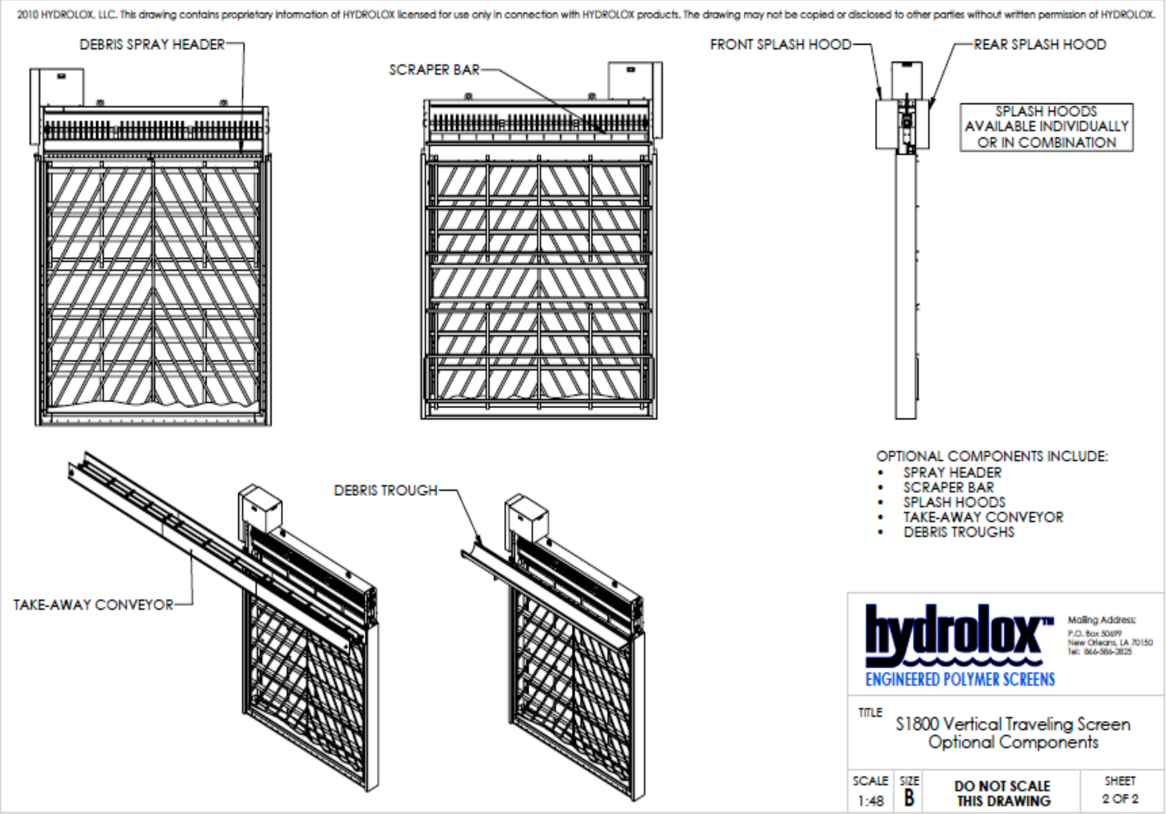
SHEET 5 - SAMBOR DAM - FARMERS SCREEN ATTENUATION BAY

APPENDIX 7.4, ATTACHMENT 2





Appendix 9.1.

Sedimentation Modelling related to Dolphin Deep Pool Areas

Sedimentation Modelling related to Dolphin Deep Pool Areas

Information provided to Beasley and Ryan by NHI with minor modification for presentation.

Sambor Dam Alternative 7 (Alt_7) Options:

Sediment modeling was undertaken as part of NHI's assessment of the feasibility of Sambor Alternatives. The locations of dolphin deep pool conservation areas according to WWF are shown in Figure 9.1.1, which also identifies the same locations on a bathymetric map of the river. In order to assess whether flow in the Mekong River will be able to evacuate sediment from the deep pools simulations were executed using HEC-RAS 2D with and without the dam for average flow conditions and with the dam for monsoon conditions.

When assessing whether Sambor Alt_7 will result in increased sedimentation in the deep pools it is necessary to also take account of the sediment properties in the Mekong River. Suspended sediment consists principally of silt and clay, while bedload principally consists of fine sand. It is also recognized that although suspended load is carried by the river throughout the year that bed load is principally transported during the monsoon only. Flows during the monsoon keeps the pools clear of sediment, while flows during the low-flow period plays an insignificant role in this regard.

The scale of velocities presented in the two figures range from zero to 2 m/s and greater. A velocity of 2 m/s is large enough to transport fine sand out of the pools; as reflected by the simulation of flow velocities without the dam. Sediment is currently absent in these pools; evidence that the prevailing flow velocities of 1.5 m/s and larger are adequate to keep the pools clear of sediment.

The simulation results shown in Figure 9.1.2. and Figure 9.1.3 indicate that flow velocities in the deep pools are generally higher than those in shallower parts of the river; corroborated by ADCP discharge measurements executed by the MRC. The figures indicate that the dam does effect 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 (Ksach 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 Figure 9.1.2. and it is reasonable to conclude that Sambor Alt_7 will have an insignificant effect on sedimentation in the deep pools. The only pool that might be affected is the pool immediately downstream of the dam (Ksach 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.

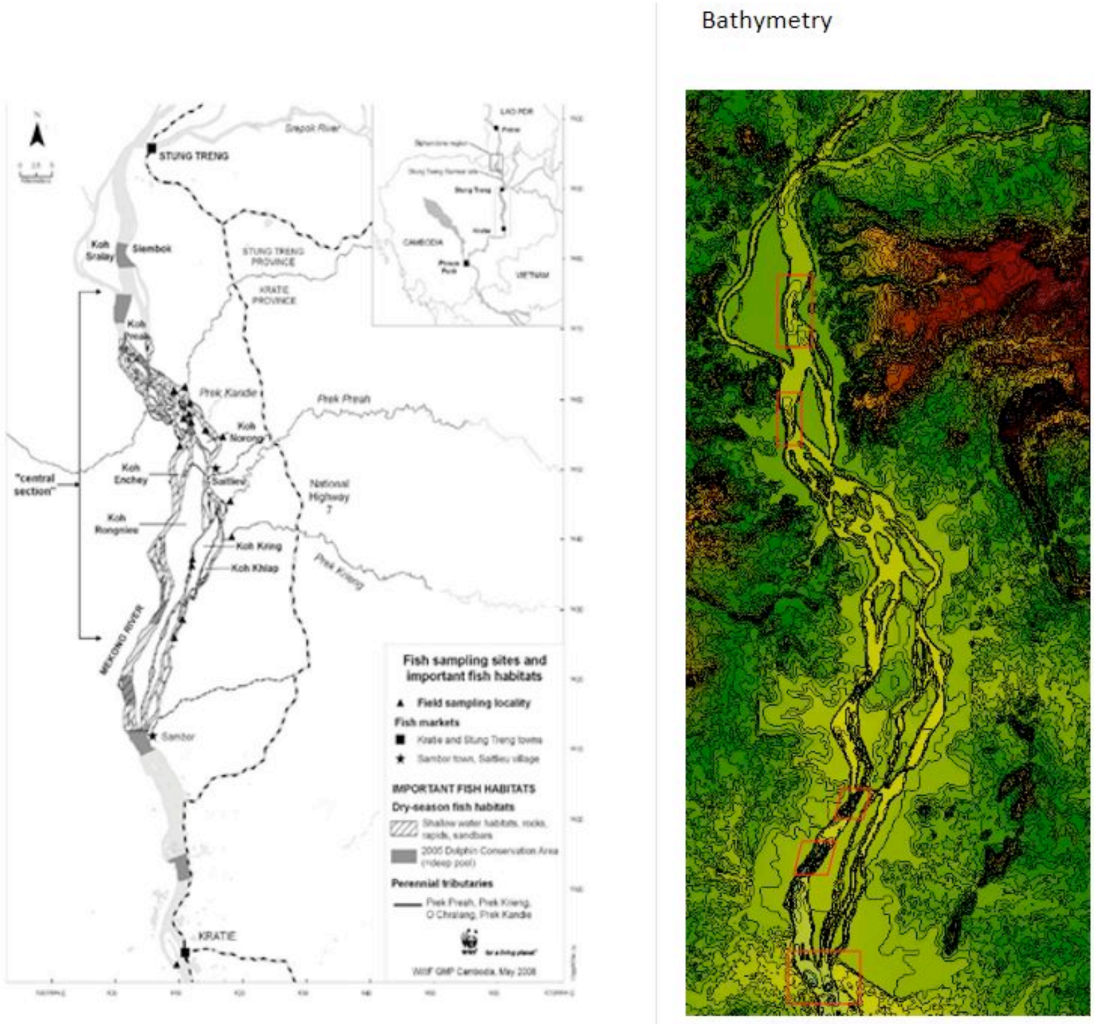


Figure 9.1.1. *WWF map showing Dolphin Deep Pool locations, replicated on a bathymetric map of the river produced by NHI.*

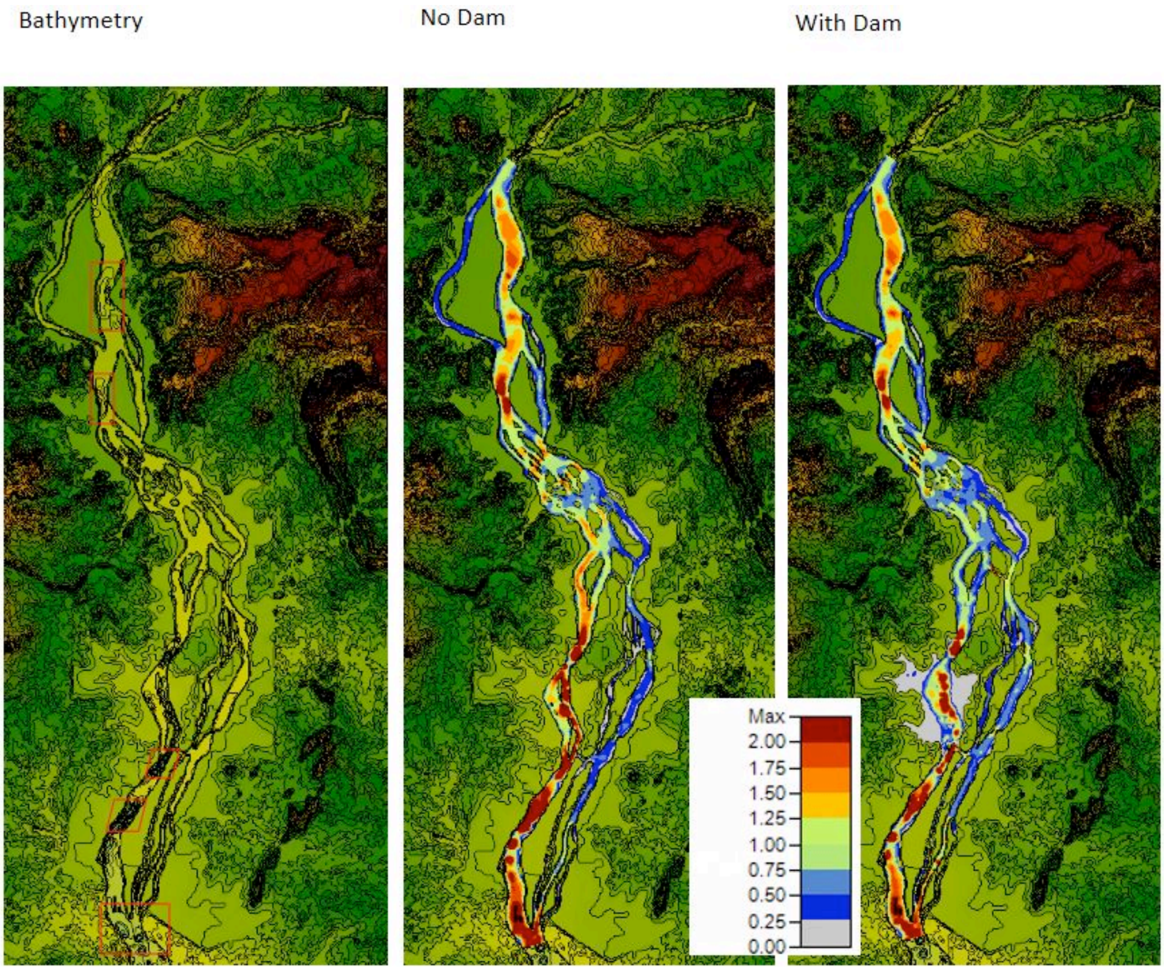


Figure 9.1.2. *Dolphin Deep Pool Areas (Red Rectangles) and flow velocities with and without Sambor 7 for average flow conditions (13,400m3/s), produced by NHI.*

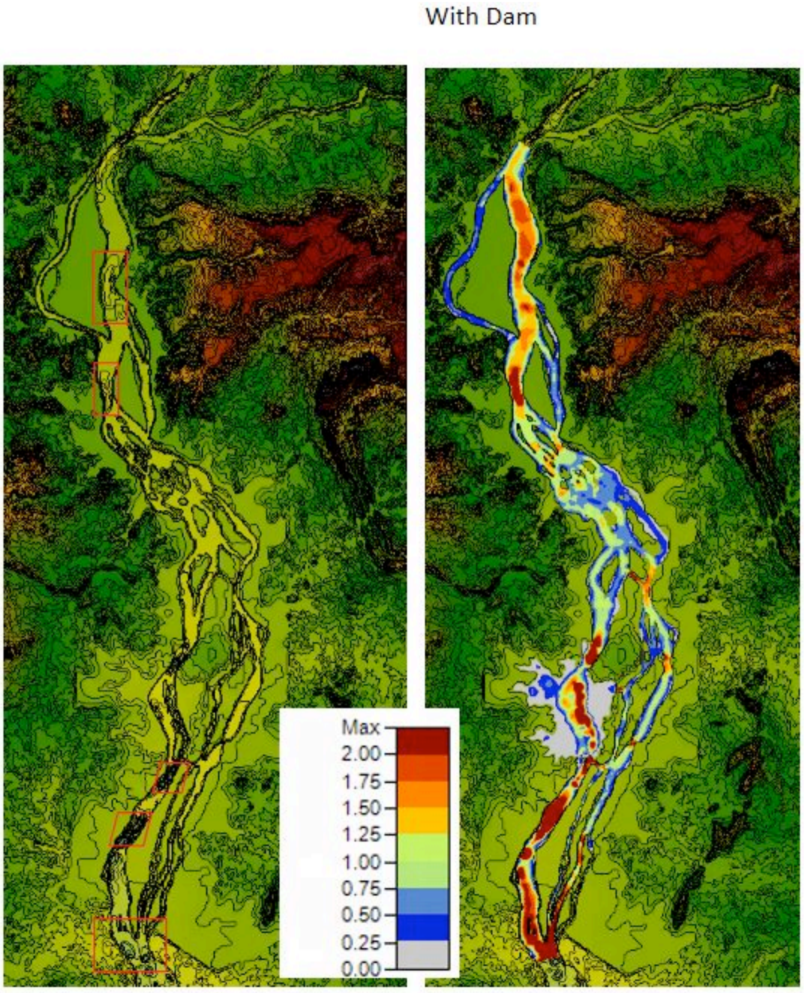


Figure 9.1.3. *Dolphin Deep Pool Areas (Red Rectangles) and Flow velocities, produced by NHI.*

Appendix 9.2.

Additional Information on Dolphin Distribution and Protection

Additional Information on Dolphin Distribution and Protection

The following Figure 9.2.1, Figure 9.2.2., and Figure 9.2.3. provide fine-scaled differentiation of data shown in Figure 9-5, Figure 9-6 and Figure 9-7 in Chapter 9.

Figure 9.2.4. shows the area gazetted under the Proclamation on the Creation of Fisheries Biodiversity Management Area (MAFF, 2013).

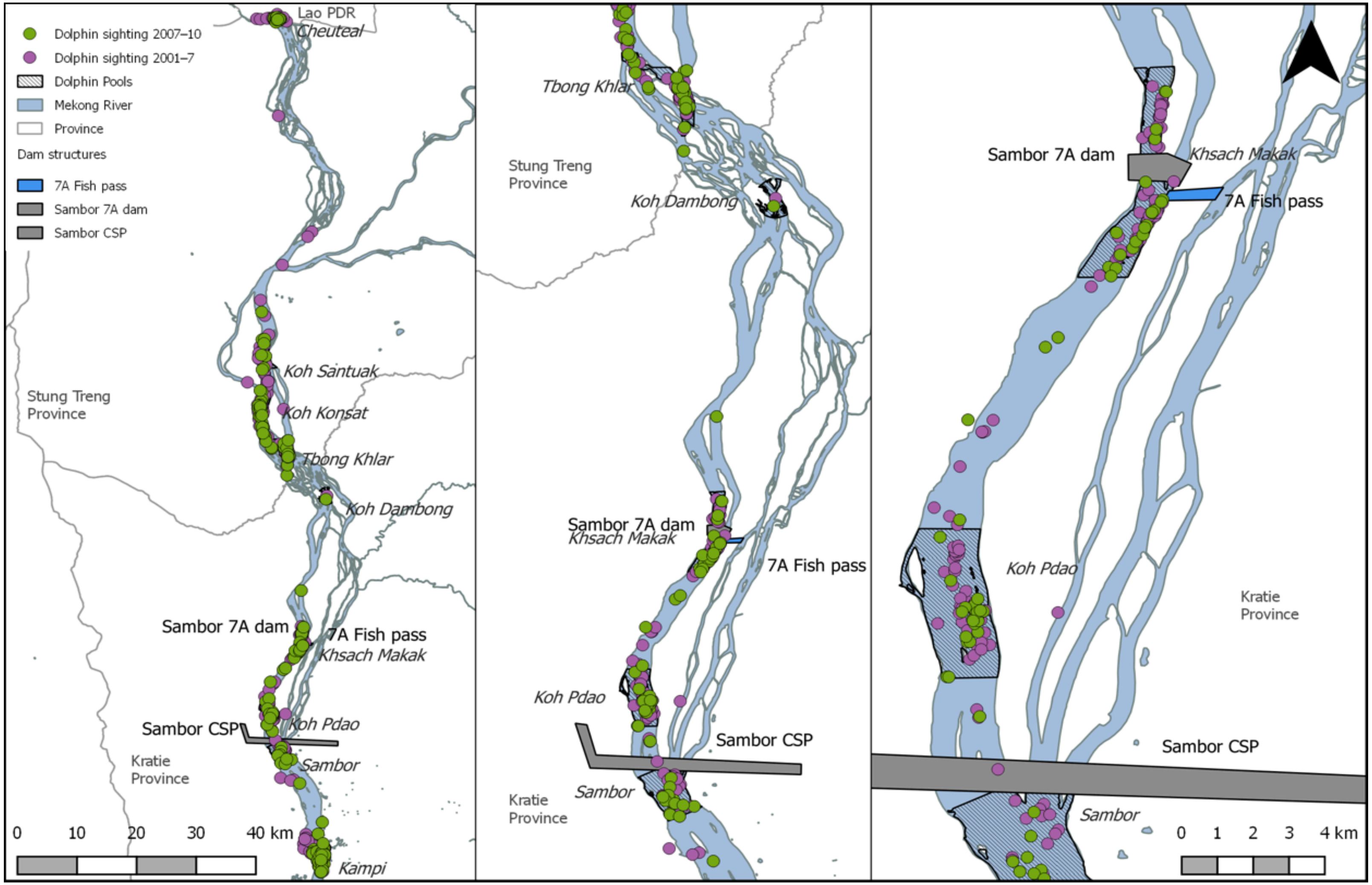


Figure 9.2.1. *Dolphin sightings from 2001–2007 and 2007–2010, both seasons. Corresponding to Beasley et al. (2013), Beasley unpublished data, and Ryan et al (2011).*

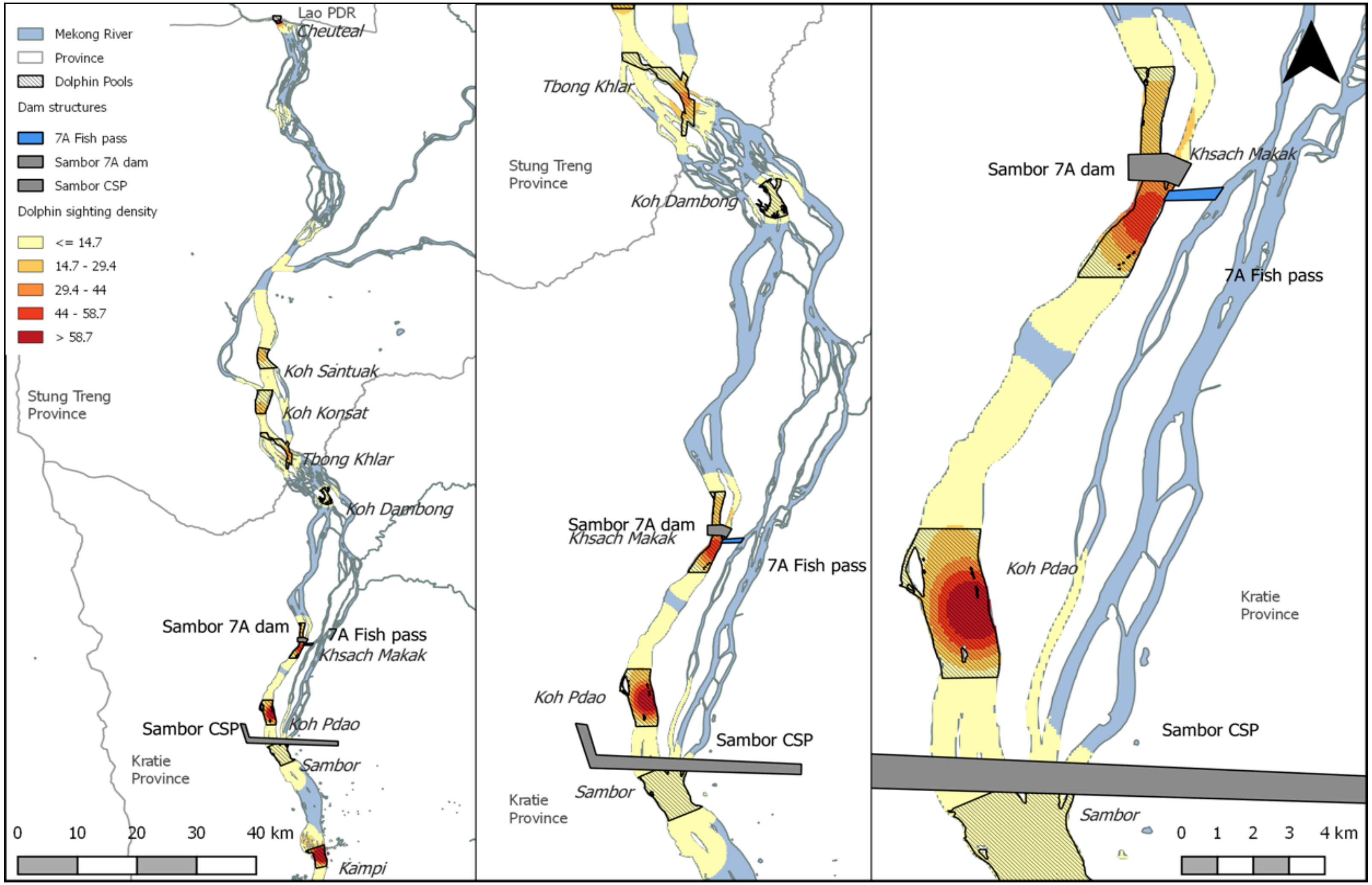


Figure 9.2.2. *Density of dolphin sightings 2001–2007, corresponding to Beasley et al. (2013), Beasley unpublished data.*

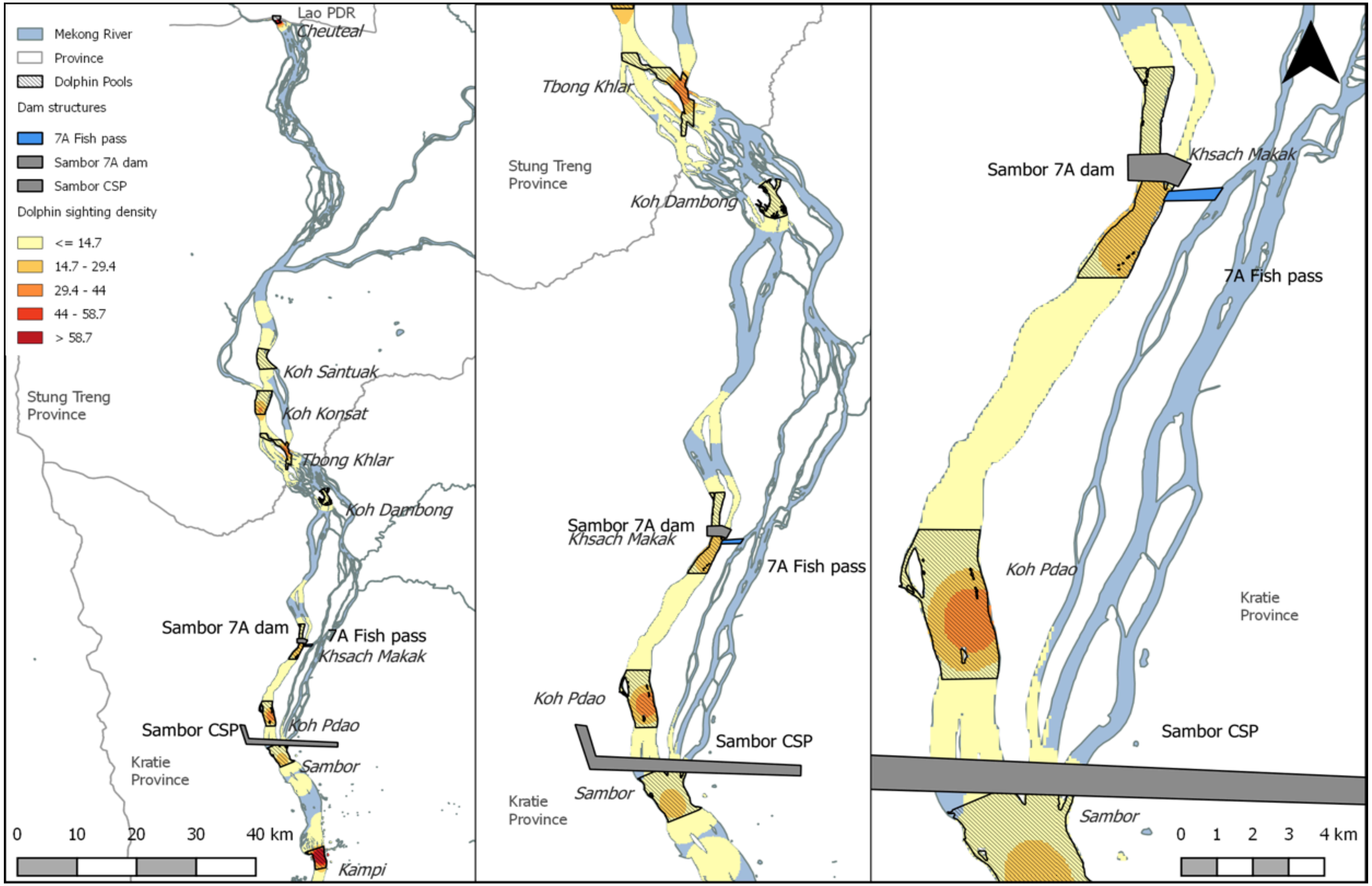
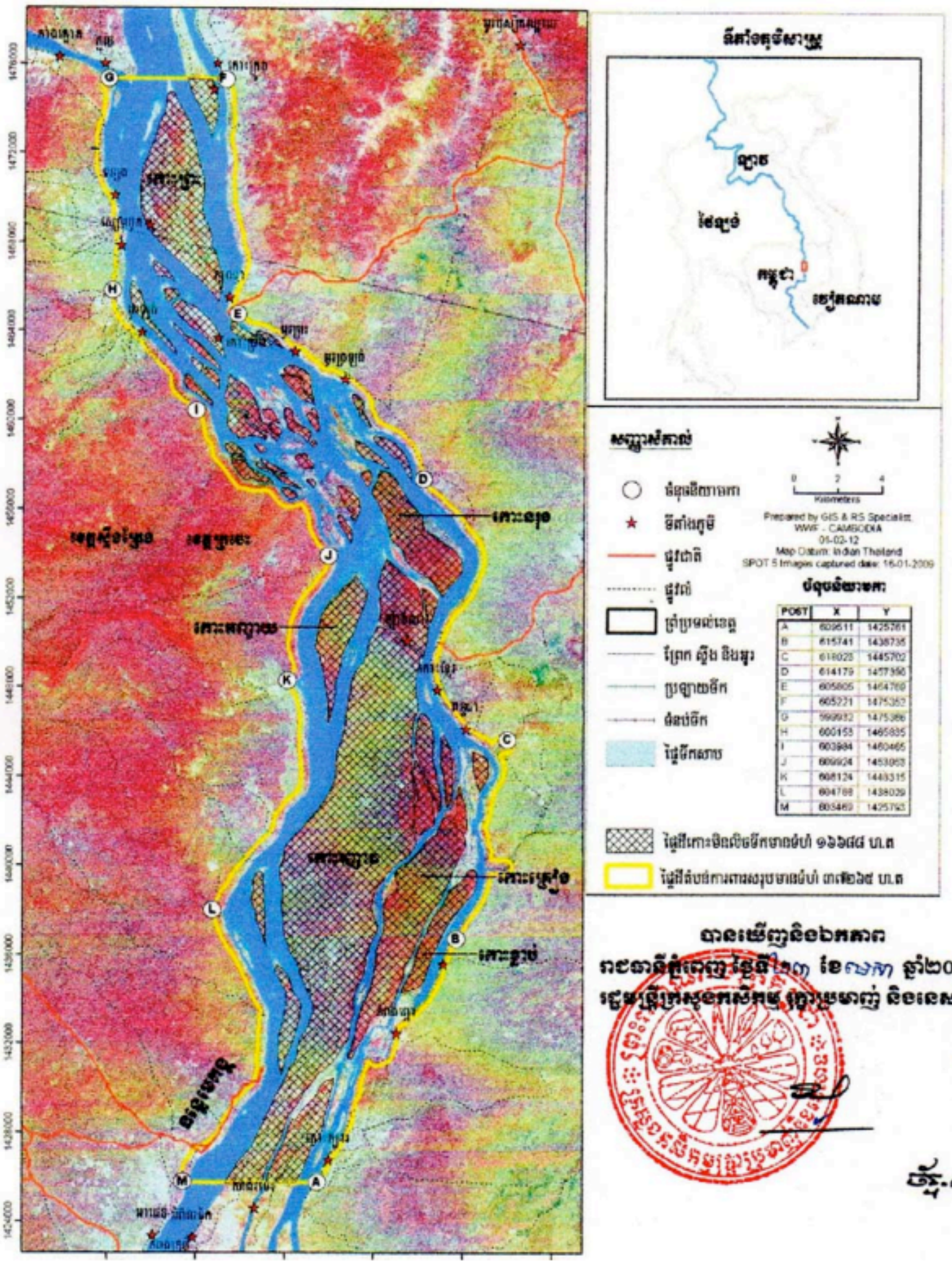


Figure 9.2.3. *Density of dolphin sightings from 2007–2010, dry season. Ryan et al (2011).*

ឧបសម្ព័ន្ធ

ភ្ជាប់ប្រកាសលេខ.១២.៥៣៨..កសក ចុះថ្ងៃទី២៣ ខែ មេសា ឆ្នាំ២០១៣

ផែនទីតំបន់គ្រប់គ្រងនិងអភិរក្សជីវចម្រុះជលផលទន្លេមេគង្គ ក្នុងខេត្តក្រចេះនិងខេត្តស្ទឹងត្រែង



POST	X	Y
A	609511	1425261
B	615741	1438735
C	618028	1445702
D	614179	1457396
E	605806	1464769
F	605221	1475352
G	599932	1475386
H	600153	1465835
I	603984	1460465
J	609924	1453063
K	608124	1449315
L	604768	1438029
M	603469	1425793

បានឃើញនិងឯកភាព

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ចាន់.សារុន

***Figure 9.2.4.** Map from Proclamation on the Creation of Fisheries Biodiversity Management Area (MAFF 2013).*

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Appendix 10.1:

The Longyangxia Hydro-Solar PV Power Station

The Longyangxia Hydro-Solar PV Power Station

The Longyangxia hydro Solar Power Station is the largest hybrid hydro-solar power station in the world and located in Qinghai province China. The power station consists of Longyangxia hydropower station and Gonghe solar photovoltaic station: the hydropower station was initially commissioned in 1989 at 1,280MW, configured as 4×320MW Francis turbines. Average annual generation is 5,940 GWh. The project is located at the entrance of the Longyangxia canyon on the Yellow River in Gonghe County, Qinghai Province. It has large carryover storage with multi-year regulation capability. The active storage is 19,350 million cubic meters (with FRL 2,600m and dead water level 2,530m).

Longyangxia Hydropower station is the first cascaded project on the main reach of the upper part of the Yellow River. It has comprehensive functions, such as power generation, flood control, ice control and irrigation. It also is the first load peaking, frequency regulation power plant in electric network in Northwest China. The hydro power station was integrated into power grid through a 363kV substation, which is equipped with 6 incoming and outgoing line bays. Five of them are in use and one is reserved.

The Gonghe solar station is 30km away from the Longyangxia hydro power station. It was first built and commissioned in 2013 with a nameplate capacity of 320 MWp (Phase I), covering 9 km^2 area (ground-mounted). The designed yearly average energy generation of phase I solar station is 0.498 GWh, annual utilization hours of installed capacity is 1556 hours. An additional 530 MWp (Phase II) was completed in 2015, which covering further 14 km^2.

The solar power station is directly connected to the reserved line bay inside the Longyangxia hydro power substation by a 330 kV transmission line. Figure 10.1.1 shows a schematic diagram of Longyangxia hydro-solar power station.

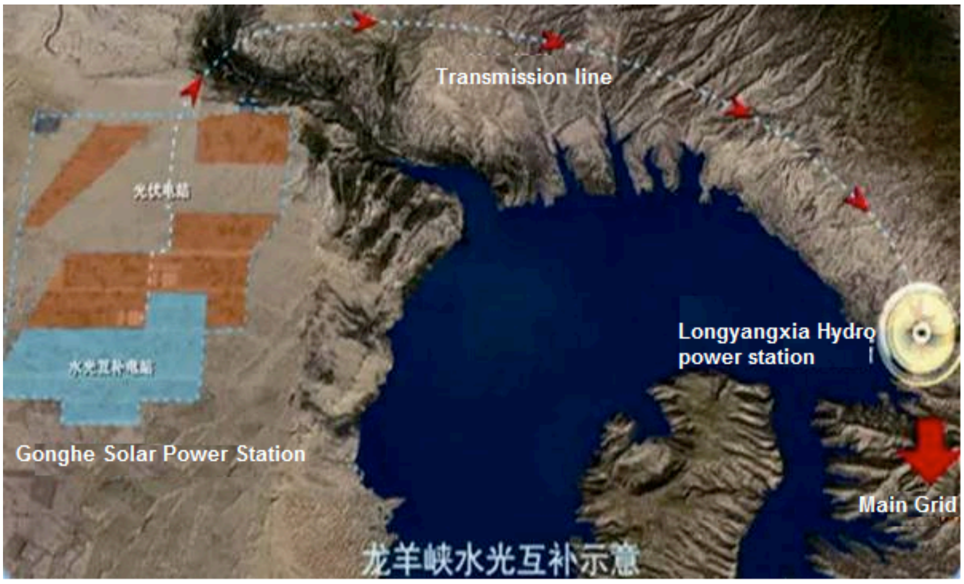


Figure 10.1.1: The configuration of the Longyangxia Hydro solar power station.

1. Complimentary operation scheme of hydro-solar power station

Longyangxia hydro-solar complimentary operation system is the core control system of the power station. In this system, the solar power station is treated as an additional non-adjustable generation unit of hydro power plant. The grid dispatcher only sent a desired total output curve to the power station through AGC system. The desired output curve has to be adjusted everyday according to daily load, solar and water conditions.

The hydro-solar complimentary operation scheme is proposed as follows: hydropower and solar power are treated as one generation source. The solar power is compensated by the hydropower: the hydro power will reduce its output by retaining the water in case of high solar output power; In case of low solar output, the hydro power will increase its output. The base load and maximum load of the hydro-solar power station remains at 200 MW and 1000 MW, which is the same as before complimentary operation. The following section explains the detailed complimentary operation under different water and season conditions.

The water inflow of Longyangxia hydro power station is at minimum level from November to April. It gradually increases from May and reaches maximum in July. After that it gradually reduces again. The operation of Longyangxia hydro power plant before the complimentary operation follows the water characteristics of the river. Figure 10.1.2 shows the average daily operation curves of the hydro power plant before complimentary operation. The output power at late July and August are always maximum due to the excess water flow. The figure also shows that the hydro power station undertakes some base load. The daily lowest loading happens at 4-5am, the maximum loading happens at 7-9pm. Table 10.1.1 shows the average daily output from Gonghe solar power station (phase 1).

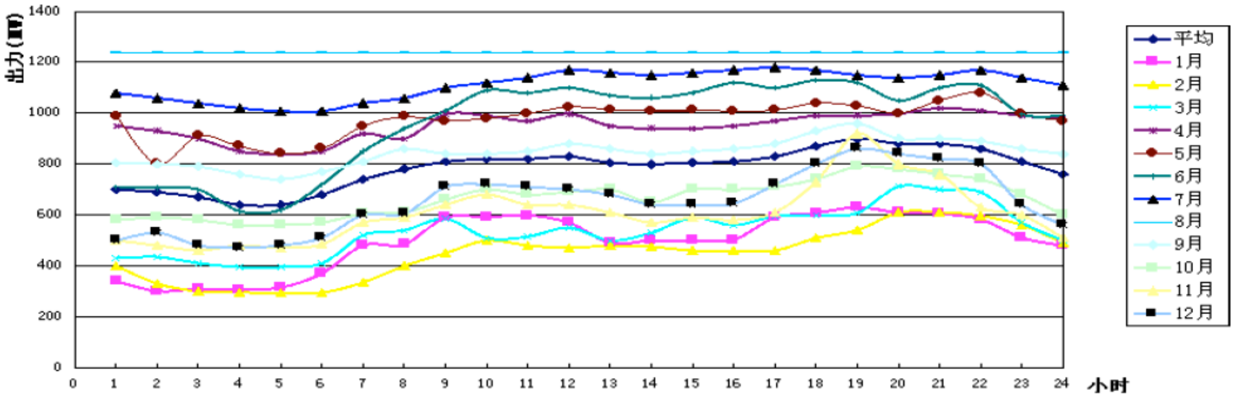


Figure 10.1.2: Monthly average and annual average daily operation in Longyangxia hydropower station.

Table 10.1.1: Statistics of average daily output in photovoltaic power station (Phase I, MW).

	Jan	*Feb*	*Mar.*	*April*	*May*	*June*	*July*	*Aug.*	*Sep*	*Oct*	*Nov.*	*Dec.*
Daily max average output	*79.2*	*88.2*	*84.2*	*81.5*	*77.2*	*81.5*	*76.4*	*76.4*	*77.4*	*68.6*	*78.4*	*69.2*
Daily min average output	*30.7*	*31.9*	*14.3*	*36.2*	*15.8*	*14.0*	*13.1*	*10.1*	*11.5*	*18.3*	*42.7*	*32.8*
Daily average	*61.6*	*64.9*	*62.7*	*59.4*	*56.3*	*48.5*	*51.0*	*53.6*	*52.5*	*49.9*	*63.7*	*59.1*

Figure 10.1.3 and Figure 10.1.4 shows the daily output curve before and after complimentary operation in July and December in a dry year. After complimentary operation, the daily output pattern from hydro power is different, but the total energy generated by hydro remains the same as before.

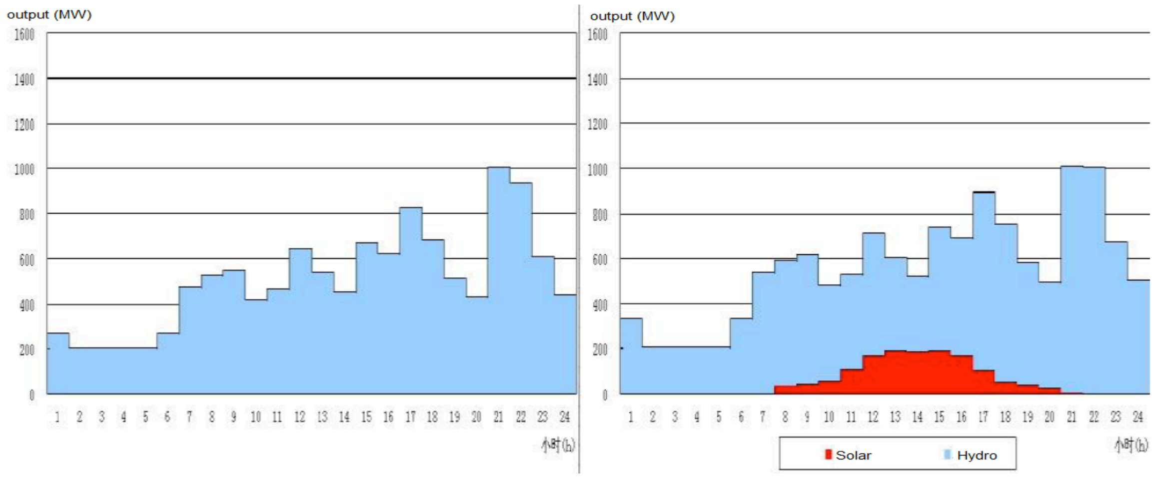


Figure 10.1.3: Daily output curve before and after complimentary operation in July (dry year).

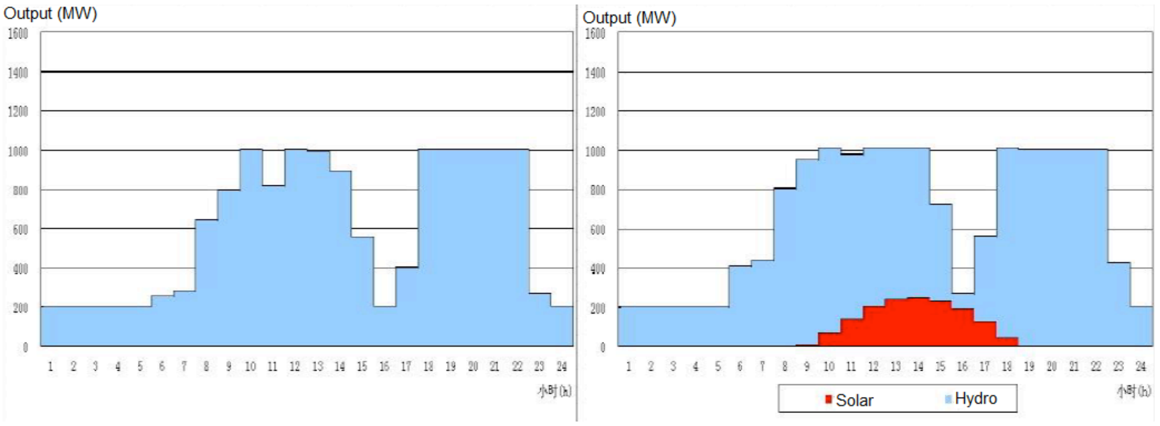


Figure 10.1.4: Daily output curve before and after complimentary operation in December (dry year).

Figures 10.1.5 and Figure 10.1.6 show the similar simulation results for a wet year. In July, due to the excess water flow, the hydro output is at maximum level for a whole day. Complimentary operation between hydro and solar is not possible. If the grid cannot absorb the excess power from solar, either water "spill" or solar curtailment will happen. In December, the power station can maintain complimentary operation, the minimum and maximum loading remain the same as before.

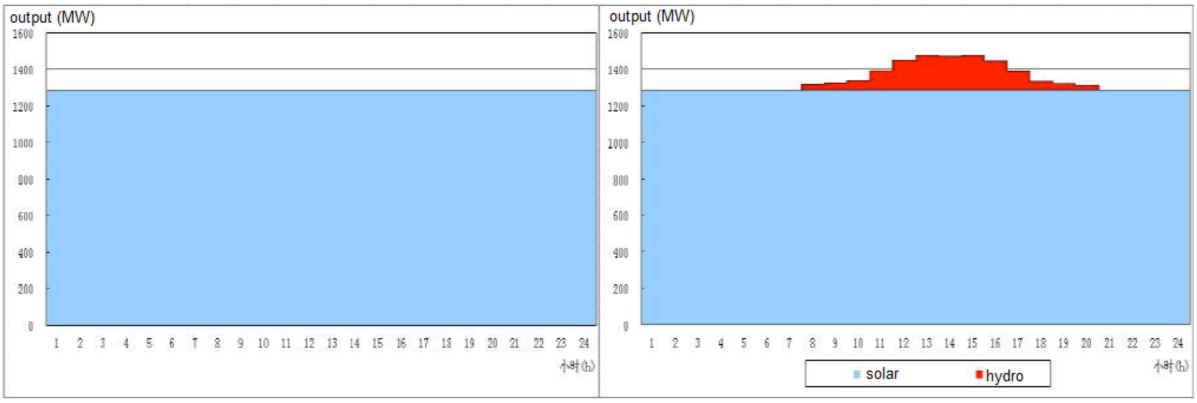


Figure 10.1.5: Daily output curve before and after complimentary operation in July (wet year).

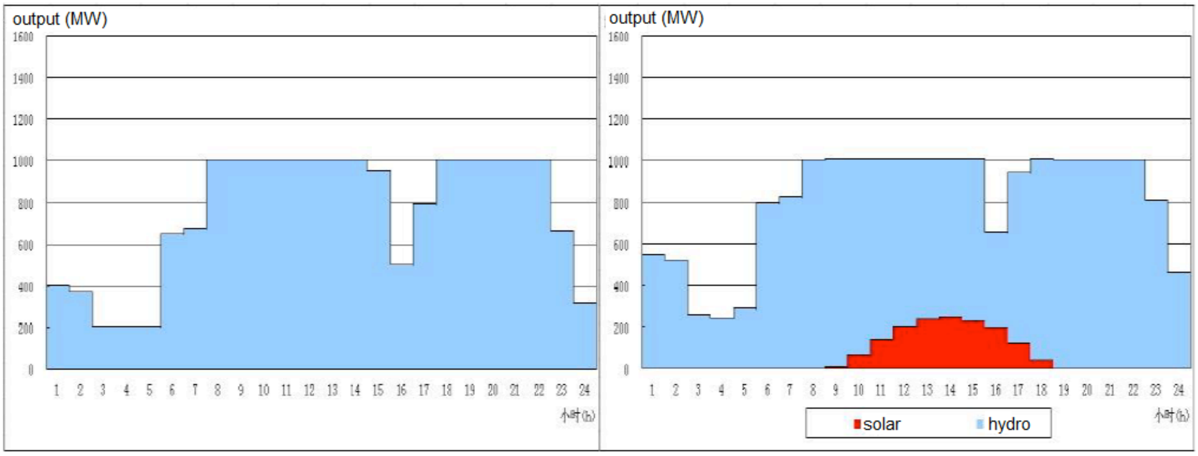


Figure 10.1.6: Daily output curve before and after complimentary operation in December (wet year).

2. AGC control principles and rules

AGC system is the core system to achieve complimentary operation of solar and hydro at the Longyangxia project. It receives the required active power curve from grid and dispatches to each unit inside the power station under a safe, reliable, optimized and economic operation principle. It has the capability of active power regulation, frequency regulation and low-frequency start-up. The major objectives of AGC systems are: (1) smooth the solar power variations in a fast and effective way; (2) meet the grid power dispatch curve; (3) minimize the active power adjustments of hydropower units to avoid wear and tear.

The major AGC control principal and characteristics are as follows:

- **The AGC active power dispatch principle**: In case of the grid dispatch set point increasing, increase the hydro unit which has the minimum utilization factor first. Utilization factor is defined as the ratio between the unit actual output and its installed capacity. The dispatch is finished by only adjusting one unit if the following conditions are fully met: (1) the increment is less than the adjust step of the unit; (2) after active power increase, the unit will not enter vibration zone; (3) the actual output will not exceed the unit maximum power limit. If either conditions cannot be met, AGC will continue to dispatch the next unit until the incremental power are totally dispatched. The same dispatch principle will follow. In case of active power decreasing, the first unit to reduce is the one which has the maximum utilization factor. The dispatch principles are the same as power increasing. With proper active power step settings, it will effectively reduce the frequency of hydro turbine regulation.

- **Strategy to minimize vibration zone crossing** In order to minimize the hydro turbines crossing vibration zone, the AGC set a vibration deadband. In case the hydro turbines are not able to track the active power set points without crossing vibration zone, it can only cross when the output power error is larger than the vibration deadband. In additional, the hydro turbines may cross the vibration zone in case of severe output power unbalance between turbines which may affect the overall performance. The field test has proven that the dead band setting effectively reduce the frequency of vibration zone crossing and maintain high generation efficiency.

- **PV variation deadband and response time interval**: AGC sets a deadband for solar power variations and response interval to avoid frequent hydro generator regulations. Hydro turbines only compensate for PV variations when the PV power variations is larger than the deadband setting. Once the hydro turbine adjust their output set point, they are not allowed to adjust again during the following pre-set time intervals. For Longyangxia project, the PV power deadband setting is 10MW and the response interval is 8 seconds.

The other rules followed by the AGC are:

- Hydro generators should not operate under vibration region;
- Avoid crossing vibration region frequently;
- In case the active power set point is higher than actual output, avoid reducing hydro generation loading as much as possible; in case of active power set point is less than the actual output, avoid increasing hydro generation loading as much as possible;
- Hydro generator output power should not be regulated frequently;
- Treat solar power station as a non-regulated virtual unit of hydro power station;
- Pre-defined active power step for each unit.
- Although the hydro and solar power station can be dispatched as one generation source, the grid operator has the option to direct dispatch and control the solar power station without going through the AGC of the hybrid system.

3. Actual performance of complimentary operation

The actual operation experience during the past few years shows that in case of high solar output and low demand conditions, the hydropower generation is reduced; however in other conditions the hydro power generation is increased. Although the daily hydro output power is changed compared to the conditions before complimentary operation, it still maintains the daily water balance.

The complimentary operation of Longyangxia hydro-solar power station can improve the energy output by 8.4 percent, annual utilization hours of installed capacity of the outgoing transmission line is increased from 4,642 hours to 5,019 hours. However in flood season when the reservoir water level reaches the maximum, complimentary operation of hydro and solar is no longer possible.

Figures 10.1.7, 10.1.8 and 10.1.9 show a series actual operation curves under different weather conditions. The field tests show that the hydro turbines do provide adequate response during load variations and PV output variations. The active power ramp rate of hydro turbines is larger than 150

MW/min, maximum output error is 60 MW which is during the hydro turbines cross the vibration zone. Average output error is 6 MW, which meets the grid dispatch requirements.

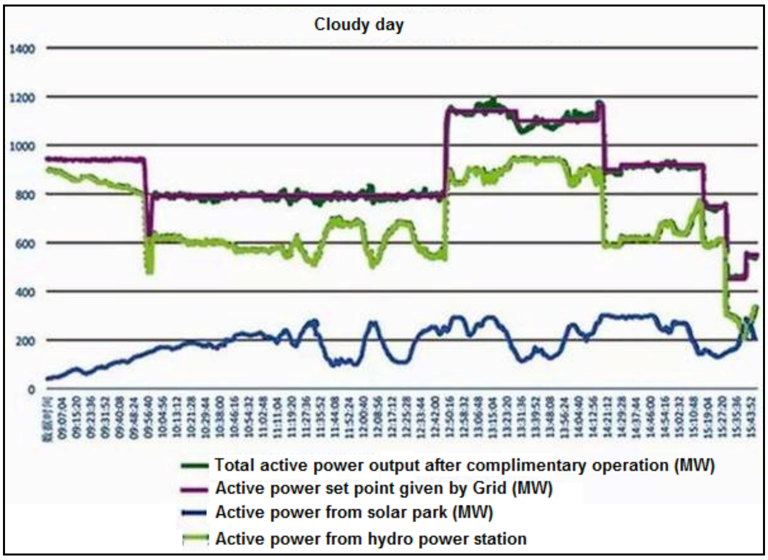


Figure 10.1.7: Active power curves under complimentary operation (cloudy day).

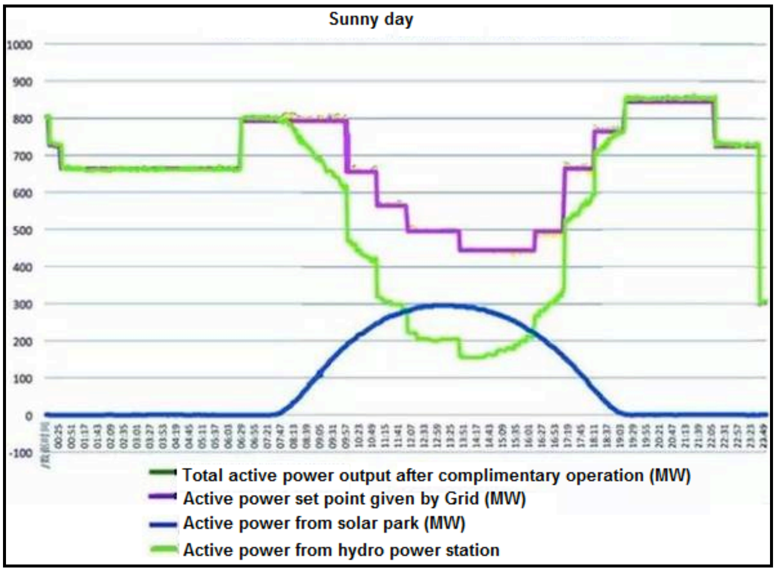


Figure 10.1.8: Active power curves under complimentary operation (Sunny day).

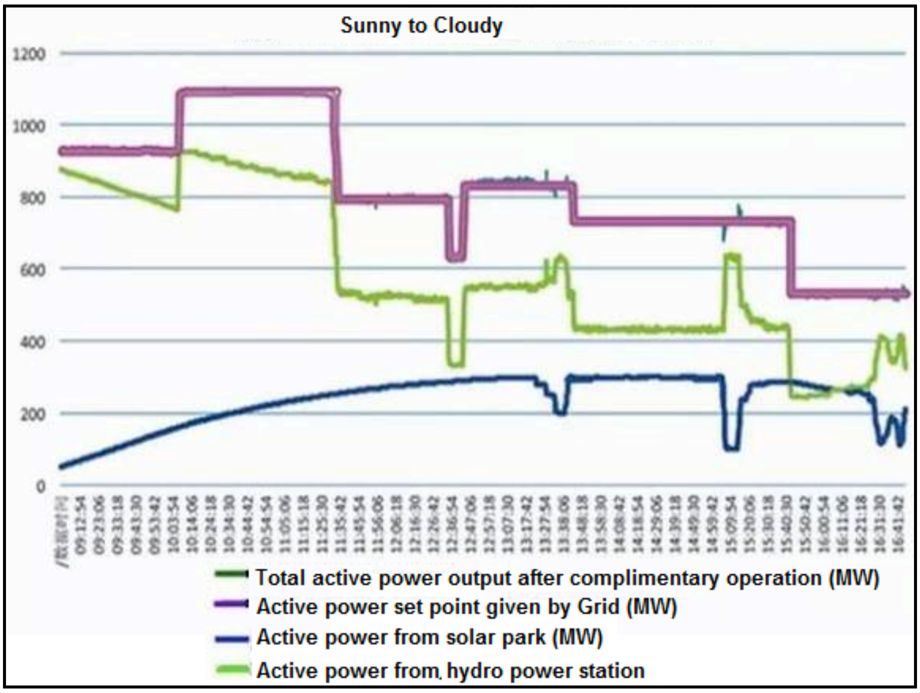


Figure 10.1.9: Active power curves under complimentary operation (sunny to cloudy day).

4. Impact on water levels

Based on the analysis of the outflow record at Longyangxia Dam from year 1988 to 2013, it can calculated that the outflow changes at maximum PV output. The results are shown in Table 10.1.2. At maximum PV output level, the outflow from Longyangxia dam can decrease by 970~4870 km^3, which is only a small part of the total 19.35 Gm^3 capacity of Longyangxia dam. The water level change at Longyangxia dam is only 1.61~ 1.82 cm, which is 0.01 percent of the average water head of 133m. Therefore, the hybrid operation will not affect the Longyangxia energy generation.

As the outflow from Longyangxia dam decreases, it requires the nearby Laxiwa hydro dams to counter regulation of 500 km^3 to maintain the downstream water flow. The 500 km^3 water is about 3 percent of the total storage capacity of Laxiwa dam. Correspondingly, the water level of Laxiwa dam decreases by 0.4m, average water head reduces 0.2m and the total energy generation at Laxiwa hydro reduces by 0. 1 percent. The influence on Laxiwa hydro is on the small side. In general, the downstream water flow can still be maintained after complimentary operation. The energy generation at Longyangxia dam and Laxiwa dam are hardly affected.

Table 10.1.2. Outflow decrease of Longyangxia Dam as PV reaches the maximum output (unit: km3).

Months	Jan	Feb	Mar.	Apr.	May	June
Outflow decrease at Max PV output	1820	2340	2160	2430	2210	4870
Months	July	Aug.	Sep.	Oct.	Nov.	Dec.
Outflow decrease at Max PV output	4450	4190	3980	2800	2420	970

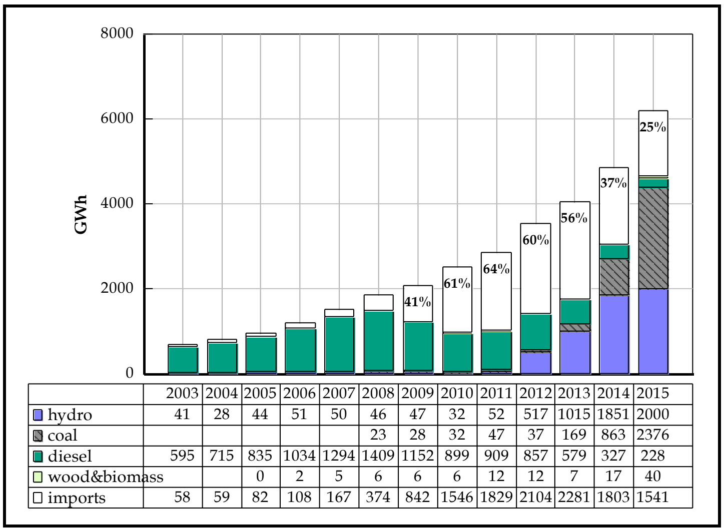
5. Key lessons of the Longyangxia project

1) From grid point of view, hydro and
2) solar power is treated as one generation source. The daily minimum and maximum loading remains the same as before complimentary operation, but the adjustable energy and the average output from complimentary system is increased. The power quality from the complimentary system is also improved compared to a single solar power station.
3) Complimentary operation increases the utilization of existing transmission line. Annual utilization hours of installed capacity of the outgoing transmission line increases from 4642h to 5019h.
4) In wet season, the hydropower is not able to compensate solar power. Solar spill or water spill may happen. In dry season, in case of high solar generation and low system demand, the hydro generators may cross the vibration region.
5) Although the daily generation curve of hydropower is different from before complimentary operation, the daily total energy generated by hydro remains the same as before to maintain daily water balance.
6) From grid point of view, the daily operation mode didn't change greatly after complimentary operation. The hydro unit maintenance should be reasonable scheduled.
7) The customized designed AGC system is the core module of complimentary operation. It receives the required active power set points from grid and dispatches to the hydro units. The AGC operation algorithm and special settings at Longyangxia project are good
8) The outflow changes at Longyanxia dam requires the downstream dam to counter regulate in order to meet the downstream water requirements.

Appendix 10.2:

The Potential for Grid-Connected Solar PV Development in the Cambodia Power System

Until 2007, power generation in Cambodia was almost entirely from diesels. As demand grew, the supply gap was filled by imports, by 2011 accounting for 64 percent of the total generation (Figure 10.2.1). With the additions of modern coal and hydro projects that started in 2012, that import dependence is decreasing, and is expected to disappear entirely once LSS2 is in full production. By 2015, the generation from high cost oil had declined to just 228 GWh, down from its 2008 peak of 1,294 GWh.



	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
🟦 hydro	41	28	44	51	50	46	47	32	52	517	1015	1851	2000
▨ coal						23	28	32	47	37	169	863	2376
🟩 diesel	595	715	835	1034	1294	1409	1152	899	909	857	579	327	228
☐ wood&biomass			0	2	5	6	6	6	12	12	7	17	40
☐ imports	58	59	82	108	167	374	842	1546	1829	2104	2281	1803	1541

Figure 10.2.1: Historical generation mix.

The corresponding growth in sales is shown in Figure 10.2.2. The rate of growth in sales has varied from year to year, but has been greater than 20 percent in several recent years. These are high growth rates, but are from a very low base: whether the 20 percent growth rate that is predicted by some can be sustained beyond 2020 remains to be seen. The forecast for sales shown in Figure 10.2.2 assumes a 20 percent growth rate.

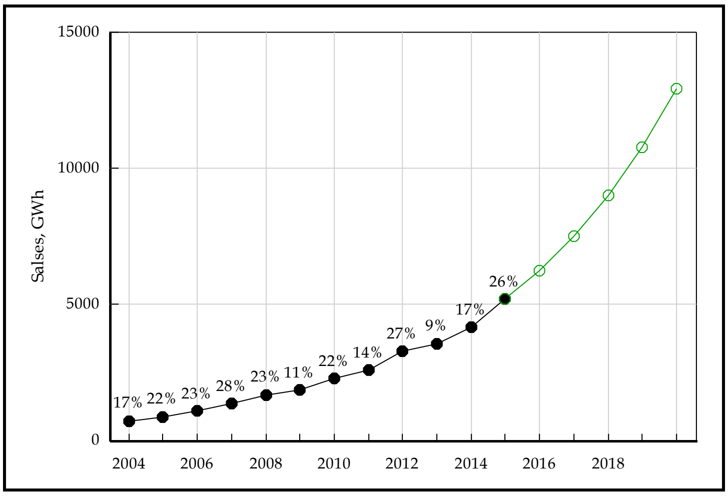
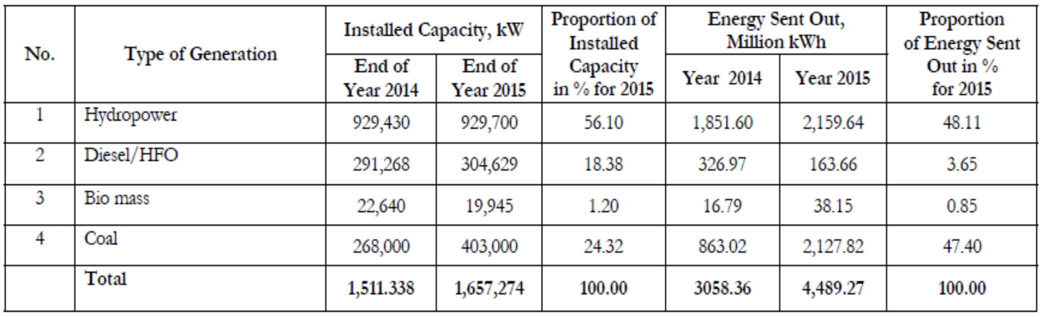


Figure 10.2.2: Cambodia grid Sales.

Table 10.2.1 shows the reconciliation of capacity and energy as presented in the 2015 EAC report.

Table 10.2.1: Capacity and energy, 2014 & 2015. Source: EAC, Annual Report 2015.



No.	Type of Generation	Installed Capacity, kW		Proportion of Installed Capacity in % for 2015	Energy Sent Out, Million kWh		Proportion of Energy Sent Out in % for 2015
		End of Year 2014	End of Year 2015		Year 2014	Year 2015	
1	Hydropower	929,430	929,700	56.10	1,851.60	2,159.64	48.11
2	Diesel/HFO	291,268	304,629	18.38	326.97	163.66	3.65
3	Bio mass	22,640	19,945	1.20	16.79	38.15	0.85
4	Coal	268,000	403,000	24.32	863.02	2,127.82	47.40
	Total	**1,511.338**	**1,657,274**	**100.00**	**3058.36**	**4,489.27**	**100.00**

From this we note very low capacity factors (Table 10.2.2); not surprising for diesels since generation from this source has dropped sharply, as noted above, displaced by coal generation. But, hydro project energy generation also seems quite low at less than 30%. By comparison, the capacity factor of LSS2 in an average hydro year is 55%.

Table 10.2.2: Capacity factors.

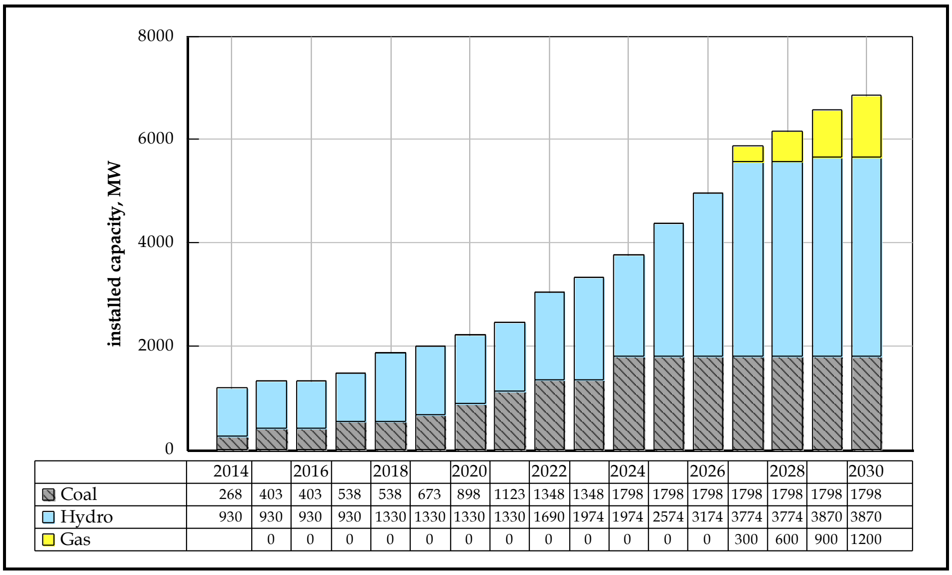
	2014	2015
Diesel	0.13	0.06
Biomass	0.09	0.22
Coal	0.37	0.60
Hydro	0.23	0.27

The official power sector development plan, dated 22 September 2016, has approved in principle the expansion plan shown in Table 10.2.3. This plan does not include renewable energy projects (other than hydro).

Table 10.2.3: Power sector development plan, MW.

	2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Coal																	
installed as of end 2014	268																
Sihanoukville Coal II		135															
coal IPP unit 1				135													
coal IPP unit 2						135											
coal plant II unit 1							225										
coal plant II unit 2								225									
coal plant III									225								
coal plant IV											450						
Hydro																	
Installed as of end 2014	930																
LowerSesan 2					400												
Sala Morn Toun									70								
Rissay Chrum Kandal									70								
Veal Thmor Kombot									100								
Prak Larng									120								
Battam Bangli										36							
Pursat										140							
Chouy Arang										108							
Sambor I												600					
Sambor II													600				
Sambor III														600			
Sesan Krom																96	
Gas/LNG													300				
Gas/coal V														300			
Gas/coal VI															300		
Gas/coal VII																300	
Gas/coal IX																	300
Cumulative Installed capacity																	
Diesel	*291*	*305*	305	305	305	305	305	305	305	305	305	305	305	305	305	305	305
biomass	*23*	*20*	20	20	20	20	20	20	20	20	20	20	20	20	20	20	20
Coal	268	403	403	538	538	673	898	1123	1348	1348	1798	1798	1798	1798	1798	1798	1798
Hydro	930	930	930	930	1330	1330	1330	1330	1690	1974	1974	2574	3174	3774	3774	3870	3870
Gas		0	0	0	0	0	0	0	0	0	0	0	0	300	600	900	1200
Total	1512	1657	1333	1468	1868	2003	2228	2453	3038	3322	3772	4372	4972	5872	6172	6568	6868

Some of the projects listed in this Official Plan are ill-defined. Thermal project unit sizes are given as ranges (e.g. “coal plant IV 400-500MW”) – for which we assume a size given by the midpoint of the range. Starting in 2027, thermal additions are identified as “coal plant-natural gas” for which we here assume combined cycle LNG. It is also not entirely clear on what basis Sambor is forecast as 3 x 600 MW.



	2014		2016		2018		2020		2022		2024		2026		2028		2030
▨ Coal	268	403	403	538	538	673	898	1123	1348	1348	1798	1798	1798	1798	1798	1798	1798
🟦 Hydro	930	930	930	930	1330	1330	1330	1330	1690	1974	1974	2574	3174	3774	3774	3870	3870
🟨 Gas		0	0	0	0	0	0	0	0	0	0	0	0	300	600	900	1200

Figure 10.2.3: The proposed generation mix.

Table 10.2.4 attempts a reconciliation of the capacity expansion plan with a demand forecast based on a 20 percent growth rate. This makes the following assumptions

- T&D loss rate of 13.5%, the rate observed in 2015.
- A system load factor of 70%

This shows that the reserve margin is adequately positive until around 2020, but thereafter, the capacity provided in the official plan does not support a sustained 20 percent increase in annual load growth. The capacity deficit in 2020 is 135 MW, increasing to 1,343 MW in 2025, and to 7,800 MW by 2030!

Table 10.2.4: Supply demand balance, 20% demand growth rate.

				2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	Sales (actual)		[GWh]	4144	5201										
2	Sales growth	0.2	[ ]	17%	26%	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200	0.200
3	Sales forecast		GWh		5201	6241	7489	8987	10785	12942	15530	18636	22363	26836	32203
4	supply required	0.15	GWh	4766	5981	7177	8613	10335	12403	14883	17860	21432	25718	30861	37034
5	estimated peak load	0.7	MW	777	975	1170	1405	1685	2023	2427	2913	3495	4194	5033	6039
6	installed capacity		MW	1512	1657	1657	1792	2192	2327	2552	2777	3362	3646	4096	4696
7	reserve margin		MW	734	682	487	388	507	305	125	-135	-133	-548	-937	-1343
8	required energy increment		GWh		1216	1196	1435	1723	2067	2481	2977	3572	4286	5144	6172
9	Assume 10% PV	0.1	GWh		122	120	144	172	207	248	298	357	429	514	617
10	Incremental PV	0.19	MW		73	72	86	103	124	149	179	215	258	309	371
11	PV as % of total peak load		MW		7.5%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%	6.1%

It is safe to conclude that 20% demand growth well into the 2020s is not sustainable, even under the highly optimistic capacity expansion plan that already includes an 1,800 MW version of Sambor – though it certainly explains why a project that is the size of Sambor is considered essential. Without Sambor, the capacity gap would be larger still.

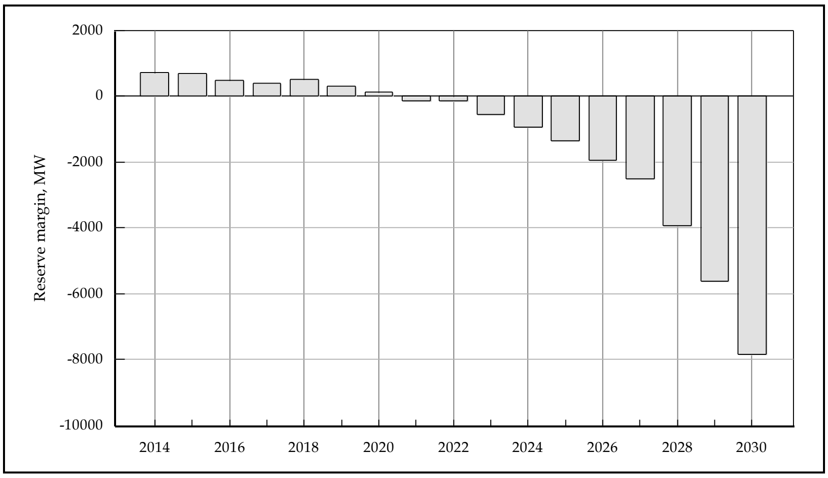


Figure 10.2.4: Reserve margin, 20% load growth.

If the rate of load growth is assumed to begin to decline from 20 percent in 2020 to 10 percent by 2026, then the situation appears more feasible (Figure 10.2.5).

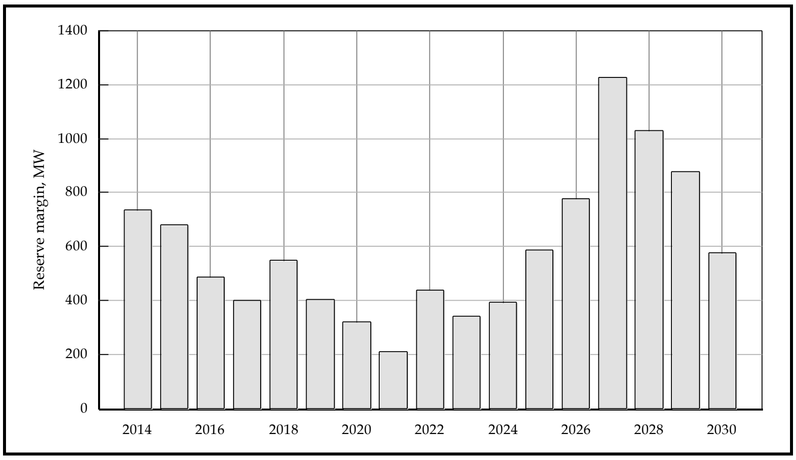


Figure 10.2.5: Reserve margin, load growth declining to 10% by 2025.

A reasonable target for PV additions to grid generation (in addition to distributed rooftop PV that would assist in lowering the grid demand growth rate) is provided in Table 10.2.5. This calculates the annual energy increment (in row 8), and assumes that PV could provide 10 percent of that annual increment without incurring integration problems (row 11 shows the total PV as a percentage of peak load, comfortably below 10 percent at which integration problems may arise).

Table 10.2.5: Supply/demand balance, lower demand growth rate.

				2014	2015	2016	2017	2018	2019	2020	2021	2022	2023	2024	2025
1	Sales (actual)		[GWh]	4144	5201										
2	Sales growth	0.2	[ ]	17%	26%	0.200	0.190	0.180	0.170	0.160	0.150	0.140	0.130	0.120	0.110
3	Sales forecast		GWh		5201	6241	7427	8764	10254	11894	13679	15594	17621	19735	21906
4	supply required	0.15	GWh	4766	5981	7177	8541	10078	11792	13679	15730	17933	20264	22695	25192
5	estimated peak load	0.7	MW	777	975	1170	1393	1644	1923	2231	2565	2924	3305	3701	4108
6	installed capacity		MW	1512	1657	1657	1792	2192	2327	2552	2777	3362	3646	4096	4696
7	reserve margin		MW	734	682	487	399	549	404	322	212	438	342	395	588
8	required energy increment		GWh		1216	1196	1364	1537	1713	1887	2052	2202	2331	2432	2496
9	Assume 10% PV	0.1	GWh		122	120	136	154	171	189	205	220	233	243	250
10	Incremental PV	0.19	MW		73	72	82	92	103	113	123	132	140	146	150
11	PV as % of total peak load		MW		7.5%	6.1%	5.9%	5.6%	5.4%	5.1%	4.8%	4.5%	4.2%	3.9%	3.7%

Thus grid-connected PV additions, and the proposed floating PV addition at LSS2, could be proposed as shown in Figure 10.2.6 without significant technical problems of integrating variable renewable energy.

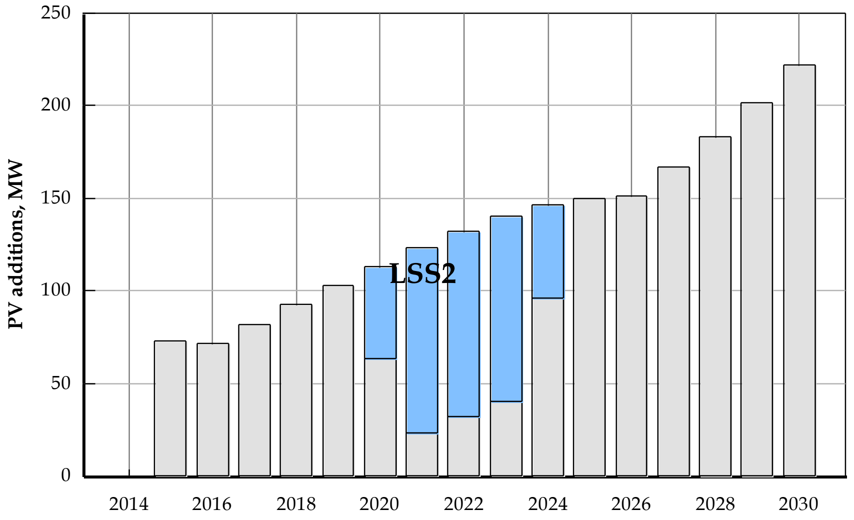
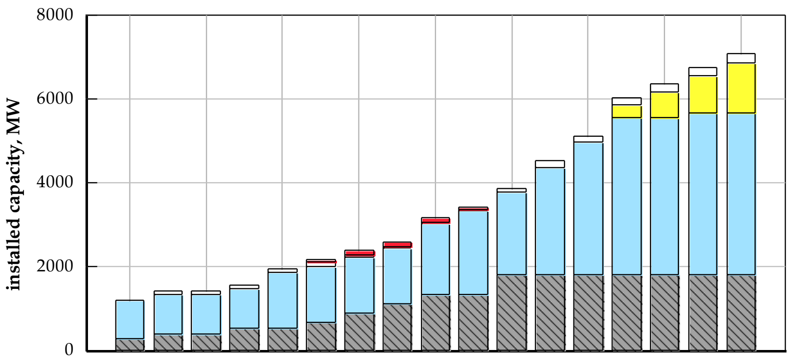


Figure 10.2.6: LSS2 scenario.

Conclusion

A reasonable baseline scenario of the addition of PV modules to LSS2 would therefore be as shown in Figure 10.2.6 – 400 MW in total, built over a 4-5 year period. The revised capacity expansion plan would be as shown in Figure 10.2.7.



	2014		2016		2018		2020		2022		2024		2026		2028		2030
▨ coal	268	403	403	538	538	673	898	1123	1348	1348	1798	1798	1798	1798	1798	1798	1798
🟦 hydro	930	930	930	930	1330	1330	1330	1330	1690	1974	1974	2574	3174	3774	3774	3870	3870
🟨 gas/lng		0	0	0	0	0	0	0	0	0	0	0	0	300	600	900	1200
☐ PV		73	72	82	92	103	63	23	32	40	96	150	151	166	183	201	222
🟥 LSS2 PV						50	100	100	100	50							

Figure 10.2.7: Capacity expansion plan plus PV.

Appendix 11.1

The Discount Rate and Valuation of Externalities

The Discount Rate and Valuation of Externalities

Much has been written recently in the literature of ecology and natural resources about discount rates and their importance to assessing the economic impact of dams. Indeed, much of this literature pleads for the use of lower discount rates than the usual 10-12% found in typical project feasibility studies prepared by engineers, and in power system planning. Some (including Costanza *et al*, 2011) invoke arguments that because "natural capital is self-renewing and does not depreciate", ecosystems services such as capture fisheries merit lower discount rates than aquaculture.[6] This logic is questionable: whether natural capital "depreciates" and is "self-renewing" does not necessarily determine how society should value (all) future costs and benefits compared to (all) present costs and benefits – which is what the discount rate *actually* captures.

Others argue for declining discount rates because they are uncertain.[7] This rationale is no less obscure, because one could equally well make the opposite argument: in the face of uncertainty, the expected rate of return on investment should be higher to offset the high probability of unfavorable results.

Yet others argue that cost and benefits experienced by the current generation should be valued differently to those experienced in future generations (Sumaila and Walters, 2005). This has at least some merit, and the principle that the welfare of future generations has the same weight as that of the present is reflected in the Ramsey Formula (see below) by setting the pure rate of social time preference at zero. But any such rationale should apply to all costs and benefits: the pure rate of social time preference is about the general principle of inter-generational equity, and is hardly a function of whether the object is aquaculture or capture fishery.[8] Indeed, as noted in Section 10 in the case of snakeheads, captured fish already command higher prices that aqua-cultured fish, so society's preference for capture fish is already reflected in a higher price, and has no need for further adjustment through a preferential discount rate.

Thus, we disagree with arbitrary selection of discount rates for some but not all impact categories. The *Costanza* report (Costanza *et al.*, 2011) argued that a 10% discount rate is inappropriate for natural resources (such as capture fisheries, reservoir fisheries and wetland areas) and used lower discount rates (1%). This was then further adjusted by the *Revised Costanza* report (Intralawan, 2015) to 3%, and to an infinite time horizon for natural resources, as shown in Table 11.1.1.

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[6] An approach advocated by Constanza *et al*., 2011.

[7] "Future rates decline in our model because of dynamic uncertainty about future events, not static disagreement about costs" (Newel and Pizer, 2004)

Why uncertainty warrants a *decrease* in discount rate is not immediately clear: certainly in financial analysis, rates of return have been argued to be *higher* than the normal hurdle rate for an investment decision, in order to offset the assessed risk level.

[8] Indeed, Nicolas Stern (2006) argues that the pure rate of social time preference is the probability of the extinction of the human race which he sets at very close to zero. As a matter of logic one can see that if the probability of such extinction by 2050 were certain (whether as a consequence of nuclear war, climate change catastrophe, or the failure to effectively combat some new virus), there would be no point to investment whose returns occur 30 years hence.

Table 11.1.1: Discount rate assumptions

	Time horizon	Discount rate
Hydropower	50	10%
Aquaculture	50	10%
Reservoir fisheries	Infinite	3%
Capture fisheries	Infinite	3%
Wetlands	Infinite	3%
Sediment/nutrients	Infinite	3%
Other	50	10%

Source: A. Intralawan, D. Wood and R. Frankel. *Working Paper on Economic, Environmental and Social Impacts of Hydropower Development in the Lower Mekong Basin,* 2015, Table 1.

The rationale for the 3% discount rate in the *Revised Costanza* report, to replace the the 1% of the original *Costanza* report, does not convince: [9]

> "This paper follows the methodology in the Costanza report but only used a 3% discount factor for natural resources as a 1% discount factor would not change any conclusions but would just result in a much higher negative economic impact for the loss in capture fisheries."

So, one changes an important assumption on grounds that the result would be inconvenient. The text then proceeds to cite a paper by Stiglitz (1994), based (presumably) on which

> "A sensitivity analysis was carried out for 4% discount rate is which is considered at the high end of discount rates used for natural resources"

though whether 4% is Stiglitz's view about the "high end", or that of someone else, is unclear.

Clearly, the choice of discount rate may change project investment decisions (as noted in the discussion of externalities in Chapter 11). But no matter what rationalization for any particular value may be advocated by engineers and economists, the social discount rate is a proxy for the relative weight given by society to costs and benefits today, as against costs and benefits in the future. It is not clear why economists or engineers should have any particular expertise to judge that balance, much less economists and engineers from the developed world, nor indeed even Nobel laureates in economics.

In any event, in the economics literature the range of views about discount rates is just as great, and includes strongly diverging views even among Nobel laureates (see e.g., Zhuang *et al*, 2007, for a good review of the discount rate controversy in the economics literature). Traditionally, development economists (and the international financial institutions such as the World Bank and ADB) have argued that the appropriate discount rate should be based on the *economic opportunity cost of capital (EOCK)*, which corrects observable interest rates (say as the average of investment rate of interest and the savings rate of interest) for taxes and market distortions: this methodology results in discount rates that are typically in the 10-12% range (Coppola *et al*., 2014), though of late these have fallen in to the 8-10% range (Lopez, 2008).

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[9] The stipulation of infinite time horizons is no less arbitrary, because under this assumption, a change from 1% discount rate to 3% discount rate results in an NPV that is 3 times higher (as algebra quickly confirms).

Others argue for a welfare economics approach, namely one based on the contribution of costs and benefits in terms of their marginal utility of consumption of the project beneficiary:[10] this approach has recently been adopted by the World Bank (World Bank, 2016) which for the purposes of its project appraisals has set the pure rate of social time preference at zero, and the discount rate at twice the expected average long term economic growth rate.[11] For a country such a Cambodia, expecting real per capita income growth of in the range of 4-6%, this approach leads to a discount rate of between 8-12%, not very different to the EOCK approach or the usual 10%.

That many OECD countries have chosen to use much lower discount rates for their own policy and economic analysis has doubtful relevance to what is appropriate for Cambodia.[12] That a developing country whose principal focus is poverty alleviation and economic development in the near future places greater weight on shorter term benefits than a wealthy country is entirely rational. In any event, even if it is true that climate change impacts of present decisions merit much longer planning horizons, that is a matter of consideration for the wealthy of the world who are largely responsible for the present stock of global GHGs.

As demonstrated in this report, fishery protection measures and good sediment flushing management make economic sense even at 10% discount rates, and do not need to be justified by special pleadings that particular categories of costs and benefits should be valued at different or declining discount rates. The potential impact of Sambor on Cambodia's fisheries (and the Tonle Sap fishery in particular) is an *immediate* threat, as is the impact of sediment capture on rice production in Vietnam's Mekong delta rice bowl.

Conclusion

We acknowledge that the choice of discount rates is controversial. However, the way to deal with this is through a sensitivity analysis to identify at what discount rate would an investment decision change. We note that the rate used by the Government of Cambodia (10%) is consistent with the welfare economics approach now used by the World Bank – with expected per capita economic growth that can reasonably be expected to be achieved for the next few decades of 5%-7%, the choice of 10% is entirely consistent with the principle of welfare economics. In any event, as shown in Section 10, the key uncertainties lie in the modeling of fish dynamics and estimates of lost fish catch, not in the choice of discount rate.

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[10] The basic assumption is that the marginal value of an additional dollar of net benefits is smaller when the recipients of those benefits are richer. If an economy is growing over time, the recipients of future benefits of a project will be richer, and so future benefits are valued less than those that occur in the present, when recipients are less well-off. This rationale is quantified in the Ramsey formula, which postulates the social discount rate, ***r***, as

$$\mathbf{r} = \delta + \gamma\,\mathbf{g}$$

where δ = pure rate of time preference, **g** is the expected growth rate and γ is the marginal utility of consumption.

[11] This reflects the following presumptions: (1) the World Bank should not value the welfare of today's individuals more than that of individuals in the future, in other words setting the pure rate of time preference to zero ($\delta = 0$), and (2) Given the Bank's focus on eliminating extreme poverty and boosting the income of the poorest 40% of the population, it appears reasonable to set $\gamma = 2$, which is within the range commonly found in the literature.

[12] For example, the discount rate in the UK is 3.5% for 30 years, declining thereafter; EU 5%; Japan 4%; the US 3-7%; Sweden 4%.

Previous Studies

The importance of discount rates is illustrated in previous studies on the valuation of externalities. For example, Table 11.1.2 compares the externality valuations in the *Costanza, Revised Costanza and NREM* reports with the original BDP2. The impact on capture fisheries is seen to be the dominant externality considered – in all four studies it is the largest single negative externality, and in the *Costanza, Revised Scenario* and NREM reports, substantially exceed the benefit of hydropower.

Table 11.1.2: Externalities and their relative importance (11 dams scenario)

		BDP2	Costanza Report	Revised Costanza.	NREM
		NPV,$USm	NPV,$USm	NPV,$USm	NPV,$USm
	Discount rate for externalities	10%	1%	3%	10%
[1]	Hydropower	32,823	32,823	32,823	6,650
[2]	Irrigated agriculture	1,659	1,659	1,659	1,832
[3]	Reservoir fisheries	215	26,058	4,331	822
[4]	Aquaculture	1,261	4,010	743	931
[5]	Capture fisheries	-1,936	-133,650	-54,854	-13,030
[6]	Wetlands	101	3,536	1,114	238
[7]	Social/Cultural Impact	0	0	-1,494	-1,665
[8]	Sediment/Nutrient	0	0	-5,414	-2,311
[8]	Eco-hotspot/biodiversity	-415	-415	-415	-458
[9]	Forest area reduction	-372	-372	-372	-411
[10]	Recession rice	278	278	278	307
[11]	Flood mitigation	-273	-273	-273	-301
[12]	Salinity mitigation	-2	-2	-2	-2
[13]	Bank erosion losses	0	0	0	0
[14]	Navigation	64	64	64	71
[15]	Total	33,403	-66,284	-21,811	-7,329

As noted, this is a classic case of adjusting assumptions to achieve a desired result. By adjusting the discount rates for negative externalities downward, but not for electricity benefits, the desired result of showing that hydropower is uneconomic is achieved. An elementary reality check will show that a negative impact of US$133 billion, even as a PV, is highly implausible. The *total* GDP of Cambodia in 2015 was US$18 billion dollars. Such unreasonable estimates do a great disservice to the presentation of a reasoned environmental arguments about the negative impacts of hydro generation.

The 2017 NREM report (Intrawalan *et al.*, 2017) wisely reverts to a 10% discount rate for all categories of costs and benefits, and updates all the cost estimates and externality values to 2016 prices. However, the basis for the adjustment to hydropower costs lack transparency.[13] Most importantly, there is much confusion about the difference between economic and financial analysis[14] and very puzzling assumptions about benefits to countries receiving hydropower: for example, the assumption that

> *countries receiving hydropower electricity will benefit from using low cost hydropower instead of electricity generated from natural gas or coal. This benefit is estimated to be 10-15% of the value of total*

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[13] The reference provided for the updated costs is "Anonymous Personal Communication with Mekong hydropower consultants"!

[14] For example, it is stated that the "NPV calculations are based on an "economic internal rate of return method which assumes self-financed projects and zero royalty and tax". That economic analysis excludes royalties and tax is correct, but economic analysis makes *no* assumptions about financing modality!

> *electricity generation from mainstream and tributary projects and a conservative figure of 10% was assumed in this study based on electricity generation, transmission and distribution data in Thailand* (Intrawalan *et al.*, 2017).

is incomprehensible. Indeed, it is quite unclear how the incremental transmission costs of export projects are included in the analysis.

In any event the assumption of a uniform 7 USc/kWh "price" seems to be based on the assumption that hydro projects generate base load power ("mainstream projects are run of river and produce electricity 24 hours/day") which is clearly not the case (see Table 10-8 for the case of Sambor – other mainstream projects will be operated in a similar way) – for most of the year they operate as *daily peaking project*s, for which the appropriate valuation of benefits is most certainly not the average price.

Another objection to all of the various criticisms of BDP2 is convenient omission of the avoidance of GHG emissions associated with the thermal counter-factual, which constitutes an important benefit of hydropower. Indeed, the *Revised Costanza* report does not mention GHG emissions at all. Climate change is mentioned only in the context that its impacts might increase the likelihood of extreme events occurring during the life of the mainstream dams.

Finally, we note a certain lack of transparency of presentation. The hydropower benefit is shown as a *net* benefit, but whatever discount rate may be applied there is a need to show what are the incremental costs, and what are the incremental benefits. The costs being up front, it is the *benefit* stream that will be most affected by the discount rate. It is also quite unclear why the BDP2 shows the NPV of hydropower in two parts – one as "hydropower generation", the other as "hydropower import/export". Table 11.1.3 shows our recalculations of the revised case, in which we decompose the net benefits shown in Table 11.1.2 into costs and benefits, and recalculate the net hydro benefits at the same discount rate as the externalities. When consistently applied, the net *cost* of US$66 billion the *Costanza* report recalculates into a net *benefit* of US$239 billion; the net cost of 21 billion in the *Revised Costanza* report recalculates to a benefit of US$149 billion.

We conclude:

- The dominant externality is the impact on capture fisheries. At whatever discount rate, downstream capture fishery impacts dominate.
- The presentations omit the largest *positive* externality of avoided GHG emissions associated with the thermal generation that is replaced.
- Discount rate assumptions are critical. Results can be manipulated to produce very high damage costs by use of arbitrarily low discount rates for selected externalities. Consequently, the Costanza studies are unreliable guides for decision-making. It is Governments who make that trade-off: Consultants (and foreign consultants in particular) have no special expertise in making that trade-off or to select the discount rate: the role of a consultant can only be to show the decision-maker what are the impacts of alternative discount rates.
- A sensible approach is to begin the benefit-cost analysis with a 10% discount rate, and then ask what discount rate would be required to change the investment decision - the so-called switching value.

- It is then for Government to consider the extent to which the switching value can be reconciled to the country's development objectives.

Table 11.1.3: Revised calculations (11 dams scenario)

		BDP2	Costanza Report	Revised Costanza.
		NPV,$USm	NPV,$USm	NPV,$USm
	Discount rate for externalities	10%	1%	3%
1	Annual power production (GWh)	*112,741*	*112,741*	*112,741*
2	PV (power production) (GWh)	*1,117,808*	*4,419,017*	*2,900,804*
3	*Hydropower*			
4	Power benefits	95,908	379,152	248,889
5	O&M cost	-10,440	-41,274	-27,093
6	Investment cost	-52,650	-52,650	-52,650
7	Net hydropower benefits	**32,818**	285,228	169,146
8	*Externalities*			
9	Reservoir fisheries	215	26,058	4,331
10	Irrigated agriculture	1,659	1,659	1,659
11	Aquaculture	1,261	4,010	743
12	Capture fisheries	-1,936	-133,650	-54,854
13	Wetlands	101	3,536	1,114
14	Social/Cultural Impact	0	0	-1,494
15	Sediment/Nutrient	0	0	-5,414
16	Eco-hotspot/biodiversity	-415	-415	-415
17	Forest area reduction	-372	-372	-372
18	Recession rice	278	278	278
19	Flood mitigation	-273	-273	-273
20	Salinity mitigation	-2	-2	-2
21	Bank erosion losses	0	0	0
22	Navigation	64	64	64
23	Net benefits [7] …[22]	33,398	186,121	114,511
24	GHG emissions benefit	**13,414**	**53,028**	**34,810**
25	Adjusted net benefit	46,811	239,149	149,320
26	Original estimate (Table 13)	***33,403***	***-66,284***	***-21,811***

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