Mekong River Commission
For Sustainable Development

THE MRC HYDROPOWER MITIGATION GUIDELINES

Guidelines for Hydropower Environmental Impact Mitigation and Risk Management in the Lower Mekong Mainstream and Tributaries

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Abbreviations and acronyms

AMCF	–	Assessment of Mekong Capture Fisheries Component
BDP	–	Basin Development Plan
BL	–	Body lengths
DEM	–	Digital Elevation Model
DCI	–	Dendritic Connectivity Index
DSF	–	Decision Support Framework
HPP	–	Hydropower Project
ISH	–	Initiative on Sustainable Hydropower
LMB	–	Lower Mekong Basin
LP	–	Luang Prabang Dam
LPD	–	Luang Prabang downstream (tailwater of Luang Prabang Dam)
LPU	–	Luang Prabang upstream (headwater of Luang Prabang Dam)
MFD	–	Mekong Fish Database
MOL	–	Minimum Operation Level
MRC	–	Mekong River Commission
PB	–	Pak Beng Dam
PBD	–	Pak Beng downstream (tailwater of Pak Beng Dam)
PBU	–	Pak Beng upstream (headwater of Pak Beng Dam)
PL	–	Pak Lay Dam
PLD	–	Pak Lay downstream (tailwater of Pak Lay Dam)
PLU	–	Pak Lay upstream (headwater of Pak Lay Dam)
PMFM	–	Procedures for the Maintenance of Flows on the Mainstream
RoR	–	Run-of-the-River
SK	–	Sanakham Dam
SKD	–	Sanakham downstream (tailwater of Sanakham Dam)
SKU	–	Sanakham upstream (headwater of Sanakham Dam)
UMB	–	Upper Mekong Basin
USACE	–	United States Army Corps of Engineers
XB	–	Xayaburi Dam
XBD	–	Xayaburi downstream (tailwater of Xayaburi Dam)
XBU	–	Xayaburi upstream (headwater of Xayaburi Dam)
OAAs	–	Other Aquatic organisms

Executive Summary

Introduction

This is the Executive Summary for the Final Phase Report, documenting the results from the Case Study on the Lao Mainstream Hydropower Cascade for the 2nd Interim Phase and the following activities in the Final Phase, which includes also the assessment of the downstream dams.

The specific objective of the Case Study is to "test selected mitigation options, recommended in the Guidelines, for effectiveness, sustainability and at the same time maximizing the operational flexibility". This has been undertaken through a detailed analysis of a range of mitigation options and scenarios using rigorous modelling to assist in the impact assessment. A chosen set of indicators has been assessed with regard to selected mitigation options, under the various selected scenarios. This is further described in the Assessment Methodology that follows on page 13 of this Executive Summary.

The mainstream cascade studied during 2nd Interim Phase constitutes hydropower plants at Pak Beng, Luang Prabang, Xayaburi, Pak Lay and Sanakham ("The Lao Cascade"). The Xayaburi hydropower project is currently under construction and planned to be operational in 2019. The other hydropower projects are at less advanced stages of development. An overview of the Lao cascade is given in Figure ES1 with some salient features of the reservoirs illustrated in Table ES1.

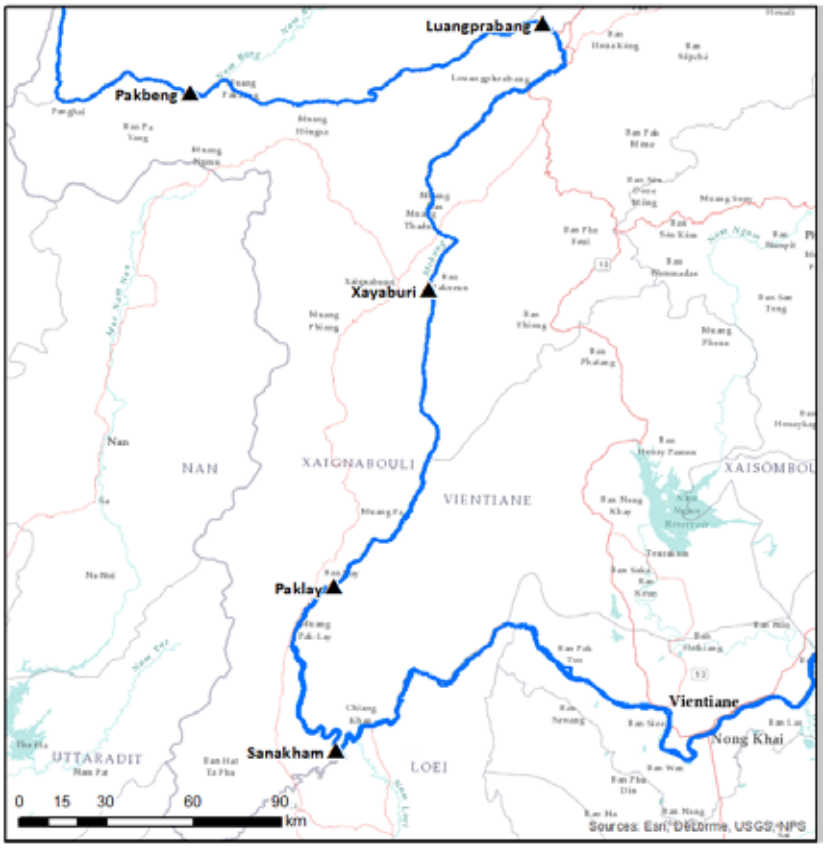


Figure ES1. *Overview of the Lao Cascade, upstream Vientiane.*

During Phase 4 all 11 mainstream dams have been studied and the assessment has mainly been derived from the modelling undertaken under the Council Study, and it's Hydropower Sub-scenarios. There are six mainstream dams planned downstream of the Lao Cascade, four in Lao (Pakchom [15] Ban Kum, Latsua, and Don Sahong) and two in Cambodia (Stung Treng and Sambor). Ancillary construction works has already started at Don Sahong. The dams are plotted in the map below.

Figure ES2. *Mainstream dams downstream of the Lao cascade.*

The Context of the Study Base Case

This study aims to understand the effectiveness of the mitigation options, in order to reduce risks and impacts associated with the construction and operation of the Lao Cascade (2nd Interim Phase)

15 Pakchom is just downstream Sanakham in the Lao Cascade, but was not studied in the 2nd Interim Phase.

plus all mainstream dams (Final Phase), mentioned in the previous section. When undertaking this assessment, it is important to understand the basin-wide context in which these dams are considered. To date eight hydropower dams have been constructed in China on the upper Mekong Basin (the Lancang cascade). These are major dams with substantial storage already causing significant changes to the seasonal pattern of inflows into the Lao cascade. The sediment loads entering the upstream end of the Laos Cascade have also been substantially reduced due to sediment trapping (see Section 3.4.2 and the Hydropower Guidelines Manual – MRC, 2015). ***It is important to stress that the Lancang Cascade has a large impact on the river reach where the Laos Cascade is located, and hence potential additional changes need to be considered within a basin scale context.*** The impact from the Lancang Cascade dismisses somewhat further downstream albeit seasonal flow changes in the Lao-Cambodian floodplain are already occurring due to the large storage dams in UMB mainstream. Concurrently, a number of the major Lao PDR tributaries flowing into the cascade have hydropower developments under construction or in operation, and further schemes are planned on these rivers in the coming 15 years (see Section 2.1 and MRC, 2015), some with major storages. Henceforth, ***mitigation of the cumulative impacts of the tributary and mainstream dams would require further transboundary dialogue on options to adapt and coordinate the operation of these respective large storage schemes, for example through joint flow releases and/or coordinated flushing/sluicing in critical periods of the season***.

Furthermore, the Mekong basin is changing rapidly as a result of human development pressure across the region for irrigation, urbanisation and other sectors. In addition, the effects of climate change are exacerbating the impact of these pressures. The combined pressure may cause future changes in the basin ecosystems, with many possibly foundering in unanticipated ways with unforeseen cascading and cumulative effects imposed on them. Therefore, as we seek to measure the effectiveness of the mitigation options for the Lao cascade, we need to recognise that the various ecosystems of the Mekong are currently in a state of relatively rapid change as the river responds to the above pressures. The change from the historical state (with no dams and less development pressures) will be long term, continuous and dynamic. In many cases, these changes will be fundamental and irreversible. Therefore, while we try to understand the impact of one dam or a cascade of dams, and seek to mitigate that impact, ***the overall changes in the basin will need to be managed at basin scale with transboundary cooperation*** (see also section on findings and recommendations at the end of the Executive Summary).

Henceforth, when undertaking the Case Study assessment, we also draw attention to the historical, current and planned context for the Mekong so that the reader can understand the relative scale of the various changes that are happening in the basin. Therefore, we have also assessed the changes from the historic via the 'BDP 2030' scenario for the 2nd Interim Phase and Council Study 2040 Scenario for the Final Phase (which both includes the Lancang cascade and Mekong tributary dams) towards the selected scenarios for the cascade. ***The impacts of the development and operation of the Lao Cascade and the further downstream mainstream dams, and the effectiveness of the proposed mitigation options, must also be considered in the context of the larger scale basin changes***.

During the 2nd Interim Phase the Lao Cascade impact relative to tributary and UMB development was investigated with regard to aquatic ecology and fisheries as well as sediments (covered in chapters 3 and 5 of the main report). Below in Figure ES3 and ES4 is an illustration of the relative

impacts of the Lao Cascade with regard to sediment loads and fisheries biomass. Note the less dramatic impact from historic to BDP2030 conditions for fish biomass compared to sediment loads, due to “unimpacted” tributary fisheries in this case. Mitigation within the cascade reduces the impacts, but the basin scale impacts will still dominate especially with regard to sediment loads.

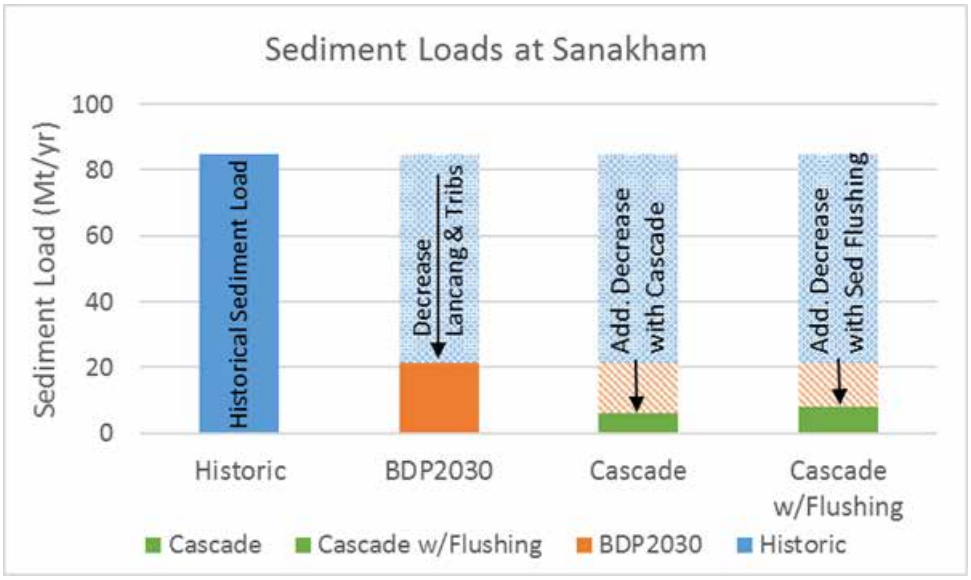


Figure ES3. *Sediment loads at Sanakham for historic, BDP2030, and Lao cascade conditions (with and without mitigation).*

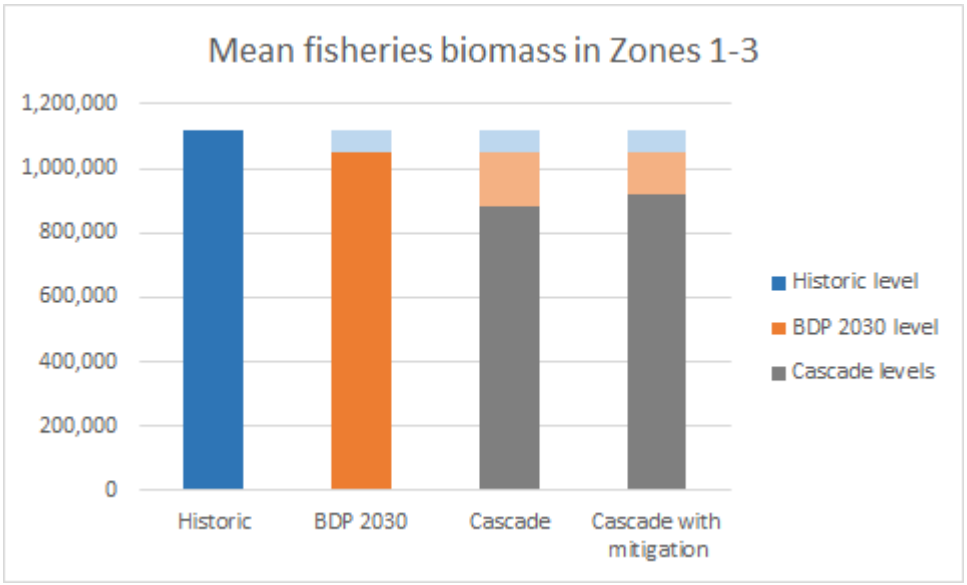


Figure ES4. *Mean fisheries biomass on the area of investigation (Zone 1-3 combined) for historic, BDP2030 and cascade (with and without mitigation) conditions.*

Assessment Methodology

Risks and vulnerabilities related to the Lao cascade development was assessed, during 2nd Interim and Final Phase, for (i) hydrology and flows; (ii) sediments and geomorphology; (iii) water quality;

and (iv) fisheries and aquatic ecology. These themes have also been rigorously covered in the Guidelines and Manual from the 1st and 2nd Interim Phases (MRC, 2015 and 2016).

2nd Interim Phase – Northern Lao PDR Case Study

To study the risks mentioned above, a specific set of mitigation measures was selected for the Lao Cascade. These were as follows[16]:

- Lower dry-season water level of the Pak Beng reservoir to reduce upstream inundation
- Flood protection at Luang Prabang by water-level draw down of Xayaburi
- Connectivity restoration with focus on fish passages
- Sediment flushing and sluicing
- Flow restrictions (for hydropower peaking scenarios) to address the following:
    - Water level ramping rates for geomorphic mitigation
    - Water level ramping rates for fish
    - Minimum environmental flows
- Limitations to reservoir level fluctuation: A 50 cm limit to reservoir level change for safety, navigational and environmental reasons

The mitigation measures above was modelled, tested, cumulatively added and analysed with regard to impacts for three main scenario groups[17], namely;

I. Scenario group 1.1 – ***Run-of-River Scenarios*** – where the hydropower plants operate as run-of-river schemes. Except during floods, the reservoirs will constantly be kept at full supply level, and the discharge through the power stations and spillway is equal to the incoming flow.

II. Scenario group 1.2 – ***The Sediment Flushing Scenarios*** – where the hydropower plants operates as in 1.1, e.g. run-of-river, but where annual flushing options are implemented to promote transport of sediment through the reservoirs.

III. Scenario group 1.3 – ***The Hydropower Peaking Scenarios*** – where the operation the hydropower plants seeks to increase revenue by prioritizing generation during the 16 hour daytime period, e.g. 06:00-22:00, resulting in daily variation in reservoir level with impacts also downstream.

The impact mitigation assessment of the scenarios was undertaken in three major zones/sections (see Figure ES5), i.e.; (i) Zone 1: in the cascade itself; (ii) Zone 2: from Sanakham to Paksan; and (iii) Zone 3: from Paksan to Pakse.

16 Described in detail in Chapter 2.3 of this report.

17 Described in detail in Chapter 2.4 of this report.

***Figure ES5**. Map over cascade reach and the three impact assessment sections/zones (Zone 1 = pink, Zone 2 = green, Zone 3 = orange).*

In addition to evaluating the effect of mitigation on the environment, the impact of the mitigation measures on power production and revenues (based on Thai energy delivery tariffs) has also been calculated for the various scenario groups. The basic framework for this is illustrated in Figure ES6. The effectiveness of the mitigation options was tested by comparing scenarios with mitigation measures (i.e. 1.1.A to 1.3.E) to scenario 1.1.0 (run-of-river without mitigation) and by evaluating relative differences by a set of environmental and economic indicators.

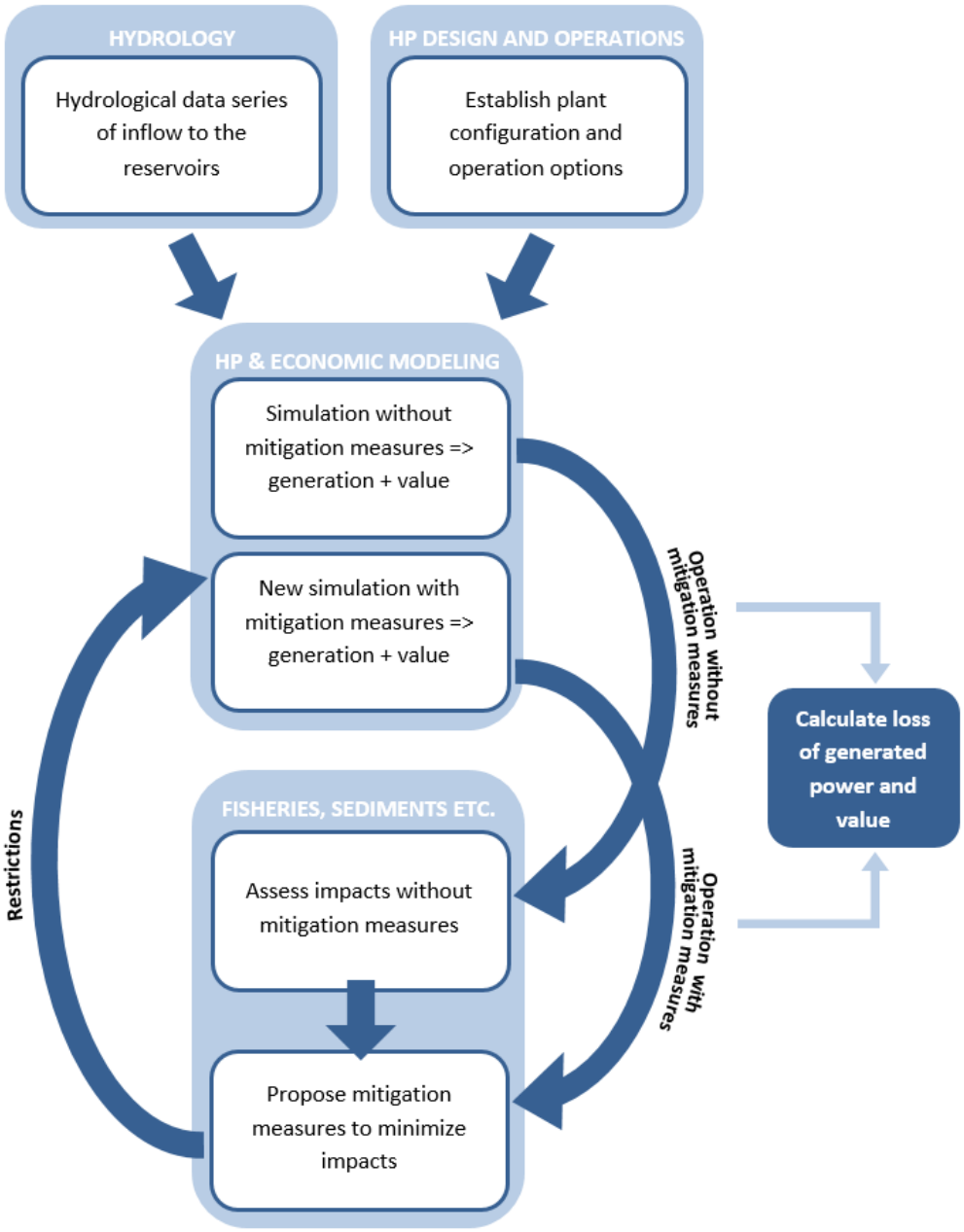


***Figure ES6**. Conceptual framework for the impact mitigation assessment (here portrayed with the HP modelling but which also includes Delft3D on the more detailed sediment and geomorphological modelling.*

For the major risks, a comprehensive set of indicators has been developed and evaluated with regard to the mitigation options and scenario groups. This has been undertaken quantitatively by use of the suite of models, and qualitatively where model use was not feasible. Details of this exercise are attached in Annex F. Section 3 of the Main Report discusses in detail the methods to assess mitigation and economics, including the selected indicators. The results of this assessment are discussed in detail in section 5, and some main conclusions from the 2nd Interim Phase are described overleaf. For the combined assessment of the proposed measures in the scenarios, a multicriteria assessment schema with scoring by indicator was developed (derived from the quantitative and qualitative values). The scoring range was set from +3 to -3 (positive to negative effect of implementing the scenarios with its mitigation options, compared to scenario 1.1.0, without

mitigation). A selected set of the most promising indicators, from the table in Annex F, which gave the greatest varieties in scores, was chosen for the multicriteria assessment. They were as follows:

1. Energy Revenues (USD)
2. Value of Fishery Products (USD)
3. Sediment Transfer (pooled for the various size ranges)
4. Nutrient Transport
5. Catchment Connectivity for Fish (pooled connectivity indices for the basin)
6. Overall Biodiversity Loss (fish and other aquatic organisms)

These were then cumulatively added (summed up) for each of the scenarios, indicating the range of benefits and impacts. The analysis of the most promising scenarios with regard to this is portrayed in Figure ES8, under Summary of Findings and Recommendations.

Final Phase

The Final Phase focussed on assessing the impacts of the mainstream dams downstream of the Northern Lao Cascade and tributary dams throughout the catchment. This assessment aligned with the Council Study, with similar scenarios considered, and the Council Study modelling results were used where applicable. The Team provided input to the Council Study Modelling Team In the development of the hydropower sub-scenarios, which are summarised in the following Table.

Table ES1. Hydropower sub-scenarios assessed during Phase 4 .

No.	Description	Sub-scenario Name	Detailed information
1	Planned Development without LMB Mainstream HPP	H1.a	Planned Development 2040 without any dams in LMB Mainstream, UMB and Tributaries
2		H1.b	Planned Development 2040 with UMB and Tributary Dams
3	Planned Development with LMB Mainstream HPP – No mitigation	H2	Planned Development 2040 with LMB Mainstream, UMB and Tributary Dams without Mitigation Measures for LMB mainstream dams
4	Planned Development with LMB Mainstream HPP – With mitigation	H3	Planned Development 2040 with LMB Mainstream, UMB and Tributary Dams with Mitigation Measures with regard to fish pass, environmental flow and flushing/ sluicing for LMB mainstream dams

The Final Phase of the Case Study assessment goes however much further than analysing outputs of the Council Study solely, as it also covers assessment of additional alternative schemes layouts (both Northern Lao Cascade and Downstream dams) as well as looking into additional solutions for mitigation.

Summary of Findings and Recommendations – 2nd Interim and Final Phase

Some general and theme-specific findings from the Case Study are listed below.

General Findings, Conclusions and Recommendations

Avoidance, Minimisation and Compensation at Basin Scale:

- A very comprehensive analysis using the latest and best available data has been implemented. It builds on data and analyses undertaken in other recent major studies in the Basin (e.g. Basin Development Scenario Assessment (MRC, 2011), Mekong Delta Study (DHI, KDR, 2015) as well as the 2nd Interim Guidelines and Manual Reports (MRC, 2016) by also linking the Case Study to Basin Scale implications).
- The information used in the analysis includes the most recently updated MRC fish and sediment monitoring data (for fish; consumption-based yield data and AMCF sampling data as well as related studies as e.g. Halls, 2010; Halls & Kshatriya, 2009; Hortle & Bamrungrach, 2015 and; for sediments Koehnken, 2015).
- The selected analyses, models, data and related input parameters have been, and are continuing to be discussed with Member Countries as part of this project.
- The impacts and related mitigation approaches for the hydropower cascade must be seen in a basin wide context. The upstream Lancang dams and the tributary dams have substantial impact on the hydrological, biological and sediment inputs to the cascade, as previously discussed. These cannot be mitigated by implementing measures in the cascade alone, but must be dealt with either at the Lancang and tributary dams themselves OR through use of basin scale offset and management approaches.
- Hence, integrated hydropower planning at the system scale (basin, catchment) should be the New Frontier for the LMB countries (see also Oppermann, 2013 and 2017 and Schmitt 2017 for discussion on the benefits of system scale hydropower planning). Loucks (2003) also neatly links this to maximization of benefits by stating – "the interdependence of system components and decisions strongly argues for managing them in an integrated holistic and sustainable manner if maximum benefits are to be obtained from them". For this to be realised the Member Countries will need even more integration than at present within the cooperation continuum and move from cooperation towards even more joint action as portrayed to the right in Figure ES7.

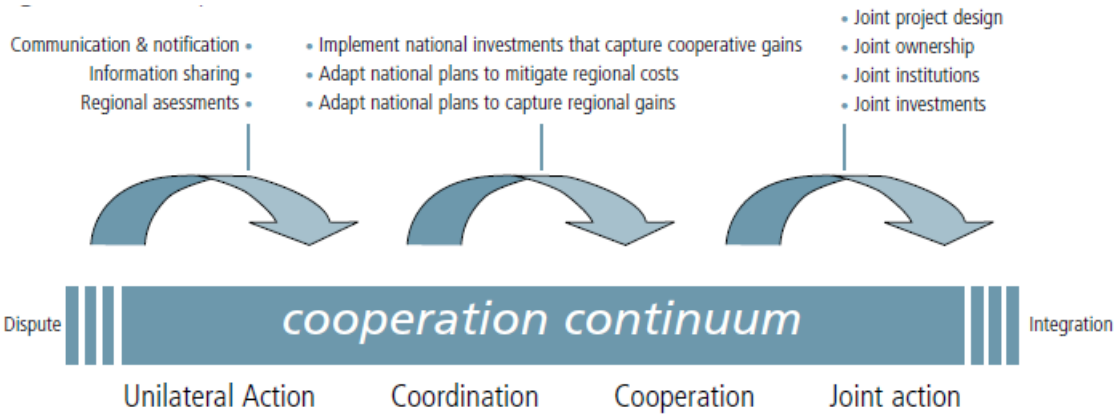


Figure ES7. *A cooperation continuum for transboundary management of water resources as portrayed by Sadoff et al. (2008).*

- Considerations for Joint Action are already vested in the Mekong Agreement (MRC, 1995) and its associated initiatives like the Basin Development Plan (MRC, 2011) and the Preliminary Design Guidance (MRC, 2009). These serve as a good starting point for further Joint Action.
- Joint Action also may include opportunities for joint development and Benefit Sharing as considered by recent MRC initiatives (MRC, 2014 and 2015). The MRC's comprehensive review of good industry practice was undertaken with the MRC Member Countries and provides a supporting framework to guide possible Joint Action. Joint Action represents the greatest level of coordination and cooperation at a Basin Scale and is normally formalized in treaties and strong institutions, where benefit sharing arrangements such as joint ownership and management of assets can form the basis (Sadoff et al., 2008 and Lillehammer et al., 2011). The Lesotho Highlands Water Project (LHWP) with its Treaty (LHWC, 1986) is an example of Joint Transboundary Action (Lesotho and South Africa). The LHWP Treaty explicitly states how benefits from cooperative development will be shared (royalties from water, electricity from HPP, other ancillary benefits etc.). Benefit Sharing can be defined as follows (Lillehammer et al., 2011) – "A framework for governments and project proponents to maximize benefits across stakeholders, through relevant spatial and temporal scales by use of various mechanisms, and consistent with the principles of sustainability".
- Integrated hydropower planning at system/basin scale is envisaged in the MRC's Strategic Plan 2016-2020 (MRC 2016) as part of the overall Integrated Water Resources Management approach. Such an approach, at basin level, will cater for the incorporation of sustainable planning within a spatial and temporal context allowing for the application of the full mitigation hierarchy, from avoidance through minimization, mitigation and compensation/offsets. This approach is particularly relevant where biodiversity offsets are planned. Cumulative impacts from upstream, tributary and instream hydropower projects which alter seasonal and diurnal flow and sediment patterns, will affect defined critical biodiversity hotspots habitats. Integrated system planning may reduce these cumulative impacts at a basin scale (Oppermann et al., 2013, Oppermann et al., Schmitt et al. 2017) making this approach highly relevant for the future hydropower planning of Mekong mainstream and its tributaries.
- When mitigating within the spatial context at basin scale, and in line with the mitigation hierarchy, the status of the LMB ecosystems will benefit from early avoidance mitigation approaches. Examples might include maintenance of intact river routes and alternative dam designs. The latter has actually been studied for Sambor, and is amongst others reported in Wild and Loucks (2015). An illustration of the original proposed Sambor Dam and the smaller alternative is shown in Figure ES8. The latter includes a natural sediment and fish bypass channel.
- In the LMB, at least at the larger full basin scale, the reality is that the level of hydropower development in the tributaries and mainstream (based on existing and under construction projects) already exerts a major impact on the physical and ecological systems in the river, and 'planning' needs to recognise the present trajectory of change in the river. Identifying important 'pathways' for sediment movement or fish migration and focussing mitigation investment (potentially retroactively) in these corridors is another planning instrument that should be considered by the Member Countries.

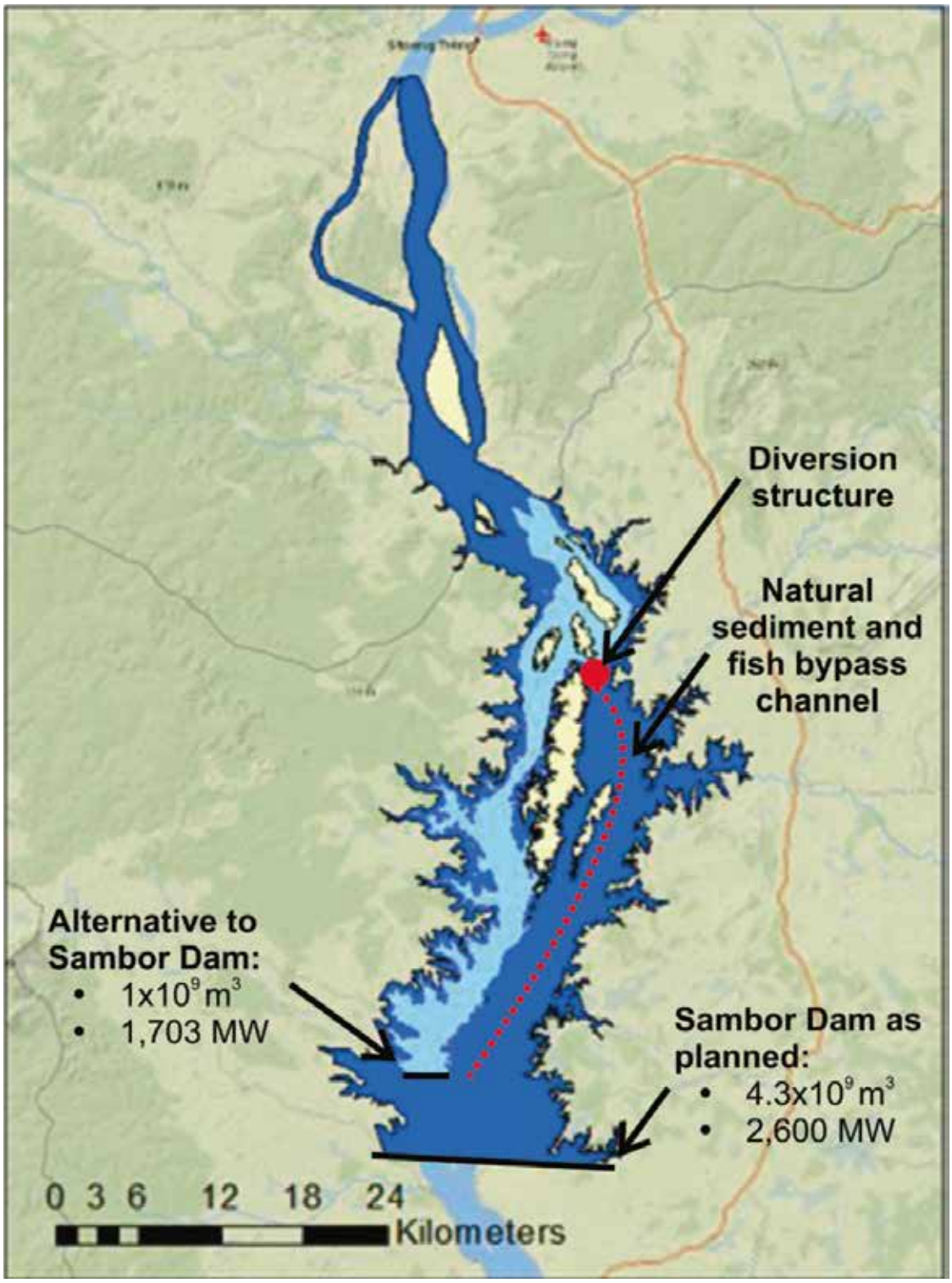


Figure ES8. *Map of the original proposed Sambor Dam and the smaller alternative (Source: Wild and Loucks, 2015).*

Mitigation at Lao Cascade Scale and Downstream Dams:

- The cascade studied in Lao PDR includes major dams and, without mitigation, these will pose significant additional environmental impacts on the basin.
- The mitigation methods documented in the Guidelines (MRC, 2016) have been applied to

seek to mitigate the impacts and risks imposed by the Lao mainstream cascade. These applications generally enhance and "operationalise" the approach taken at the Xayaburi project, which are based on recommendations in the PDG (MRC, 2009).

- The extensive and detailed assessment carried out in this study concludes that:
    - The mitigation options tested reduce the downstream impacts compared to "no mitigation" scenario to varying degrees;
    - The investment in the cost of construction and operation of the mitigation solutions is well justified by the reduced loss in economic value and benefits from reduced environmental impacts in the cascade reach and further downstream;
    - There remain a number of basin scale impacts from the Lao mainstream cascade that cannot be fully mitigated (for example transport of coarser sediments).
    - These same conclusions will also be the same with regard to downstream dams and tributary systems as assessed during Phase 4.
- In addition, as can be expected, with these large-scale and pioneering application of mitigation approaches, there are a number of uncertainties with regard to the effectiveness of some mitigation measures (specifically the upstream and downstream fish passage).
- The application of these mitigation approaches needs to be intensively and jointly monitored by MRC member countries at Xayaburi (currently under construction) to assess the effectiveness of mitigation and to build important knowledge that may be applied in the design and operation of potential future dams in the mainstream and tributaries of the Mekong.
- These findings are based on all projects in the cascade having mitigation infrastructure (fish pass, large low-level sediment sluicing gates) similar to Xayaburi. If this level of infrastructure is not included in future projects, the potential for mitigating impacts decreases.
- In addition, residual impacts and risks arising from this cascade of dams need to be considered at a basin scale (see above section on basin scale findings and recommendations) to understand potential transboundary management and cooperation options to overcome these impacts (including those of benefit sharing discussed above).

Overall, when the environmental mitigation for the Northern Lao cascade is considered jointly, the following findings are relevant:

- Draw down of the Xayaburi operating level during floods was found to be only marginally beneficial in reducing flood level at Luang Prabang, with the models used. Further work is needed to optimise this rule to maintain operational flexibility and to ensure no effect on flood levels at Luang Prabang; (Scenario 1.1B)
- Water level draw down at Pak Beng as proposed by CNR (2009) allows for reduced dry season flooding of areas upstream on the Thailand border area. Again, this operation and the benefits need to be re-assesses. (Scenario 1.1B)
- The analysis found that the drawdown approach at the above two structures reduced revenue from the two schemes (Pak Beng and Xayaburi) by an average of 3.2% per year ($60m).
- The installation of advanced fish passage facilities for upstream and down stream migration was beneficial. However, certain larger migratory species would be significantly affected and potentially be driven to extinction. Even with mitigation a significant loss in

biomass within the cascade reach could be expected. Residual loss of migratory species (biomass and biodiversity) are also expected, even with fish passage mitigation, in reaches downstream (zones 2&3; Scenario 1.1B). Fish passage operations were estimated to reduce annual revenues by approximately 1% per year ($19m).

- The cascade will trap approximately 14 MT of the 20 MT entering the impoundment, with only silt and clay readily transmitted through cascade as part of normal operations. Coordinated sediment flushing of each cascade dam over a period of about 60 days was found to mobilise fine sand from the impoundments and increased sediment discharge by up to ~2 MT/yr. Flushing operations initiated in August produced the highest sediment discharge due to the higher sediment concentrations entering the impoundments and being maintained in suspension during the flushing events. Only minimal quantities of coarse sands and gravels were mobilised by the flushing operations, however, the effectiveness of flushing coarser material will increase as sediment deposition within the impoundment progresses closer to the dam wall and low-level outlets. These flushing operation reduced revenue in the cascade by approximately 2.8% ($51 M/year).
- Within the downstream reaches (zone 2 and zone 3) flushing of sediments was found to benefit the aquatic habitats due to replenishment of sediments (Scenario 1.2.C and D) and the associated nutrients.
- Geomorphological changes both within and downstream of the cascade were shown to occur over longer time frames (decades). A clear “erosion wave”, was observed to move downstream of Sanakham at a rate of approximately 20 km per year, affecting Vientiane after approximately 8 years. The ‘wave’ removes available sediment, resulting in a deepening and / or widening of the channel and an increased exposure of bedrock. The actual rate of channel erosion following implementation of the cascade will depend on the quantity of sediment available for transport in the channel, and the hydrologic variability (e.g., large floods will remove more sediment as compared to dry years). Within the impoundments, sediment deposition created a ‘delta’ that increased in size from the upstream end of the impoundment towards the dam wall over time.
- The introduction of peaking operations, to take advantage of higher daytime tariffs, has significant impact on all indicators downstream and within the cascade. These impacts were found to be mitigated by the introduction of ramping restrictions on all dams (Scenario 1.3.D) or only Sanakham (Scenario 1.3.E) and the introduction of a minimum flow in the cascade reach and downstream. However, the introduction of these ramping restriction and minimum flow almost negated the peaking revenue benefits. (Net across the cascade of $xm per year). Further work is required to optimise and mitigate this operation if peaking operations are to be envisaged.
- In general, scenarios that include a combination of fish passes, minimum flows, provisions of flushing/sluicing and for hydropeaking limitations on ramping rates will benefit the widest array of indicators as shown in the Figure ES9.

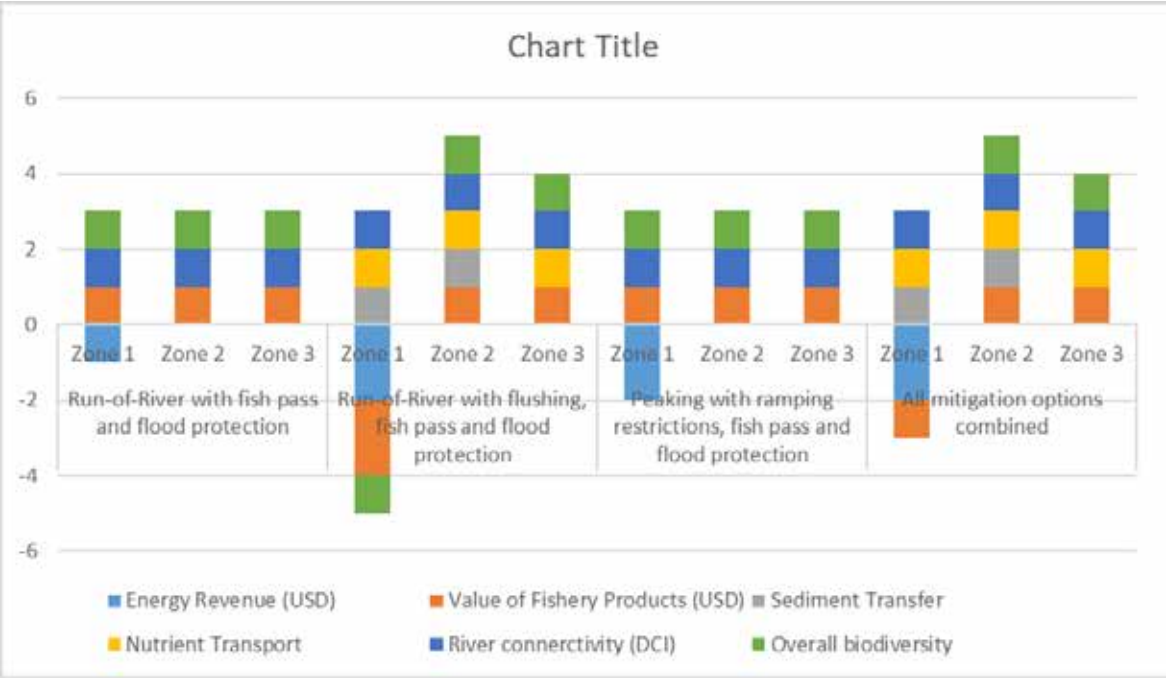


Figure ES9. *Change in Key Selected Indicators relative to the "no mitigation" Option.*

For each indicator in Figure ES8 above the scoring indicate as follows:

+3 = high increase

+2 = medium increase

+1 = low increase

0 = no change

-1 = low decrease

-2 = medium decrease

-3 = high decrease

Most indicators scores in the range of +1 to -1 (low increase to low decrease). The scenarios with the lowest energy revenues (flushing and ramping rate restrictions on all dams) scores -2 for this indicator.

Recommended Management Strategy for the Northern Lao Cascade

Given the results from the combined assessment above the strategies that benefits the widest array of themes, issues and users will be those of all mitigation options combined. Peaking with limitations on ramping rates will need to be studied further in order to optimize environmental benefits and economic impacts. To cater for the revenue loss due to sluicing a central authority for dispatching optimal cascade performance should be considered. Tariff adjustment would need to be negotiated within the Power Purchase Agreement after consideration of the ESIA and prior to the signing of the concession agreement to cover the required operational changes (see also last section in the Executive summary).

When considering the most promising management strategies, optimization of design for the cascade projects should be considered. Allowance should also be made for coordinated operations. This could include, among other options, optimization and flexible designs for pumping stations and auxiliary turbines connected to the fish passages as well as a combination of low and high level sluices, throughout the cascade, for optimal and coordinated flushing and sluicing. Lastly, further optimization for joint operation of the cascade would need to be looked into, and this is also further discussed in the last section of this Executive Summary.

Thematic Findings and Recommendations

1. **Mitigation of Impacts on Hydrology and Flows**

2nd Interim Phase - Northern Lao PDR Cascade

Risks and Impacts

- Changes to seasonal flow are most prominent between the historic conditions and those projected to be experienced in the 2030 timeframe (BDP 2030 scenario, (MRC, 2011)) due to the Lancang cascade and the tributary storage dams. The Lancang and tributary storage dams have higher influence on the seasonal flow distribution than the five cascade dams in Lao PDR. Under undisturbed historic conditions the onset of the wet season used to be earlier in the year, tended to have higher flows, to be a little longer and less variable compared to the BDP 2030 and our reference scenario (1.1.0).
- The sub-daily flow distribution varies greatly between the Lao cascade scenarios with the highest values and greatest variation in the peaking scenario group (1.3.0-E). This is illustrated in Figure ES10 with mean dewatered area for the five reservoirs across all scenarios. Note the huge difference between scenario 1.3.0 (peaking with no mitigation) and 1.3.D (peaking with ramping rate limitations)
- The amplitude of peaking waves from the peak scenarios gradually decreases downstream in impact zones 2 and 3. However, considerable peaking/oscillation occurs down to Vientiane in January and to Kong Chiam in June.

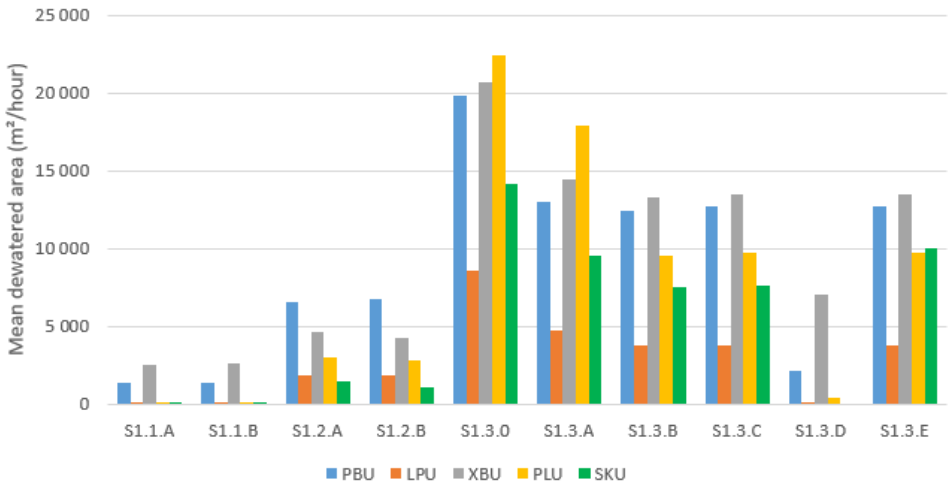


Figure ES10. *Mean dewatered area in m²/hour (for all hours) for all five reservoirs across the various scenarios (also used as an indicator for hydropeaking impacts on fisheries and aquatic ecology).*

Mitigation Effectiveness

- With regard to sub-daily flow changes introduction of mitigation restrictions on ramping rates in the peaking scenarios decreases peaking intensity and mean dewatered area within the cascade (see also Figure ES10 above, scenario 1.3.D).
- Ramping restrictions on all dams (1.3.D) as well as only for Sanakham (1.3.E) reduces the peaking waves downstream of the cascade (zone 2 and 3).

Conclusions and Recommendations

- Due to changes in the basin already occurring and affecting the criteria in the Procedures for Maintenance of Flow on the Mainstream (PMFM), the PMFM should be revisited.
- The short-term (sub-daily) variations in discharge and water levels due to operation of the cascade can be mitigated by imposing feasible limitations on ramping rates and sound criteria for environmental flow.
- The impacts of the Lao cascade, with regard to flow, seems to be minor downstream of Pakse, on the Tonle Sap system, and further down to the Delta. However, this will be subject to investigations in the Final Phase of the Study (2017), where the output of the modelling and assessment will be aligned and connected to the Council Study (and hence DSF) modelling and assessment.

Final Phase LMB and Tributary Dams

Risks and Impacts

- Changes to seasonal flow are most prominent between the historic conditions and those projected to be experienced in the 2030 and 2040 timeframe due to the Lancang cascade and the tributary storage dams.
- The sub-daily flow distribution depends primarily on the variations from operations such as power peaking.

Mitigation Measures

- For the seasonal flow changes a basin wide approach is needed as discussed earlier, including possible coordinated flow releases from storage dams in UMB and the LMB tributaries.
- The sub-daily flow distribution can as for the Northern Lao PDR Cascade be mitigated by imposing ramping rates.

2. **Mitigation of Impacts on Sediments and Geomorphology:**

2nd Interim Phase Northern Lao PDR Cascade

Risks and Impacts

- The largest changes in total sediment loads through the Lao cascade reach, and dowstream of Vientiane, are associated with the changes occurring between the historic and BDP 2030 scenarios with sediment loads decreasing from ~80 MT/year to 20 MT/ yr. Implementation of the Lao cascade without mitigation leads to an additional ~14 MT/

year reduction in gravel and sand loads at the Sanakham damsite. This will lead to an 'erosional wave' progressing downstream of the final dam site with erosion of sand bars, bank erosion, channel incision and eventual armouring of the channel. Sandy deposits overlying bedrock controlled river reaches will be ultimately lost. In the short to medium time frame, the erosion of sediment from the river channel downstream of Sanakham will maintain sand transport downstream of Paksane at levels similar to the BDP2030 model runs as the 'wave' progresses downstream at approximately 20 km per year.

- The cascade will also promote a considerable shift in the grain size distribution of the suspended load downstream of the cascade from being predominantly sand to predominantly silt and clay. This is due to trapping of the coarser sediments in the reservoirs (scenario group 1.1 towards BDP 2030).
- Reservoirs sedimentation will occur and eventually fill deep pools in inundated reaches. Downstream of Sanakham pools might deepen due to the long-term reduction in sediment loads. Rapids within the cascade reach will be inundated and disappear, while downstream of the final dam they might increase as sediments are removed from the channel due to erosion. In the short-term rapids downstream of Paksane are unlikely to be affected due to continued sediment supply associated with erosion in the upstream channel.

Mitigation Effectiveness

- Sediment flushing mobilised up to 2 MT per year of sediment, which is small compared to the 'natural' or 'pre-cascade' sediment load, but considerable compared to the post-cascade sediment load (e.g. 6 MTper year). The sediment loads able to be mobilised via flushing are expected to increase over the longer term as more sediment is trapped within the reservoirs and sediment deposits progress towards the dam wall.
- Many factors affect the efficacy of flushing: The sediment and water inflow rates at the time of flushing, the rate of water level draw down, the level of the sediment flushing gates and rate of reservoir refilling all affect the outcome. In general, the higher the water and sediment loads entering the impoundment at the initiation of flushing, the more successful the results, the faster the water level decrease and slower the reservoir filling the more successful the 'flush'.
- Under a hydropeaking regime, the ramping rates identified as suitable for reducing risks to the aquatic ecology will also reduce geomorphic risks associated with increased erosion due to rapid and frequent water level changes.

Conclusions and Recommendations

- The volume of sediment mobilised during flushing, although small, is considered to provide a positive benefit in the river reach downstream of the final dam, and the benefit could be maximised by managing the timing of flushing events to coincide with periods when there is a greater likelihood that sediment will deposit in the channel.
- It is recommended to apply coordinated flushing of the cascade, involving the timing of water level decrease in successive reservoirs. This promotes movement of a sediment 'plug' through multiple impoundments, and is likely to improve the overall success rate as compared to the flushing of individual impoundments (see also hydropower section and comments on joint operation at the end of the Executive Summary).
- Adaptive management should be introduced with respect to flushing, and the downstream ecosystem condition. The maintenance of a fine-sand supply to the downstream river should be of high priority.

- Longer model runs of 16-years demonstrated the progression of sediment deposition along the reservoir, and suggest that flushing has the potential to mobilise larger sediment loads in the future.

Final Phase LMB and Tributary Dams

Risks and Impacts

- Sediment trapping in the mainstream and tributary dams have the potential to reduce sediment delivery to the Mekong delta by 97% based on the modelling completed for the Council Study. This level of sediment reduction will have substantial geomorphic impacts on the river, including channel erosion, channel incision, and the distribution and quality of aquatic ecosystems. The reduction in sediment supply to the delta will promote erosion of the delta front and alter channel morphology and hydraulics.
- The dams will preferentially trap coarser sediment and bedload, leading to the sediment load in the river having a reduced grain size distribution;
- Because of the high trapping rates in the tributary dams, the delivery of sediment to the mainstream Mekong will be greatly reduced, and decades will pass before substantial volumes of sediment are available for flushing from the mainstream dams.

Mitigation Effectiveness

- The complexities of the river and differences among the suite of models used to evaluate hydropower mitigation in the Council Study modelling prevented the inclusion of all recommended actions in the hydropower 'mitigation' scenario. The modified sediment flushing regime that was implemented demonstrated that flushing has the potential to increase sediment transport in the river, however the lack of deposition of sediment in mainstream dams due to trapping in the tributaries precluded this approach increasing sediment loads in the short-term;
- A substantial increase in sediment delivery was realised associated with the smaller design of the Sambor hydropower project in Cambodia, with sediment loads discharged from the dam increasing by over 3-fold. Because Sambor is the most downstream impoundment, increasing sediment discharge has benefits for the lower river, the delta and the Tonle Sap system.

Conclusions and Recommendations

- The level of impact on sediment transport and geomorphology under the 2040 development scenario will be extreme and significantly alter the nature of the river (consistent with the findings of BioRa).
- Mitigation approaches need to include the tributary dams as well as the mainstream dams if the impacts from the full-development scenario are to be reduced.
- The present level of development in the catchment (existing and under construction projects) will also exert a substantial impact on sediment transport and geomorphology, and it is recommended that significant sediment pathways be identified and prioritised for 'mitigation'. Mitigation may include; (1) altering, moving or removing tributary and mainstream hydropower projects such that sediment connectivity is retained and optimised in the catchment; (2) requiring a minimum standard of mitigation infrastructure in projects that could provide a substantial increase in sediment delivery to the mainstream (such as the Nam Ou); (3) implementing joint operations of hydropower projects such that activities such as sediment flushing can be coordinated to provide maximum benefit and minimum impacts.

Mitigations of Impacts on Water Quality:

2nd Interim Phase Northern Lao PDR Cascade

Risks and Impacts

- There will be an increased risk of algal blooms in the cascade due to longer residence times, increased water clarity and the associated warming of the water in the reservoirs. A risk analysis undertaken as part of the assessment found that there is a high risk of algal blooms occurring under all scenarios.
- Water quality changes occurring within the cascade will also impact the river system downstream of the final dam, with impacts generally proportional to the distance from the discharge point and the number and volume of tributary inflows entering downstream.
- There is a risk of elevated concentrations of sediments associated with flushing. In the short term, these concentrations are projected to be within the range of historical suspended sediment concentrations, but may increase in the long term depending on the rate of accumulation of sediments with the impoundments and the frequency of flushing.
- There is projected to be a low risk of widespread reservoir stratification due to the high inflows and short residence time of water within each impoundment. There is a moderate risk of localised stratification near HPs with low-level inlets, and at tributary junctions.

Mitigation Effectiveness

- No specific mitigation measures were modelled during the Case Study.

Conclusions and Recommendations

- Mitigation measures that can reduce water quality risks associated with increased sediment concentrations during flushing operations include: completing flushing operations during periods of moderate tributary inflow (other lower sediment and nutrient sources entering the river), and informing downstream water users about the timing of any flushing events such that water intakes can be managed accordingly.
- The best strategy to mitigate water quality risks include adaptive management and catchment management, as water quality issues are related to catchment inflows as well as the management and characteristics of the impoundments.

Final Phase Lower Mekong dams

- Water quality modelling in the Council Study was limited to nutrient transport, and based on the assumption that 50% of the total N and 40% of the total P was associated with sediments, and would be removed proportionately to sediment trapping;
- The same water quality risks pertain to the lower Mekong dams as the Northern Laos cascade with the large reduction in sediment loads in the river will increase light penetration likely leading to increased water temperatures and an increased risk of algal blooms throughout the lower basin.
- The same conclusions and recommendations apply to the lower Mekong basin as identified for the Northern Lao PDR cascade.

Mitigations of Impacts on Fisheries and Aquatic Ecology- 2nd Interim and Final Phase:

Risks and Impacts

- There is already a large decrease in connectivity from historic to BDP 2030 conditions. The Lao cascade without mitigation (reference scenario 1.1.0) will additionally reduce this connectivity (affecting migration of fish amongst others) with its five dams on the mainstream.
- There is also a loss in fish biomass from historic to BDP 2030 conditions. The Lao cascade as described above will also superimpose additional reduction in biomass in all impact zones (1-3).

Mitigation Effectiveness

- The modelling results indicate, that the mitigation of habitat fragmentation (i.e. the construction of fish pass facilities) has a clear positive effect within the cascade and downstream. This is illustrated in Table ES2 below.
- However, the degree to which negative impacts can be mitigated depends to a high degree on the functionality of the fish pass in both directions, as well as additional factors (as e.g. the continuation of passive drift of larvae in the impoundment or losses related to turbine/ spillway passage).

Table ES2. Scenarios with (fish pass = yes; assuming a passage efficiency of 100%) and without fish pass (fish pass = no) with their respective connectivity indices[18].

Scenarios	Fish pass	$DCI_{Strahler}$	DCI_{Migr}
1.1.0, 1.1.A, 1.2.A, 1.2.B, 1.3.0, 1.3.A, 1.3.B	no	28	74
1.1.B, 1.2.C, 1.2.D, 1.3.C, 1.3.D, 1.3.E	yes	37	81

- Similarly, restrictions on the ramping rate (scenarios 1.3.D and E) when peaking is undertaken will be beneficial for the aquatic ecosystem and fisheries.
- Flushing events (scenario group 1.2) will greatly affect aquatic habitats in the cascade (zone 1) but be beneficial for aquatic habitats in impact zones 2 and 3 in the long run.
- With regard to fish biomass, the most distinct differences among the scenarios can be detected in impact zones 1 and 2, while the effects in zone 3 are less pronounced. For zone 1 especially scenarios 1.1.B and 1.3.D show considerable higher values compared to the other scenarios. For zone 2 scenarios 1.1.B, 1.2.A to D as well as 1.3.D and E are beneficial, as this zone will benefit from the flushing events and the ramping restriction downstream of the cascade.

Conclusions and Recommendations

- Assuming that the fish pass is functional for most species and age classes (which can only be shown by long-term monitoring), most species and life stages will benefit and the extinction of small migratory species can be mitigated within the cascade.

18 See chapter 3.6.1 for an explanation of these indices.

- Nevertheless, migratory species might still drastically decline in the long run due to the potential high losses caused by turbine mortalities and interrupted larval drift in the reservoirs. Turbine mortality could be reduced by the implementation of finer screens, which would benefit larger/long-lived species. Interruption of larval drift cannot easily be mitigated with the present hydropower design and would require the alteration of the hydropower scheme to facilitate smaller reservoirs and improved flow conditions in the impoundment. Further studies on mitigation possibilities are recommended (see also the Sambor alternative discussed earlier and portrayed in ES7).
- Flushing can be carried out in a way that fish are not significantly affected in the long run in the downstream zones (2 & 3). However, flushing is always associated with impacts on the fish community within the reservoirs. Furthermore, as mentioned above, suspended concentrations during flushing may increase in the long term (depending on the rate of accumulation of sediments and the frequency of flushing) and may therefore put additional pressure on the aquatic ecosystem downstream. Therefore, detailed monitoring of suspended concentrations and the related negative effects on fish and other aquatic organisms is recommended.

According to the Council Study and this project, the greatest impacts on fish are related to;

- fragmentation of up- and downstream migration routes,
- sedimentation in impoundments and related morphological alterations downstream,
- change of flow characteristics to hybrid water bodies in impoundments.

Even though the tested mitigation measures can bring some local improvements, they might not be able to sufficiently improve the conditions for the aquatic ecosystem.

This, once more, highlights the importance of avoidance as one important part of the mitigation hierarchy. Despite the fact that many tributary dams were already developed or are currently under construction, additional impacts for migratory species should be avoided by considering the following recommendations:

- Identification of important un-fragmented migration routes within the LMB.
- Critical review of planned hydropower plants within this range (ideally also under consideration of other aspects, as e.g. key habitats, sediment pathways, hydrology etc.).
- Assessment of expected impacts and their mitigation potential.
- Waiver of hydropower plants in sensitive locations (i.e. downstream of existing dams and within important migration routes), with high expected impacts and low mitigation potential.
- Investigation of impacts caused by existing tributary dams; prioritisation based on their relative impact (e.g. with regard to fragmentation) and the possibility to implement mitigation measures subsequently (e.g. implementation of fish passes). This is also recommended for irrigation dams.

Hydropower Operation and Economic Cost of Mitigation Options – 2nd Interim Phase and Final Phase

- Flood draw down at Xayaburi and lower dry season levels at Pak Beng represents a reduction in cascade revenue of 3.2%.
- Introduction of sediment sluicing and flushing (scenario group 1.2) gives an additional loss

of 2.8% bringing the overall revenue loss to approximately 6%. This is substantial and might need to be offset by an upward tariff adjustment, when the PPA's are negotiated.

- Reservoir draw down (for floods or flushing) is the type of mitigation measure that causes the largest losses of power generation and revenue.
- The provision of a fish passage system on each project with similar design as Xayaburi introduces an additional revenue loss of approximately 1%. It is however possible that this figure can be reduced by optimisation of pumping stations and auxiliary turbines.
- If we compare Scenarios 1.1.B and 1.3.E, i.e. comparing mitigated Run-of-River with mitigated Peaking, we see that peaking still reduces the overall generation by 1%, while peaking increases the revenue by only 1%. In scenario 1.3.E, a number of mitigation measures have been implemented, but ramping rates only at Sanakham. The evaluation is that such a scenario is relative harsh on the Cascade reach, although re-regulated further downstream by Sanakham. In the light of this, one can question whether a (only) 1% increase of the revenue justifies the environmental - and to some degree social - stress by peaking.
- A challenge with respect to both management and financial viability is the scenario group 1.2 with flushing and sluicing. It is recommended to establish a central authority for dispatching optimal cascade performance and according to which the developers are paid for available capacity and not for energy.
- Further optimization on joint operation of the cascade (rule curves, routing of water through the reservoirs, coordinated flushing) might increase revenues giving also more room for implementing sound mitigation options. Benefits from such joint operation, through optimization of operation rules, was in fact modelled and reported by Marchand et al. (2014) in 4 tributary cascades of Red River, Vietnam.

Alternative Schemes Layouts

- The comparison between a typical full height mainstream project and the equivalent two half height schemes indicates that the combined construction cost of the two half height schemes will be approximately 15% greater. Conversely, the project finance cost for the two half height schemes is lower because energy and revenue is available approximately four years earlier. The overall implication is that the cost of energy from the half height schemes is approximately the same, and possibly lower, than the single full height scheme. This conclusion is based on river discharges, foundation conditions and cross sections being typical of the Low Cascade reach of the Mekong.
- The impact on energy output has been examined in Section 6.2.5 of this report by considering sub division of the Pak Lay and Samakham projects. The average energy of the sub-divided projects is approximately 7% lower than the full height alternative. The reduction is mostly attributable to the increased impact of raised tailwater levels.
- A three month wet season shut down results in an energy reduction of approximately 30%. This energy reduction is not a product of sub diving the projects, it is a result of shut down. This loss would need to be assessed against the advantage of mainstream hydropower development on the Mekong that has the potential to preserve the ecology of one of the world's most important rivers.

1. Introduction

1. Introduction

1.1 Overview

This Final Phase Report is a standalone document that draws on the technical recommendations included in the Mitigation Guidelines and the related Manual. It summarizes the impact mitigation assessment of the 2nd Interim Phase scenarios for the Case Study of the Lao Mainstream Cascade, planned and under construction north of Vientiane as well as the Final Phase scenarios for all the mainstream dams, derived from the Hydropower sub-scenarios under the Council Study. During the Final Phase alternative schemes layouts for the Lao Cascade and as well as Sambor have also been assessed. The Final Phase follows due after the three previous phases, e.g. Inception, 1st and 2nd Interim Phases.

1.2 Specific Objective of the Case Study

The specific objective of the Case Study has been to "*test selected mitigation options for effectiveness, sustainability and at the same time maximizing the operational flexibility*", for the Lao PDR mainstream HPP cascade upstream Vientiane[15] as well as the dams further downstream. This has been undertaken through rigorous modelling and associated impact mitigation assessment (outlined in Chapters 4, 5 and 6), the latter based on a chosen set of indicators (described in Chapter 3.1.1), under various scenarios as described in Chapter 2.5 and 2.6. The mitigation options and measures studied and proposed under the various scenarios emphasize on changes to hydrology and the alternation to flows, fisheries and aquatic ecology (migrations, diversity, productivity and its links to livelihood), sediments and geomorphology as well as water quality.

1.3 Specific Case Study Activities, Outputs and Deliverables

1.3.1 2nd Interim Phase

Output 5a: Case Study: Mainstream Upper Cascade Operation and Cumulative Impact Mitigation Options.

The Output had four components:

1. Create hydropower operational model of the potential mainstream cascade options including:

    a. Inflows from upstream (Lancang) and estimates of the China dam's operational characteristics;

    b. Inflows from tributaries including the changes to seasonal outflows from tributary hydropower operations;

    c. Assumptions of mainstream power station operation and spillway operation;

    d. Sediment flushing operations;

    e. Alternative fish passage flow requirements;

15 Pak Beng, Luang Prabang, Xayaburi, Pak Lay and Sanakham.

f. Ability to cover a range of scenarios of development – i.e. include or exclude hydropower developments as required.

2. Using appropriate hydrodynamic models, model of sediment trapping efficiency of representative mainstream dams and flushing operations including:

   a. Acquisition of required river cross sections, sediment flux/grading information and any other required data;

   b. Modelling at appropriate scale and dimensionality (2D, 3D);

   c. Trialling of a limited number of flushing options to test their effectiveness;

   d. Make recommendations on the possible duration and timing of flushing and operation coordination requirements; and

   e. Provide understanding of the need for joint flushing of dams.

3. Combine the analysis of the above models to make an assessment of the effectiveness of alternative mitigation techniques and development scenarios including:

   a. Assess the economics of a limited number of the most promising sediment management and fisheries impact mitigation options (e.g. energy loss);

   b. For the most promising mitigation option, provide an assessment of the effectiveness of management/mitigation on cumulative sediment trapping in the cascade under the 2040 development scenario[16]; and

   c. Provide a qualitative assessment of resulting sediment flux in the basin under the range of development scenarios and the effectiveness of mitigation options.

4. Document findings in a Case Study Report Version 1.0 and consult at national and regional levels.

16 BDP 2030 from BDP2 has been used as the Case Study reference case.

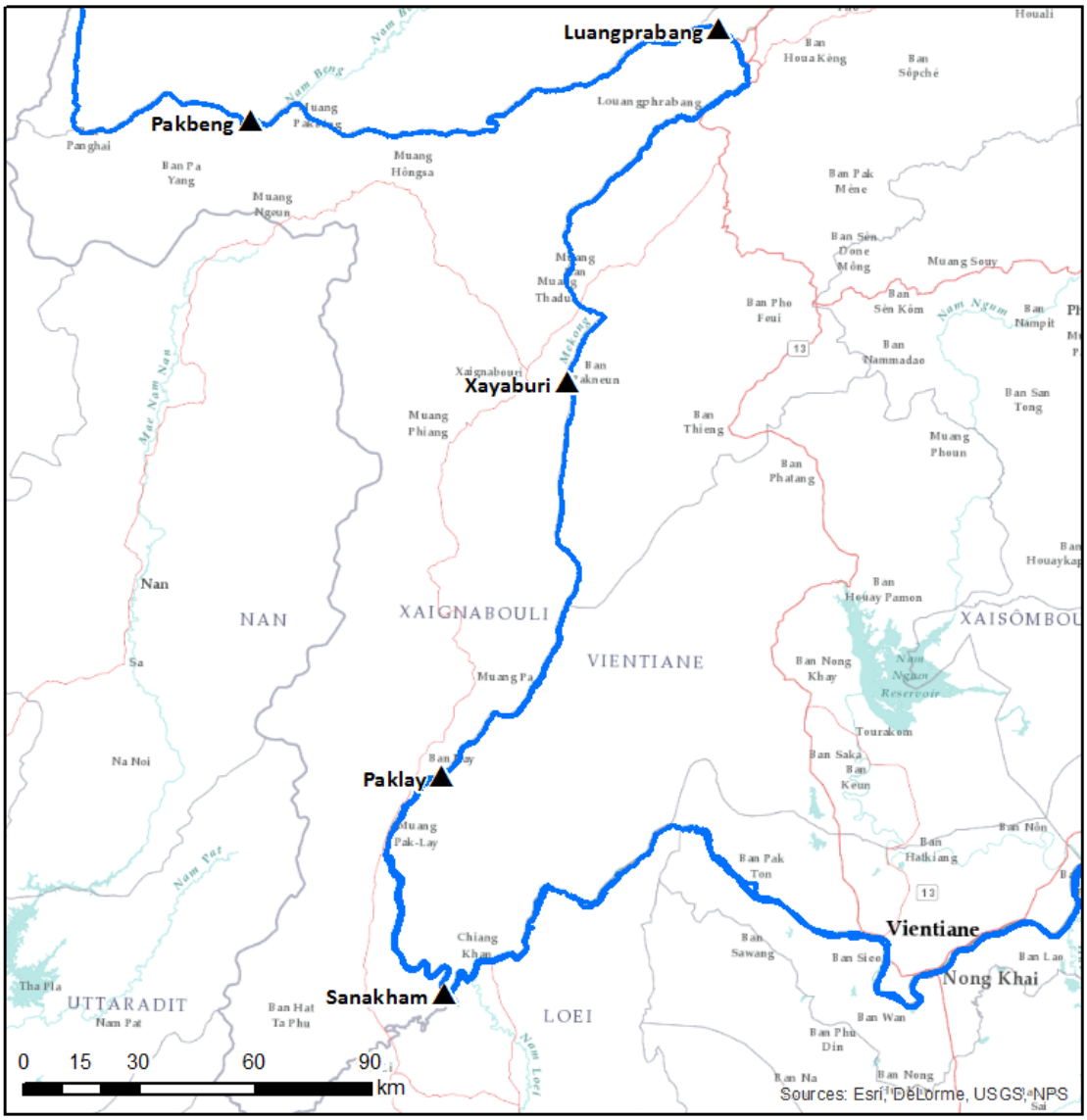


Figure 1.1. *Overview of the mainstream hydropower cascade, upstream Vientiane, with its reservoirs.*

1.3.2 Final Phase

Output 6a: Alternative Hydropower Scheme Layouts – inputs to the MRC Council Study hydropower sub-scenarios.

One mainstream project proposal (Thakko) has a design layout that proposes an off-river diversion with substantially reduced impact on fish passage, sediment trapping etc., but also with significantly reduced power capacity and generation. Several of the mitigation options and techniques highlighted above may assume alternative hydro scheme layouts.

1. This output should explore at a conceptual level, alternative mainstream hydropower scheme layout options that may be considered for mainstream dams that will substantially improve their sustainability.

a. Laos cascade: based on the case study, consider if design or operational changes to the structures, as currently proposed, require alteration and the benefits of these changes to mitigating impacts. (e.g. more low level gates, different fish passage options) (Scenario 1.4), (Scenario 3,4 and 5 comparisons to Scenario 1.2 as before)

b. Laos Cascade: effects of partial development of the cascade (2 or 3 dams only) and issues associated with the likely phased development of the 5 dams (e.g. Xayaburi followed by Pak Beng followed by Pak Lay etc) (Scenario 2)

c. Downstream dams (Latsua/Phoun Noi, Don Sahong, Stung Treng, Sambor): the analysis in the Delta Study and the BDP Scenarios shows the significant impacts from the lower mainstream Dams. Alternative layout and design options should be investigated given upstream understandings. (e.g. by-pass channel at Sambor based on the work of NHI).

2. These redesign proposals should contain conceptual layout general arrangement drawings and initial commentary on potential changes to energy production and costs.
3. The effectiveness and importance of these options should be assessed against the criticality of environmental and social risks and vulnerabilities and their economic feasibility.

Output 6b: Review of Case Study Analysis with additional Scenarios including layout options

1. The further analysis should be of sufficient accuracy to provide guidance on the practicality, environmental benefits and economics of these options.
2. Provide commentary on flood management (within the upper cascade), dam safety considerations, emergency response etc. of these mainstream dams (Laos Cascade).
3. The above analysis should be included in a revised/enhanced the Case Study Report (Version 2) to include the additional findings from this additional analysis.
4. These design modification options should be in a form (design and operational rules) that can be input to the DSF models for the Council study assessment.

Output 6c: Inclusion of assessment of mitigation operations in the MRC Council Study to assess the mitigation below Pakse

1. Liaison with MRC Council Study modelling team on the results of the Upper Laos cascade assessment (and redesign and operational rules for lower mainstream dams) in the above steps including:

   a. Modelling and assessment techniques used (August 2016)

   b. Reconciliation of all input and output parameters with the view to gaining similar representations of key processes in the CS modelling;

   c. Advice to the MRC Modelling Team on operating rules with and without mitigation for input to the DSF models. (H2 and H3).

Review of the CS modelling outputs to make an assessment of the impacts of mitigation in the upper Laos cascade and potential project design/operation modification in the Zones downstream of Pakse.

Figure 1.2. *Mainstream dams downstream of the Lao cascade.*

2. Case Study

2. Case Study

2.1 The Context of the Study Base Case

This study aims at understanding the effectiveness of the mitigation options, in order to reduce risks and impacts associated with the construction and operation of the Lao Cascade (2nd Interim Phase) plus all mainstream dams (Final Phase), mentioned in the previous section. When undertaking this assessment, it is important to understand the basin-wide context in which these dams are considered.

The map below shows the catchment area of Lancang/UMB and the dams under consideration. To date eight hydropower dams have been constructed in China on the UMB mainstream. These are major dams with substantial storage, which are already causing significant changes to the season pattern of inflows into the Northern Lao Cascade and further downstream. In addition, the sediment loads, measured at the upper end of the Northern Lao Cascade, have been substantially reduced (see Section 3.4.2), as well as further downstream. In addition, a number of the major Lao PDR tributaries flowing into the cascade have hydropower developments constructed, or under construction, and further schemes are planned on these rivers in the coming 15 years.

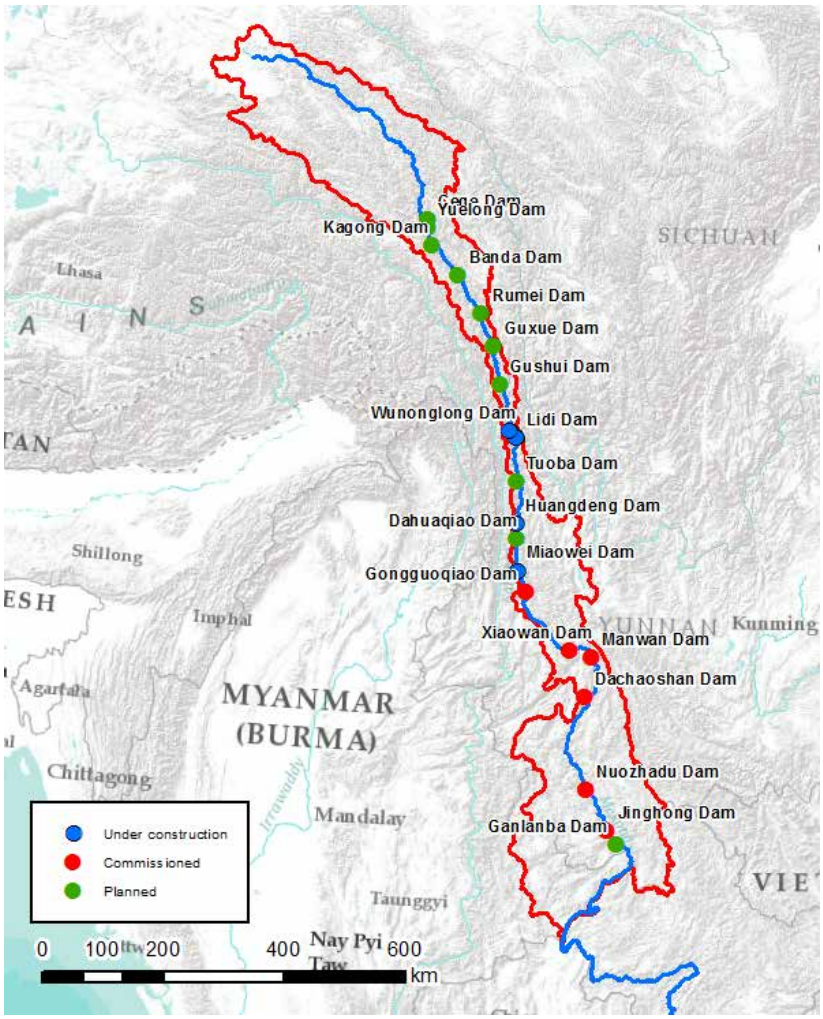


Figure 2.1. *Commissioned, under construction and planned mainstream dams along the Lancang River in the UMB.*

2.1.1 The Historic Conditions and Basin Scale Management

The hydrology, geomorphology, biodiversity and aquatic ecology of the Mekong has been formed through thousands of years of natural processes. The historical seasonal and intra-seasonal hydrological variations across the topography of the Mekong basin have allowed the development of the highly productive natural resource on which the populations of the Mekong basin rely on for water, food and now, more recently, energy.

For this project, we needed to understand the historical pattern and scale of the natural hydrological, geomorphological and aquatic ecological parameters across the whole Mekong system. The basin is changing rapidly because of human development pressure across the region for irrigation, urbanisation and hydropower development. In addition, the effects of climate change are exacerbating the impact of these pressures. These multiple pressures on the basin may lead to that the ecosystem status will founder in unanticipated ways with unforeseen cascading and cumulative effects. This has been observed for other similar and large basin ecosystems with multiple pressures, for example the Lake Victoria Basin in East Africa (Lillehammer et al., 2010) [15].

Therefore, as we seek to measure the effectiveness of the mitigation options for the dams in question, we need to understand that natural processes of the Mekong are currently in a state of relatively rapid change as to the river adjusts to the above pressures. The change from the historical state will be long term, continuous and dynamic. In many cases, these changes will be fundamental and irreversible. The effects will be cumulative in nature. Therefore, while we try to understand the impact of one dam or a cascade of dams, and seek to mitigate that impact, the changes in the overall basin must be managed through basin scale mitigation techniques, joint action and transboundary cooperation as well as where possible, joint operation.

In this study, we draw attention to the historical, current and planned context for these natural systems so that the reader can understand the relative scale of changes that are happening in the basin as a result of all of the above developments.

2.1.2 The BDP 2030 Scenario and Council Study 2040 Scenario

The development of the dams in the cascade under consideration are planned to occur in the next 15 to 20 years. The exact timing of these developments is uncertain. The Council study 2040 scenario modelling results, with the associated hydropower development, were not available in time for the 2nd Interim Phase. The BDP2030 scenario (MRC, 2011) however, contains most of the Lancang and tributary dams relevant to the assessment of this mainstream cascade. In addition, these dams have been modelled using the MRC's DSF and therefore the resulting hydrological inflows post development are able to be meaningfully used as inputs for this study. For the Final Phase the 2040 Council Study scenarios have been used, when found applicable.

15 Lillehammer L., Kleven T., Hagen T. Bain M. and D. Lewis. 2010. Developing Sustainability Priorities with a Participatory Process: Lake Victoria Basin, East Africa. In Beheim E., Rajwar G.S., Haigh M.J. and Krecek J. 2010. Integrated Watershed Management: Perspectives and Problems. Springer Verlag. pp 55-66.

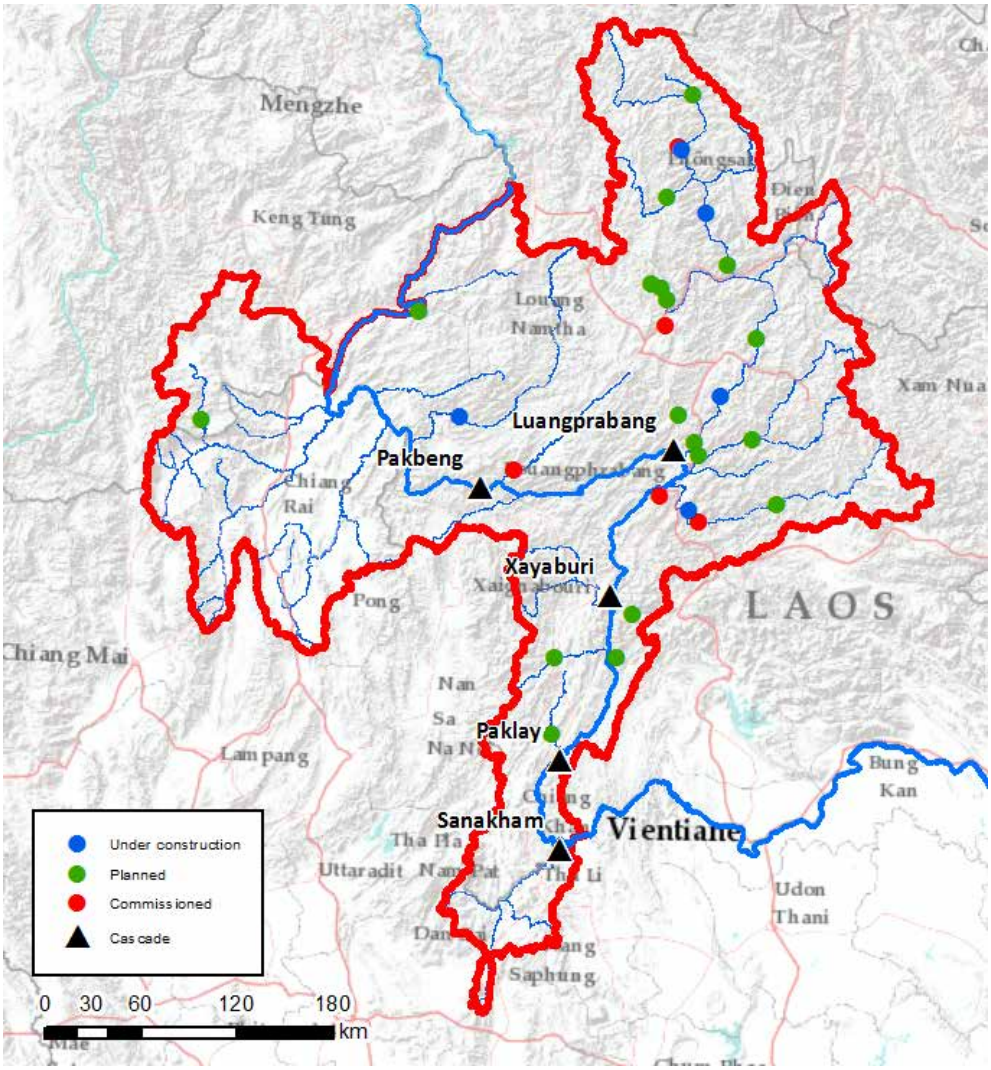


Figure 2.2. *LMB catchment upstream of Sanakham including the Lao mainstream cascade as well as tributary dams commissioned, under construction and planned for the BDP 2030 scenario.*

2.1.3 Development of the Base Case for Assessment of Mitigation Effectiveness

2.1.3.1 The Lao Cascade

The impacts of the development and operation of the Lao Cascade and consideration of ***the effectiveness of the proposed mitigation must be seen in the context of these large Mekong Basin scale changes*** (as illustrated in Figure 2.1 and 2.2 and also discussed in chapter 2.1.1). While the study focuses on illustrating the effectiveness of mitigation of the impacts of the Lao Cascade and the mainstream dams further down, the cumulative impacts from all developments will be substantial and will need careful management at basin scale level.

The Lao cascade impact relative to tributary and UMB development has actually been investigated with regard to aquatic ecology and fisheries as well as sediments in the Case Study (covered in chapters 3 and 5 of the main report). Below in Figure 2.3 and 2.4 is an illustration of one of the relative impact of the Lao cascade with regard to sediment loads and fisheries biomass. Note the less dramatic impact from historic to BDP2030 conditions for fish biomass compared to sediment

loads, due to “unimpacted” tributary fisheries in this case. Mitigation within the cascade reduces the impacts, but the basin scale impacts will still dominate especially with regard to sediment loads.

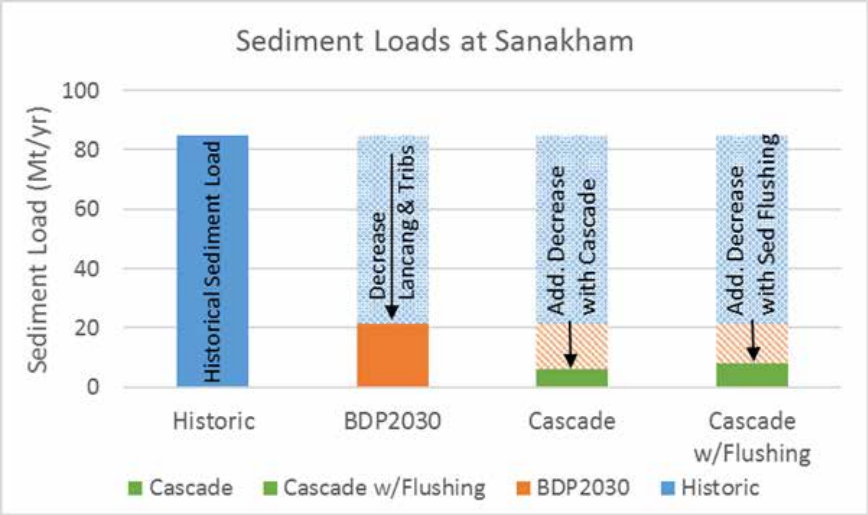


Figure 2.3. *Sediment loads at Sanakham for historic, BDP2030, and Lao cascade conditions (with and without mitigation).*

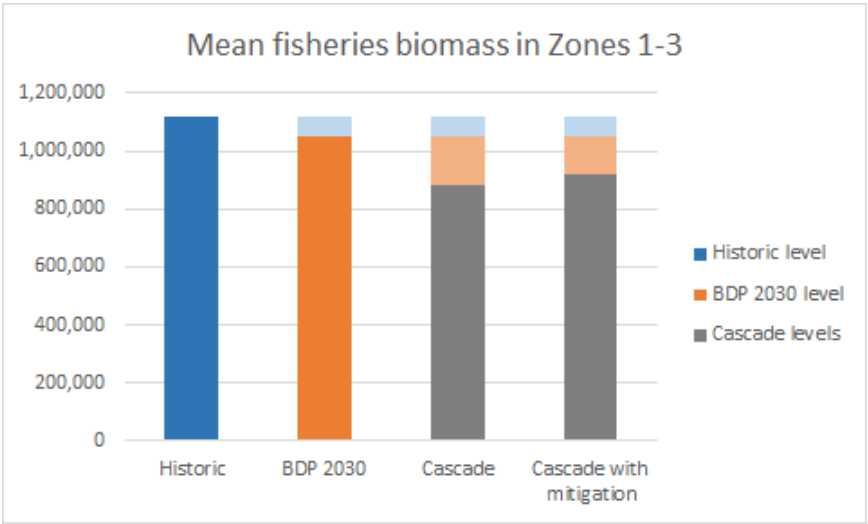


Figure 2.4. *Mean fisheries biomass on the area of investigation (Zone 1-3 combined) for historic, BDP2030 and cascade (with and without mitigation) conditions.*

2.1.3.2 LMB Mainstream Dams and Tributary Development in the CS 2040 Scenario

The basin scale impacts becomes even more evident when assessing the impact of all mainstream dams and tributary development under the CS 2040 scenario. Distribution of sediment loss, and cumulative sediment trapping, for the LMB mainstream dams is given in Figure 2.5, whilst those of the tributary dams are given in Figure 2.6.

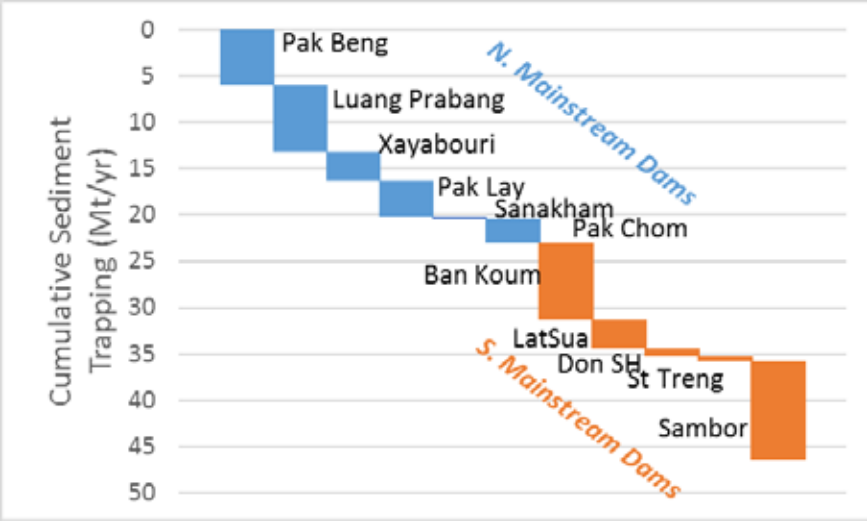


Figure 2.5. *Distribution of sediment loss, and cumulative sediment trapping for the LMB mainstream dams in the CS 2040 scenario.*

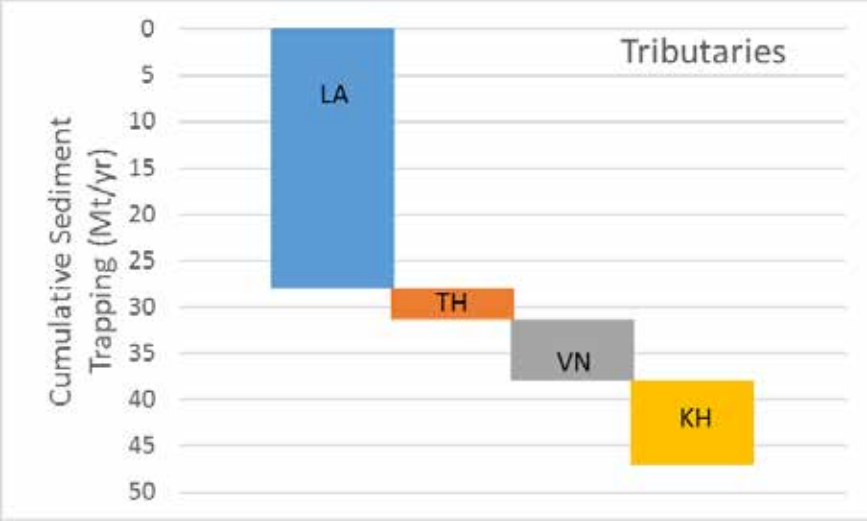


Figure 2.6. *Distribution of sediment loss, and cumulative sediment trapping for the LMB tributary dams in the CS 2040 scenario.*

Similar volumes (~47 Mt/yr) of sediments are trapped in the LMB mainstream and tributary storages. If UMB dams are added to this (see previous section) 157 of 160 MT/yr of sediment will be trapped. This is dramatic, and cater for basin scale mitigation approaches, including also for the tributary dams, and over 50% of tributary sediment capture occurs in Lao PDR.

Basin scale impacts is also illustrated for connectivity with regard to migratory fish species (DCI_{migr}) in Figure 2.7 for two different levels of passability through the mainstream dams (0% passability and 50% passability, with the latter introducing fish passage as a mitigation measure). The graph highlights the clear impact of the mainstream dams and the importance of mitigation measures such as fish pass facilities or enhanced passage routes via side channels (e.g. for Don Sahong). However, there is still a high uncertainty in the functionality or efficiency of such fish pass facilities (e.g. with regard to biomass, species diversity etc.).

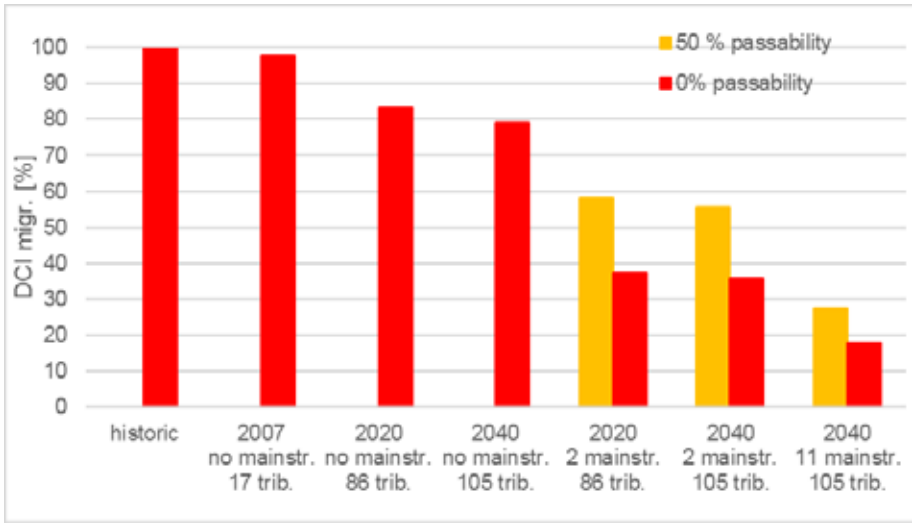


Figure 2.7. *Impact on existing and planned projects on the DCI_{migr} under consideration of different passabilities for the mainstream dams (i.e. Xayaburi and Don Sahong in scenarios with 2 mainstream dams)*

2.2 Description of the Mainstream Dams

2.2.1 The Lao Cascade

The Lao Cascade comprises five run-of-river dams with hydroelectric power plants: Pak Beng, Luang Prabang, Xayaburi, Pak Lay and Sanakham. Xayaburi hydropower plant is currently under construction, planned to be operational in 2019, but the other hydropower plants are at less advanced stages of development.

The Lao Cascade Case Study assessment (2nd Interim Phase) comprises the reach from the Burmese/Lao/Thai border and gauging station Chiang Saen down to short upstream of Vientiane. The modelled reach starts however 50 km short of the Chiang Saen and has a total length of 732 km. Until the Sanakham dam site, the Mekong runs entirely within Laos. From Sanakham dam site, the Mekong divides Thailand and Laos.

Over the modelled reach, the present total head is from 342 masl to 166 masl, i.e. a fall of 176 meters. Thus, the average slope on this reach is 0.24 m/km, which is gentle, but still steeper (around double) than further downstream from Vientiane.

Apart from Vientiane, the only major town located along the river is Luang Prabang. The Xayabury dam construction site is 100 km downstream of Luang Prabang town.

The table below gives an overview on the planned dam locations within the Cascade reach. As indicated in the table, the reservoirs have lengths ranging from around 60 to 100 km. From the upstream end down to Sanakham, around two-thirds of the distance will be reservoirs and one-third free flowing river sections. It should however be noted that these figures are highly approximate since there is not a sharp transition from river to reservoir. Furthermore, the distribution between the two groups is based on the dry season situation. During the wet season, the gradient through the upper reaches of the reservoirs will be larger and the transition between reservoir and river will be even more difficult to identify.

Two gauging stations are located within the modelled Lao Cascade reach, providing data for calibrating the model (Luang Prabang and Chiang Khan). The Luang Prabang station is located at the town of the same name, i.e. close to the tail end of the Xayaburi reservoir. The Chiang Khan gauging station is located around 22 km downstream of the Sanakham dam site, i.e. downstream of the Lao Cascade.

Table 2.1. Length of reservoirs and river reaches in the Lao Cascade.

Reach from:	Reach to:	Cumulative distance from u/s boundary km	Reach length km	Reservoir length km	River reach km
Model Boundary	Pak Beng	0	127	73	54
Pak Beng	Luang Prabang	127	143	100	43
Luang Prabang	Xayaburi	270	129.5	80	49.5
Xayaburi	Pak Lai	399.5	121.5	80	41.5
Pak Lai	Sanakham	521	81	58	23
Sanakham	Model Boundary	602	130		

Figure 2.8 portrays a longitudinal profile of the Lao Cascade. The lower outline of the blue polygon illustrates the thalweg in the Mekong (i.e. the lowest elevation in each cross-section), which clearly varies quite a lot along the longitudinal scale, and frequently some 20 m over a few km. The upper outline of the blue polygon illustrates the water surface after construction of all five dams. The black lines visible above the water illustrate the elevation of the extreme ends of each cross-section.

Due to the scale, it is difficult to discern in this figure the river reaches below each reservoir, except for upstream the Xayaburi reservoir. With a finer scale it, however, it would be possible to discern that there is a gradient of roughly 0.5 - 2 m before the transition into the reservoirs (largest upstream Xayaburi, smallest upstream Sanakham). The mentioned magnitude of gradients occurs in the dry season; in the wet season, the gradients are much larger.

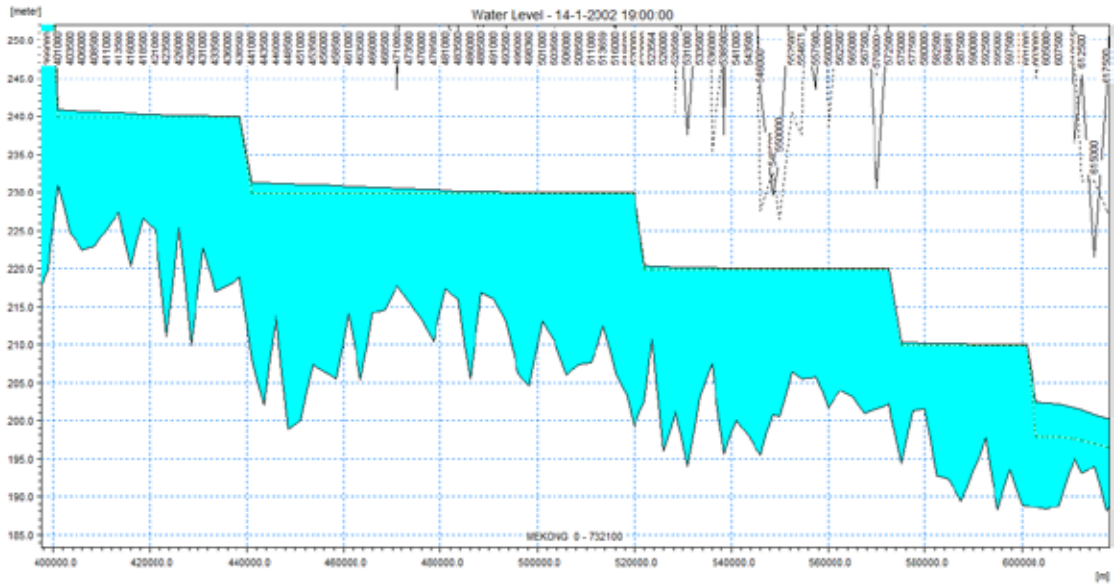


Figure 2.8. *Longitudinal profile of the Lao Cascade.*

Design flow and reservoir water level

The technical details of the Xayaburi hydropower plant are finalized, although not for the other four dams. As the information available is incomplete, we have chosen to use the Xayaburi design as a "template" for the other hydropower plants when it comes to design flow, fish passage design and gate capacity, during the 2nd Interim Phase. ***These projects will need to meet the design parameters included in the MRC's Preliminary Design Guidance (MRC, 2009), as a minimum standard.*** The design flow is scaled relative to the median flow at the different sites, while the fish passage and gate capacity was copied from Xayaburi. The key hydropower data for the cascade is presented in Table 2.2.

Table 2.2. Key numbers for the dams in the Lao Cascade.

	Design flow	Full supply level	Capacity	Annual generation	Status
Pak Beng	4110 m³/s (5771 m³/s)	340/335 masl	912 MW	4 800 GWh	Prior Consultation concluded. Expected 2023
Luang Prabang	4110 m³/s	310 masl	1200 MW	6 100 GWh	Expected 2030
Xayaburi	5140 m³/s	275 masl	1285 MW	7 200 GWh	Under construction Expected finished in 2019
Pak Lay	5140 m³/s	240 masl	1000 MW	4 500 GWh	Expected 2030
Sanakham	5140 m³/s	220 masl	700 MW	3 600 GWh	Expected 2025

2.2.2 The Mainstream Dams below Pakse

There are six mainstream dams planned downstream of the case study cascade, four in Lao and two in Cambodia. The dams are plotted in the map below (Figure 2.9), and key numbers are presented in the following table.

Figure 2.9. *Mainstream dams downstream of the Lao cascade.*

Table 2.3. Key numbers of the mainstream dams downstream of the Lao Cascade.

	Design flow	Full supply level	Capacity	Annual generation	Status
Pakchom	5 720 m³/s	192 masl	1 080 MW	5 300 GWh	Expected 2025
Ban Kum	11 700 m³/s	115 masl	1 800 MW	8 400 GWh	Expected 2030
Latsua	9 600 m³/s	97.5 masl	600 MW	1 700 GWh	Expected 2025
Don Sahong	1 600 m³/s	73 masl	260 MW	2 000 GWh	Under construction. Expected finished in 2019.
Stung Treng	9 834 m³/s	52 masl	980 MW	5 000 GWh	Planned
Sambor	17 668 m³/s	40/35 masl	1 700/ 2500 MW	5 500/12 000 GWh	Planned

While most of the dams are expected to have similar design as in the Lao Cascade, there are some exceptions. Don Sahong, currently under construction, is located in within multiple channel reach of the 4000 Islands area, in a channel adjacent to the Khone Falls.

For the Sambor dam, at least two different designs have been suggested. The original design consists of a dam, with a crest length of 18 km covering the whole river width, while the alternative design is a smaller dam that only occupies a part of the river. Both alternatives are included in the table above and the smaller alternative is illustrated in the Figure below.

Figure 2.10. *Google Earth illustration of the smaller alternative of Sambor (Loucks, 2017).*

2.3 Description of Risks

2.3.1 Hydrology and Flow

As part of the inventory of potential risks of hydropower development on the Mekong River and its tributaries, a list of risks related to hydrology was identified. In the following table, reproduced from the Guidelines and Manual in the 2nd Interim Report (MRC, 2016), these risks are summarized.

Table 2.4. Summary of hydrology and flow risks associated with the development and management of hydropower.

Change	Key Risks, Impacts & Vulnerabilities
Annual / inter-annual changes to flow	
Changes in seasonality & continuous uniform release	Change of timing & duration of floods and low flows, changes in flows Tonle Sap, changes in flood plain inundation in the delta, and changes in salt intrusion in the delta
Modification of flood intervals: Reduction in occurrence of minor floods & no change in large events	Changes to flood peaks and low flows; smoother hydrograph
Daily / short-time period changes in flow	
Hydro-peaking	Safety and navigation related changes caused by sudden rise or drop of water levels

A distinction can be made into two groups of potential changes in flow regime:

- Annual / inter-annual changes to flow
- Daily / short-time period changes in flow

For the larger annual and inter-annual time scale, the changes depend heavily on the size of the reservoirs. From the analysis of the historical flow series and the comparison with recent years, it becomes evident that the impacts mentioned in the table are already noticeable along the entire Mekong main river. ***In comparison, the Lao Cascade and the mainstream dams further downstream will have only small influence on the overall annual flow regime (with a possible exemption of the "big" Sambor) and there are few possible measures that might mitigate the effect of the change in inflow from the Chinese developments on UMB*** (see also Chapter 3.3.1, where this is treated in detail). Any storage development on the tributaries will be more important for the annual flow regime, and it is likely that their impact, particularly for the case of the 3S river basins, will be noticeable on both the Tonle Sap reverse flow system regime as well as the hydrology (and related salt water intrusion) in the Mekong Delta (see also Wild and Loucks, 2014).

For the daily/short term changes in flow, the impact of the Chinese dams is of course noticeable directly downstream from the Chinese border, but these changes quickly diminish downstream as the contribution of the tributaries along the main river course start to become more dominant. This has been described in detail in the chapters on the overall hydrology of the river in the Manual (Chapter 2). Daily/short term changes in flow will however be more noticeable from the Lao Cascade and dams further downstream than long-term changes, especially if peak operation is implemented, but will eventually be dampened out downstream (see also Chapter 5.3.1.3).

The potential impact of a series of reservoirs on the flow regime in the Mekong river should not be underestimated if such reservoirs are placed at another location, for example on the Mekong tributaries where they might lead to a major changes in flow characteristics. The change in hydrology itself is not a major problem, but can lead to associated problems for the other related fields, particularly the (fish) environment, the water quality and the sediment transport. This is further discussed in the following paragraphs.

2.3.2 Sediments and Geomorphology

Geomorphic and sediment transport risks associated with the implementation and management of hydropower projects are linked to flow changes (see Chapter 2.2.1 above), and the changes to the magnitude and pattern of sediment delivery that can occur due to hydro developments. Table 2.5 (below) is taken from Guidelines and Manual in the 2nd Interim Report (MRC, 2016), and this volume should be referred to for a detailed discussion of the risks as they relate specifically to the LMB.

The case study is directing effort at investigating the risks associated with trapping of sediments within the impoundments of the cascade, and how flow and sediment changes affect sediment characteristics, processes and rates within and downstream of the cascade. Sediment flushing is investigated in detail, ***consistent with the PDG that recommends flushing as an effective sediment management strategy***.

Table 2.5. Summary of sediment transport and geomorphic risks associated with the development and management of hydropower (risk specifically studied in detail for the case study outlined in grey).

Change	Key Risks, Impacts & Vulnerabilities
Annual / inter-annual changes to flow	
Changes in seasonality & continuous uniform release	Water logging & loss of vegetation leading to increased bank erosion Increased erosion due to increased scour (bed incision, bank erosion)
	Winnowing of smaller sediment leading to bed armouring & reduction in downstream sediment supply
	Bank scour focussed over limited range leading to increased bank erosion
Modification of flood intervals: Reduction in occurrence of minor floods & no change in large events	Channel narrowing through encroachment of vegetation Increased risk in upstream of flooding and floodplain stripping during large (>1:10 ARI) flood events
Change in relationship of flow & sediment transport	Decoupling of tributary & mainstream flows Erosion and / or deposition due to tributary rejuvenation
Daily / short-time period changes in flow	
Hydro-peaking	Rapid wetting & drying of banks increases susceptibility to bank erosion and seepage processes
	Increase in shear stress during flow changes increases erosion and bed incision
Loss of river connectivity	
Disconnect between flow and sediment delivery	Sediment availability not timed with periods of recession leading to decreased deposition
	Loss of sediment ‘pulse’
Creation of impoundments	
Trapping of sediments	Reduction in sediment availability downstream of dam leading to increased erosion
	Changes to the grain-size distribution of sediment downstream contributing to channel armouring and alteration of habitats
Water level changes within impoundment	Lake bank erosion, increased risk of landslips
Diversions or intra basin transfers	
Decreased flow in donor basin	Channel narrowing due to vegetation encroachment
	Armouring of beds and bars due to reduced sediment transport
	Decrease in frequency of high flow events increases impacts of extreme events (upstream flooding, floodplain stripping)
Increased flow in receiving basin	Increased bank erosion and bed incision to accommodate increased flow

2.3.3 Water Quality

The water quality risks associated with hydropower development include changes to physical and chemical water quality parameters that can affect impounded- and downstream ecosystems. A summary of potential risks is presented in Table 2.6.

The water quality parameters that are important to consider in hydropower developments and identified in the Preliminary Design Guidance (MRC, 2009) include temperature, pH, dissolved oxygen (DO), Biological Oxygen Demand (BOD), nutrients (total and dissolved phosphorus and nitrogen) and coliform bacteria. These parameters can be altered during storage within a reservoir and especially under conditions where thermal stratification can lead to the development of stagnant water at depth.

Guidance for maintaining water quality includes the design and management of reservoirs, which will achieve the water quality guidelines as set out in the MRC Technical Guidelines for Procedures on Water Quality. The PDG state the necessity of site – specific water quality monitoring, with the results to be interpreted within larger scale trends provided by the Water Quality Monitoring Network and Ecological Health Monitoring Network.

The Northern Lao PDR cascade case study does not include water quality modelling, so risks associated with stratification, low dissolved oxygen or metal / nutrient cycling within impoundments are not included in the model runs. However, the changes in the physical attributes of the system (increase in water clarity, reduced water velocities and increased residence time in the cascade reach) are considered within the context of increasing the risk of algal blooms. Also included is a qualitative discussion about the potential to alter nutrient transport using the silt and clay transport as surrogates for nutrients.

Water quality modelling in the Council Study scenarios was limited to total nutrients (nitrogen and phosphorus) and removal was assumed to be in proportion to sediment removal, with 50% of the N and 40% of the P assumed to be associated with nutrients. The Council Study modelling results shows a decrease in nutrients associated with sediment trapping, but also additional inputs associated with increased urban and agricultural runoff. No temperature, dissolved oxygen or dissolved nutrient modelling was included, so in-impoundment water quality risks cannot be quantified. The same risk based analysis of the Council Study results was applied to the results.

Table 2.6. Summary of water quality risks associated with the development and management of hydropower (risk specifically studied in detail for the case study outlined in grey).

Change	Key Risks, Impacts & Vulnerabilities
Annual / inter-annual changes to flow	
Changes in seasonality & continuous uniform release	Changes / loss of seasonal temperature patterns downstream
Change in relationship between flow and sediment delivery	Increased water clarity increasing risk of algal growth Increased water clarity increasing water temperature
Daily / short-term changes in flow	

Change	Key Risks, Impacts & Vulnerabilities
Hydro-peaking or fluctuating discharge	Fluctuating water quality including increase in variability of temperature and nutrients
	Altered concentrations of downstream discharges or inputs
Loss of river connectivity	
Changes to nutrient transfer	Trapping of nutrients within impoundment leading to change in downstream delivery
Creation of impoundments	
Conversion of river to lake	Lake stratification leading to low dissolved oxygen bearing water and release of nutrients, metals or pollutants from sediments
	Increased water clarity in lake increases risk of algal blooms
	Temperature change in lake (warmer or cooler)
	DO and temperature of discharge affected by impoundment – Low DO or high gas supersaturation
Diversions or intra basin transfers	
Diversion of water from one catchment to another	Change in nutrient and other water quality parameters in both donor and receiving catchments

2.3.4 Fisheries and Aquatic Ecology

As rivers represent complex systems, any alteration to the system may cause impacts on aquatic organisms. In this context, changes to a river's hydrology may not only affect fish by the alteration of hydrological triggers, but also by related habitat alterations or impacts on other aquatic organisms in which then might be transmitted via the food-chain to the level of fish productivity.

The implementation of a dam or, as tested in this study; cascades of dams, its associated changes to the river system are related to potential negative effects and risks on aquatic organisms. The following table provides an overview of the most important changes, their potential effect and related risks. A more detailed description is provided in the Guidelines and Manual in the 2nd Interim Report (MRC, 2016).

Table 2.7 is reproduced from the Manual cited above and the risks addressed by the mitigation measures in the case study are highlighted in grey.

Table 2.7. Summary of fisheries and aquatic ecology risks associated with the development and management of hydropower (risk specifically studies in detail for the case study outlined in grey).

Change	Key Risks, Impacts & Vulnerabilities
(Annual / inter-annual changes to flow	
Changes in seasonality (e.g. delayed floods, increase of dry and decrease of wet season flows)	Habitat alteration/ loss related to increased erosion (river bed incision, bed armouring, bank erosion etc.; see also Table 3.2)
	Habitat alteration/ loss related to water quality changes (e.g. temperature, water clarity, salinity (relevant for the Delta), nutrient transport; see also Table 3.3.)
	Loss of ecological functions (e.g. migration/ spawning triggers)
	Loss of productivity due to reduced flood pulse (increase in permanently flooded areas and decrease in seasonally flooded areas)
Daily / short-time period changes in flow	
Fast increase of flow	High drifting rate of fish and macroinvertebrates, loss of food sources, offset of migration triggers, stress for aquatic organisms
Fast decrease of flow	Stranding/ loss of fish and macroinvertebrates, stress for aquatic organisms
Morphological alterations	Increased erosion and riverbed incision causes habitat degradation (see also Table 3.3.)
Thermopeaking	Unnatural (fast changing) temperature regime, stress for aquatic organisms, offset of migration triggers
Barriers/ loss of river connectivity	
Disconnect between flow, sediment and nutrient delivery	Habitat loss related to morphological alterations (see also Table 3.3.), offset of migration triggers, reduced productivity with regard to nutrient trapping and limited delivery downstream
Habitat fragmentation	Blocked/ reduced spawning and feeding migrations, potential isolation of sub-populations
Turbine passage	Stress, fish damage and kills
Spill flow passage	Stress, fish damage and kills
Creation of impoundments	
Trapping of sediments	Morphological alteration and habitat loss. Upstream: sedimentation, possibly filling up of deep pools, reduced vertical connectivity, change of choriotopes (fish, benthic invertebrates), degradation of shoreline habitats; Downstream: loss of habitat structures (e.g. sand bars), reduced habitat quality (e.g. change of choriotopes, river bed armouring), reduced connectivity to tributaries and floodplains (related to river bed incision)

Change	Key Risks, Impacts & Vulnerabilities
Loss of free flowing river sections	Delay/ deposition of drifting eggs & larvae
	Loss/ reduction of fish species adapted to free flowing rivers
	Loss of orientation for upstream migrating fish
Increased visibility	Algae growth and changes in temperature, oxygen
Stratification & temperature changes	Stress due to water quality changes (temperature, oxygen)
Water level changes within impoundment	Stranding of fish and macroinvertebrates, degradation of shoreline habitats
Reservoir flushing	Flushing of benthic organisms and fish, potentially high losses related to high turbidity, destruction of habitats
Diversions or intra basin transfers	
Reduction of river dimension	Reduced productivity, species alteration (e.g. loss or large species), reduced depth may impact connectivity, water quality changes
Homogenisation of flows	Armouring of beds and bars due to reduced sediment transport, habitat loss
Increased flow in receiving basin	Increased bank erosion and bed incision to accommodate increased flow
Water quality changes	Stress
Combined effects	Reduction of biomass and diversity of fish and other aquatic organisms

As can be seen in Table 2.7, most of the potential effects are related to the alteration of abiotic parameters (e.g. flow, water quality, sediments). Consequently, the risk assessment for aquatic organisms has to incorporate both first (abiotic parameters) and second order impacts (habitat alteration). While some state-of-the art mitigation measures are studied in the Lao Cascade and the mainstream dams further downstream, and focusing on some of the impacts (e.g. fish passes for restoring connectivity), other pressures may rather be mitigated indirectly or, in certain cases, not at all. Figure 2.11 highlights the most important risks and possible mitigation options, which will be described in more detail in Chapter 2.5.5.

It has to be highlighted, that although seasonal flow alterations are considered with no mitigation options in this figure, the negative impacts could of course be offset by the implementation of environmental flow rules, which also restrict seasonal flow changes. However, since this impact is mostly related to larger storage hydropower plants, which are already in place in the Upper Mekong Basin and LMB tributaries, and not directly related to the mainstream dams under consideration, it is considered as not mitigatable in the context of this study. Mitigation of these impacts would require further transboundary dialogue on options to adapt the operation of these respective large storage hydropower plants.

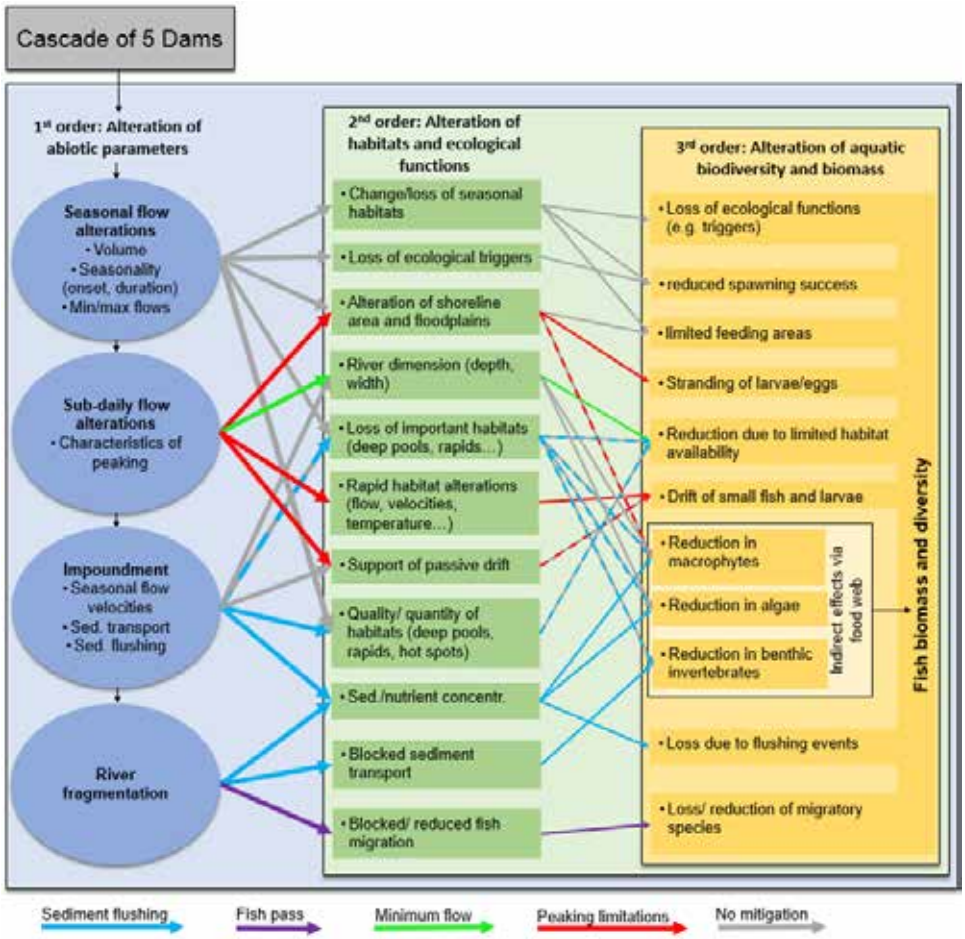


Figure 2.11. *First, second and third order impacts and aquatic organisms and the influence of the mitigation measures (dashed lines indicate a partial effect).*

2.4 Description of Mitigation Options

To cater for the risks and impacts discussed under Chapter 2.3, a set of mitigation options has been developed and is described in the following sub-chapters.

2.4.1 2nd Interim Phase Mitigation Options

2.4.1.1 Lower Dry-Season Level at Pak Beng

This mitigation option is proposed in the feasibility study for Pak Beng to avoid impacts on the Keng Pha Dai reefs and the Thai-Lao border during the dry season. The normal operating level must be reduced during the dry season in order to avoid this impact. This measure is closely related to hydro-political and transboundary issues core for the development of mainstream Mekong dams as set forth in the PNPCA.

To achieve this, Pak Beng is operated at a lower reservoir level during the dry season (start of December to end of May). According to the Pak Beng Feasibility Study, the normal operating level dam site will be 340 masl from June to November and 335 masl during the dry season. The impact of the impoundment is considered to be adverse only during the dry season.

2.4.1.2 Flood protection at Xayaburi

This mitigation options is included in various feasibility and design reports for Xayaburi and is proposed to avoid flooding at the Luang Prabang town in the wet season.

The Xayaburi Design Report states that the head water level will be lowered during flood conditions to mitigate the possibility of flooding at Luang Prabang town. It is suggested that the water level near the dam should be lowered to a level of 265.9 masl for a flow of 15 000 m³/s. It has been assumed that the drawdown must start gradually when reservoir inflow exceeds 10 000 m3/s. The Case Study however illustrated that to achieve the drawdown without creating dangerous flood peaks downstream of the dam due to rapid gate opening, the drawdown must start at a considerable smaller flow than 10 000 m³/s. In the analysis, the flood draw-down starts when the flow exceeds between 7 000-8 000 m³/s. For flood peaks larger than 15 000 m³/s, the reservoir is kept as low as possible, with all gates fully open.

2.4.1.3 Connectivity Restoration (Fish Passage)

The disruption of river connectivity is considered the main cause of impact to aquatic organisms and especially migratory fish. In order to mitigate the effect of hydropower plants on aquatic organisms, fish passes should be considered for all existing and planned hydropower plants as referenced in the PDG (MRC, 2009). This does however; require a sound understanding of the ecosystem, fish passage types as well as their efficiency and effectiveness under certain aquatic, ecological and biological conditions. Furthermore, not only upstream passage but also safe downstream passage has to be ensured to sustain healthy populations.

For the Lao Cascade, it is assumed that all five dams will install, as a minimum, similar mitigation measures for connectivity restoration as it was planned and constructed for Xayaburi. The design criteria for the individual facilities with its measures for up- and downstream migration are explained in detail in Chapter 3.1.2 (Hydropower Design Criteria for Mainstream Cascade).

As a minimum, these facilities should include:

- Fish passages of appropriate slope and scale to allow the wide array of fish species and sizes to move upstream.
- Adaptive and flexible design systems.
- Properly sited and implemented attraction flows
- Proper downstream migration structures

2.4.1.4 Sediment flushing and sluicing

2.4.1.4.1 Sediment movement through reservoirs

Sediment flushing and/or sluicing is used to move sediment through reservoirs through the manipulation of water levels to increase water velocities in the impoundment. In general, during sediment flushing water levels are reduced in impoundments as near as possible to original river levels to promote maximum erosion of sediments that may be deposited in the original channel. Sediment sluicing involves a similar approach as sediment flushing; however, lake levels are

reduced to pre-impoundment levels, enabling the 'river' to erode deposited sediments. This approach is efficient for re-mobilising sediments deposited in the pre-impoundment river channel, but is expected to be less effective in eroding deposits located on floodplains. These techniques have been implemented in many reservoirs internationally, and have been previously identified as being applicable to the Laos Cascade (Thorne et al., 2011). A detailed discussion of sediment management using these techniques and a range of international examples is contained in the Manual of the 2nd Interim Report (MRC, 2016), and should be consulted for details.

Sediment flushing of the cascade was included in the Case Study for a variety of reasons:

- Remobilising sediments has the potential to mitigate transboundary impacts associated with a reduction in sediment and nutrient transport downstream of the cascade;
- Dam safety; sedimentation close to the lower spillway gates will gradually reduce their capacity and hamper a potential emergency drawdown;
- Preventing an increase in upstream flooding attributable to bed level rises at the upstream end of impoundments due to sedimentation.

The details, sequencing and rule curves associated with how sediment flushing is applied to the entire cascade is presented in Section 2.5.2.2. In general, the following principles were used to develop the sediment flushing mitigation measure within the case study:

- Downstream flows and water level changes associated with sediment flushing should be consistent with the MRC Procedure on the Maintenance of Flows in the Mainstream (PMFM), and should not present a risk to the community or the environment;
- Water level changes within impoundments should be managed to minimise risks to the community and the aquatic environment;
- Flushing should be carried out at a sufficient frequency and under appropriate constraints so that turbidity levels in the downstream river do not compromise the aquatic ecosystem;

Indicators relevant to the flushing and sluicing scenarios include the volume of sediment mobilised from the reservoir by the event, the sediment grain-size distribution of the mobilised material, and the concentration of sediment in the downstream river.

The effectiveness of these flushing/sluicing events is measured using relevant indicators including:

- the volume of sediment mobilised from the reservoir by the event,
- the sediment grain-size distribution of the mobilised material, and
- the concentration of sediment in the downstream river.

2.4.1.4.2 Ecological considerations for reservoir flushing operations

As discussed above, reservoir flushing is an important mitigation measure for sediment re-mobilisation and, thus, the restoration of natural sediment dynamics including the formation of type-specific habitats. Nevertheless, it is also associated with negative effects on physical-chemical conditions (e.g. turbidity, oxygen deficiency, hydropeaking) impacting fish directly (e.g. increased drift, gill and skin injuries, stress, fish kills) and indirectly (e.g. reduced food supply caused by increased drift and loss of benthic invertebrates, reduced growth, lost habitats due to sedimentation) (Kemp et al. 2011; Jones et al. 2012; Crosa et al. 2009; Henley et al. 2000).

To mitigate those negative effects, the definition of certain turbidity thresholds and their compliance during flushing is of high importance. The intensity of impacts depends mainly on the concentration and duration of exposure (see Figure 2.12), but also the size and texture of particles, water temperature, chemical and physical conditions (Stone & Droppo, 1994). In addition, other flushing-related water quality changes, as e.g. the release of organic matter and the consecutive oxygen depletion may lead to suffocation of fish and benthic invertebrates (Waters, 1995; Garric et al., 1990).

For the Mekong, high turbidity thresholds occur naturally (i.e. 1,400 mg/l at Chiang Saen in June, see Figure 5.49 in chapter 5.4.1) which is why, compared to other rivers, higher thresholds can be considered as tolerable.

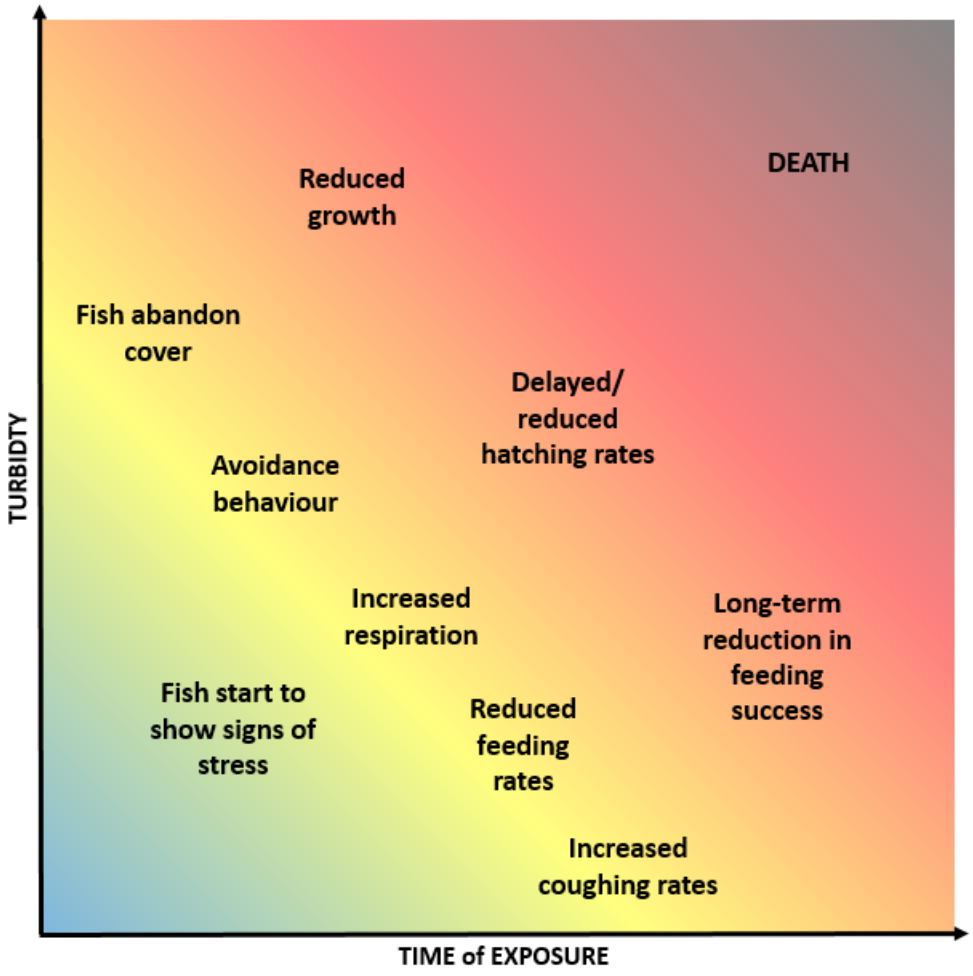


Figure 2.12. *Relational trends of freshwater fish activity to turbidity and time (based on www.lakesuperiorstreams.org/understanding/param_turbidity.html and Newcombe & Jensen 1996).*

2.4.1.5 Flow Restrictions

2.4.1.5.1 Ramping of water level changes for geomorphic mitigation

Hydropeaking has been linked to accelerated erosion rates in downstream river banks. Rapid changes in water level can increase bank erosion through two mechanisms. Frequent water level changes can temporarily increase the surface slope and thus the shear stress and in turn the bed and bank erosion (see Figure 2.13 overleaf).

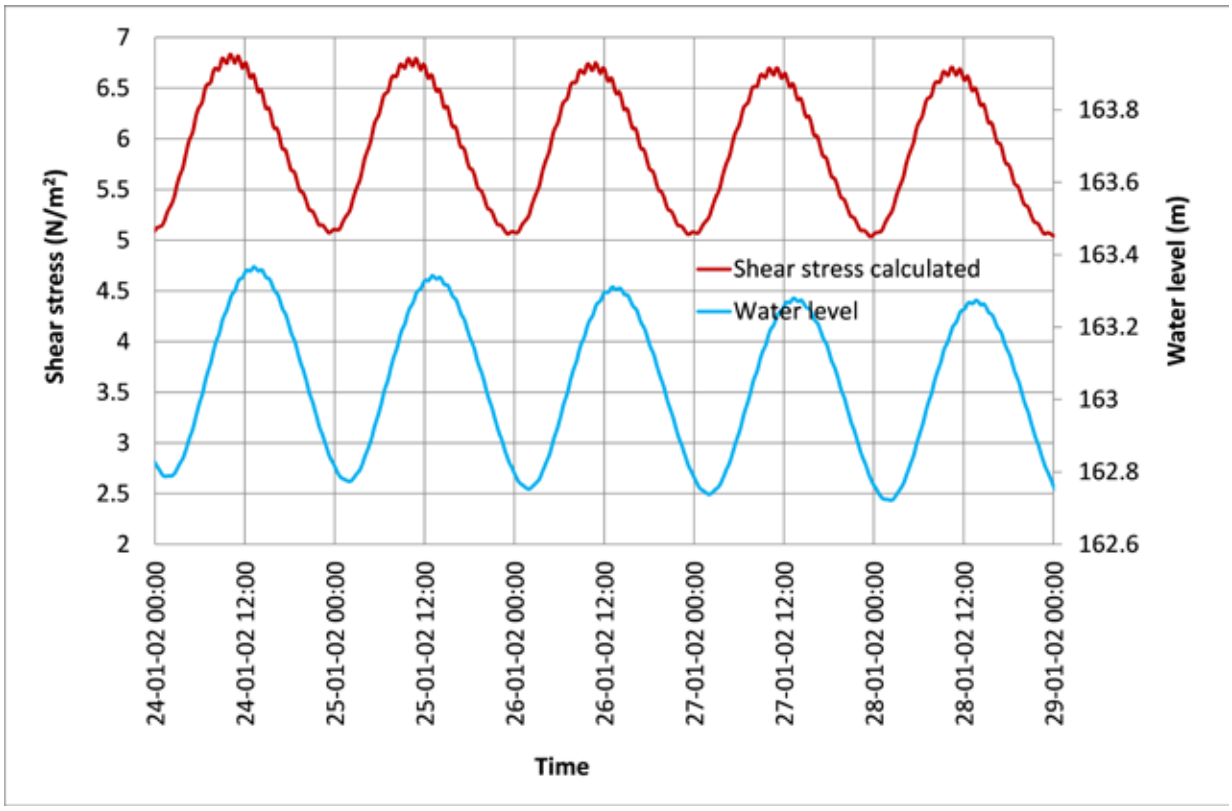


Figure 2.13. *Calculated shear stresses and water levels (Delft3D model) for dry-period (January 2002) upstream of Vientiane for power peaking scenario.*

A second potential impact is the successive saturation and draining of riverbanks, due to the water level changes. Saturated riverbanks has an increased risk of bank collapse due to the elevated water pressures that remain in the bank following draw down in the river.

Both of these risks can be reduced by restricting the rate at which water level decreases in a river. Slower changes to water level will maintain water slopes at lower grades and hence limit shear stress. Low draw down rates will also allow water to drain from rivers at a similar rate to the decrease in water level, thus reducing the slope and energy of the water draining back into the river. The defined ramping rates are considered suitable to offset some of these risks.

2.4.1.5.2 Ramping rates for control of water levels under hydropeaking and flushing operations

Peaking operations

The impact pathways from hydropeaking are highly complex and there are still substantial knowledge gaps with regard to cumulative effects and impact mitigation. Especially for the development of suitable mitigation measures, knowledge and clear understanding of mechanisms and relationships causing the impacts are necessary. In general, hydropeaking has a high impact on ichthyoplankton and juvenile age classes, which are exposed to the risk of high drift rates (during upramping events) and stranding (during downramping events). Although stranding may also occur naturally, the high frequency of flow fluctuations can cause cumulative mortalities with significant fish losses (Bauersfeld, 1978; Hamilton & Buell, 1976; Olson & Metzgar, 1987).

Schmutz et al. (2014) used an extensive field dataset to analyse the impact of different types of hydrological and morphological indicators in combination with fish community data. Their results demonstrated that fish react to a combination of peak frequency, ramping rate and habitat conditions, with an equal importance of habitat and flow criteria. Consequently, effective mitigation measures should consider the complexity of hydromorphological processes determining the functional (hydraulic) habitat conditions (Schmutz et al., 2014).

The negative effects of hydropeaking can be mitigated (or reduced) by adapting the operation mode (ramping rates) of the hydropower plant. The most important aspect in this context is the deceleration of downramping after a peak period. Comparisons with the natural hydrograph of the Mekong resulted in the following values.

Table 2.8. Natural flow variations in m/hour (based on daily means of historic water level changes).

	decreasing water level (~60% of the time)		**increasing water level (~30% of the time)**	
	1% percentile	5% percentile	95% percentile	99% percentile
Luang Prabang	-0.030	-0.020	0.041	0.076
Sanakham Dam	-0.025	-0.015	0.028	0.051
Vientiane	-0.022	-0.013	0.024	0.045
Paksane	-0.020	-0.013	0.025	0.037

(Percentiles were calculated independently for decreasing and increasing events)

As the table indicates, decreasing events occur over 60 % of the time and slower than increasing events (which occur only 30 % of the time). Since these values were calculated based on daily data, within-day variations remained undetected and could result in higher values. However, these values might only occur for short periods over the year (e.g. after heavy precipitation events) and can also go hand-in-hand with natural high drift rates and stranding. Under consideration of the presented values and literature (e.g. Schmutz et al., 2014) downramping was initially limited to 0.05 m/hour and upramping to 0.2 m/hour. However, since the modelling process allowed only the consideration of one threshold for up- and downramping, the ramping was limited to 0.05 m/hour for rising and falling water levels.

In general, also the reduction of the peaking amplitude (e.g. by increase of the base flow and/or decrease of the hydropower capacity) should be considered. Within this study, however, limitations were only given to the variation of headwater levels (see Chapter 2.4.5.4).

Flushing operations
Flushing is meant to be timed with natural flood peaks with the aim of removing accumulated sediments. Since it usually does not occur more than once a year, higher ramping rates can be considered, compared to daily peaking-operations. Within this study, draw down operations were limited to a rate of 0.1 m/hr and filling operations to 0.2 m/hr.

2.4.1.5.3 Minimum environmental flow

MRC Preliminary Design Guidance (PDG, 2009), stipulates to incorporate “instream” flow (environmental flow, minimum flow) considerations. While minimum flow limits are mostly defined for out-of-river-diversions, they should of course also be considered for other types. For the Mekong mainstream, minimum flow limits may be relevant for hydropower dams allowing some degree of hydropeaking, to ensure that the river does not fall dry during the drawdown hours. Minimum flow limits should be based on natural flow conditions in the respective river (as also set forth in the PMFM, MRC, 2009). For the Lao Cascade, Q95 of the annual discharges (for historic conditions, before the Chinese and tributary dams were implemented) was defined as a minimum flow limits, which resulted in the following values for the respective sites:

- Pak Beng and Luang Prabang 830 m³/s
- Xayaburi 910 m³/s
- Pak Lay and Sanakham 925 m³/s

These values should represent the absolute minimum discharge provided by the hydropower plant, to support downstream ecosystem functioning and their flow requirements.

2.4.1.5.4 Limitation to reservoir level fluctuation

A maximum limit of 50 cm up and down in reservoir level each day is introduced in some of the peaking scenarios. The 50 cm amplitude in reservoir level was originally discussed at Xayaburi as a possible mode of operation, and is a value that is expected not to cause safety, navigation or environmental problems. In addition, if a minimum flow limit is applied, the daily amplitude could be much bigger than 50 cm in the dry season anyway; else, the reservoir would not have sufficient time to re-fill in the eight-hour off-peak period.

2.4.2 Final Phase Mitigation Options

2.4.2.1 Conceptual Level Mitigation Options Assessment

2.4.2.1.1 Alternative Schemes Layouts and Partial Cascade Development

The modelling undertaken in this Case Study report to assess the impact of the mainstream cascade has indicated that the incorporation of advanced fish passages and sediment flushing strategies can be beneficial, but significant impacts remain because long reservoirs with almost zero flow

velocity are created. These reservoirs are a barrier to fish migration and they trap sediment. Since the mainstream schemes are pure run of river, and limited peaking operation has very little commercial benefit, the stored water has no commercial value.

The most effective form of alternative scheme layout will therefore be an arrangement that reduces the creation of reservoirs.

A series of fully gated low head barrages could replace a single mainstream dam and would capture a similar amount of energy if the cumulative head was the same. These structures would impound smaller volumes of water and keep the river closer to its natural regime. At critical times of year (or on a regular basis such as weekends), the gates could be opened and the river returned to entirely natural conditions to allow sediment transport and fish migration in either direction.

Low head barrages would be suitable for horizontal axis bulb turbines. These machines are more compact than vertical axis Kaplan units and will reduce the cost of the civil works. Horizontal bulb turbines can be designed for lower fish injury and can provide safe passage for migrating fish in either direction when shut down and placed in sluicing mode.

A low head barrage would also permit the adoption of rising sector gates for overshot spilling. This form of spilling will permit safe downstream fish passage during times of flood. The adoption of rising sector gates would also permit the gates to be fully lowered so that natural river conditions are restored. This condition would permit natural fish migration in either direction, and facilitate natural sediment transport.

The depth impounded by a low head barrage would be in the range 10 to 15 m, similar to the natural flood surcharge in the Mekong. Typically, one mainstream project can be replaced by two low head barrages and the combined energy output will be very similar.

The concept is examined in detail in Section 6.2 of this report. Comparative cost estimates and financial modelling are provided. The results indicate that this alternative concept has comparable commercial viability to the full height mainstream projects that are currently planned.

2.4.2.2 Mitigation Options Defined for Council Study Hydropower Sub-Scenario

Minimum Flow, Ramping Rates and Fish Pass

In general, the same mitigation measures as considered for the Lao cascade were considered for all mainstream dams. The minimum environmental flow should be based on natural flow conditions and was set to Q95% of the annual discharges (for historic conditions, before the Chinese and tributary dams were implemented; see also chapter 2.4.1.5.3). For Don Sahong and Sambor (small version), which do not cover the whole mainstream but only one channel, more detailed habitat modelling would be required to come up with suitable minimum flow rules for the unexploited channels – especially if these channels should also serve as a natural bypass for fish migration. Due to the lack of detailed modelling in the side channels (especially for Sambor), the same minimum flow rule (i.e. Q95%) was applied for the two diversion projects. However, additional flow was considered for the Khone Falls located in a side channel of Don Sahong to continue their existence as tourist attraction. Furthermore, the remaining side channel at Sambor should be provided with

at least Q95% of the whole Mekong (not Q95% of the side channel), since it is a rather long section which should also serve as a bypass for fish migration. However, it has to be highlighted that the chosen values represents an absolute minimum flow and the release of higher flows might be required and is highly recommended from an ecological point of view.

Also with regard to ramping rates, the same rules as developed for the Lao cascade (see chapter 2.4.1.5.2) were applied for the whole cascade of eleven dams. In general, headwater sections tend to have a more variable flow compared to lowland rivers, which usually exhibit a more temperate flow regime. Consequently, stricter ramping rates might be required for dams located further downstream. However, the application of uniform ramping rates seems justifiable for testing purposes in this study, especially since more detailed analyses at each dam site would be required to define suitable ramping rates. Consequently, downstream water level changes have been limited to 5 cm/hour. For exceptional (i.e. annual, multi-annual) flushing events, draw down operations has been limited to a rate of 0.1 m/hour and filling operations to 0.2 m/hour.

Finally, with regard to connectivity restoration (see chapter 2.4.1.3) it is assumed that all eleven dams have a similar fish pass as constructed for Xayaburi. With increasing discharge in downstream direction, also the fish pass needs to be supplied with higher attraction flows. In line with previous calculations for the Lao cascade, it is assumed that the fish pass causes a loss of 1% of the mean flow for hydropower production. However, it has to be highlighted that this amount is only relevant for calculating energetic losses while higher discharges might be required to operate the fish pass and to ensure its functionality and traceability for fish. Again, it is assumed that attraction flow turbines can be used to reduce the related energetic losses. More details on the design criteria (e.g. for the fish pass or required attraction flow) can be found in chapter 3.1.2 (Hydropower Design Criteria for Mainstream Cascade). For Sambor (small version, where only a certain proportion of the flow is used for hydropower production), 1% of the design flow should be considered as “lost” for energy production since it might also be required to include a fish pass at the dam and/ or the diversion weir. At Don Sahong, no additional fish pass is required, assuming that remaining side channels can compensate the fragmentation of Hou Sahong. Additional adaptations (e.g. increase of flow, additional excavations etc.) might be required if monitoring shows that the passage efficiency is not sufficient (Cowx et al. 2014).

Recommended Sediment Mitigation Options and Strategy

- Draw down all reservoirs to a minimum level at the **beginning of the wet season** (so not a full shut down), and maintain the low level for a month. This operation is used to maximize movement of sediment and minimise deposition in the onset of the wet season (when concentrations are usually somewhat higher than later in the season). In the case of 2nd Interim Phase, we called this **‘sediment sluicing’**, to differentiate with the rapid drawdown flushing operation that will have a stronger erosion potential. The latter is not justified in the first decades as there are limited quantities of sediment accumulating close enough to the toe of the dam to make sediment flushing worthwhile (findings from case study). Although we used a sequential lowering of the reservoirs in the 2nd Interim Phase, it is not needed for Phase 4 and all mainstream dams, as we only consider a form of ‘slow flushing’ or ‘sluicing’.
- Note that these procedures allow a significant drop of reservoir level, but do not necessarily mean that the power stations be shut off. For instance, in Pak Beng the power units can continue to produce energy until the head drop below 7.3 m (according to the developer).

We may assume that turbines can operate roughly down to 1/3 of the design head. Energy generation will only cease if all (low-level) gates are open, and such low levels are achieved combined with high tailwater levels (which is the case during flood).The cumulative impact of multiple drawdowns occurring simultaneously must be considered, and may have to be managed, but there is no sequential lowering of the reservoirs as recommended in the recommended Council Study mitigation scenario (as in the Lao Cascade during the 2nd Interim Phase).

- The suggested ramping rates aim to minimise impacts on fish and riverbanks.
- For filling after the period of minimum water level, we propose an up-ramping rate of 0.2 m/hr as described previously. And a downstream to upstream filling pattern, to prevent the river from 'drying-up' downstream of the cascade. It might be more equitable to the individual dam operators to fill all reservoirs simultaneously, but the coordination of filling and cohering with the prescribed ramping rates, such that all dams have more or less the same power output (discharge times head), is likely too difficult to implement. It is probably easier and more controllable to fill each lake to normal operating level using a normal ramping rate, starting with the lower reservoir first (e.g. Pakchom), and then moving up to the top (e.g. Pak Beng) in the case of the upstream cascade. The downstream and upstream cascades can be considered independent, and can commence filing at the same time.
- The period of 1 month for keeping the levels low is arbitrary and aimed at determining how much sediment can be sluiced within such a timeframe. The actual length of any drawdowns would need to be negotiated between countries and developers, and include consideration of lost energy generation.

These recommendations were not fully implemented in the MRC hydropower modelling 'mitigation' scenario for a range of reasons relating to the complexity of the river system and differences between the numerous models required for use in a project as complex as the Council Study. Because of this, the Council Study results do not necessarily reflect the full potential of implementing mitigation options at the hydropower projects. Despite any limitations, the Council Study modelling results clearly demonstrate the role the tributary dams play in altering fish and sediment passage through the system, and the long-time scales that will be required for sediment equilibrium to be established. Additional research and modelling are warranted and recommended by the Council Study modelling team and Mitigation Guideline study team to provide greater detail and insight as to the potential for mitigation of hydropower impacts the LMB.

Some comments on the recommended operating levels:

- We assume that turbines can operate down to 1/3 of the design head. The minimum water-levels are chosen such that the power stations can operate during sediment sluicing.
- **Pak Beng**: In the 2nd Interim Phase, water level was lowered from 340 m to 323 m. In the PNCPA for Pak Beng the absence of low-level gates limits the level to 332 m at discharge approaching 15000 m3/s. For the time being, it may be useful to go for a 17 m lowering similar as was proposed in Xayaburi, i.e. minimum level would be 323 m (and still allow power production).
- **Luang Prabang**: We have not achieved much information as per date, except that LP will have an operation level between 310 and 315 m. This gives about 35 m of water-level difference over the dam, hence we would expect a lower 'sluicing' level of 295 m if we lower similar as Xayaburi and other dams to a 15 m decrease (from 310 to 295 m).

- **Xayaburi**: In the 2nd Interim Phase water level was lowered from 275 to 256 m, so 19 m lowering is suggested.
- **Pak Lay**: Operation level is 240 to 245 m, so we can apply the lowering from 240 to 229 m to reproduce the sluicing operation.
- **Sanakham**: In the 2nd Interim Phase, we lowered from 220 to 213 m (so only 7 m from full operation level, because of tailwater).
- **Sangthong-Pakchom**: We consider a level of 192 m, and we propose the lowering to 182 m, which means a 10 m lowering (realistically based on the dam height, as there are not much data).
- **Ban Kum**: We consider the level 115 m, and propose lowering to 105 m to achieve a reduction of 10 m).
- **Latsua**: We consider the level 97 m, and propose lowering to 90 m which is the lowest supply level.
- **Don Sahong**: There will be no sluicing operations as far as we know (due to the nature and design of this dam)
- **Strung Treng**: We consider a level of 52 m, and it can be lowered to 50 m (the dam is only 10 m high). At present, we do not have more information.
- **Sambor**: the mitigation is in the choice of a smaller dam. This does not involve the sluicing operation (see also Table 2.3 and Figure 2.8).
- In all dams, the tailwater (and remaining headloss over the structure) remains the limiting factor for the minimal water depth. The numbers mentioned above will probably not be met when tailwaters are high during high flow conditions.

Table 2.9 summarizes the recommended sediment mitigation options and strategy for the mainstream dams.

Table 2.9. Summary of sediment mitigation options and strategy for the mainstream dams.

	OL	TWL at design flow	Min L	Down-ramp	Up-ramp
	m+MSL	m+MSL	m+MSL	m/hr	m/hr
Pak Beng	340	313	323	0.1	0.2
Luang Prabang	310	280	295	0.1	0.2
Xayaburi	275	244	256	0.1	0.2
Pak Lay	240	222	229	0.1	0.2
Sanakham	220	206	213	0.1	0.2
Pakchom	192		182	0.1	0.2
Ban Kum	115		105	0.1	0.2
Latsua	97		90	0.1	0.2
Don Sahong	-		-	-	-
Stung Treng	55		50	0.1	0.2
Sambor	-		-	-	-

2.5 Description of Scenarios

2.5.1 2nd Interim Phase – Northern Lao PDR Cascade

2.5.1.1 Overview

A tentative list of scenarios and options was discussed with MRC member countries in August 2015 and described in Volume 3 of the 1st Interim Report (December 2015). These scenarios was refined and detailed during the 2nd Interim Phase. For the 2nd Interim Phase and the Lao Cascade, focus was on scenarios/sub-scenarios with options related to fisheries and sediment impact mitigation whilst assessing their impact on flow, fisheries and aquatic ecology, geomorphology and sediment transport as well as water quality. The impact assessment was undertaken in three predefined sections, namely:

I. Zone 1: In the cascade itself (Pakbeng reservoir to Sanakham dam),

II. Zone 2: From Sanakham dam to Pakxan, and

III. Zone 3: From Pakxan to Pakse.

Figure 2.14. *Map over cascade reach and the three impact assessment sections/zones (Zone 1 = pink, Zone 2 = green, Zone 3 = orange).*

Tables 2.11, 2.12 and 2.13 give an overview of the scenarios and sub-scenarios in detail and the mitigation options (described in Chapter 2.4) that were tested, cumulatively added and analysed in 3 main scenario groups, namely;

I. The Run-of-River Scenarios (Table 2.10),

II. The Sediment Flushing Scenarios (Table 2.11), and

III. The Hydropower Peaking Scenarios (Table 2.12).

A more detailed description of the scenarios are given in the text following these tables (Chapter 2.4.2).

Table 2.10. Scenarios 1.1 – Run-of-River

	Overview of mitigating measures included in each modelling scenario		
Scenario	**Lower dry-season WL at Pak Beng**	**Flood drawdown of Xayaburi**	**Fish pass (40 m3/s)**
1.1.0	-	-	-
1.1.A	X	X	-
1.1.B	X	X	X

Table 2.11. Scenarios 1.2 – Run-of-River with Sediment Flushing.

	Overview of mitigating measures are included in each modelling scenario				
Scenario	**Lower dry-season WL at Pak Beng**	**Flood drawdown of Xayaburi**	**Minimum flow (Q95)**	**Fish pass (40 m3/s)**	**Start of flushing**
1.2.0	X	-	-	-	1. Aug
1.2.A	X	-	-	-	20. Jun
1.2.B	X	-	-	-	1. Aug
1.2.C	X	-	X	X	1. Aug
1.2.D	X	X	X	X	1. Nov (fast flushing)

Table 2.12. Scenarios 1.3 – Hydropower Peaking.

	Overview of mitigating measures are included in each modelling scenario					
Scenario	**Lower dry-season WL at Pak Beng**	**Flood drawdown of Xayaburi**	**50 cm operation interval**	**Minimum flow (Q95)**	**Fish pass (40 m3/s)**	**Ramping: limitation (< 5 cm/h)**
1.3.0	-	-	-	-	-	-
1.3.A	X	X	X	-	-	-
1.3.B	X	X	X	X	-	-
1.3.C	X	X	X	X	X	-

	Overview of mitigating measures are included in each modelling scenario					
Scenario	**Lower dry-season WL at Pak Beng**	**Flood drawdown of Xayaburi**	**50 cm operation interval**	**Minimum flow (Q95)**	**Fish pass (40 m3/s)**	**Ramping: limitation (< 5 cm/h)**
1.3.D	X	X	X	X	X	X
1.3.E	X	X	X	X	X	Sanakham only

2.5.1.2 Scenarios 1.1 Run-of-river

In Scenarios 1.1, the hydropower plants operate as run-of-river schemes. Except for during floods, the reservoirs will constantly be kept at full supply level, and the discharge through the power station and spillway is equal to the incoming flow. The sub-scenarios constitute the following:

1.1.0 No mitigation measures were applied in this scenario.

1.1.A Introduction of the low water and flood mitigations: Lower reservoir level at Pak Beng by 5 m during the dry season (December to June). Flood protection draw-down at Xayaburi for floods exceeding 7000 - 8000 m^3/s.

1.1.B Same as 1.1.A, but also included the flow requirements for fish passages (40 m^3/s).

2.5.1.3 Scenarios 1.2 Sediment flushing

For routing and scouring sediments in the reservoirs, flushing and sluicing operations aim at drawing down water levels to increase flow velocity and shear rates. This operation is more effective when the water level is drawn down to its lowest possible level and at a faster rate; this will increase the erosion and transport capacity.

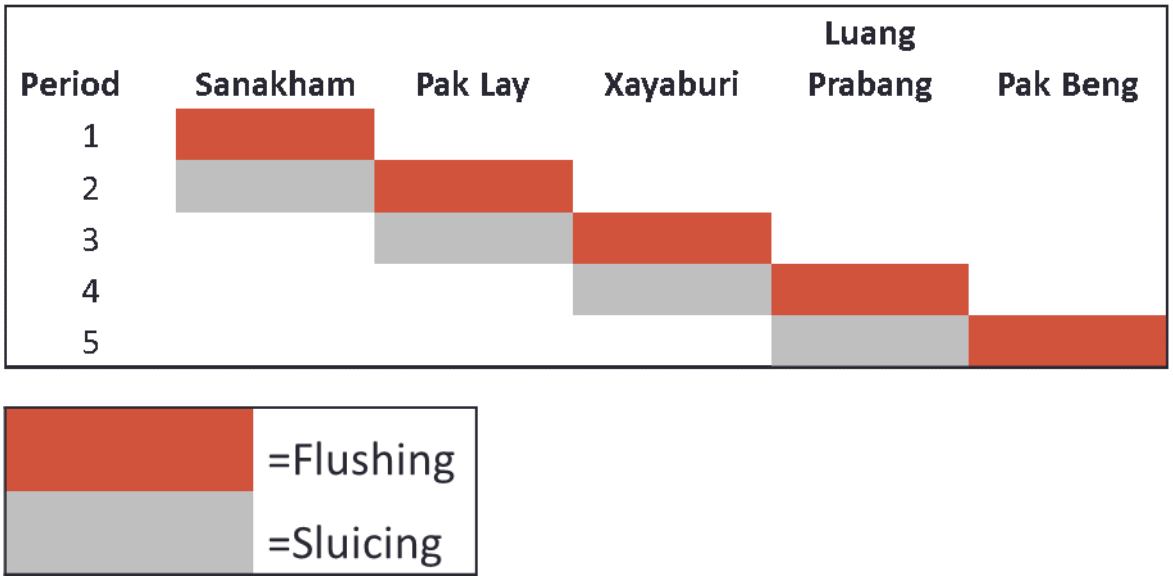
In the sediment flushing scenario's we considered 2 modes:

- Flushing = water levels are drawn as low as possible, with a fixed down-ramping rate of 0.1 m/hr (for minimizing environmental side effects). Faster rates are also tested (for increasing the effect and reducing the duration). During the operation, the power station will go offline when the head water level drops below the MOL. When the lake is fully empty, gates are kept open for 1 day, before the start of filling. For filling a faster rate is proposed (e.g. 0.2 m/hr) than for emptying (0.1 m/hr).
- Sluicing = water level is reduced to and maintained at MOL (minimum operating level, such that power stations can remain online) while the project immediately upstream is being flushed.
- Return the lake to FSL at rate of 0.2m/hr.

In Scenario 1.2, when flushing the full cascade, we proposed a progressive flushing operation, in which reservoirs are flushed sequentially, starting from downstream. The rationale behind this progression is to limit the magnitude of the sediment 'pulse' released from Sanakham to the downstream environment. If the impoundments were sequentially flushed from upstream to downstream, there

is the potential for a very large sediment pulse, as sediment from five impoundments could be released at once. Completing flushing in an upstream direction effectively limits the quantity of sediment to be released downstream to the volume contained in one impoundment only.

Flushing and sluicing operation is then carried out in the following way: start flushing Sanakham (lower reservoir) first with down-ramping 0.1 m/hr, then fill to MOL (allowing power station operations to recommence), and then start flushing of the next reservoir (Pak Lay). Some of the sediment from the lake upstream is sluiced through the downstream reservoir, since it is kept at MOL for that period allowing increased sediment transport (due to increased water slope). After flushing is finished at Pak Lay, the water level in Pak Lay is increased to MOL, and the water level in Sanakham is increased back to normal supply level. This sequence is continued for all reservoirs. The procedure is illustrated schematically in the following diagram. In the model, the first flushing of Sanakham always starts at a fixed date, for simplicity.



Remarks regarding the flushing strategy:

- The start date of the flushing procedure should coincide with the projected onset of high water flows and sediment loads, as flushing is more effective when the flow and sediment inputs to the reservoirs are high.
- The choice of a fixed start date in this analysis was adopted as it allows easier planning and analysis for this study, and decouples the operation from uncertain hydrological conditions. However, it is very well possible that a start date based on forecast floods is a more appropriate choice to improve the effectiveness in real time.
- The progressive flushing sequence should start at the downstream dam and sequentially move upwards. When starting from upstream, the flushed sediment of each dam is expected to accumulate in the next impoundment. Hence, while working downstream, this sediment from upstream cumulates further down, and may lead to increasing sediment loads in the lower reaches. By starting downstream, sediment is pulsed through the cascade in a more controllable way.

The way to operate the cascade is proposed for 4 sub-scenarios as follows:

1. Scenario 1.2a: Carry out flushing and sluicing every year in the proposed progressive

sequence, by starting the draw down every year on **June 20**. Drawdown rate is 0.1 m/hr. The start date refers to roughly the start of the wet season (BDP2030 series), with a 50% exceedance probability discharge of 2100 m3/s and a 90% exceedance probability discharge of 2800 m3/s at Chiang Saen, and with a 50% exceedance probability discharge of 3400 m3/s and a 90% exceedance probability discharge of 4200 m3/s at Sanakham. In this period it is expected that the highest concentrations of fine sediments occur. Filling rate is 0.2 m/h.

2. Scenario 1.2b: Carry out flushing and sluicing every year in the proposed progressive sequence, by starting the draw down every year on **August 1**. Drawdown rate is 0.1 m/hr. The start date refers to a period with high discharges, with a 50% exceedance probability discharge of 3900 m3/s and a 90% exceedance probability discharge of 6000 m3/s at Chiang Saen, and with a 50% exceedance probability discharge of 7300 m3/s and a 90% exceedance probability discharge of 10,000 m3/s at Sanakham. Filling rate is 0.2 m/h.
3. Scenario 1.2c: Carry out flushing and sluicing every year in the proposed progressive sequence, by starting the draw down every year at August 1. Apply a minimum flow requirement during filling, and include fish passage flow during the full flushing cycle. Drawdown rate is 0.1 m/hr, filling rate 0.2 m/h. This scenario is similar to 1.2b, except for the environmental flow and fish passage.
4. Scenario 1.2d: Carry out flushing and sluicing every year in the proposed progressive sequence, by starting the draw down every year on November 1. Apply minimum flow requirement during filling, and include fish passage flow during the full flushing cycle. Drawdown and filling rates is increased to 1.0 m/hr. The start date refers to a period with dropping discharges after the peaks of the wet season. It has a 50% exceedance probability discharge of 3000 m3/s and a 90% exceedance probability discharge of 5000 m3/s at Chiang Saen, and with a 50% exceedance probability discharge of 4600 m3/s and a 90% exceedance probability discharge of 6500 m3/s at Sanakham. A late flushing operation may benefit from the reduced sediment loads coming from the catchments in the second half of the wet season.

All sub-scenarios under 1.2 include dry season draw down at Pak Beng reservoir.

2.5.1.4 Scenarios 1.3 Hydro-Peaking

The 1.3-scenarios have peaking operation. In peaking operation, the hydropower plant is operated to increase the income by generating more power during the peak hours, and less power during the off-peak hours. This is undertaken by storing some of the inflow during the off-peak hours to be used in the peak hours. The reservoir is lowered during the peak period, and filled during the off-peak period. The peak- and off-peak periods is based on the Thailand weekday tariffs (see chapter 3.2). Peak period is from 06:00 to 22:00 hours, while off-peak period is from 22:00 to 06:00 hours.

The following sub-scenarios are used:

1.3.0 No mitigation measures. Peaking of 1-1.5 metres.

1.3.A Lower supply level at Pak Beng during the dry season. Flood protection draw-down at Xayaburi. Maximum peaking is 0.5 metres.

1.3.B Same as 1.3.A, but a minimum flow equal to the Q95 is introduced.

1.3.C Same as 1.3.B, but flow for the fish passages (40 m^3/s) is included.

1.3.D Same as 1.3.C, but limit to the ramping rate during peaking operation (max 5 cm/hour)

1.3.E Same as 1.3.C, but limit to the ramping rate during peaking operation (max 5 cm/hour) at Sanakham only.

2.5.2 Final Phase – Council Study Hydropower Sub-Scenarios

The Final Phase focussed on assessing the impacts of the mainstream dams downstream of the Northern Lao Cascade and tributary dams throughout the catchment. This assessment aligned with the Council Study, with similar scenarios considered, and the Council Study modelling results were used where applicable. The Team provided input to the Council Study Modelling Team In the development of the hydropower sub-scenarios, which are summarised in the following Table. The hydropower sub-scenarios departed from the Council Study Main Scenario 2040 ME with Climate Change (M3CC 2040) and were defined as follows:

Table 2.13. Hydropower sub-scenarios assessed during Phase 4.

No.	Description	Sub-scenario Name	Detailed information
1	Planned Development without LMB Mainstream HPP	H1.a	Planned Development 2040 without any dams in LMB Mainstream, UMB and Tributaries
2		H1.b	Planned Development 2040 with UMB and Tributary Dams
3	Planned Development with LMB Mainstream HPP – No mitigation	H2	Planned Development 2040 with LMB Mainstream, UMB and Tributary Dams without Mitigation Measures for LMB mainstream dams
4	Planned Development with LMB Mainstream HPP – With mitigation	H3	Planned Development 2040 with LMB Mainstream, UMB and Tributary Dams with Mitigation Measures with regard to fish pass, environmental flow and flushing/ sluicing for LMB mainstream dams

Notes:

- Sub-scenarios in the Council Study are based on 2040 development, while the sub-scenarios in the 2nd Interim Phase are based on 2030 development according to BDP (Basin Development Plan).
- The modelling work for the hydropower sub-scenarios in the Council Study were implemented in a way that does not fully quantify the full potential of the proposed mitigation measures. As mentioned previously, notably the sediment mitigation scenarios, but also operations for hydropower are showing differences between the various models, which can very well be explained by limitations of the modelling approaches in the complex system of the Mekong. More rigorous modelling, such as carried out during the 2nd Interim Phase, will provide more realistic and useful quantitative output. Despite these limitation,

the Council Study modelling results clearly demonstrate the role the tributary dams play in altering fish and sediment passage through the system, and the long-time scales that will be required for sediment equilibrium to be established. Additional research and modelling are warranted and recommended by the Council Study modelling team and the Mitigation Guideline project team to provide greater detail and insight as to the potential for mitigation of hydropower impacts the LMB.

Figure 2.15. *Central Mekong floodplain areas near the confluence of Mekong and Tonle Sap, Phnom Penh, Cambodia (Source: ESA, Space Images)*

3. Methods to Assess Mitigation and Economics

3. Methods to Assess Mitigation and Economics

3.1 General Overview

3.1.1 Multicriteria Assessment and Indicator Framework – 2nd Interim Phase – Northern Lao Cascade

The multicriteria assessment and indicator framework developed for the project comprises four large scale criteria that address the potential economic, physical, ecological and biodiversity dimensions associated with development of the cascade, and identifies desired outcomes with respect to hydropower mitigation measures (See table 3.1). Each of the desired outcomes is characterised by one or more sub-criteria that can be linked to quantitative and qualitative indicators. The indicators are further applicable to each scenario group and sub scenarios (1.1 to 1.3) and also assessed at 3 spatial scales as described in chapter 2.5, namely (i) Zone 1 - within the cascade; (ii) Zone 2 - from Sanakham dam to Paksan; and (iii) Zone 3 - from Paksan to Pakse (see also chapter 2.5.1).

Wherever possible, indicators have been identified that can be quantitatively assessed using the modelling results with recent or historic monitoring or modelling results (BDP, Council Study, DSF) providing a context or reference for evaluation, if applicable. Where indicators cannot be directly measured, a qualitative assessment of the indicator has been made based on known relationships and responses of indicators, using Mekong specific information wherever possible.

The indicators coincide well with indicators previously identified by the BDP and other MRC initiatives (Mitigation Guidelines, Council Study). This will make this assessment of the relevant to other investigations and projects.

Table 3.1. Multicriteria indicator framework for ranking for mitigation measures in each scenario group (filled in tables are found in Annex F with main reporting and discussion of results in chapter 5).

Desired generic outcomes	Indicators	Measures
Net economic benefit	Energy revenue	* USD
	Investment in mitigation	* USD
	Value of fishery products	* USD
	Value of sand & gravel downstream	* Million USD Sand & gravel
	Value of silt & clay downstream	* Million USD silt & clay
Maintain flows (flood pulse)	Near natural river flows	* flow volume of the wet season (Mio m^3)
		* duration of the wet season (days)
		* onset of wet seasons (date)

Desired generic outcomes	Indicators	Measures
Maintain existing river channel habitats		
	Sandbanks, riparian zone	* hourly dewatered area for quick downramping operations (ha/hr)
		* length of downstream river section impacted by peaking
		*Changes to channel volume over 1st 7 years (Mm3/yr): + = deposition, - = erosion
	Deep pools, rapids	* quality/quantity of deep pools
		* quality/quantity of rapids
	River dimension	* mean water depth in the cascade
		* mean water surface of the cascade compared to historic condition
Maintain river connectivity	Sediment transfer	* sediment transport - medium sand and larger (*103 ton)
		* sediment transport - fine sand (*103 ton)
		* sediment transport - silt and clay (103 ton)
		* seasonal timing of sediment delivery (% Sed Load during Aug'-Dec)
		* median sediment grain'-size being transported
	Connectivity for fish	* DCI Strahler
		* DCI Migr
		* cumulative upstream passage efficiency in cascade
		* cumulative downstream mortality (large species)
		* cumulative downstream mortality (small species)
		* months with flow velocities <0.2 m/s within the cascade
		* delay of larvae drift in days (for months with velocities <0.2m/s in the cascade)
Maintain water quality	Water Quality	* residence time impoundment during Dry Season (days)
		* turbidity/water clarity (% of time suspended solids <50 mg/L)
		* percent of time with vel <0.4 m3/s
		* turbidity during flushing events
		* nutrient transport (Silt & clay used as surrogate)

Desired generic outcomes	Indicators	Measures
Maintain fish production	Overall fish biomass	* overall fish biomass
Biodiversity	Overall biodiversity	* Biodiversity of fish and aquatic organisms (qualitative)

The initial assessment of the mitigation scenarios is presented and discussed by thematic area (geomorphology, sediment transport, water quality, fish, aquatic ecology, biodiversity) in Chapter 5. These results are then integrated and ranked with respect to the 'desired outcomes' identified for each mitigation scenario. Finally, the rankings are combined to provide an overall assessment of each scenario with respect to the four overarching generic outcomes.

For the cross indicator ranking, a common assessment schema has been developed and constitutes as follows:

Table 3.2. Common assessment schema for indicators.

Scoring by indicators based on measures	Level of significance
+3	Most of the risks are mitigated
+2	There is a significant and substantial increase, some of the risks are mitigated
+1	There is a significant increase, but the increase is still weak
0	No significant effect of mitigation measures (no increase or decrease) compared with base case (no risks are mitigated)
-1	There is a significant decrease, but the decrease is still weak, worse than the base case
-2	There is a significant and substantial decrease
-3	There is a significant and severe decrease
--	Not relevant (indicator not targeted by mitigation measure)

The range set above, indicating positive to negative impact of implementing the scenarios with its mitigation options, used scenario 1.1.0 as the reference for the scoring of the other sub-scenarios and mitigation options. A select set of the most promising indicators, from the table in Annex F, which gave the greatest varieties in scores was chosen for the multicriteria assessment. They were as follows:

1. Energy Revenues (USD)
2. Value of Fishery Products (USD)
3. Sediment Transfer (pooled for the various size ranges)
4. Nutrient Transport

5. Connectivity for fish (pooled DCI indices for the basin)
6. Overall biodiversity loss (fish and other aquatic organism)

These were then cumulatively added (summed up) for each of the scenarios, indicating the range of benefits and impacts. The analysis of the most promising scenarios with regard to this is discussed and reported in Chapter 5.7.

3.1.2 Phase 4 Multicriteria Assessment Approach: Lower Mekong Dams

In Phase 4, multicriteria assessment has been done for geomorphology and sediments solely. The modelling results provided from the Council Study exercise do not include information related to channel geomorphology or sediment grain-size distribution, and do not reflect the full operational details of mitigation measures proposed for investigation. Based on this, a quantitative assessment of 'change' to the geomorphology and sediment transport indicators is not possible, and an evaluation of the potential for mitigation measures to reduce impacts cannot be completely based on modelling results. For these reasons, the indicators contained in Table 3.3 have been qualitatively assessed for potential changes associated with the 2040 hydropower scenario, and the impacts have been assessment with respect to the potential for mitigation based on the range of mitigation options identified by the study team for use in the Mekong. The assessment scale is summarised in Table 3.4, risk assessment of the 2040 scenario, and the assessment draws on modelling results, reports prepared by the Council Study modelling team, and the Council Study BioRa team.

Table 3.3. Indicator framework for the Phase 4 assessment.

Desired generic outcomes	Indicators	Measures
Maintain existing river channel habitats	Sandbanks, riparian zone	*Changes to channel volume + = deposition, - = erosion
	Deep pools, rapids	* quality/quantity of deep pools
		* quality/quantity of rapids
	River dimension	* mean water depth in the cascade
		* mean water surface of the cascade compared to historic condition
Maintain river connectivity	Sediment transfer	* sediment transport - medium sand and larger
		* sediment transport - fine sand
		* sediment transport - silt and clay
		* median sediment grain'-size being transported

Desired generic outcomes	Indicators	Measures
Maintain water quality	Water Quality	* residence time impoundment during Dry Season (days)
		* turbidity/water clarity (% of time suspended solids <50 mg/L)
		* percent of time with vel <0.4 m3/s
		* turbidity during flushing events
		* nutrient transport (Silt & clay used as surrogate)

Table 3.4. Phase 4 assessment scale.

Potential degree of impact	Potential for successful mitigation
1 – Low: Post-2040 scenario will not result in substantial change relative to baseline	1-There is a high potential for mitigation measures to substantially reduce impacts
2-Moderate: Post-2040 scenario will result in substantial change relative to baseline	2-There is a moderate potential for mitigation measures to substantially reduce impacts
3-Post-2040 scenario will result in major change relative to baseline	3-There is very low potential for mitigation measures to substantially reduce impacts

3.1.3 Hydropower Design Criteria of Lao Cascade and Downstream Dams

The layout and design of the mainstream Mekong hydropower schemes will be conventional and follow established practice for projects of this type in other parts of the World. However, the introduction of environmental mitigation measures will require additional design considerations, also with reference to the PDG (MRC, 2009). The most important of these considerations are described in the subsequent sub-chapters. The design details for the majority of the cascade were not available to the study team apart from the Xayaburi project, which has been studied in detail for the PNPCA process over a number of the preceding years.

3.1.3.1 Upstream migration facilities

The design criteria for upstream and downstream fish passage have been discussed in detail in the Manual (MRC, 2016). As noted above, very few details of fish passage design were available for this analysis. Therefore, as the Xayaburi project includes a complex fish passage system for upstream and downstream migration, we assumed in our study that similar arrangements will also be implemented for the other mainstream schemes (see also Chapter 2.2). An important consideration for the Mekong projects are the very large attraction flows that are required, these systems have been designed to minimise the generation loss that would otherwise be associated with large attraction flows. The general arrangement is shown in Figure 3.1.

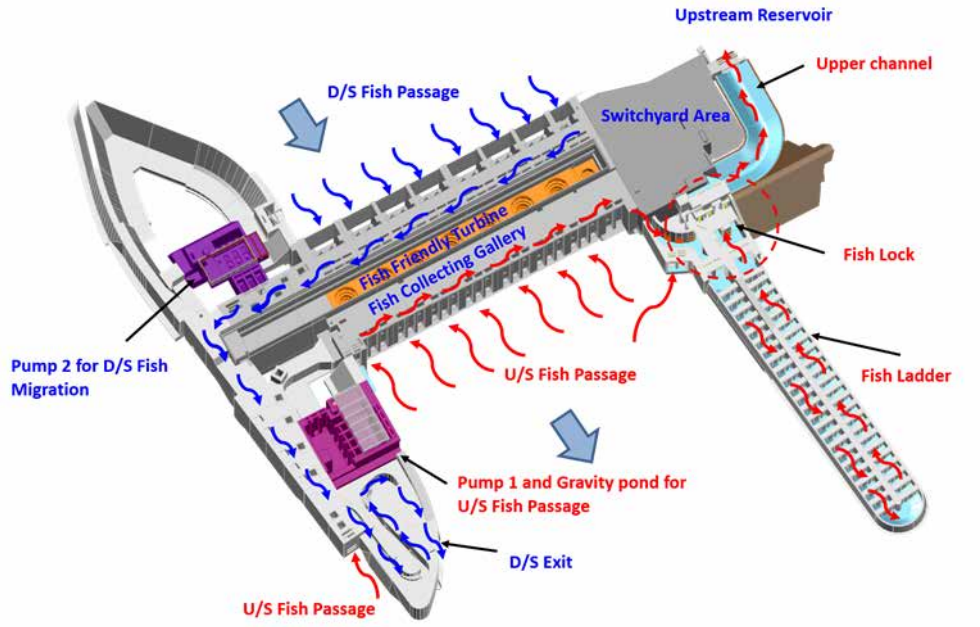


Figure 3.1. *Xayaburi Fish Passage System (Source: XPLC).*

The upstream fish passage system comprises a series of collecting galleries with various openings above the turbine draft-tube outlets, entrances at the lower velocity zones at the left and right ends of the power station, and an entrance at the spillway sidewall in the intermediate block. This system requires a combined attraction flow of 90 m3/s during the dry season and 240 m3/s during the wet season. These figures are significant when compared to the design generation flow for the project of 5,352 m3/s. To minimise energy loss some of the attraction flow is delivered from the tailwater by Pumping Station No 1. When the river discharge increases above the full station capacity in the wet season, water from the head pond can be used to feed the system without generation loss.

The design head for Pumping Station No 1 is 2.85 m and the discharge varies between 73 and 160 m3/s depending on tailwater level. The remainder of flow in the system comes from the fish ladder and from the head-pond once spilling is in progress. A scheme of the system is shown in Figure 3.2.

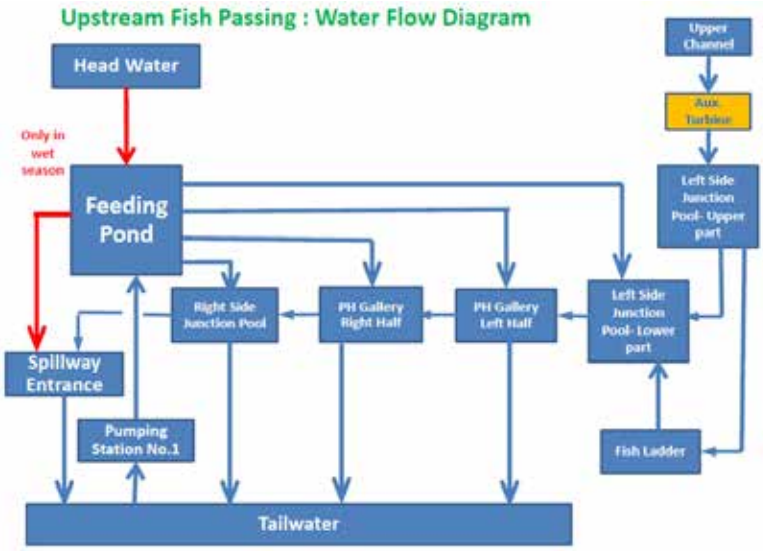


Figure 3.2. *Upstream Fish Migration Scheme (Source: XPLC).*

Once fish have been attracted into the system a fish ladder and double lock system on the left bank provides passage to the head pond. The ladder requires a discharge of up to 40 m3/s, which is delivered via 2 x 4 MW auxiliary turbines powered by water from the head pond. This arrangement recovers some of the energy loss resulting from the flow bypassing the power station. The head on the auxiliary turbines is approximately 22 m. This energy is used for station services. The combined system largely avoids the generation loss that would otherwise occur during the dry season to provide the required upstream attraction flow of 90 m3/s. The assumed loss due to the fish passage is estimated to 40 m³/s. This value is chosen as a constant release for all dams (see also Chapter 2.4).

Fish migration has been extensively studied in the Xayaburi project. Some key issues are summarized as follows:

A DIDSON camera was used to assess the time and biomass of migrations. The results identified a migration peak in May (onset of the wet season) with 1,200 kg/hr on average and peaks up to 5,000 kg/hr. 60 to 70 % of the species were less than 30 cm long. A total of 120 species were sampled which are also widely found throughout the middle Mekong, with several considered as migratory. 28 species were selected for further assessments (e.g. swimming abilities) considered for fish pass design. The tests resulted in swimming speeds of 8-20 BL/second. Consequently, the maximum flow velocity was set to 1.4 m/s with some slots also providing lower velocities (see figure 3.3). The slots are between 0.5 and 1.6 m wide. The individual pools are 10 m long and 18 m wide and have an energy density of <45 W/m. The total length of the fish pass is 460 m and has a slope of 1.2 %. At the upstream end of the technical fish pass, two transfer facilities (i.e. combinations of fish lifts and fish locks) are installed which show a minimum depth of 4 m and are 5 m wide. The small channel connecting the fish lift to the headwater is equipped with a monitoring station (Coe, 2015).

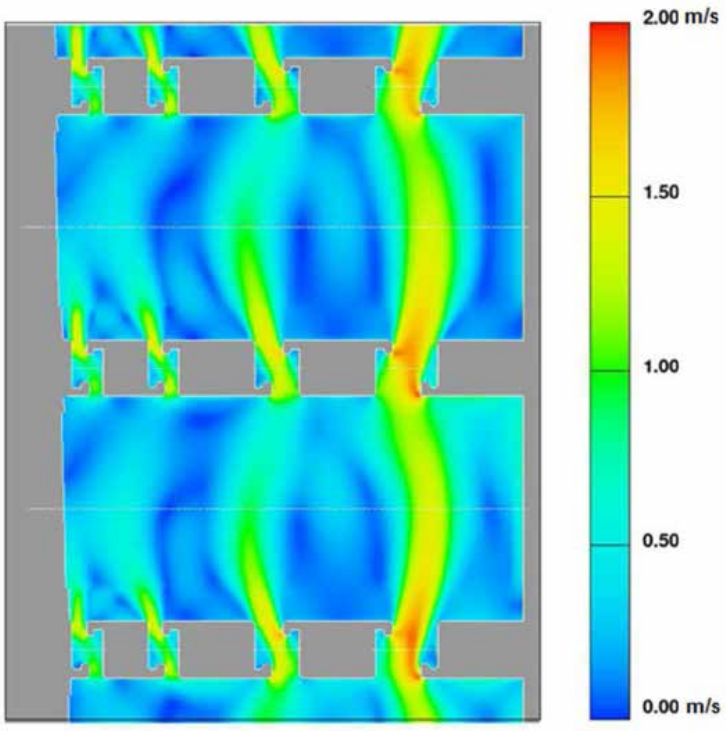


Figure 3.3. *Flow velocities in the upstream fish pass (Coe, 2015).*

In addition to the fish pass, the ship lock was fitted for fish passage during the construction period and equipped with a crowder. However, as this option might not be perceptible without sufficient spillflow on the right side of the dam, this option is only supported during the wet season. There is room for an additional fish lift, which could be added at a later stage if considered necessary.

The effectiveness of the fish pass system needs to be studied and monitored once Xayaburi is put in operation in 2019.

3.1.3.2 Downstream migration facilities

For downstream migration, three different passage routes are available for fish: the turbines, the spillway and the downstream migration facility (chute). Some individuals might also find their way through the ship lock, but their proportion is considered as negligible.

In general, the power generation flow will be the most dominant attraction for downstream migration. Since most fish follow the main current or are passively transported by it (especially ichthyoplankton), a large proportion of downstream migrating fish will choose this route. In order to reduce fish injury and mortality the turbine design has been modified as follows:

- the number of blades has been reduced from 6 to 5;
- the machine speed has been reduced from 125 to 83.3 rpm;
- introduction of minimum gap geometry;
- improved guide vane geometry and
- adoption of oil free runner hub designs.

Similar designs adopted on other “fish friendly” turbines result in reduced fish injury and mortality. Reducing the rotational speed of a turbine requires a physically larger machine and power station building.

The clear bar spacing on the trash screens at Xayaburi is 120 mm wide, which will exclude fish larger than 100 cm in length. A conventional rectangular screen bar profile has been adopted. Rounded leading edges and curved profiles can contribute to reduced fish injury. Retrofitting is possible, if required.

When the river discharge exceeds the full station capacity the opened spillway gates will provide an additional route for downstream fish migration in the right channel. However, since both turbine and spillway passage may be related to injuries, a collecting gallery with openings above the power intakes is provided for surface oriented fish. An attraction flow of 120 m3/s for this system is provided from the head pond. This discharge into an upper collecting pond, which is then intermittently sluiced down a chute to the tailwater once sufficient fish have been collected. A minimum depth of 2 m is ensured in the chute. It is anticipated that sluicing will occur approximately three times per day. Water in the collecting pond is then pumped back to the head pond by Pumping Station No 2. With this arrangement, only a small proportion of the downstream attraction flow of 120 m3/s is lost to generation (Morier-Genoud, 2015).

3.1.3.3 Low Level Sluices

The reservoir sluicing strategy envisaged in Scenario Group 1.2 (of the 2nd Interim Phase) requires the incorporation of low-level sluices in the design of the mainstream Mekong projects. Low-level sluices are specifically required for the Xayaburi project to limit upstream back water levels during flood events. Low-level sluices provide a component of the required spillway discharge capacity and their provision is therefore not additional. However, it is generally more costly to provide low-level flood control structures than simple gated crest arrangements. The division of spillway capacity between surface gates and low-level sluices depends on the release capacity required to draw down the reservoir.

A typical distribution of high and low level gates is shown in Figure 3.4. An important consideration when selecting the gate configuration for this type of arrangement is to avoid re-circulation in the downstream discharge since this can cause damage and inefficient operation. Longitudinal dividing walls between the high and low level sluices are often required to supress this phenomena. A physical model is generally required to finalise the layout and determine acceptable sequences for gate opening. This has been undertaken for the Xayaburi design.

Low-level sluices are also required to convey sediment loads and this requires consideration in their design. A lintel sealed radial gate is generally adopted for this application because this type of gate does not require slots in the sidewalls. Slots tend to become locations for sediment accumulation although water jets can be incorporated in the base of the slots to keep them clear.

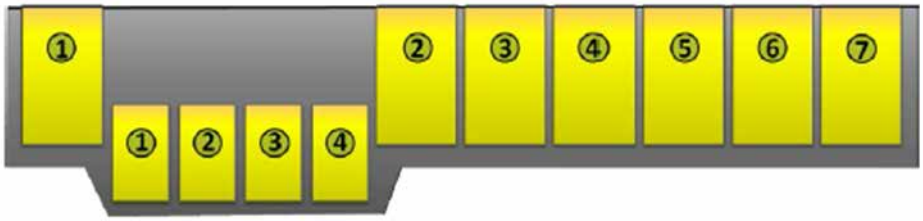


Figure 3.4. *Typical High and Low Level Outlet Gates.*

Sluices designed for sediment discharge can be subject to abrasion. This can normally be resisted by suitable choice of concrete mix design, particularly compressive strength and selection of a high aggregate abrasion value. The introduction of polypropylene fibres is sometimes adopted when the sediment comprises gravels and cobbles that might otherwise cause impact damage.

3.1.3.4 Navigation Locks

The normal operation of the mainstream projects in Scenario Group 1.1 and the peaking operation envisaged in Scenario Group 1.3 will not require any usual design provisions for the navigation locks. However, the large reservoir level changes proposed in Scenario Group 1.2 will require careful consideration. Similar considerations needs to be taken into account for the H3 hydropower sub-scenario for the Final Phase. River navigation will not be possible during the reservoir sluicing and flushing as most river craft will be stranded during this operation (estimated duration for fast flushing is 4 days, more modest down-ramping rate of 0.1 m/hour will take 11-12 days for Xayaburi). The large changes in river level will impose usual design conditions on the navigation locks and lock gates and these conditions will need to be taken into account when the structures are designed.

3.1.3.5 Turbine Design

The sluicing and flushing programme proposed in Scenario Group 1.2 (second interim Phase) and H3 (Final Phase) will result in high volumes of sediment in suspension passing through the waterways. It may be possible to reduce the commercial loss resulting from this process by keeping the turbines running for some of the sluicing and flushing cycle. The density of sediment in suspension and the minerology should be monitored during this operation and the generating plant should be shut down if damaging levels of sediment concentration are reached. Abrasive minerals, particularly quartz, can cause extensive metal loss and damage the profile of the turbine runner blades, causing a permanent loss of efficiency. Various types of surface hardening and protective coatings are available for turbine blades but these require specialist maintenance. Guide vane and stay vane assemblies are also susceptible to abrasion damage and are less straightforward to repair.

A further challenge caused by high turbidity is the choking of cooling water filters. Low cost cooling water designs are usually based on a primary circuit where water is drawn from the river, passed through the plant cooling water system and then returned to the tail bay. These raw water systems need inline strainers to remove suspended particles from the cooling water, and these strainers can become quickly clogged if sediment loads are too high. Duty and standby systems are always provided but if the back flushing process cannot be undertaken sufficiently quickly then the filter will choke and generating plant will need to be shut down.

3.1.4 Criteria for Different Modes of Hydropower Operation

The normal operating Scenario Group 1.1 does not represent any usual operating challenges since it is a pure run of river approach. Generation forecasting will form an important part of the normal declaration procedure and data from a catchment hydrometric system and dispatch patterns of upstream schemes will be required. Protocols for information sharing will need to be developed by the owners of the different schemes on the cascade.

Similarly, the peaking operations considered in Scenario Group 1.3 will not create any unusual operational challenges provided the peaking cycle remains within agreed limits and operating plans are shared between the projects. A key constraint for peaking will be the time required to restore the reservoir level during the off peak period whilst maintaining a suitable minimum downstream flow. Peak and off peak discharges and periods will need to be developed within agreed constraints and details of the proposed sequence will need to be shared with projects downstream.

The reservoir sluicing and flushing strategy proposed in Scenario Group 1.2 will require a much greater level of co-ordination and planning between the projects on the Mekong. ***This is achievable but the commercial challenges and cost of lost generation will be considerable*** (see also results on effect of revenue in chapter 5.2). The current structure of Concession Agreements and Power Purchase Agreements is not designed to accommodate such detailed co-ordination between projects. ***It is likely that a river basin management authority would be required to manage such process and to regulate commercial arrangements with power off takers***.

In the long term, a more manageable approach would be for the developers to be paid for available capacity and not energy. The projects could then be dispatched by a central authority to achieve optimal cascade performance within defined environmental limits. Examples of such an arrangement with successful undertaking can be found for the Glomma and

Laagen Basin Management Authority in Norway (Lillehammer, 2011) [15]. This approach would make it more straightforward commercially for the downstream scheme to be operated differently in order to re-regulate disturbances to the natural river discharge introduced by the upstream projects.

3.2 Sites for criteria assessment

3.2.1 2nd Interim Phase – Northern Lao PDR Cascade

For the impact and mitigation assessment, some criteria were assessed on a larger scale, while others were calculated for discrete sites along the study area (i.e. within and downstream of the cascade; see also Figure 3.5). Furthermore, some of the sites were named according to cities or villages, while others were chosen on the basis of their respective locations within or downstream of the cascade (e.g. based on a certain distance). For those cases, the ISIS cross section code was used as a reference.

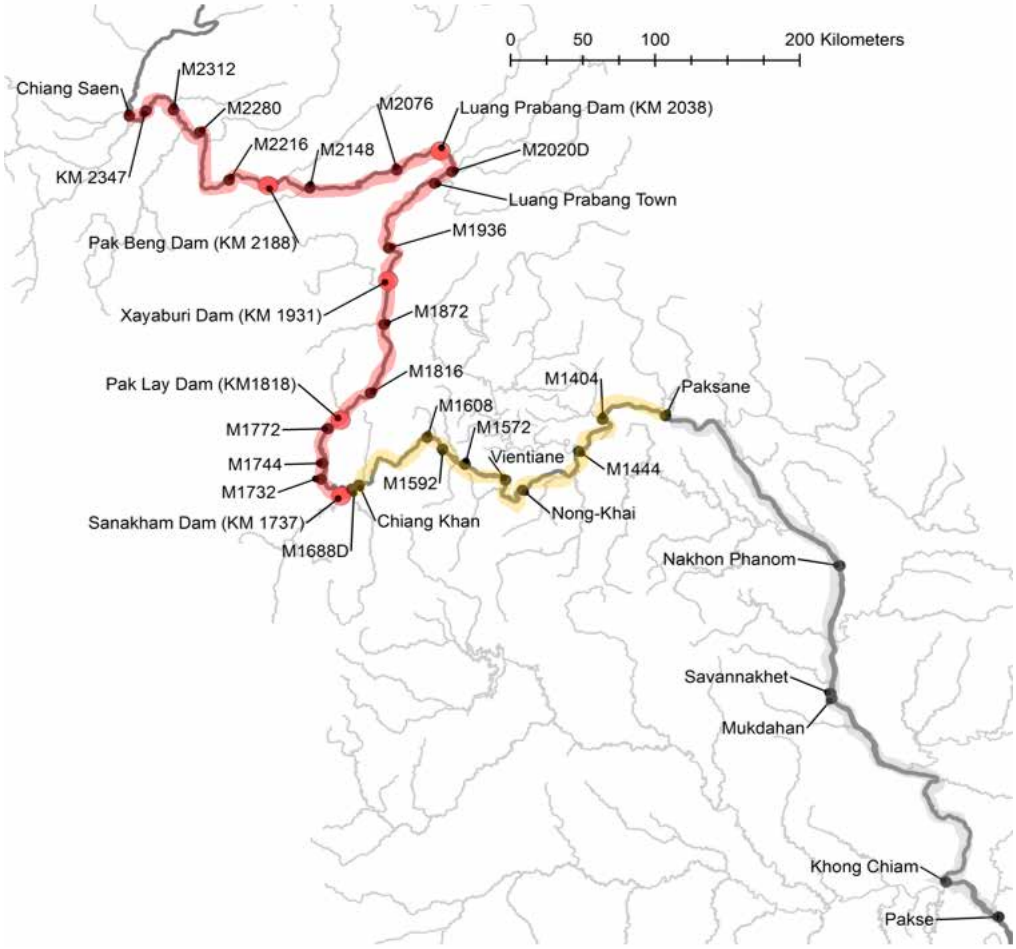


Figure 3.5. *Assessment sites (points) and zones (red = upstream of Sanakham dam; yellow = between Sanakham dam and Paksane; grey = Paksane to Pakse) along the Mekong mainstream (for some sites, river-km are indicated in brackets).*

At the dam sites, there has to be a distinction between measurements taken a) upstream of the dam (headwater), b) on the upstream side of the dam wall or c) downstream of the dam (tailwater). This is for instance relevant for the differentiation of water level measurements (e.g. in the headwater

vs. in the tailwater) and discharge measurements, which take place at the dam site. Therefore, the following codes were utilized (see table 3.5).

Table 3.5. Differentiation of measurement locations (i.e. dam, headwater and tailwater) at the hydropower plants.

Hydropower plant	Dam	Headwater (dam + U for "upstream")	Tailwater (dam + D for "downstream")
Pak Beng	PB	PBU	PBD
Luang Prabang	LP	LPU	LPD
Xayaburi	XB	XBU	XBD
Pak Lay	PL	PLU	PLD
Sanakham	SK	SKU	SKD

The results of the impact- and mitigation assessment will be presented for different zones along the Mekong mainstream (see also figure 3.5).

1. Red The cascade itself (upstream of Sanakham Dam)
2. Orange Immediately downstream of the cascade (Sanakham Dam to Paksane) and
3. Grey The section downstream of Paksane to Pakse, without the main-stream dams of the lower cascade.

The area downstream of Pakse to the delta, including the Tonle Sap system Has been studied in the Final Phase of the project, see next sub-section.

3.2.2 Final Phase – Lower Mekong Dams

Hydrology: For the lower cascade and downstream reaches, the most relevant criteria for seasonal and sub-daily flow variations can be assessed by considering a fixed number of locations at water-level gauging sites, as well as up- and downstream (tailwater) of the main-stream dam sites. Similar to the assessments in the 2nd interim phase, there is a distinction between assessments within the lower cascade, and far downstream of the cascade (such as impacts to Tonle Sap, and the delta).

Geomorphology & water quality: The sites assessed with respect to geomorphology, sediment transport and water quality in Phase 4 are limited to locations downstream of hydropower dam sites, and the 'Focus Area' locations identified by the BioRa component of the Council Study.

Fisheries and Aquatic Ecology: Since no in-depth modelling was performed in the final phase with regard to fisheries and aquatic ecology, no distinct locations were used. However, the qualitative assessment considered the assessment of other thematic fields which were either drawn at distinct locations (e.g. dam sites) or at a larger scale (e.g. downstream of the cascade or BioRa zones used in the Council Study).

3.3 Methods to Assess Hydrologic and Flow Changes

3.3.1 2nd Interim Phase – Northern Lao PDR Cascade

3.3.1.1 Seasonal flow distribution

The flow regime of the Mekong is characterized by a distinct hydrological cycle of wet- and dry seasons. The Mekong's rich ecosystem has evolved in accordance with this cycle, which is why any alteration can impact distinctive ecosystem functions (MRC, 2009). While the Chinese (UMB) and tributary dams have already altered the hydrologic cycle (e.g. higher dry season flows, delay of wet season, lower wet season flows) it is expected that the ***case study cascade has a comparable low impact on the seasonality of flows*** (see also chapter 5.3 for a more detailed discussion on this).

For this study wet season is defined as the time when the 5-day averaged flow exceeds or undercuts the long-term annual mean flow (MRC, 2009). For the impact- and mitigation assessment, the following parameters are considered as important and were calculated on the basis of the output of the DSF models in combination with additional models for more specific purposes, such as HEC-ResSim, Mike 11 and Delft3D:

- The ***change of flow volume of wet and dry season*** is important for assessing the overall distribution of annual flows to the wet and dry season. Especially wet season flows provide a good indication on the flow reversal at Tonle Sap and inundated areas. Therefore, a shift of flows from the wet to the dry season can have a huge impact on floodplain habitats.
- The ***onset of the wet season*** plays a key role in triggering spawning and feeding migrations. Especially a delay of the wet season can therefore cause delays in spawning and consequently limit the subsequent time for feeding, both for adult and juveniles.
- As not only the onset of the wet season, but also its duration is of ecological importance e.g. reflecting the time available for feeding, any ***changes to the duration of the seasons*** may cause an impact.
- As aquatic organisms show a strong reaction to hydrologic extreme values, ***maximum and minimum flows*** are assessed and compared between scenarios. The dry season flows reflects the time of the year when aquatic organisms suffer from limited habitat availability and poor water quality. The lowest discharge in this season represents a good indicator for the stress experienced by the ecosystem. While an increase of dry season flows might be beneficial for aquatic organisms, a reduction of high flows can cause the loss of floodplain habitats and reduce overall productivity.

Consequently, the following indicators were selected:

Table 3.6. Seasonal flow indicators.

Indicators	Assessment methodology	Sites and scenarios
5-day averaged flow [m³/s] (as basis for the other indicators)	Hourly data of MIKE-11 transformed to 5-day averaged flow by calculating the mean for the previous 4 days and the actual day	- Zone 1 (M2020,upstream of Luang Prabang town) - Zone 2 (M1572, upstream of Vientiane) all scenarios (except 1.2.C and 1.2.D)
Wet season onset [date]	First day of the year the 5-day averaged flow exceeds the mean flow	
Wet season end [date]	First day of the year the 5-day averaged flow undercuts the mean flow	
Wet season duration [days]	Wet season end minus wet season onset = duration in days	
Flow volume of the wet season [Mio m³]	Summed up wet season flows	
Daily flow characteristics	Statistics based on the daily average flow	

The indicators were calculated for all scenarios except 1.2.C and 1.2.D, which followed at a later stage of modelling. However, due to the marginal modifications of these scenarios compared to scenarios 1.2.A and 1.2.B, similar results are assumed. The sites were selected to assess the condition within the cascade (i.e. at M2020 upstream of Luang Prabang Town), and downstream of the cascade at M1572 upstream of Vientiane, which is the most downstream assessment point of Mike11/HEC-ResSim. No assessments were made downstream of Paksane, but the upstream two sites are considered to be sufficient for transferring the outcomes to the third impact zone (i.e. downstream of Paksane).

3.3.1.1.1 Seasonal changes in zone 1 (historic, BDP 2030 and Scenario 1.1.0) – Lao Cascade

The following graphs and tables compare the above described indicators for the historic, the BDP 2030 Scenario and Scenario 1.1.0. The wet season onset and duration are provided in table 3.7. The end of the wet season is not given separately, as it is included in the duration of the wet season. However, the detailed results are given in Annex D1. ***It is clearly visible that the greatest change occurs between the historic and the BDP 2030 scenario, since the Chinese cascade and storage dams in the tributaries have a higher influence on the seasonal flow distribution than the five cascade dams in the upper LMB***. Under undisturbed conditions (i.e. historic) the onset of the wet season used to be earlier in the year, tended to be a little longer and less variable, compared to the BDP 2030 and 1.1.0 Scenario.

Table 3.7. Onset and duration of the wet season in zone 1 (M2020) for the historic, BDP 2030 and 1.1.0 Scenario.

	Wet season onset	Wet season duration
historic	14 Jun ±36 days	152 days ± 36 days
BDP 2030	26 Jun ±39 days	142 days ± 37 days
Sc. 1.1.0	25 Jun ±39 days	142 days ± 37 days

The flow volume of the wet season used to be higher under historic conditions but is comparable between the BDP 2030 and the 1.1.0 Scenario. Figure 3.6 shows the minimum, mean and maximum wet season flow volume upstream of Luang Prabang town (M2020).

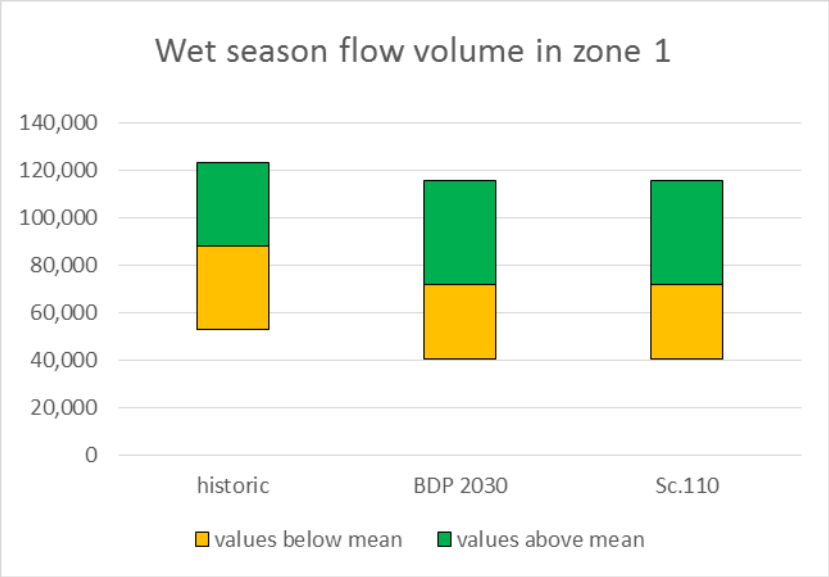


Figure 3.6. *Summed wet season discharge (in Mio. m³) in zone 1 (M2020).*

3.3.1.1.2 Seasonal changes in zone 2 and 3 (historic, BDP 2030 and Scenario 1.1.0) – Lao Cascade

The same results were prepared for zone 2 on the basis of the site M1732 (upstream of Sanakham dam). It can be seen that the variability of the onset of the wet season is lower compared to zone 1, however the date and duration are approximately the same. For the three different scenarios, the same picture as for zone 2 can be seen, which is a clear change from historic to BDP 2030 but no significant further alteration with the cascade. Table 3.8 and Figure 3.7 show seasonality and the summed flows of the wet season in zone 2.

Table 3.8. Onset and duration of the wet season in zone 2 (M1572, Vientiane) for the historic, BDP 2030 and 1.1.0 Scenario.

Scenario	Wet season onset	Wet season duration
historic	21 Jun ±18 days	146 days ± 24 days
BDP 2030	24 Jun ±18 days	142 days ± 23 days
Sc. 1.1.0	21 Jun ±19 days	143 days ± 24 days

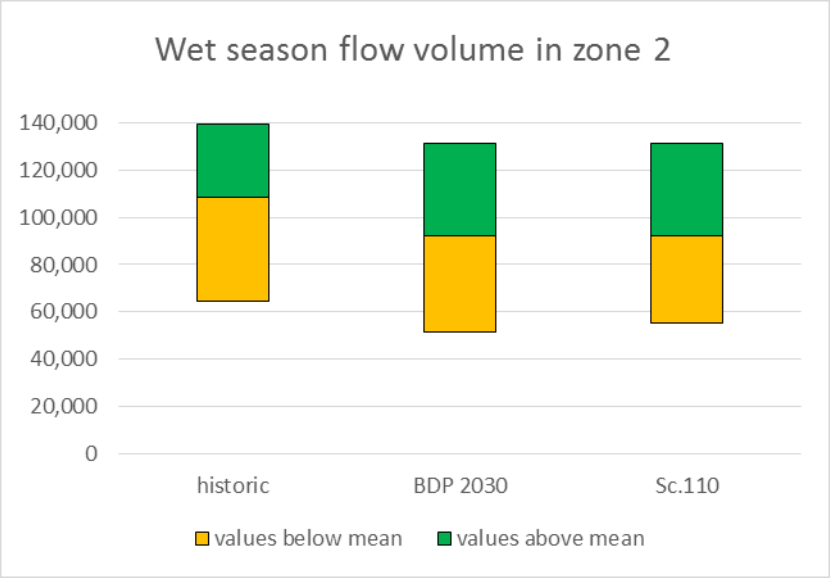


Figure 3.7. *Summed wet season discharge (in Mil. m³) in zone 2 (M1572, Vientiane).*

For zone 2, also the daily flow characteristics were assessed and compared for un-impacted (historic) and impacted conditions (BDP 2030 and 1.1.0 Scenario). Figure 3.8 provides a comparison of the flow duration curve for the three scenarios. While the BDP 2030 and the 1.1.0 Scenario are barely distinguishable, there is a clear difference to the historic condition. Figure 3.9 provides a more detailed picture of the individual values, which shows that the BDP 2030 and the 1.1.0 Scenario differ slightly especially for low and high flows. However, these differences are mostly caused by short-term fluctuations in modelling and are therefore considered to be negligible.

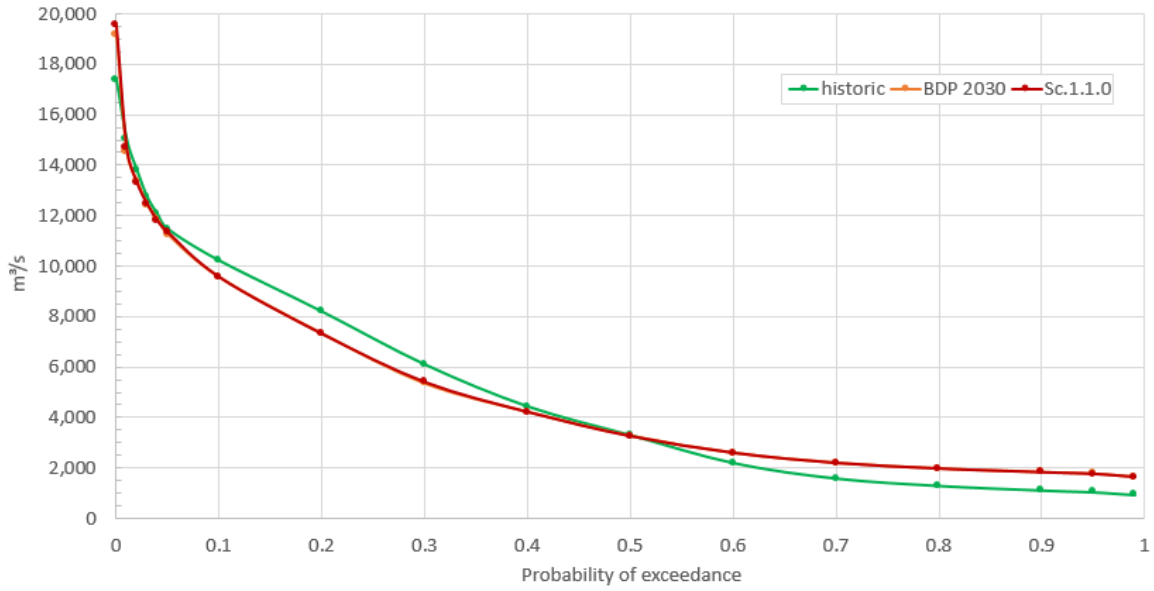


Figure 3.8. *Flow duration curve downstream of the cascade (M1572, Vientiane) for historic, BDP 2030 and 1.1.0 Scenario.*

No additional assessments were made for zone 3, but it can be concluded from the similarity of zone 1 and 2 (see Figure 3.10.) that the same reaction can be expected in zone 3.

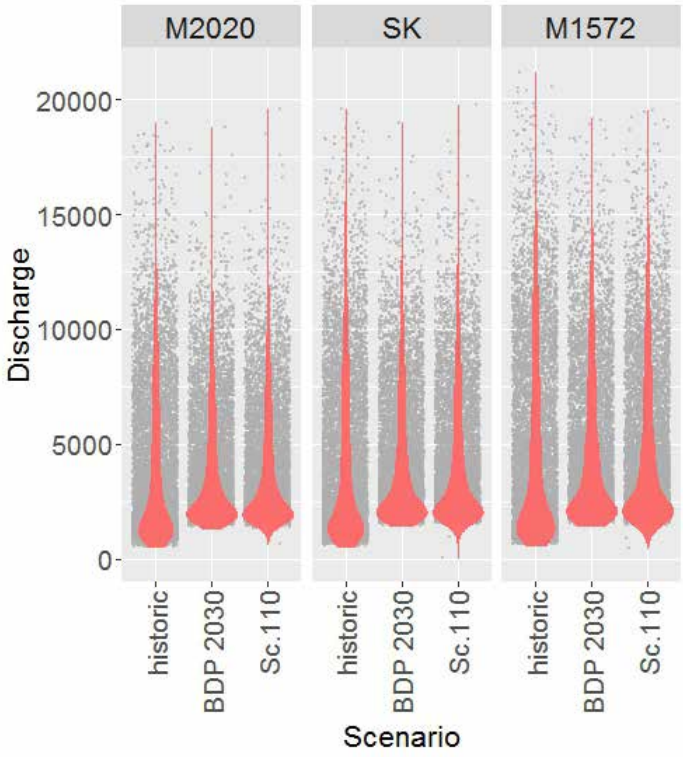


Figure 3.9. *Violin plots showing the daily flow distribution (in m³/s) for historic, BDP 2030 and 1.1.0 Scenario in zone 1 (for M2020, Luang Prabang, and Sanakham dam) and zone 2 (M1572, Vientiane).*

3.3.1.2 Sub-daily flow distribution

3.3.1.2.1 Lao Cascade

Besides seasonal flow shifts also daily and sub-daily variations in flow have to be assessed. As already described in chapter 2.4 scenario 1.3 assesses possible impacts and mitigation measures with regard to hydro peaking.

As hydropeaking events are not present in the historic, BDP 2030 or 1.1.0 Scenario, the assessment of peaking indicators is not relevant for these scenarios. It can only be stated, that the three scenarios do not differ with regard to hydropeaking. However, the indicators selected for comparing scenarios 1.3 (peaking scenarios) and maybe 1.2 (flushing scenarios) are described in this chapter.

The hydropeaking events are assessed within the cascade as well as downstream of the cascade. In general, it is important to assess how often downramping occurs faster than 5 cm/hour. Furthermore, since we are assessing a cascade of several peaking dams in scenarios 1.3.0 to 1.3.E the behaviour of peaking waves within the impoundment is of interest. This is, however, undertaken in a qualitative way. Furthermore, as detailed information is available for the impoundments (extracted from the Delft3D model (described in chapter 4.3.3 and Annex A, see also table 3.9) the dewatered area for downramping events can be assessed. In a first step, the impounded area was calculated for the highest and lowest water level of each impoundment. Assuming a linear relationship the impounded area can be calculated for each intermediate water level (see figure 3.10). Consequently, the dewatered area for each downramping event occurring faster than 5 cm/hour (assessed on the basis of MIKE11 data) can be calculated and compared between different months and scenarios.

Table 3.9. Impoundment characteristics (source: Delft3D schematisation).

	Length (km)	Water level (masl)	Volume (Mio. m³)	Area (km²)	Mean depth (m)	Mean width (m)	Dewatered width (m)	Dewatered area (km²)
Pak Beng	183.2	340	664.7	47.94	13.87	261.68		
	183.2	335	455.3	36.08	12.62	196.94	64.74	11.86
Luang Prabang	137.4	310	1,211.0	47.22	25.65	343.67		
	137.4	305	985.3	43.27	22.77	314.92	28.75	3.95
Xayaburi	127.5	275	1,107.0	66.09	16.75	518.35		
	127.5	270	795.1	55.74	14.26	437.18	81.18	10.35
Pak Lay	117	240	1,312.0	69.01	19.01	589.83		
	117	235	988.2	60.88	16.23	520.34	69.49	8.13
Sanakham	75	220	749.5	56.05	13.37	747.33		
		215	485.3	51.36	9.45	684.80	62.53	4.69

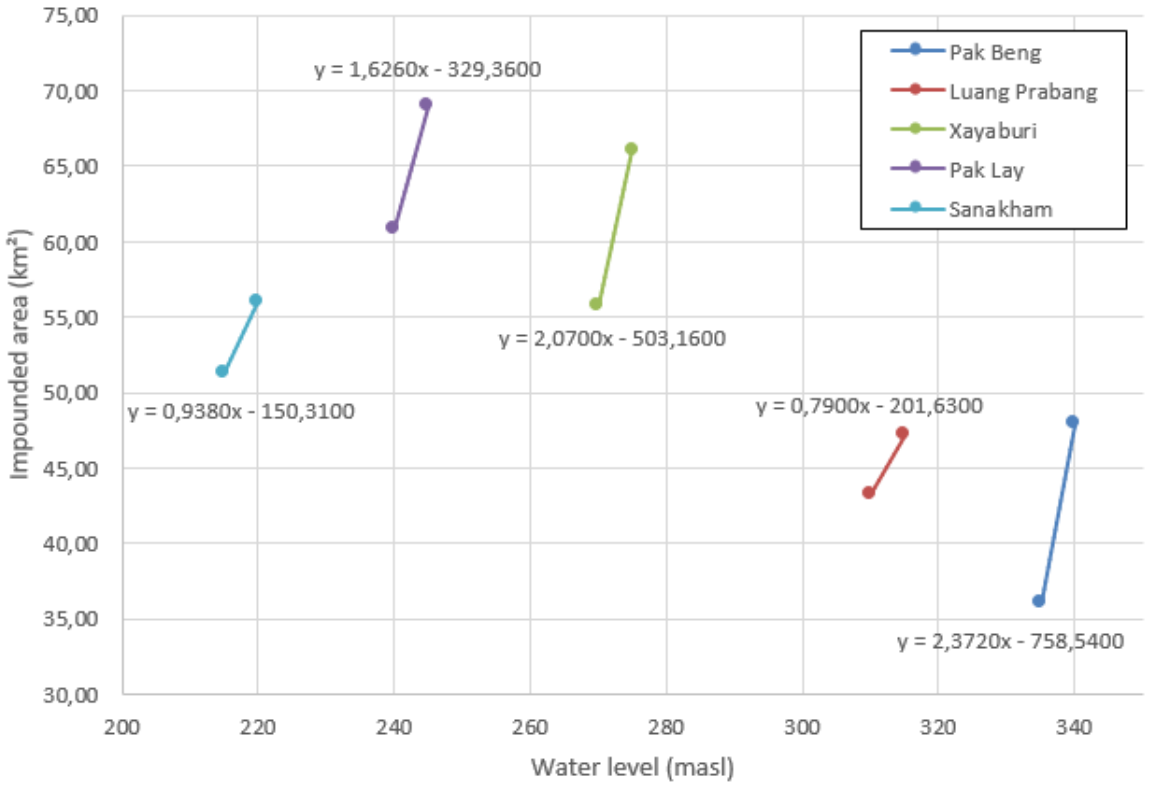


Figure 3.10. *Formula used for calculating the impounded area based on the headwater level.*

In downstream direction, the calculation of the dewatered area is not possible since the river does not show a more or less constant water level (as it is the case in the impoundment). Therefore, only the distance over which severe peaking events (>5 cm/hour) occurs before the waves are smoothened by flow retention and entering tributaries, is measured.

The following Table 3.10 provides a summary of the above described indicators:

Table 3.10. Indicators for sub-daily flow conditions.

Indicators	Assessment methodology	Sites and scenarios
Percentage of hours per month where downramping occurs faster than 5 cm/hour	MIKE-11 hourly data, calculation of water level changes and subtraction of values exceeding the threshold	For scenarios 1.2 and 1.3 and 4 sites within each impoundment as well as Luang Prabang town
Behaviour of peaking waves in impoundments	Qualitative comparison of 7-day period in January (dry season)	
Dewatered area for downramping event occurring faster than 5 cm/hour	Calculation of impounded area at each water level – calculation of hourly area-changes	For scenarios 1.3 and headwaters of each dam (PBU, LPU, XBU, PLU and SKU)
Length of downstream river section impacted by severe peaking	Measurement of downramping rates and amplitude at several sites downstream of the cascade	For scenario 1.3.C in January and June and several sites downstream of the cascade

3.3.2 Final Phase

3.3.2.1 Conceptual Level Assessment

3.3.2.1.1 Lao Cascade - Alternative Schemes Layout and Partial Cascade Development

Similar to the previous phase, the indicators for seasonal flow and sub-daily flow variations, apply to the modified schemes. As in general the mainstream dams in the Lao Cascade are all operated as 'run-of-the-river' schemes, meaning that their active volume is small, the downstream impacts have been shown to be quite small. This will not change for the alternative scheme layouts and partial development. The larger impacts of the Chinese dams and the tributaries completely overshadows any minor influence of the Lao mainstream cascade.

3.3.2.1.2 Downstream Dams

The design principles investigated in the Case Study are equally applicable to dams further downstream. The same indicators for seasonal flow and sub-daily flow variations apply to the downstream dams.

3.3.2.1.3 Tonle Sap and Delta

The hydrological indicators of the seasonal flow distribution directly affect the characteristics in the delta. Therefore, the same hydrological indicators are used and the potential impacts in the delta that are caused by these indicators are included. The sub-daily fluctuations caused by hydropeaking of the Sambor dam are assessed in the effects of downstream dams. For the delta areas the following assessment criteria are also taken into account:

- Dry season 5-day average discharge and waterlevels
- Wet season 5-day average discharge and waterlevels
- Waterlevel fluctuations in Tonle Sap lake
- Timing flow reversal Tonle Sap
- Inundation period of the floodplains

Due to changes in the hydrograph, also the salinity distributions in the coastal regions will change over the seasons. Higher salinity concentrations also endanger the ecology of the delta area and therefore the analytically predicted salt intrusion has been added as an assessment criterion.

3.3.2.2 Hydropower Sub-Scenarios – Council Study

The Council-Study hydropower sub-scenarios model results add to the conceptual-level assessment presented in the previous sub-section. In the Council-Study simulations, the Source/IQQM-model and ISIS model were used simultaneously, and some of the results were overlapping but not completely consistent. Therefore, it is important to consider the results only in a more qualitative sense, rather than a full quantitative assessment.

Also for these assessments, it is relevant to distinguish again between the seasonal impacts and the sub-daily impacts and their mitigation. The proposed relevant indicators for seasonal impacts are identical as those shown in Table 3.6 in sub section 3.3.1.1.

Table 3.11. Seasonal flow indicators and assessment methodology.

Indicators	Assessment methodology
5-day averaged flow [m³/s] (as basis for the other indicators)	Daily data of DSF transformed to 5-day averaged flow by calculating the mean for the previous 4 days and the actual day
Wet season onset [date]	First day of the year the 5-day averaged flow exceeds the mean flow
Wet season end [date]	First day of the year the 5-day averaged flow undercuts the mean flow
Wet season duration [days]	Wet season end minus wet season onset = duration in days
Flow volume of the wet season [Mio m³]	Summed up wet season flows
Daily flow characteristics	Statistics based on the daily average flow

For the locations of these indicators in the lower cascade it is relevant to consider a section within the upper part of that cascade, preferably Pakse; a location near Don Sahong; and a location just downstream of the 3S inflow upstream of Sambor reservoir. The need to consider Don Sahong separately is because it is affecting only one channel of multiple channels in that reach. For the Sambor reservoir, it is the important inflow from the 3S tributary system, as well as the choice of a smaller version of the dam, that requests for special attention.

For the locations further downstream, it is relevant to consider conditions in Kratie, conditions at Phnom Penh (at the mouth of the Tonle Sap River), the Tonle Sap system (with its reversal as specific indicator), flow distribution to Bassac and Mekong, and flows in the delta branches and flood plains in Cambodia and Vietnam.

The simulations for hydropower sub-scenarios in the Council Study provide the daily flow variations at relevant stations for a 30 year period. However, as mentioned earlier, the set-up of these simulations and some deviations between different modules of the DSF do not allow a full quantitative assessment An example of a typical DSF-simulation output result for Kratie water-level station is presented in the figure below. The results only show the sub-scenarios that illustrate the impacts of tributary and Chinese dams on the seasonal flows for a typical year (scenario H1a and H1b). The figure shows that water-levels in the dry season are almost 2 m higher, while the onset of the wet season is delayed, and the first peak of the flood season is reduced.

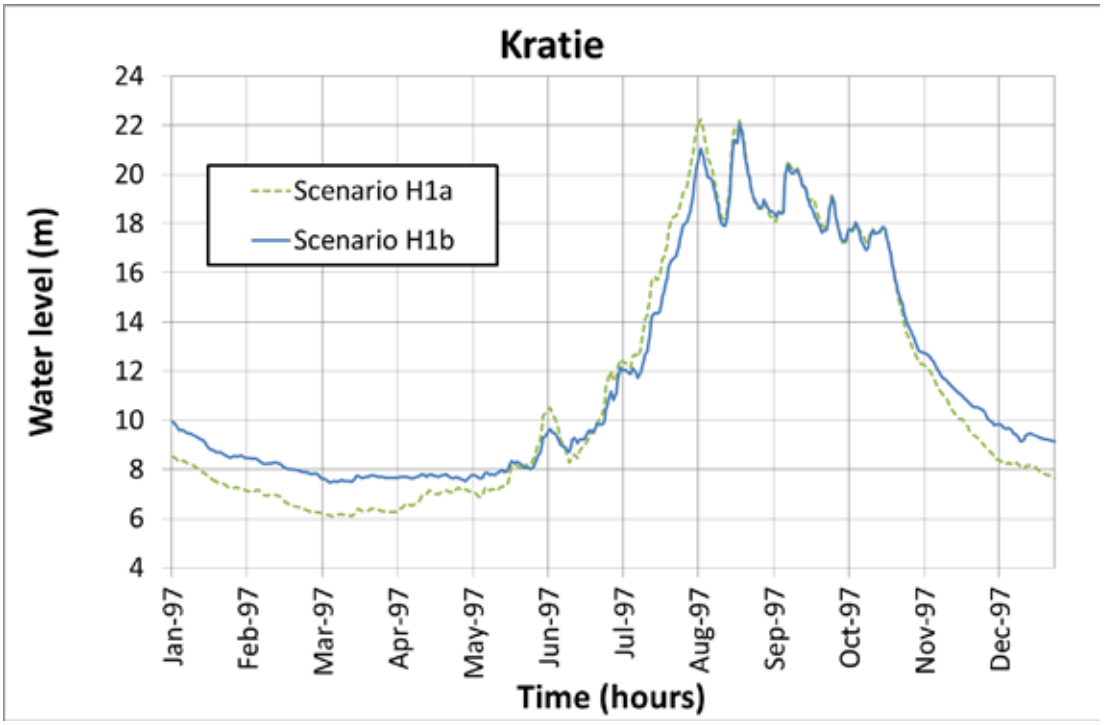


Figure 3.11. *Water level at Kratie computed for sub-scenario H1a (2040 no dam development) and H1b (2040 with Chinese dams and tributary dams)*

The proposed relevant indicators for sub-daily impacts are identical as those shown in Table 3.12

Table 3.12. Indicators for sub-daily flow conditions.

Indicators	Assessment methodology
Percentage of hours per month where downramping occurs faster than 5 cm/hour	ISIS hourly data, calculation of water level changes and substraction of values exceeding the threshold
Behaviour of peaking waves in impoundments	Qualitative comparison of 7-day period in January (dry season)
Dewatered area for downramping event occurring faster than 5 cm/hour	Calculation of impounded area at each water level – calculation of hourly area-changes
Length of downstream river section impacted by severe peaking	Measurement of downramping rates and amplitude at several sites downstream of the cascade

The most relevant sub-daily fluctuations caused by power peaking have not been included in the operations of the dams in the hydropower sub-scenarios of the Council Study. The outcomes of the model runs are daily values, and further assessment for these sub-daily variations has not been pursued.

3.4 Methods to Assess Sediment Impact Mitigation

3.4.1 2nd Interim Phase – Northern Lao PDR Cascade

3.4.1.1 Sediment Impact Mitigation Indicators

Mitigation measures are implemented in hydropower projects with the aim of maintaining the processes and characteristics that exist in the river that are important for the geomorphic and ecological functioning of the river. In the Mekong, the magnitude and timing of sediment delivery is important for maintaining the river channel and associated habitats. Sediment transport is also directly linked to the maintenance of water quality, which is discussed in section 3.5.

The assessment of sediment transport and geomorphology changes associated with the hydropower mitigation scenarios is based on inputs from the hydrological analysis, measured sediment loads, maps of current and historic river morphology and models of sediment transport through the reservoirs and downstream using the Delft 3D sediment model. Details of the data used and the model are provided in Annex A. The following indicators reflect the important sediment transport and geomorphic processes in the river and have been selected to assess the mitigation measures:

Table 3.13. Summary of indicators based on sediment modelling output for assessment.

Indicator	Model output used for assessment
Sediment transfer	• Sediment load / volume entering each impoundment • Sediment load / volume of sediment discharged into the downstream river from the most downstream impoundment • Relative proportions of sand / silt & clay • Timing of sediment deliver (% in Flood season);
Geomorphology	• Distribution and volume of sediment deposition / erosion within impoundments; • Distribution and volume of sediment deposition / erosion downstream of impoundments (Sanakham to Paksane); • Bed elevation changes in the cascade reach; • Flow and water level fluctuations as indicator of channel erosion (for hydropeaking) • Depth of deep pools; • Distribution of rapids

Where possible model results were used to evaluate the indicators. Where model results were not available, such as for changes to the depth of pools or distribution of rapids the indicators are assessed based on the interpretation of the model results or qualitative assessment based on other parameters.

Not all of the scenarios included in the Case Study have been run using the sediment model. This is because some of the variations of the scenarios had little or no relevance to the issue of sediment transport, and because running the sediment model requires long periods thus limiting the total number of scenarios able to be completed.

Output from the Delft 3D sediment model is available for the following scenarios and flow regimes:

Table 3.14. Summary of sediment mitigation scenarios.

Scenario	Description of mitigation	Flow Regime
BDP 2030 Chinese and tributary dams included	None.	Smoothed sequence of 7 years
Scenario 1.1.0 Run of River cascade with flood protection rules	None.	Smoothed sequence of 7 years
Scenario 1.2.A 1.2.B&C 1.2.D	Run of River cascade with coordinated sediment flushing of impoundments. Sub-scenarios differ by timing of sediment flushing, and by the draw down rate	10 -14-day period at the end of the Dry Season (June) for scenarios 1.2.A, and at the end of the beginning of the dry season (1.2.B&C, 1.2.D)
Scenario 1.3.0 1.3.D/E Hydro peaking in cascade with and without ramping constraints	Ramping constraints of 5 cm/hour applied to water level changes downstream of Sanakham	24-year hydrologic record from MIKE11 output

The assessment of sediment mitigation measures encompasses the three spatial scales (as do fisheries and aquatic ecology, (see also chapter 2.5.1 and 3.1.4):

- The cascade reach (upstream of Pak Beng to Sanakham): This area incorporates the river reach that is developed into the cascade. Sediment and geomorphic changes occurring within this area are assessed using model output. An example is the comparison of the total annual sediment discharge from an impoundment with and without sediment flushing;
- Sanakham to Paksane: This area is included within the Delft 3D sediment model, and modelled results are available for direct assessment. An example includes change to the river channel volume due to deposition or erosion within the impoundments;
- Paksane to Pakse: This river section is downstream of the sediment and flow models used by the project team to test the scenario. The assessment of mitigation measures in this reach is based on the qualitative assessment of how the sediment and flow changes associated with the Lao PDR cascade will propagate downstream of Paksane. The additional water and sediment inflows are taken into consideration, as are the geomorphic attributes of the reach. For example, it is recognised that high channel shear stress associated with short-duration high flow events are required within the reach each year for maintenance of the deep pools, which are important habitat. Not all indicators are assessed for this reach.

3.4.1.2 Sediments and geomorphology – Comparison of Historic to BDP 2030 Scenario

The BDP 2030 Reference Scenario used to calibrate pre-cascade conditions in the sediment model differs from 'historic' conditions due to the inclusion of the Lancang Cascade in China, and a large number of tributary dams. The Case Study sediment model includes tributary dams on the Nam Tha, Nam Beng, Nam Ou, and Nam Suong. Additional dams are under development in the area that are not included in the BDP 2030 Scenario, hence not reflected in the sediment model.

The implementation of the Lancang Cascade and tributary dams included in the BDP 2030 Reference scenario have and will continue to reduce sediment transfer from the UMB and tributaries into the mainstream Mekong. This process is well advanced, with suspended sediment loads at Pakse estimated as decreasing from ~75 to ~175 Mt/yr historically, to about ~55 to ~80 Mt/yr in the early 2010's (Koehnken, 2015), even in the absence of many of the planned tributary dams. There are no grain-size analyses available for historic sediment loads, but it is probable that there has been a reduction in the delivery of gravels and coarser material to the LMB from the UMB. At present, some of this material is being 'replaced' through erosion of coarser sediments from within the channel, but in the future this source will become depleted. As this occurs, and an erosional 'wave' progresses downstream, geomorphic channel changes will increase, including an increase in the exposure of bedrock and a decrease in the occurrence and diversity of alluvial habitats. Bank stability is likely to decrease as the river incises and banks and shorelines become steeper.

The time required for these impacts to propagate downstream will depend on the volume of sediment available for transport in the Mekong river channel downstream of the Lancang Cascade, and in the tributary river channels downstream of the final dam sites in each tributary. As this is exhausted, the rate of downstream geomorphic change will likely accelerate.

The decreasing sediment loads has presented challenges for establishing the BDP2030 'reference' baseline with regard to model establishment and calibration. The loads used for calibration reflect 'recent' sediment loads in the LMB that are considerably lower than historic sediment loads due to trapping of sediments in the Lancang cascade and in the tributary dams in the LMB, but higher than loads that are likely to prevail in the future. To provide a context for the BDP 2030 Reference scenario, estimates of historical sediment loads at Chiang Saen, Luang Prabang and Nong Khai are provided in Table 3.15 (no grain-size distributions available for the historical results). The magnitude of the sediment reduction is shown in Figure 3.12 where historic sediment loads at Chiang Saen are compared to the BDP 2030 Reference Scenario sediment loads upstream of the cascade. The BDP ***2030 Reference scenario has a sediment input of 12 Mt/yr for median flow years, and 18 Mt/yr for the 'wet' year in comparison to the historical results, which range from 30 to 147 Mt/yr with an average sediment load of 84 Mt/yr***.

Table 3.15. Summary of annual sediment loads based on 'historic' modelling results and on the results of the Delft sediment model used in this project.

Indicator	Historic Pre-Lancang Cascade	0.2 BDP 2030 Median Year (Avg 5 yrs)
Annual Sediment Load upstream of Cascade (Mt/yr) Km 2344	**~60 – 120 Mt/yr** No grain-size info available (Chiang Saen)	**12.2 Mt/yr** Grav: 2% C Sand:8% M Sand: 23% F Sand: 63% Silt+Clay: 5%
Annual Sediment Load at Luang Prabang Dam site Km 2038 Input to Xayaburi	**~60 – 110 Mt/yr** (Luang Prabang)	**10.7 Mt/yr** Gr: <1% C Sand:6% M Sand 11% F Sand: 63% Silt+Clay: 20%

Indicator	Historic Pre-Lancang Cascade	0.2 BDP 2030 Median Year (Avg 5 yrs)
Annual Sediment Load at Vientiane / Nong Khai	**~30 – 80 Mt/yr** (Nong Khai)	**19.3 Mt/yr**

Assessing and quantifying the impacts associated with the BDP 2030 Reference Scenario is not part of the project brief, but ***it is important to recognise the large scale changes that will inevitably occur in the Mekong under the 2030 BDP Reference Scenario even in the absence of the development of mainstream dams and interpret subsequent changes associated with development of a hydropower cascade within this context***.

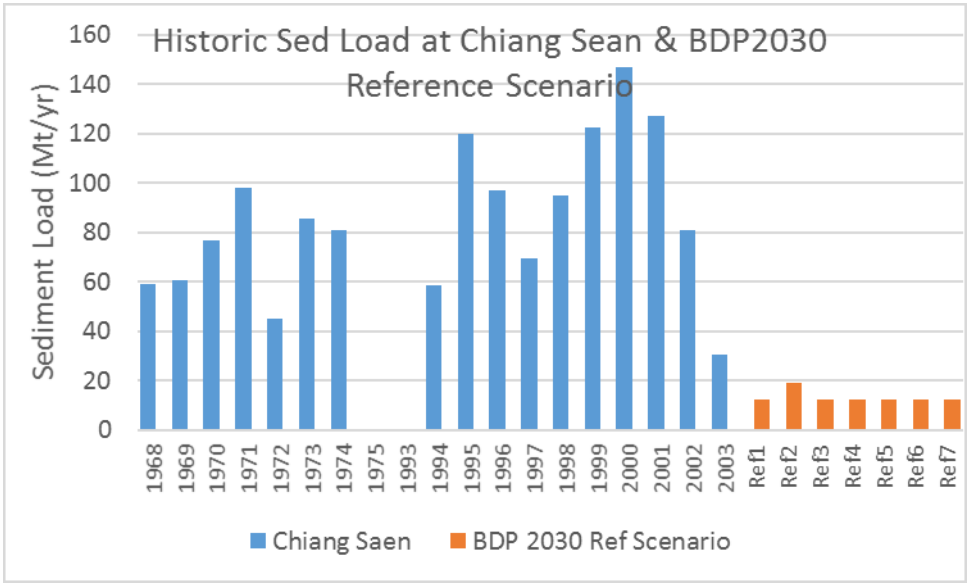


Figure 3.12. *Comparison of historical suspended sediment loads at Chiang Saen and modelled sediment at Km 2344 upstream of the northern Lao PDR cascade for the BDP2030 Reference scenario. Note: Year Ref2 is the 'wet' year in the hydrologic sequence, which accounts for the higher sediment load.*

3.4.2 Final Phase

The Final Phase of the assessment is based on the interpretation of model results produced by the MRC modelling team for the Council Study. The Final Phase has focussed on the tributary impoundments as well as the mainstream dams, and highlighted changes at a whole of basin scale as well as project scale. This assessment is based on identifying potential risks associated with the development scenarios as identified in the earlier phases of the project.

The Council Study results have been reviewed in the context of identifying potential mitigation measures that are applicable to the full development scenario (2040).

3.5 Methods to Assess Water Quality Impact Mitigation

3.5.1 2nd Interim Phase

No water quality modelling was completed as part of the case study. To assess water quality changes associated with the implementation of the northern Lao cascade and the various mitigation approaches, quantifiable physical attributes have been used as surrogates to assess potential changes to water quality. These assessments are based on known relationships between physical attributes, such as the residence time of water in an impoundment, or flow velocity, and water quality risks, such as algal blooms, or metal release or metal-cycling within impoundments. The following table highlights these relationships and summarises how the available results have been used to assess potential changes.

It is recognised that there are many other important water quality indicators (nutrients, metals, metalloids, temperature, dissolved oxygen) and these are discussed in the accompanying volumes. The intent here is to evaluate risks where possible about potential changes to water quality associated with the physical changes associated with the development of the cascade.

Table 3.16. Water Quality indicators, assessment methodology and scenarios.

Indicator	Assessment methodology	Scenarios
Residence time in reservoirs as indicator of risk of algal blooms	Reservoir volumes divided by the mean monthly inflows • Total volume used as maximum residence time indicator • Active volume used as minimum residence time indicator HEC-ResSim and MIKE-11 output used for assessment	All scenarios considered collectively as risk of algal blooms is similar between scenarios
Months with water velocities <0.4 m/s as indicator of risk of algae blooms	Average monthly water velocities as determined by Delft 3D	All scenarios considered collectively as risk of algal blooms is similar between scenarios
Water clarity as indicator of risk of algal blooms	Suspended sediment and suspended sediment grain-size distribution results from Delft 3D sediment mitigation scenarios	All scenarios considered collectively as risk of algal blooms is similar between scenarios
Nutrient transport as indicator for impoundment water quality and downstream habitat quality	Suspended sediment and suspended sediment grain-size distribution results from Delft 3D sediment mitigation scenarios and recognised relationships between sediment and nutrient concentrations	All scenarios considered collectively as risk of algal blooms is similar between scenarios
Sediment concentrations as an indicator of risks to downstream habitat quality during sediment flushing or sediment sluicing	Suspended sediment and suspended sediment grain-size distribution results from Delft 3D sediment mitigation scenarios during flushing events	Scenario 1.2 only

Water quality changes are assessed for the following two spatial scales:

- Within the impoundments (cascade reach – Zone 1) water quality changes are assessed through the comparison of conditions pre- and post- establishment of the cascade. For some parameters (such as water clarity) the changes attributable to the establishment of the Lancang Cascade and tributary dams are considered as well to provide a context for the changes attributable to the cascade;
- Downstream water quality changes (Sanakham to Paksane and Paksane to Pakse – Zone 2 and 3) are assessed through the qualitative assessment of flow and sediment parameters at or downstream of Sanakham, and known relationships between these parameters and water quality processes.

3.5.2 Final Phase

Water quality modelling in the Council Study was limited to Total Nutrients (Nitrogen and phosphorus) and based on the assumption that a fixed percentage of nutrients was associated with sediments. Nutrient removal was estimated for each of the development scenarios based on sediment trapping in impoundments. For this assessment, water quality risks are identified based on potential risks previously identified through the Northern Lao Case Study, and applicable mitigation measures are identified at a conceptual level. The analysis adopts a whole of catchment rather than project specific approach.

3.6 Methods to Assess Fisheries and Aquatic Ecology Impact Mitigation

As already discussed in chapter 2.3.4, fish are impacted by all changes affecting their habitat. Relevant hydrologic indicators were already discussed in chapter 3.3. The description already includes relevant parameters (e.g. dewatered area for peaking events) for fish and other aquatic organisms. Also with regard to river morphology (sediment impact mitigation; chapter 3.4) and water quality (chapter 3.5), the above described indicators will be used to assess the overall impact on fish. Therefore, in this chapter, only indicators directly related to fish or aspects, which were not already covered in other chapters will be discussed.

3.6.1 2nd Interim Phase – Northern Lao PDR Cascade

3.6.1.1 Connectivity

The ecosystem productivity of large tropical river-floodplain systems like the Mekong is highly dependent on the undisturbed longitudinal (mainstream & tributaries) and lateral habitat connectivity (floodplains) (Bayley, 1995). Many species rely on those habitats to fulfil their life cycles (e.g. spawning and nursery habitats) (King et al., 2009; Louca et al., 2009; Tonkin et al., 2008) and perform migrations between them. The following table provides an overview of the indicators, which will then be discussed in detail in the consecutive chapters.

Table 3.17. Connectivity indicators.

Indicator	Assessment methodology	Sites and scenarios
Dendritic connectivity index weighted by Strahler ($DCI_{Strahler}$)	Adapted from Grill et al. 2014	Whole Mekong Basin, connectively for all scenarios without fish pass considered
Dendritic connectivity index weighted by migration ranges ($DCI_{Migr.}$)	Adapted from Grill et al. 2014	
Upstream migration efficiency via cascade	Expert judgement for fish pass efficiency	Only within the cascade, connectively for all scenarios with connectivity mitigation
Downstream mortality for large species via cascade	Halls & Kshatriya (2009)	
Downstream mortality for small species via cascade	Halls & Kshatriya (2009)	
Support of passive drift of ichthyoplankton	Assessment of seasonal flow velocities in the cascade	

3.6.1.1.1 Overall connectivity

The DCI (Dendritic Connectivity Index; Cote et al., 2009) represents a suitable indicator for assessing the overall connectivity in a catchment. Thereby, the DCI calculates the proportion of length of disconnected fragments in relation to the entire network (Cote et al., 2009). This method, however, neglects the location of the individual dam within the river network. Thereby, a barrier upstream in a tributary results in the same DCI as barrier close to the river mouth, although the latter would cause much higher impacts. To overcome this methodological disadvantage, the DCI can be extended by different weighting factors (e.g. river classes or migration corridors) (Grill et al., 2014). Within this study, two different DCIs with different weighting factors were calculated and compared. The DCI_{Migr} focuses on the importance of sections for migratory species. Therefore, the minimum distribution range of migratory species was delineated by integrating the Mekong Fish Database (MFD; Visser et al., 2003) and the map on fish migration patterns in the LMB included in the BDP Planning Atlas (MRC, 2011). For this index, the number of species caught at the different sites (based on the Mekong Fish Database) was used to weight the sections with regard to their importance for migratory species. If a section was defined as migration route in the BDP planning atlas but no sampling data were available, the minimum number of migratory species (i.e. 1-4) was assumed. However, as there are also several species migrating within sub-basins, connectivity assessments should also take place on a larger scale and, if possible, also under consideration of river sections upstream of the LMB. Therefore, the $DCIS_{trahler}$ includes a larger proportion of Mekong tributaries which are then weighted by the Strahler order of the river section.

The baseline-data for the two different DCIs is show in Figure 3.13 (A) and Figure 3.14 (A). As highlighted in Figure 3.14 (A), the Mekong mainstream and lower sections of larger tributaries are of high importance for a large number of mainly long-distance migratory species. The map A in Figure 3.13 shows the considered river network for the $DCI_{Strahler}$, where the Mekong mainstream and larger tributaries are weighted higher based on the Strahler order.

Under historic conditions, the entire Mekong basin was unfragmented and both DCIs showed a value of 100 %. However, with the BDP 2030 scenario, the Chinese cascade and tributary dams caused already some degree of fragmentation, which, however, does not impact the LMB mainstream. However, with the Xayaburi dam, the first mainstream dam is under construction and considering the addition of four more dams in the LMB cascade, the connectivity index further declines (see table 3.18).

The $DCI_{Strahler}$ results in 37 % for the BDP 2030 scenario and in 28 % for Scenario 1.1.0 (2nd Interim Phase). Figure 3.13 shows the Strahler order (A), and the connected and disconnected section under historic conditions (B), the BDP 2030 scenario (C) and scenario 1.1.0 (D). While already large proportions of tributaries are disconnected under the BDP 2030 scenario, the $DCI_{Strahler}$ declines by another 9 % once the cascade is in place (see Figure 3.13 and Table 3.18).

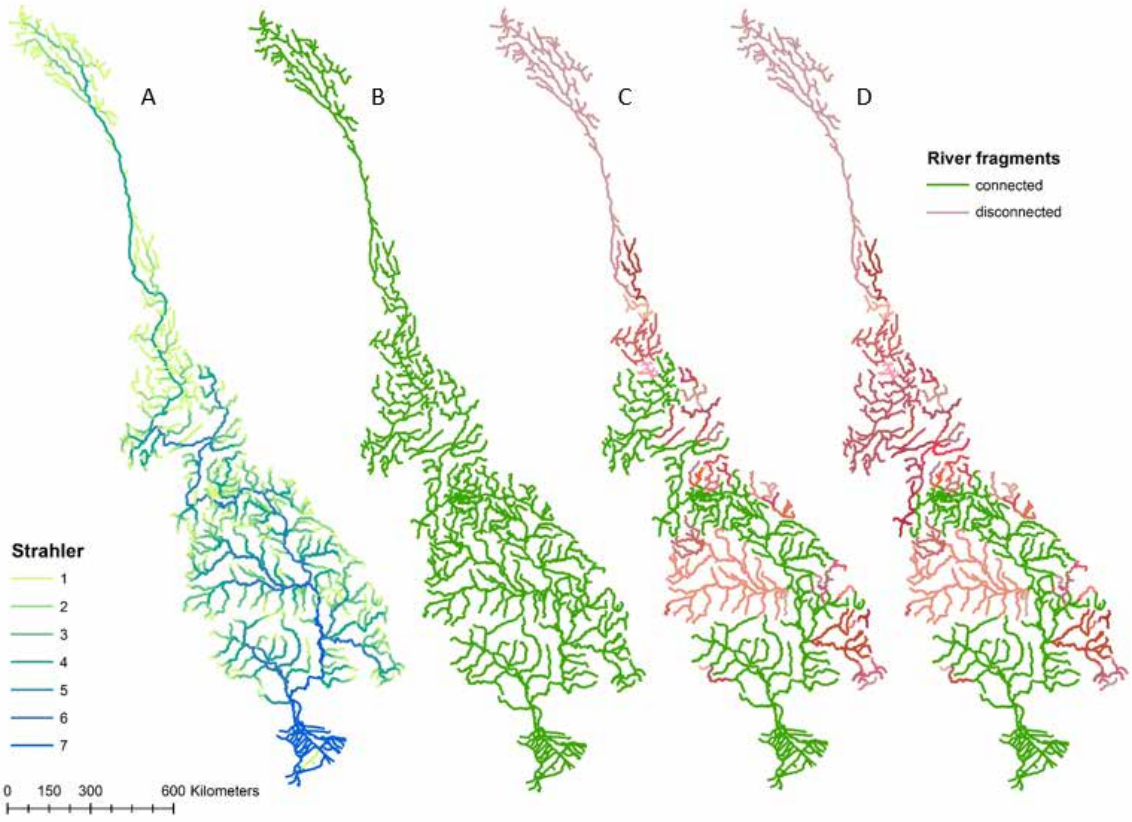


Figure 3.13. *DCI for Mekong Basin: A) Strahler order of rivers, B) reference condition, C) baseline condition (BDP 2030 scenario), D) Scenario 1.1.0 (all scenarios without fish pass).*

Looking at the DCI_{Migr}, which is based on a much smaller proportion of the catchment, the decline is less pronounced. The DCI_{Migr} declines to approximately 80 % in the BDP 2030 scenario and by further 7 % in scenario 1.1.0 (see figure 3.14 and table 3.18). These results are also related to the fact that upstream sections include less migratory species and are therefore weighted less compared to downstream sections, which remain connected.

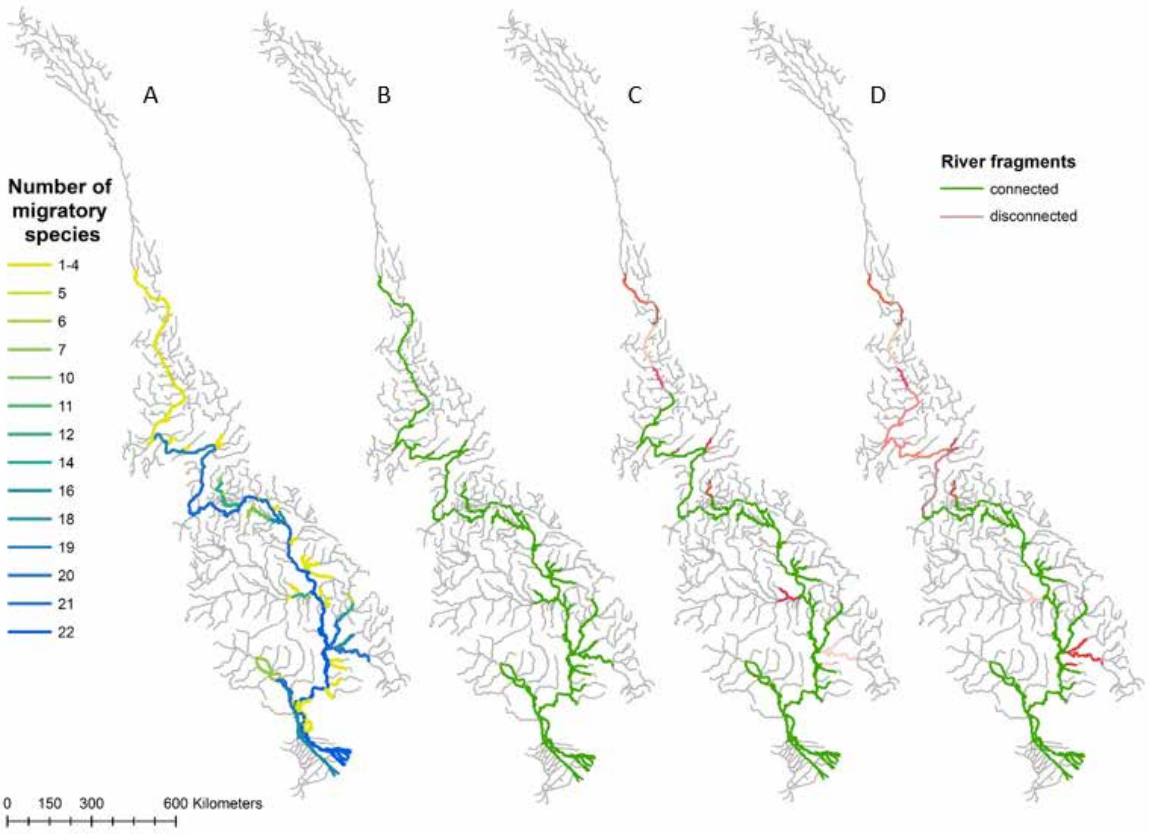


Figure 3.14. *DCI_{Migr} for Mekong Basin: A) LMB migration range and number of migratory fish species (based on Mekong Fish Database; Visser et al., 2003 and BDP planning atlas; MRC, 2011); B) historic condition, C) BDP 2030 scenario, D) Scenario 1.1.0; (grey sections not considered).*

Table 3.18. $DCI_{Strahler}$ and DCI_{Migr} for historic, BDP 2030 and 1.1.0 scenarios.

	Historic	BDP 2030	Scenario 1.1.0
$DCI_{Strahler}$	100.00%	36.69%	28.12%
DCI_{Migr}	100.00%	81.03%	74.10%

Without the implementation of mitigation measures as e.g. fish passage facilities, fish are not able to perform their migrations. If crucial habitats for spawning or feeding cannot be reached, fish are not able to complete their life cycle or interact with other sub-populations. The resulting stock declines will also cause losses for fisheries. However, even if fish passes are considered, it has to be assessed how efficient they are and if there are possible limitations to downstream migrations as well (see below).

The passage efficiency is a very important factor for cumulative impact assessment of several consecutive dams. Since the effect is multiplicative (i.e. each dam potentially reduces the number of fish successfully passing a barrier), low passage efficiencies can significantly impact fish populations (see chapter 3.6.1.1.2 for more details). Within phase 4 , different passage efficiencies were included in the DCI calculation (see sub-chapters on fisheries and aquatic ecology within chapter 6).

3.6.1.1.2 Up- and downstream passage efficiency

Without connectivity mitigation, fish are not able to migrate upstream. In downstream direction, they can only migrate via the turbines or the spillways, two options, which are likely to cause injuries or fish kills. To restore the connectivity, fish pass facilities need to be implemented. However, even if fish pass solutions are considered, they have to be assessed with regard to their efficiency and their role to sustain healthy populations. The assessment of up- and downstream fish passage efficiency within the cascade is only relevant for Lao Cascade scenarios (i.e. 1.1.0 to 1.3.E), since the historic and BDP 2030 scenarios are free of LMB mainstream dams.

For each of the five dams within the cascade, facilities as implemented for the Xayaburi dam are assumed (see also chapter 2.4.5). Figure 3.15 provides a schematic overview of the cascade and the passage routes in up- and downstream direction for different age classes. In upstream direction, the passage efficiency over the entire cascade will be calculated to estimate the loss of migratory adult individuals upstream and the reduction of reproduction success (i.e. assumed to be related to the number of spawning individuals). In downstream direction, the support of passive downstream drift for larvae and eggs will be discussed. Furthermore, different mortalities are considered for downstream migrating adults passing through the turbines or spillways. More details on these indicators will follow in the result chapter 5.6.1.

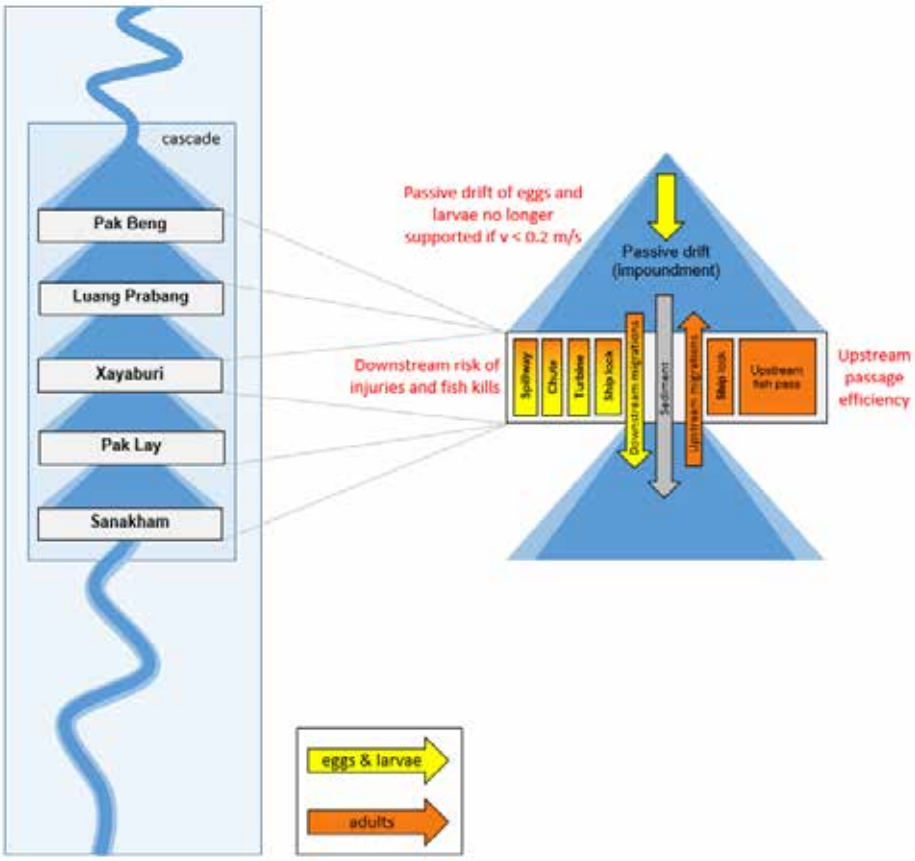


Figure 3.15. *Assessment schema for up- and downstream connectivity within the cascade for different age classes.*

3.6.1.2 River channel habitats

Fish biodiversity and fisheries yield depends to a high degree on the availability and accessibility of important habitats. Any type of hydro-morphological alteration is inevitably also connected to habitat alterations, which is why most of the indicators discussed in this chapter were already covered by other chapters.

3.6.1.2.1 Hydrology

The ecological integrity of a river depends to a high degree on an intact hydrological regime. The magnitude, duration, frequency, timing and rate of change of the flow are responsible for type-specific sediment compositions (e.g. prevention of clogging), water quality conditions (e.g. temperature, oxygen), availability of energy sources (e.g. nutrients) and biotic interactions (e.g. spawning) (Karr, 1991; Bunn & Arthington, 2002). The selected indicators and the method for assessing hydrological changes were already discussed in chapter 3.2. With regard to seasonal changes occurring between the historic and the BDP 2030 scenario, it can be assumed that aquatic organisms within the three impact zones will react to some degree to these changes. However, larger effects will occur in the lower section of the LMB (i.e. Delta and Tonle Sap), where modifications of the flood volume may have significant impacts on the local fisheries. However, the cascade itself does not really cause a modification of the seasonal hydrology, which is due to the small storage capacity of the impoundments.

3.6.1.2.2 Morphology

The overall assessment of the sediment impact, including the filling up of deep pools and the impoundment of rapids was already discussed in chapter 3.4. All of the discussed indicators are of high importance for aquatic organisms since they represent measures of their habitat quality. Furthermore, the river dimension (area, depth) can provide an indication on habitat alterations. The most important indicators, which will then be used for the assessment of the fish biomass, are given in the Table 3.19 and are described below.

Table 3.19. Habitat indicators.

Indicator	Assessment methodology	Sites and scenarios
Quality of the river bed composition	Based on “Median sediment grain-size being transported” (see chapter 3.4)	See chapter 3.4
Quality/ quantity of deep pools	Qualitative assessment of changes within cascade and downstream (see chapter 3.4)	
Quality/ quantity of rapids	Qualitative assessment of changes within cascade and downstream (see chapter 3.3)	Only relevant for cascade (no differentiation between scenarios)

Indicator	Assessment methodology	Sites and scenarios
Mean water surface in the cascade	For historic condition: area calculation on the basis of GIS-data; for the cascade: measurement of the impounded area;	Entire cascade, scenarios without (historic, BDP 2030) and with the LMB cascade (Sc.1.1.0 to Sc.1.3.E collectively)
Mean river depth	Qualitative assessment	

Detailed results were already discussed in chapter 3.4. The morphology in the BDP 2030 scenario is already impacted and habitat quality will further decrease in Scenario 1.1.0. Due to the impoundments and the reduced flow velocity, sedimentation processes will prevail within the cascade, while the downstream reach will suffer from erosion. Thus, also the sediment distribution will be altered, putting species adapted to the local substrate composition at risk, and consequently also fish feeding on those organisms. Deep pools represent an important habitat for several species. The availability of deep pools habitats along the Mekong mainstream can be seen in Figure 3.15, where also the pool depth and area is illustrated.

Deep pools within the cascade (see Figure 3.15) are at risk of being filled up with substrate and covered with fine sediments. Downstream of the cascade, the lack of sediment and related erosion processes might even cause a deepening of deep pools. However, if substrate in those pools or adjacent habitats is eroded, fish might lose their source of nutrition and the positive effect of deeper pools might be offset by other negative effects. Downstream of Pakse, no negative impacts are expected for several years. However, once the ***erosion wave*** reached this reach, negative impacts will most likely also affect this area (see also chapter 5.3.3 for a discussion on this).

While the influence on the rapids might still be negligible (i.e. compared from historic to BDP 2030 scenario), the rapids located within the cascade will be lost due to impoundment, while the rapids downstream of the cascade might also suffer from erosion processes. The location of rapids along the Mekong mainstream is also provided in Figure 3.16.

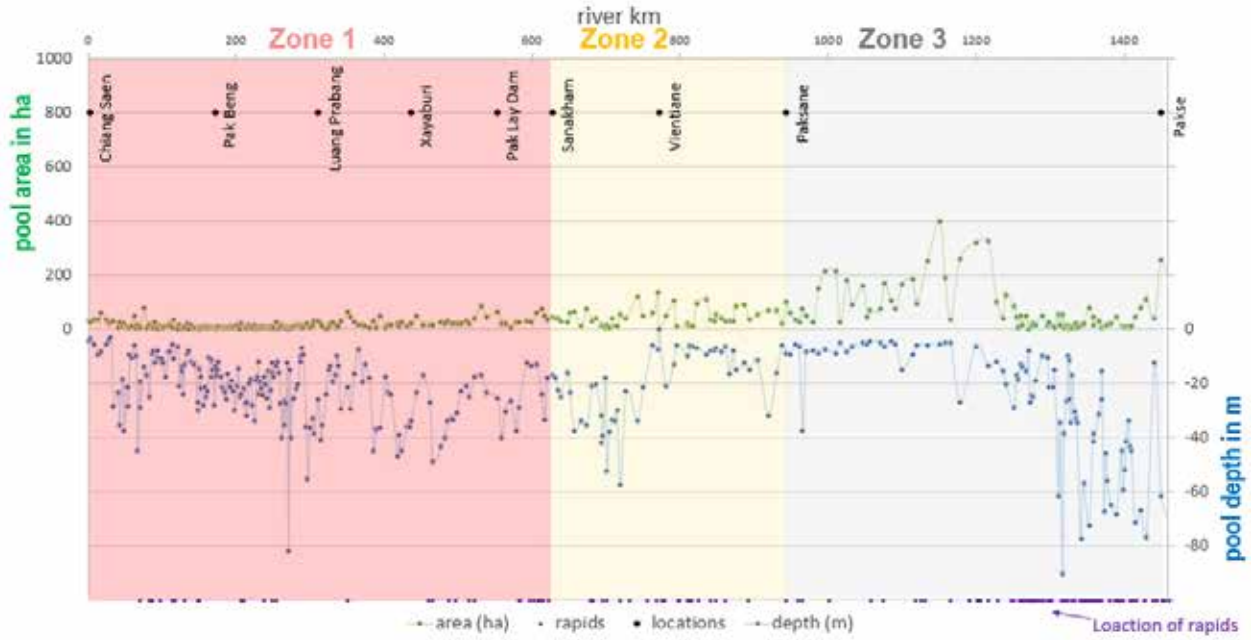


Figure 3.16. *Location, depth and area of deep pools and location of rapids along the Mekong mainstream (red: cascade; yellow: downstream of the cascade; white: downstream of Pakse) (note: the line between the pools does not reflect the riverbed elevation but is there to support the readability of the figure).*

While the river dimension does not differ between the historic and BDP 2030 scenario (neglecting marginal changes caused by seasonal flow alterations), a large change will occur once the cascade is in place (i.e. in Scenario 1.1.0). As a consequence of damming, the free flowing Mekong mainstream will be transformed into a cascade of impoundments upstream of the LMB mainstream dams. Along with several other habitat alterations, the dimension of the Mekong will substantially increase in this zone, covering not only a larger area but also a greater depth. Data on the area covered by water for historic and BDP 2030 conditions are calculated on the basis of GIS files featuring the current shoreline of the Mekong. These data, however, provide only a rough estimation and do not consider varying water levels for different seasons. These values are then compared to area-measurements of the impoundments, which were extracted from the modelling results for different water levels. As indicated in table 3.20, the reservoirs cause an increase in water surface by a factor of 1.3-1.5 in this zone.

Table 3.20. Water surface comparison of the cascade for historic/ BDP 2030 and 1.1.0 scenario.

	Historic/BDP 2030	Scenario 1.1.0
Area	154-188 km²	247-286 km² (depending on the reservoir level)
Increase to historic condition	0%	30-50%

Although the area increase could be interpreted as positive for aquatic organisms, this is not necessarily the case. Quite the contrary can be true, since the increase in area goes hand in hand with an increase in water depth. This can make the middle section of the river less suitable for certain organisms, as e.g. macrophytes, which might suffer from insufficient light penetration. In addition, benthic organisms might be reduced in density, related to the deposition of sediments

and loss of the hyporheic interstitial. Thus, an increase in fish biomass related to the area and increased volume of the water body seems very unlikely.

3.6.1.2.3 Water quality

Hydro-morphological parameters discussed in the previous chapter are also linked to water quality parameters, which were already discussed in chapter 3.4. Water temperature and oxygen were not evaluated in this first stage, but would provide useful information for assessing the impact on fish. With regard to water quality, the following indicators are used to compare the historic, BDP 2030 and 1.1.0 scenario (see Table 3.21). These indicators were already discussed in chapter 3.5.

Table 3.21. Water quality indicators.

Indicator	Assessment methodology	Scenarios
Sediment concentration/ clarity	% of time suspended solids <50 mg/L (see chapter 3.5.)	All scenarios collectively
Nutrient transport (silt & clay used as surrogate)	See chapter 3.5	
Sediment concentration during flushing events	Qualitative assessment of harmful character of flushing events	Scenario 1.2 only

3.6.1.3 Fish biomass

The potential impacts of dams and effects of mitigation measures on fisheries were expressed in fish biomass changes whenever data availability and causal relationships will allow drawing quantitative conclusions. However, it has to be considered that the stated values represent only rough estimates. Biomass values are often aggregated per country, which is not adequate for this study considering zones with different impact intensities along the Mekong (see also chapter 3.7.1). However, as the data availability and distribution did not always allow a detailed and accurate allocation of fish biomass along the Mekong mainstream as well as towards tributaries and floodplains, the impacted fish biomass were assessed on the basis of some general assumptions and expert judgement. The detailed steps, as well as related uncertainties are described in the following paragraphs.

Due to the high number of fish species inhabiting the LMB, the impact and mitigation assessment focused on a guild-based assessment. Furthermore, cascade-related effects may have different consequences for different fish guilds. A detailed description of the guilds and their ecological requirements were discussed in Vol. 2 of the Inception Phase Literature Review and Knowledge Base (2015). Consumption based yield estimates are discussed in several other studies (e.g. Hortle, 2007, Halls, 2010, Hortle & Bamrungrach , 2015). Halls (2010) performed an estimation of annual yield of fish by guild in the LMB on the basis of national consumption data and the species distribution at AMCF sampling sites. The results were, however, again presented per country.

To receive the biomass and guild distribution per impact zone, consumption based yield data per province were sub-divided to reflect the three impact zones (see chapter 3.2). The delineation made on the basis of the provinces is shown in figure 3.16 and does not precisely coincide with

the selected impact sections. The section between Sanakham and Paksane extends a little further downstream, as it is also the case for the area from Paksane to Pakse (which includes the entire rest of Laos and Thailand – indicated in grey in the map in figure 3.17. However, it is assumed that these small deviations will not affect the general outcome of the assessment.

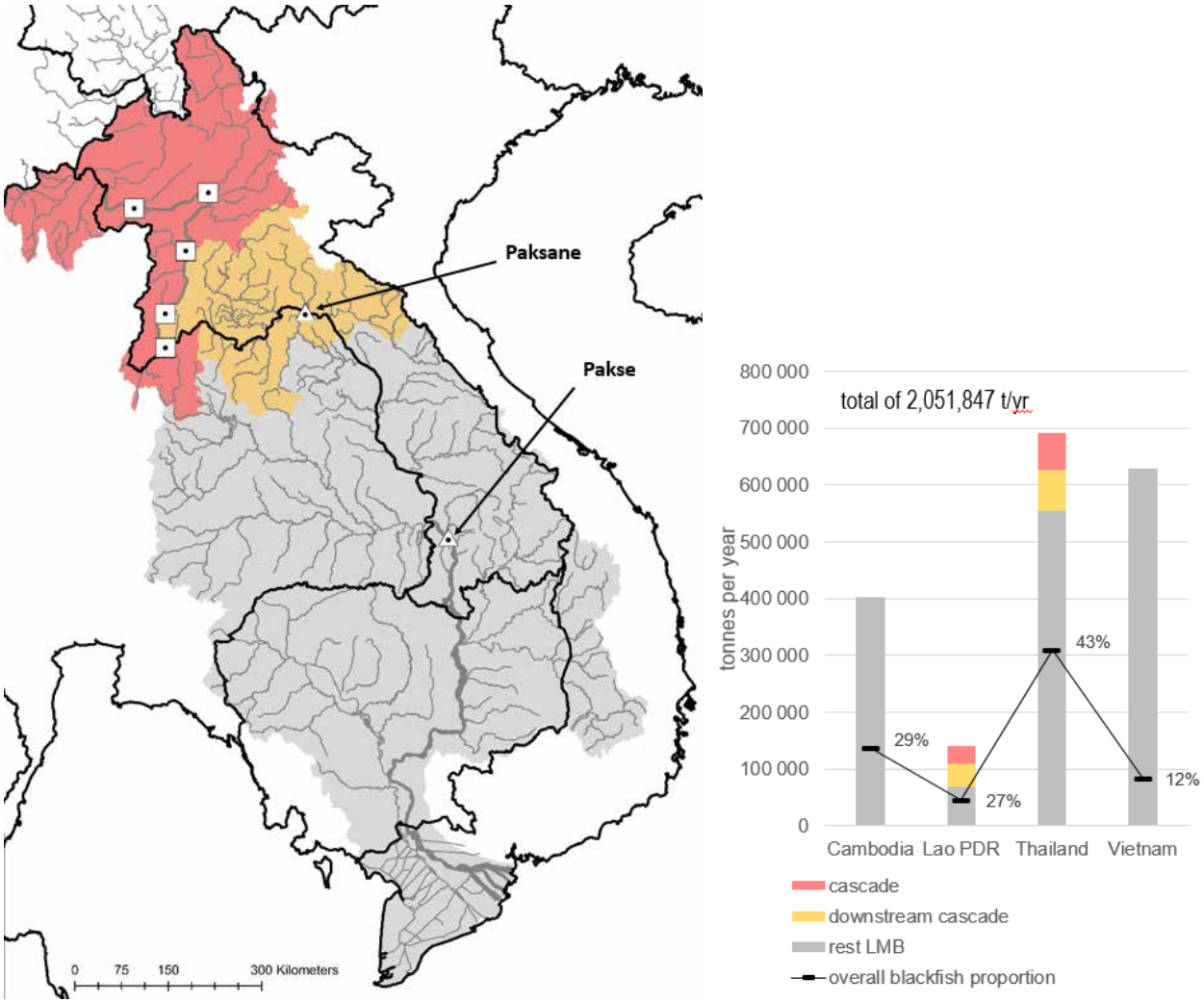


Figure 3.17. *Consumption based fish yield (based on Halls, 2010 and Hortle et al., 2015) divided in three impact zones.*

The assignment of fish biomass to the different guilds was done on the basis of the AMCF (Assessment of Mekong Capture Fisheries Component, MRC) sampling sites, which are shown in Table 3.22. As the proportion of blackfish species is under-represented in the catch data the share of blackfish species (i.e. floodplain guild) was estimated by Hortle & Bamrungrach (2015) and Halls (2010) for each country. Likewise, for Cambodia and Vietnam, those shares (i.e. 29 and 12 %) were adopted for this study without recalculation, since no differentiation for impact zones is made for these countries (due to their downstream location and distance to the cascade). For Lao PDR and Thailand, the shares of black fish were assumed to be lower in upstream sections (e.g. within the cascade) compared to downstream sections due to the limited presence of floodplains. Therefore, the blackfish yield of these countries (i.e. 27 % for Lao PDR and 43 % for Thailand) were compared with the total yield of each zone and the following assumptions were made: 10 % blackfish in the cascade and 20 % blackfish from Sanakham to Paksane. Downstream of Paksane, the shares

of 39 or 50 % (for Lao PDR and Thailand respectively) were calculated to resemble the overall blackfish yield of each country. It is shown, however, that these shares are 7-12 % higher than the overall proportion per country (which seems reasonable due a higher floodplain density compared to the rest of the country). Consequently, the blackfish yield was calculated per impact zone.

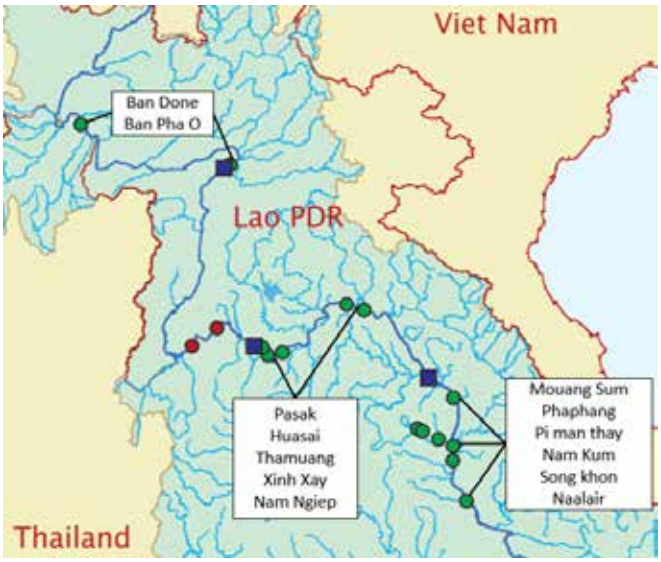
Table 3.22. Estimation of blackfish yield for cascade, immediately downstream and the rest of the LMB (based on Hortle & Bamrungrach (2015) and Halls (2010); * indicate recalculated values within this study).

(t/year)		Lao PDR	Thailand	Cambodia	Vietnam
total fish yield (t/year)	cascade	37,545*	67,118*	-	-
	downstream cascade	47,366*	75,486*	-	-
	rest LMB	80,656*	577,898*	473,661	692,117
	overall	165,567	720,502	473,661	692,117
blackfish percentage	cascade	10*	10*	-	-
	downstream cascade	20*	20*	-	-
	rest LMB	39*	50*	29	12
	overall	27	43	29	12
blackfish yield (t/year)	cascade	3,755*	6,712*	-	-
	downstream cascade	9,473*	15,097*	-	-
	rest LMB	31,292*	288,949*	137,362	83,054
	overall	44,703	309,816	137,362	83,054

Once the blackfish biomass was defined, the other guilds were calculated on the basis of the AMCF catch data. Therefore, the sites were combined into three groups based on the defined impact zones.

Table 3.23. Grouping of AMCF sites in Thailand and Lao PDR.

Impact zone	Country	Sampling site
1) cascade	Lao PDR	Ban Done
	Lao PDR	Pha O
2) downstream cascade	Thailand	Pasak
	Thailand	Huasai
	Lao PDR	Thamuang
	Lao PDR	Xinh Xay
	Lao PDR	Nam Ngiep
3) rest LMB (Thailand and Lao PDR)	Lao PDR	Mouang Sum
	Thailand	Phaphang
	Thailand	Pi man thay
	Thailand	Nam Kum
	Thailand	Song khon
	Thailand	Naalair



Since the consumption data reflect the status of the years 2003/2004 and represent the condition before the implementation of the Lancang cascade (except for Manwan dam, which was already in place), already occurred losses have to be considered. For this purpose, the estimated losses of the BDP 2030 scenario were used likewise for all guilds (MRC, 2011) which resulted in a total loss of ~187,000 t/y. Furthermore, also the loss of OAAs has to be considered. Also here, the same percentage losses as for fish were assumed (see table 3.24).

Table 3.24. Estimating the losses caused by the Chinese cascade and tributary dams (based on MRC, 2011).

Fish	Lao PDR	Thailand	Cambodia	Viet Nam	Total
Historic (2003/2004) (t/yr)	165,567	720,502	473,661	692,117	2.051,847
Estimated BDP 2030 losses (%)	-15%	-4%	-15%	-9%	-10%
Estimated BDP 2030 losses (t/yr)	-24,835	-28,820	-71,049	-62,291	-186,995
Estimated BDP 2030 yield (t/yr)	140,731	691,682	402,612	629,826	1.864,852
OAAs					
Historic (2003/2004) (t/yr)	40,011	190,984	103,712	160,705	495,412
Estimated BDP 2030 losses (%)	-15%	-4%	-15%	-9%	-10%
Estimated BDP 2030 losses (t/yr)	-6,002	-7,639	-15,557	-14,463	-43,661
Estimated BDP 2030 yield (t/yr)	34,009	183,345	88,155	146,242	451,751

On the basis of the values in Table 3.23 the guild distribution was calculated for each impacts zone and transferred to the non-blackfish biomass. The following graph shows the distribution of guilds for the cascade, immediately downstream of the cascade and the rest of the LMB for Thailand/ Laos PDR, Cambodia and Vietnam.

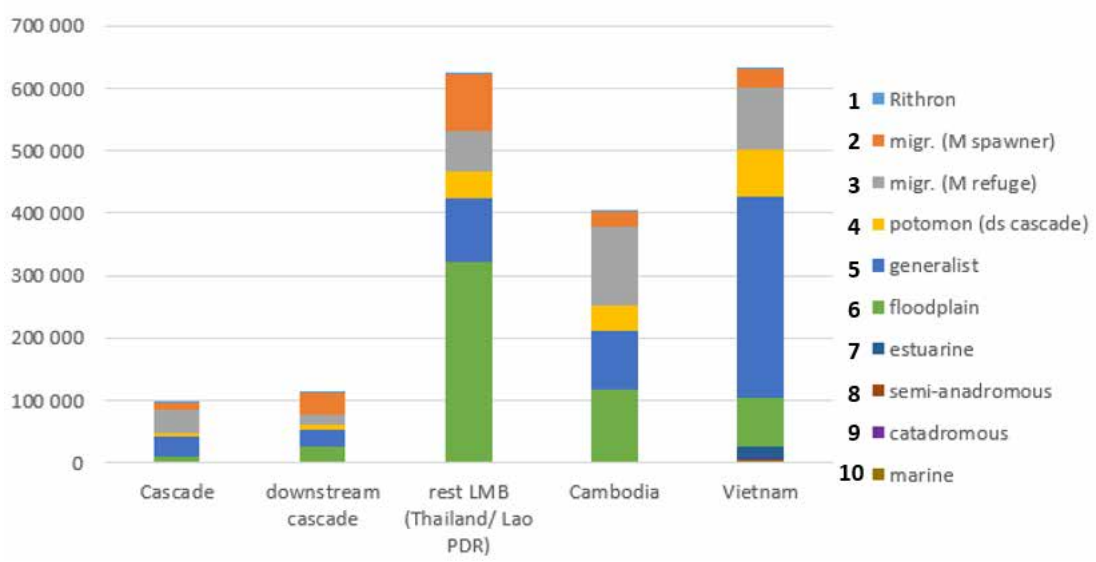


Figure 3.18. *Fish biomass (t/yr) per guild for the respective impact zones (M spawner = migratory main channel spawner; M refuge = migratory main channel refuge).*

For the assessment, the two migratory guilds 2 & 3, which are highly vulnerable to mainstream dam development (see Table 3.25) were combined to one group. However, since certain impacts are also size-related, a differentiation in large (≥40 cm) and small (<40 cm) fish was considered. To assess, how much biomass of guild 2 and 3 is related to large and small species, those species, that make up a large proportion of the migratory biomass, were used to assess the related proportions (see table 3.30).

Table 3.25. Mekong guilds vulnerable to the LMB cascade (adapted from Baran, 2010 and Halls & Kshatriya, 2009).

Migratory guild	Potential range of habitat utilized	Typical characteristics*	Likely impact of mainstream dams on migrations.
Migratory main channel spawner guild	Floodplains to running river upstream	• Spawn in the mainstream, in tributaries and around floodplains • Adults and drifting larvae return to floodplains to feed. • May migrate to deep pools in the mainstream during the dry season. • Sensitive to damming	Very high
Migratory main channel refuge seeker guild	Floodplains to slow river downstream	• Spawn in floodplains • Migrations between floodplains and mainstream deep pools in the dry season. • Sensitive to damming	Very high

Halls & Kshatriya (2009) identified 58 highly migratory species threatened by mainstream dams, which contribute 38.5% to the total weight of all recorded species in the catch surveys (see Annex E, Table E1). Furthermore, important species mentioned by Hortle et al. (2015) were considered (see Annex E, Table E2). The following table shows the species, which were included in this survey, and how they contribute to the overall biomass of guilds 2 and 3. Assuming that the selected species are representative, small species contribute ~70 % (2/3) and large species ~30 % (1/3) to the biomass of guilds 2 and 3. These values were finally used for dividing the overall biomass of guilds 2 & 3 into the biomass of large and small migratory species (see also Table 3.25).

Table 3.26. Summary and characteristics of species considered for estimating the proportion of small and large migratory fish in the impact assessment.

Species	Max length (cm)	Size class	Guild	Larvae per ml (Hortle et al. 2015)	% of guilds 2 & 3 (Halls & Kshatriya 2009)	% of large vs. small species
Henicorhynchus siamensis & lobatus	20	small	3	12.2	32.96	
Gyrinocheilus pennockii	28	small	2	-	4.41	
Paralaubuca typus	20.5	small	3	1.1	4.49	70,6
Pangasius macronema	40	medium	2	63.7	-	
Hypsibarbus malcolmi	50	large	2	-	4.01	
Cosmochilus harmandi	100	large	3	4.5	7.78	
Pangasius conchophilus	120	large	2	-	5.61	
Pangasius macronema	40	medium	2	63.7	-	29,4
				81.5	**59.26**	**100**

Generalist species, which are highly adaptable to environmental changes and, therefore, less vulnerable to impacts, were considered as an individual groups. Floodplain species are mostly located in floodplains adjacent to the Mekong mainstream, although, depending on the season, they also inhabit the Mekong mainstream. Since they are less vulnerable to water quality changes but react to floodplain alterations, they constitute an individual group. Three guilds 1, 4 and 7 to 10 (i.e. rhithron, potamodromous, estuarine, semi-anadromous, catadromous and marine guild) occur only in small proportion and were therefore combined to “others”. The assessment, therefore, focuses on the following five groups:

- Migratory Large (guilds 2 & 3, ≥40 cm)
- Migratory Small (guilds 2 & 3, < 40 cm)
- Generalist (guild 5)
- Floodplain (guild 6)
- Others (guilds 1, 4, 7-10)

The resulting estimated proportions of grouped fish guilds per impact zones as well as for Cambodia and Vietnam are provided in Table 3.26.

Table 3.27. Proportion (%) of grouped fish guilds for each impact zone and country.

	Cascade	Downstream of the cascade	Rest of Lao PDR and Thailand	Cambodia	Vietnam
Migratory Large	17	16	9	12	7
Migratory Small	35	31	18	25	14
Floodplain	10	20	49	29	12
Generalist	32	26	17	23	52
Others	6	7	8	11	16
Total	100	100	100	100	100

It has to be highlighted that these values reflect the distribution per zone, but not necessarily the values in the impacted area, which is mostly located in the Mekong mainstream. The following results are, therefore, only valid for habitats in or close to the Mekong while the overall assessment will qualitatively incorporate the results of these assessments (see below).

To assess the additional loss from BDP 2030 to Scenario 1.1.0 we analysed the risks associated with the cascade for the combined five groups in each of the impact zone. Due to the lack of detailed ecological data and studies on effects of large dams on rivers with fish comparable to the Mekong the biomass losses can only be indirectly estimated based on predicted physical/ chemical changes of the environment. In order to account for these uncertainties only three levels of alteration for increase and decrease of biomass are used (low, medium, high). A 66-100 % loss (i.e. drastic loss or extinction) is rated with -3, while -2 reflect a medium loss of 33-66 % and -1 a low loss of up to 33 %. If no impact is expected compared to the BDP 2030 scenario, the rating 0 is used (see also chapter 3.1.1. for the common rating matrix), while "-" shows that this pressures is not present. From BDP 2030 to Scenario 1.1.0, no positive effects were expected.

Table 3.28. Ratings for the assessment of impacts and mitigation measures

Rating	Biomass (% change)
3	+67 to +100
2	+34 to +66
1	0 to +33
0	+/- 0
-1	0 to -33
-2	-34 to -66
-3	-67 to -100
-	not relevant

As discussed in chapter 3.3.1, the cascade has no (or only a minor) influence on the seasonal flow distribution, which is why this indicator group has no effect (0) on the fish biomass. Furthermore, sub-daily flow alterations (as discussed in chapter 3.3.2) do not occur in this run-of-river scenario, and are therefore shown with "-". With the dams fragmenting the river and no mitigation (i.e. fish pass, fish friendly turbines etc.) in place, migratory species will become extinct (-3) within the cascade and most likely also immediately downstream due to lost upstream spawning habitats. With increasing distance to the cascade the impacts are expected to diminish as other spawning habitats (if available and accessible) can offset the impacts to some degree. However, it is very likely that also migratory species located downstream of Paksane will be impacted, e.g. by limited exchange with upstream populations (-2). Floodplain species, generalists and other species are less dependent on connectivity and are therefore less impacted by longitudinal continuity fragmentation (i.e. -1 within

and downstream of the cascade). Caused by the low flow velocities, increase in river dimension and sedimentation processes, the habitat conditions (morphology) in the cascade is rated with -2, and downstream of the cascade with -1. In zone 3, no direct effects will be visible for years to decades, which is why a rating of 0 was applied. However, on the long run impacts are also expected to migrate further downstream once the erosion wave reached these habitats. Water quality changes will most likely only occur within and downstream of the cascade (zones 1 and 2) and since no detailed data are available on oxygen and temperature conditions, it was currently rated with -1 for all species.

Table 3.29. Rating of expected impacts of the cascade (Scenario 1.1.0) on fish guilds and estimated biomass change as a result of alteration of the environmental conditions reflected by five indicator groups.

Indicator groups	Fish groups	S1.1.0 (baseline for other Scenarios)		
		Impact zone		
		1	2	3
Seasonal flow	Migr. large	0	0	0
	Migr .small	0	0	0
	Floodplain	0	0	0
	Generalists	0	0	0
	Others	0	0	0
Sub-daily flow	Migr. large	-	-	-
	Migr .small	-	-	-
	Floodplain	-	-	-
	Generalists	-	-	-
	Others	-	-	-
Connectivity	Migr. large	-3	-3	-2
	Migr .small	-3	-3	-2
	Floodplain	-1	-1	0
	Generalists	-1	-1	0
	Others	-1	-1	0
Habitats (Morphology)	Migr. large	-2	-1	0
	Migr .small	-2	-1	0
	Floodplain	-2	-1	0
	Generalists	-2	-1	0
	Others	-2	-1	0

Indicator groups	Fish groups	S1.1.0 (baseline for other Scenarios)		
		Impact zone		
		1	2	3
Water quality	Migr. large	-1	-1	0
	Migr .small	-1	-1	0
	Floodplain	-1	-1	0
	Generalists	-1	-1	0
	Others	-1	-1	0
Overall status	Migr. large	-3	-3	-2
	Migr .small	-3	-3	-2
	Floodplain	-2	-1	0
	Generalists	-2	-1	0
	Others	-2	-1	0

The overall rating of each fish guild is assessed according to the limiting environmental conditions of the five analysed indicator groups, i.e. the worst score is used for the overall rating (see Tables 3.28 and 3.29). Based on the qualitative rating of expected impacts the biomass losses from BDP 2030 to Scenario 1.1.0 in the Mekong mainstream is estimated. Within the cascade, migratory species will become extinct, while all other guilds will be reduced at a medium level (up to 66 % biomass loss likely).

Further downstream in zones 2 and 3, migratory species are expected to be much more effected compared to other species, since the impact on habitat fragmentation can impact the entire catchment. However, assuming that downstream populations of migratory also have other spawning areas outside of the cascade, the rating was set to -2 in zone 3.

With regard to morphology, no influence will be visible for some decades in the Mekong downstream of Paksane. In the long run, morphological alterations will, however, also show a negative impact on species in this area; especially, if the riverbed deepens and floodplain areas become disconnected. With this assessment focusing on the impacted sections of the Mekong itself, in the overall assessment it has to be considered, that the biomass in tributary and floodplain habitats might be less affected. Therefore, it has to be estimated how the biomass of each impact zone (incl. tributaries and floodplains) responds to these impacts. The following assumptions were made (see also table 3.30):

- Since large and small migratory species rely heavily on the Mekong mainstream, the results of impact zones 1 is adopted for the zone 2 also. In zone 3 (downstream of Paksane), only half of the impact occurring in the Mekong mainstream is assumed for the extended impact zone.
- Floodplain species inhabit both floodplains close to the Mekong and at a larger distance. In zones 1 and 2, the density of floodplains is low and several occur close to the Mekong mainstream. Therefore, half (zone 1) and one third (zone 2) of the impact occurring in the Mekong mainstream is transposed to the respective impact zones. Further downstream, in impact zone 3, floodplains occur frequently not only along the Mekong but also tributaries, which is why only one sixth of the impact is transposed to the impact section.

- Generalist species in zones 1 and 2 are assumed occur in both in the Mekong, tributaries and floodplain habitats. Therefore, half of the impacts assumed in the Mekong mainstream are transposed to these impact zones. Also here, the density of generalist species outside of the Mekong mainstream increases in downstream direction, which is why zone three receives only one third of the impacts assumed for the Mekong mainstream.

Table 3.30. Assumptions for transferring the Mekong mainstream impacts to the biomass of the entire zone for individual groups of fish guilds.

	Migratory species			Floodplain species			Generalists/others species		
	zone 1	zone 2	zone 3	zone 1	zone 2	zone 3	zone 1	zone 2	zone 3
Factor for transferring the impacts of the Mekong mainstream to the entire impact zone	1	1	0.5	0.5	0.33	0.17	0.5	0.5	0.3

Since the impact on other aquatic organisms (OAAs) was not assessed in detail in this study, but a negligence of the related biomass loss might bias the overall situation, the loss of OAAs is assumed to be comparable to the loss of non-migratory fish. Therefore, the mean percentage value of floodplain, generalist and other species was used to assess the percentage loss (see table 3.27).

By translating the rating per scenario and fish group into percentage losses (see Table 3.24) a maximum and minimum biomass loss can be calculated (see Table 3.31). Only for large and small migratory species in zones 1 and 2 no ranges were applied, since it is very unlikely that these species can sustain without intact migration corridors.

Table 3.31. Calculation of the overall biomass loss in the respective zones.

Indicator groups	Fish groups and OAAs	S1.1.0 (baseline for other Scenarios)		
		Impact section		
		1	2	3
Overall biomass loss (in %)	Migr. Large	100	100	17 to 34
	Migr .small	100	100	17 to 34
	Floodplain	17 to 34	0 to 11	0
	Generalists	17 to 34	0 to 17	0
	Others	17 to 34	0 to 17	0
	OAAs	17 to 34	0 to 15	0
Overall biomass loss (in kt/yr)	Migr. Large	-17	-18	-9 to -18
	Migr .small	-34	-35	-19 to -37
	Floodplain	-2 to -3	0 to -3	0
	Generalists	-5 to -10	0 to -5	0
	Others	-1 to -2	0 to -1	0
	OAAs	-4 to -9	0 to -4	0
Total loss (kt/yr)		-63 to -75	-53 to -66	-28 to -55

*calculated as a mean value from the %-loss of floodplain, generalist and other species

Overall, the highest impact is expected in zone 1 (losses of 51-61 %) and zone 2 (losses of 37-47 %) while the biomass losses in zone 3 are comparably small (i.e. 4-7 %). However, this reflects only the short-term outcome and both the impacts of the cascade as well as impacts already caused by the Chinese cascade will become more visible in zone 3 (and also further downstream) within the next decades.

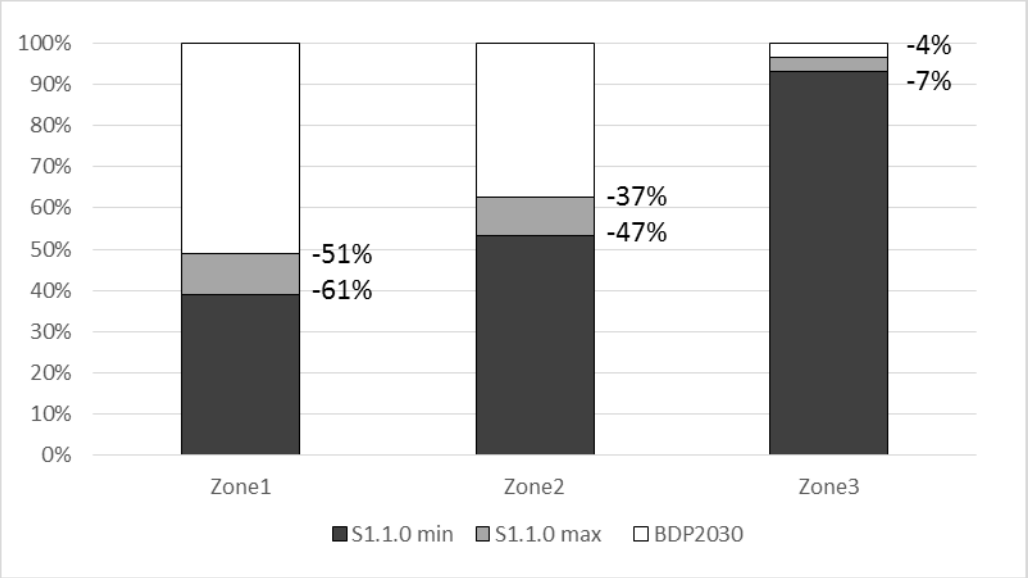


Figure 3.19. *Range of biomass changes related to S1.1.0 per zone.*

The same assessment was performed for other scenarios including the cascade, which was then, however, compared to Scenario 1.1.0 to evaluate positive impacts related to the mitigation measures (see chapter 5.6). The same ratings were used including likely increases as a consequence of mitigation. It has to be iterated that the biomass losses are only calculated indirectly based on the risk analyses of physical/chemical changes of the environmental conditions in order to identify general decreasing or increasing trends.

3.6.1.4 Biodiversity

The Mekong represents a regional hotspot for biodiversity (Termvidchakorn & Hortle, 2013). With a fish fauna of at least 1,000 fish species, the Mekong has the second highest richness of species in the world after the Amazon River (Halls & Kshatriya, 2009; FishBase, Froese & Pauly, 2010, Baran & Myschowoda, 2009). Fish species diversity increases from headwaters to the lower sections, as usual in rivers (Schmutz & Mielach, 2014), which is why the cascade itself hosts less species than the lower part of the LMB.

Several fish species are listed on the IUCN Red List of threatened species. Furthermore, with approximately 220 endemic fish species (Lu & Siew, 2005), endemicity is fairly high, especially in the upper catchments (van Zalinge, 2003). Furthermore, the Mekong has the highest number of giant freshwater fish in the world (i.e. at least seven species; Stone 2007). It includes the critically endangered Mekong giant catfish (Pangasianodon gigas), giant pangasius (Pangasius sanitwongsei) and giant barb (Catlocarpio siamensis) as well as the endangered seven-striped barb (Probarbus jullieni) (Hortle, 2009b, Hogan et al., 2004, Baird, 2006). Halls & Kshatriya (2009)

identified 58 highly migratory species threatened by mainstream dams, which contribute 38.5% to the total weight of all recorded species in the catch surveys.

With the cascade-related impacts, biodiversity is very likely to decrease, especially in zone 1 but most likely also in zone 2. As shown by the previous chapters, especially migratory species will be affected by the implementation of the cascade. In addition, species highly relying on certain habitat features (e.g. sand bars, deep pools, rapids) will decrease in stocks or might become extinct. Therefore, it is very likely that the biodiversity in zones 1 and 2 will include less migratory and specialized species, causing increasing shares of generalist and floodplain species. In zone 3, biodiversity loss will most likely be limited to migratory species within the next few years to decades. However, once morphological alterations migrate further downstream, additional biodiversity losses are to be expected.

Of course, biodiversity is not limited to fish but also includes other aquatic organisms (e.g. benthic invertebrates), but with less detailed data available on the latter, the deduction of detailed conclusions is difficult. In any way, it is clear that the inclusion of the cascade will cause an overall biodiversity loss, which will not be limited to the loss of fish species (see also Chapter 6 in the Manual for more info on biodiversity).

3.6.2 Final Phase

In the final Phase, the assessment takes place at a larger scale (i.e. under consideration of the whole LMB cascade and with greater focus on the basin scale, i.e. including the tributaries) and under consideration of the Council study results. Since the assessment took place at a conceptual level without detailed calculations (as performed for the Upper Lao cascade), it was not possible to draw detailed conclusions on changes related to the impacts and mitigation measures. With this regard, hydromorphological aspects are only discussed in a qualitative manner. However, detailed assessments were performed with regard to the overall connectivity in the LMB and under consideration of different hydropower scenarios and passability rates. Since biomass data currently allow no differentiation between mainstream and tributaries, no clear conclusion can be drawn on the actual biomass loss caused by the respective hydropower scenarios. With this regard, the results of the Council study, which include relative biomass changes for different sections along the Mekong mainstream, are summarized and discussed.

3.6.2.1 Connectivity

As already discussed in previous chapters, the overall connectivity and passage efficiency of individual dams is a very important factor for cumulative impact assessment of several consecutive dams. Since the effect is multiplicative (i.e. each dam potentially reduces the number of fish successfully passing a barrier), low passage efficiencies can significantly impact fish populations (see chapter 3.6.1.1.2 for more details). Within phase 4, different passage efficiencies were included in the DCI calculation (see sub-chapters on fisheries and aquatic ecology within chapter 6). Furthermore, different development scenarios (with regard to the number, location and passage efficiency of hydropower plants) were assessed and compared with regard to their overall connectivity (i.e. based on DCIs). These analyses took place independent of the Council Study outcome to provide better insights into the negative effect of habitat fragmentation as well as beneficial effects related to continuity restoration (e.g. in the form of a fish pass or alternative

hydropower design) or abandonment of selected projects in very sensitive locations.

3.6.2.2 River channel habitats

Abiotic responses to impacts and mitigation measures are covered in the respective chapters (e.g. Hydrology, Geomorphology and Water Quality). The content of these chapters combined with the Council Study results will serve as a basis for the assessment of habitat alterations/improvements in the LMB. Where possible (e.g. Don Sahong, Sambor), more detailed discussions of expected impacts and potential mitigation measures will take place under consideration of existing documents and literature review. Thereby, a qualitative assessment will be performed for five distinct sections.

3.6.2.3 Fish biomass and biodiversity

The Council study concludes on guild-based biomass changes in different sections along the Mekong mainstream (i.e. BioRA zones including a buffer of 15 km on both sides of the Mekong). To allow a comparison with previous biomass assessments within this report data were summarized to reflect five main sections along the Mekong and five groups of guilds (i.e. used in previous assessments ofthe project, extended by non-native fish). The sections were selected with regard to the main impact areas along the Mekong mainstream, i.e. upper cascade (~zones 1 & 2), middle reach (~zone 3), lower cascade (~zones 4 & 5), Tonle Sap River and Lake (~zones 6 & 7) and Delta (zone 8). To be able to set biomass changes in relation to the actual abundance within each zone, the following table provides the share of each fish guild per BioRA zone.

Table 3.32. Percentage contribution of each fish guild / indicator to the overall catch in each zone (based on Council study BioRa Final Technical Report, Appendix G; grey cells highlight dominating guilds).

BioRa Zones		1	2	3	4	5	6	7	8
Council study	Mitigation Guidelines	Upper cascade		Middle section	Lower cascade		Tonle Sap (river & lake)		Delta
Main channel resident (long distance white)	Migratory	1.81	26.22	43.06	5.20	2.68	8.19	5.71	0.04
Main channel spawner (short distance white)		56.88	43.16	37.90	37.81	15.64	28.42	23.09	39.15
Floodplain spawner (grey)	Floodplain	1.74	0.00	2.28	13.03	15.57	22.46	18.56	4.32
Floodplain resident (black)		3.70	5.68	1.63	10.93	63.60	22.49	20.16	13.12
Eurytopic (generalist)	Generalist	0.07	0.00	0.05	5.81	0.21	6.68	16.96	10.27
Estuarine resident	Others	0.00	0.55	1.24	4.37	0.46	0.62	4.83	14.98
Anadromous		0.00	0.00	0.45	0.88	0.01		0.24	0.80
Catadromous					0.17			0.04	0.03
Marine visitor		0.00	0.00	0.00	2.73	0.77	0.18	1.59	2.10
Rhithron resident		13.25	16.09	8.85	11.56	0.20	9.39	5.43	0.04
Non-native	Non-native	22.54	8.30	4.53	7.53	0.88	1.56	3.39	13.06

Changes (with regard to impacts and mitigation measures) will again be assessed using the colour coding provided in table 3.28 in chapter 3.6.1.3. However, it has to be emphasized that the efficiency of mitigation measures can only be assessed on a rough qualitative basis due to the lack of detailed modelling. Council Study results will also be used to discuss the effects on biodiversity.

3.7 Economic Evaluation

3.7.1 Valuation of Sediment Trapped/Flushed

A high-level economic assessment of the sediment impacts and mitigation measures (outlined in Chapter 3.4) associated with the Laos Cascade was included in the multi-criteria analysis of the 2nd Interim Phase. The value of sediment being transported in the Mekong mainstream at Sanakham and Paksane was estimated based on the methodology developed in the ISH02 Project (MRC, 2015). This approach is based on market values and assumes a different value for sand and gravel, and silt and clay. The values of sand and gravel is estimated at $3 USD/m3 based on a literature review of market prices. Silt and clay is assigned a value of $1.5 USD/m3, based on an assumption of its potential use in the production of bricks. It is recognised that this method does not assign a monetary value to the 'ecosystem services' provided by the sediment in the river system. These services are assessed in the study as part of the non-monetary indicators (e.g., sediment and nutrient transport).

3.7.2 Valuation of Fisheries

Aquatic ecology and fisheries can be evaluated by indirect and direct values. While marketed products can be directly valued on the basis of market prices, biodiversity and cultural values (e.g. the importance for sustaining livelihoods) can only be valued indirectly (Hortle, 2009; Baran et al., 2007). Within this study, only direct values (i.e. market price of fish) was used, as for sediments.

Hortle (2009) estimated the typical retail market prices for first-sale products to $ 1-1.8 USD/kg. Considering an inland yield of 2,062 kt of fish and 498 kt of OAAs (i.e. 2,560 kt in total) this would result in a value of 2.6-4.6 billion dollars. By adding another 1,000 t produced by aquacultures (mainly in Viet Nam), with the value of 1-1.8 billion dollars, the first-sale value of all fishery products of the LMB would result in $ 3.6-6.5 billion dollars – a figure which is frequently cited by other studies (e.g. Hogan, 2011; Ferguson et al., 2011). However, since aquaculture is not impacted by the cascade, these products were excluded from the assessment. For fish and OAAs a price of $ 1.8 USD/kg was used for calculating the economic losses and benefits per scenario. However, it has to be stressed that this price is rather conservative, since So Nam et al. (2015) assume higher first-sale prices with differences per country (i.e. 5.2 USD/kg in Lao PDR, 6.9 USD/kg in Thailand, 3.6 USD/kg in Cambodia and 2.1 USD/kg in Viet Nam). On average, this would result in a mean price of 4.5 USD/kg. However, since the first assessment (in Phase 3) was restricted to Lao PDR and Thailand, a mean price of 6 USD/kg could be assumed, which would be much higher than the value stated by Hortle (2009).

Also for aquatic ecology, it is recognized that other ecosystem services provided by the Mekong are extremely valuable. However, the capture of their economic value is complex and may never include all relevant aspects. Therefore, the economic assessment focuses on market products, while qualitative aspects are put aside to be discussed in a qualitative manner.

Furthermore, the assessment only considers the biomass of the three impact zones (i.e. Laos and Cambodia), while the assessment for the Tonle Sap and Delta (i.e. Cambodia and Vietnam) will follow in the next phase. Therefore, the overall biomass, for the 2nd Interim Phase, was estimated as follows (see chapter 3.6.3 for details):

Table 3.33. Economic evaluation of biomass loss from BDP 2030 to Scenario 1.1.0.

Yield and revenue indicators	S1.1.0 (baseline for other Scenarios)		
	Impact section		
	1	2	3
Yield in BDP 2030	122,598	141,498	785,672
Yield in Scenario 1.1.0	53,885	81,890	744,257
Mean yield loss compared to BDP 2030 (t/yr)	-68,713	-59,608	-41,415
Mean yield loss compared to BDP 2030 (%)	-56	-42	-5
Revenue in BDP 2030 (Mil. USD/yr)*	220.7	254.7	1414.2
Revenue in Scenario 1.1.0 (Mil. USD/yr)*	97.0	147.4	1339.7
Revenue loss (Mil. USD/yr)*	-123.7	-107.3	-74.5

* assuming a conservative price of 1.8USD/kg

3.7.3 Valuation of energy loss

The basic approach to assess the financial implications (for the owner/developer) of the mitigation scenarios will be to determine the change of energy generation compared to the base case without the mitigation measure. The financial value of the energy difference can then be determined.

To calculate the financial impact for the developer the lost energy generation shall be valued at the tariff the developer receives. However, the economic value for the society of the lost energy generation might be higher. If the lost generation is replaced by an alternative generation source, the economic value will be the generating costs of this source. If the lost generation leads to demand not being met, the economic value will be the value of not delivered power, which normally is several times higher than the tariff. For simplicity in the study we have restricted it to look at the financial value for the owner/developer, e.g. power revenues. In ISH02 the power revenues were 1 of 6 parameters in the financial valuation (MRC, 2015).

Currently all water power export schemes from Laos to Thailand are energy sales agreements and there is no separate capacity tariff (i.e. HP developers are paid not by installed capacity but by energy delivered). Some current projects have time of day and day of the week tariffs divided into Primary, Secondary and Excess energy periods. The typical definition of these periods is shown in Figure 3.20. These agreements normally include annual supply targets for Primary and Secondary energy and / or requirements for minimum Primary Energy availability in terms of hours per day over monthly and yearly periods. Liquidated damages are often included in these agreements for failure to achieve the specified supply targets. The supply targets are sometimes mitigated by a dispatch recovery process, which allows shortfall in a dry year to be recovered in a subsequent wet year. These shortfall recovery arrangements normally run in cycles of several years with a compulsory financial settlement process at the end of each cycle and a limit on how much shortfall and excess can be accumulated. The power off-taker usually has energy purchase commitments in the Primary and Secondary tariff bands and these commitments are sometimes different for each month of the year.

Agreements for domestic energy purchase in Laos are typically not time of day agreements and offer a flat rate for energy. These agreements will usually include a supply and purchase commitment and a dispatch shortfall recovery process similar to the export agreements.

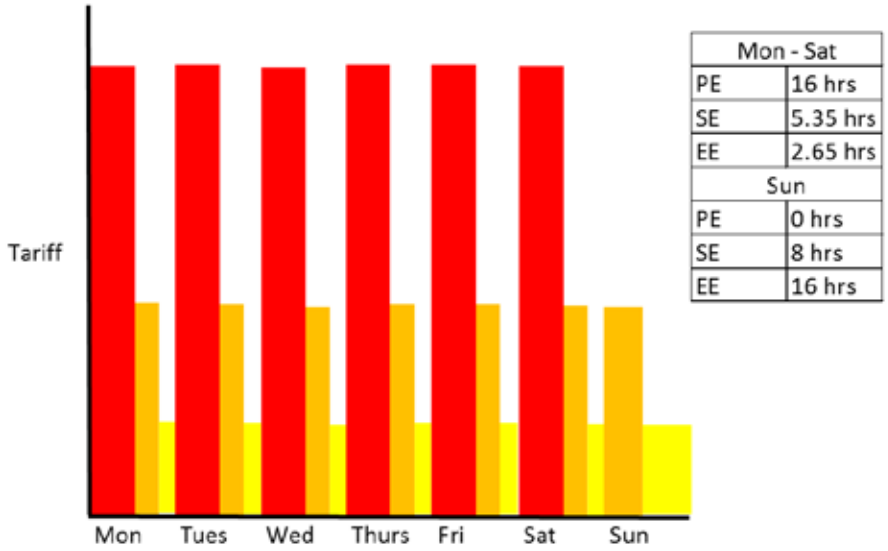


Figure 3.20. *Energy Tariff Periods.*

It is anticipated that most mainstream projects that are the subject of this case study will supply the export and domestic energy markets through separate power purchase agreements and dedicated units for each power off-taker.

The details and tariff levels in power purchase agreements between developers and the power off-takers are confidential. However, for the purposes of this case study it is necessary to estimate a commercial value for energy. Based on knowledge of regional conditions and commercial arrangements that are in the public domain it is suggested that the purchase prices for energy in Table 3.34 are likely to be typical for the mainstream projects at 2016 rates. Some power purchase agreements make provision for escalation but this is typically not an annual adjustment and is managed by a tariff change in blocks of 5 or 10 years. Such adjustments are normally not full escalation corrections and the real value of energy going forward therefore reduces.

Table 3.34. Typical Energy Generation Tariffs.

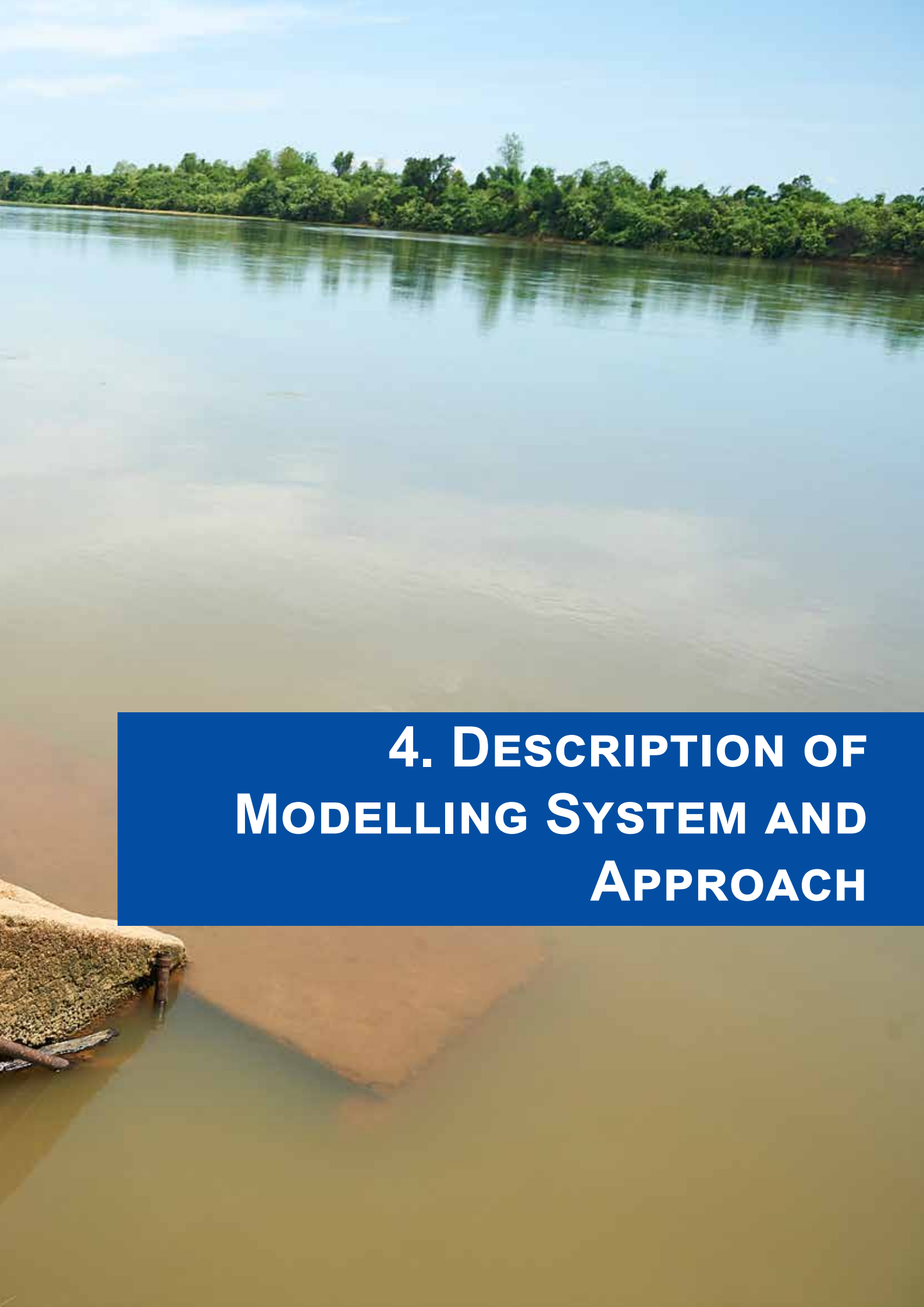
Energy Type	Sale Price
(USc)	
Primary energy for export	8
Secondary energy for export	5
Base load energy for export	7
Domestic energy	6

In the event that the energy output of a main stream project is reduced by the requirement for an environmental mitigation measure this must be foreseen by the project developer. The project developer must negotiate a tariff PPA on the basis of the overall project economics and risks involved. If the mitigation measures are found not to be sufficient to meet the targets of the Environmental Management Plan (EMP) the developer/operator must absorb the additional cost of adapting operations if this was not foreseen in their initial PPA. A higher energy tariff can also be negotiated and then the economic cost of mitigation will be borne by the consumers through an adjustment in the end user tariff.

In order to make the Case Study hydropower modelling task more manageable, a simplification was made in assuming that hydropower energy is exported. Consequently, the last row in the table above can be disregarded.

The daily peaking strategy considered in Scenario 1.3, of the 2nd Interim Phase, can readily be accommodated in a conventional energy sales PPA and should typically represent a revenue enhancement to the developer. The sediment flushing strategy considered in Scenario 1.2 is more challenging. Reservoir draw down and flushing causes loss of energy but the determination of loss in each year will be very difficult to assess because of the interaction between the projects and the absence of a baseline against which loss can be measured. The challenge will be even greater if a programme of adaptive management is pursued, since this will require a continuous change in operating requirements. This challenge will be most easily taken care of if the projects are dispatched by a central authority to achieve optimal cascade performance (see also Chapter 3.1.3).

An additional consequence of an environmental mitigation measure that reduces energy output is that the energy reduction must be made up from an alternative source of supply. The alternative source will most probably have a different production cost and can in some cases be more environmentally damaging. The transfer of generation from hydropower to coal fired generation, for example, is unlikely to be a positive environmental undertaking.



4. Description of Modelling System and Approach

4. Description of Modelling System and Approach

4.1 Description of Mekong system to be modelled

4.1.1 Geographical subdivision

In order to select the correct models for hydropower risk and environmental impact mitigation in the Mekong, the geographical layout or the position of the model in the basin, is an important criterion.

The LMB can be divided into the following stretches for the purpose of the modelling:

1. Chiang Saen – Vientiane
2. Vientiane – Phnom Penh
3. Tonle Sap system
4. Phnom Penh – start Mekong Delta
5. Mekong Delta

The first stretch is chosen to represent the reach with and without the dam cascade (and mainstream reservoirs), as well as the transition from a bedrock dominated channel to a fully alluvial sand-bed channel. This stretch forms the subject of the case study of the Lao cascade (see also details in chapter 2.2).

The next stretch from Vientiane to Phnom Penh represents the main river and the tributaries that are now modelled using the DSF modelling suite. The boundary at Phnom Penh is chosen as this is the location of the start of the point of inflow towards the Tonle Sap system.

A special case is the Tonle Sap lake system with the bi-direction flow system connected to the Mekong River at Phnom Penh.

The fourth stretch is the last part of the Mekong River, with tributaries up till the point of noticeable impact of the tides on the flow. Evidently, this is not a well-defined location, but for the purpose of the present study, it is sufficient to use a point below which the impact of the mitigation measures on the salt intrusion might become noticeable. This specific reach of the river is influenced significantly by diversion of flows to flood-plains during the wet season.

The fifth stretch represents the Mekong Delta, which is a very complicated system with tidal influence. Here, particular attention needs to be given to salt-water intrusion that has a direct impact on irrigation water availability and fishery.

Considering the application of models in the case study of IHS0306, the geographical layout can be roughly lumped into three parts, as shown in Figure 4.1.

1. Upper Mekong Basin, upstream from Chang Saen
2. Lao cascade reach, including the Pakbeng, Luangprabang, Xayaburi, Paklay, Sanakham and dams and their reservoirs (impact zone 1) as well as impact zones 2 and 3 (see Chapter 2.5.1).
3. Lower Mekong Basin.

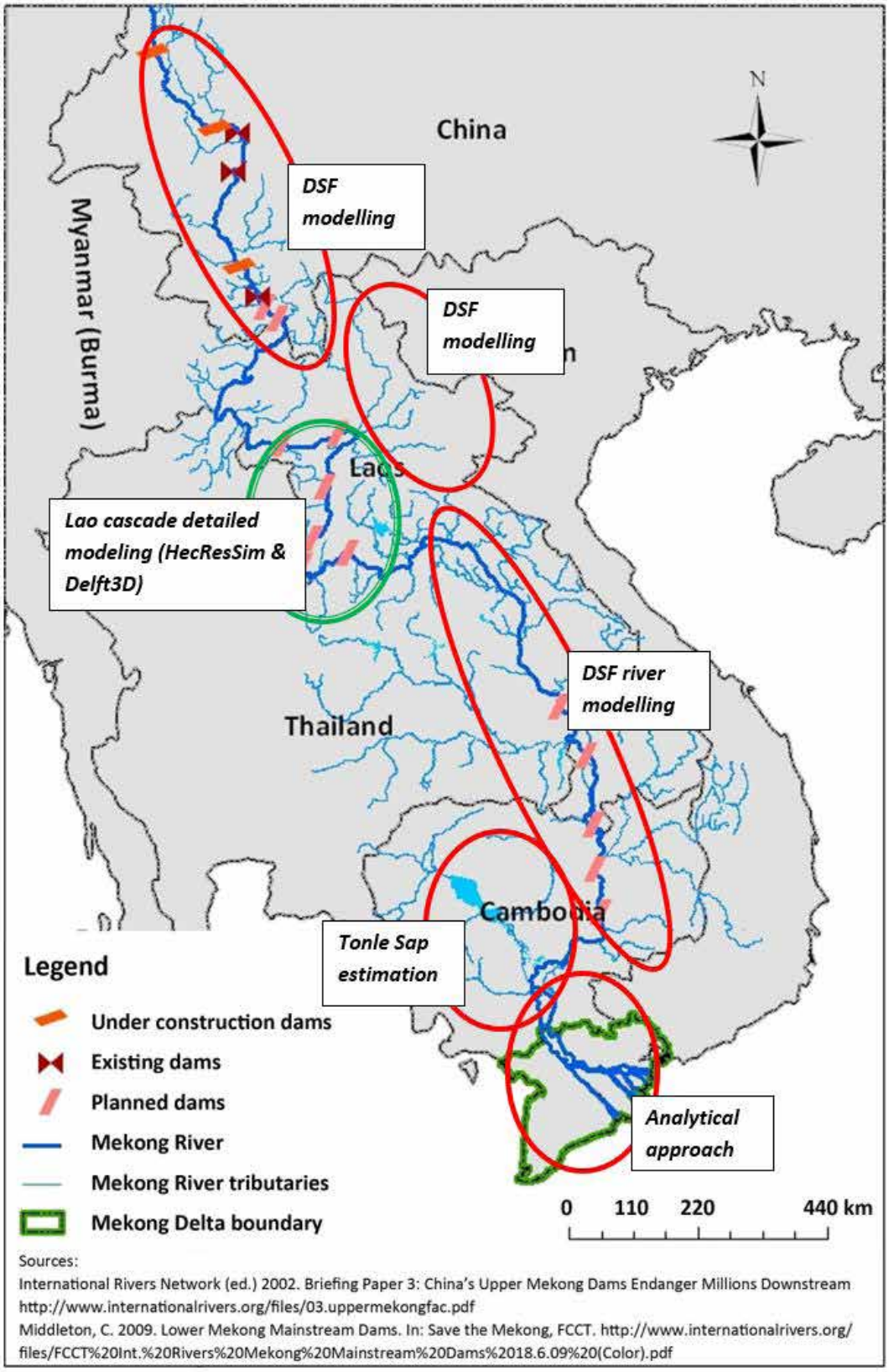


Figure 4.1. *Geographical layout of the modelling domain, applied to the upper Lao Cascade.*

In order to assess the impacts of dams and measures, simulations are required of the entire LMB. Depending on the location of the considered dam cascade, certain parts of the domain can be

replaced/added with additional hydropower-modelling and reservoir models. For the case study , impacts will be assessed at and downstream of the Lao Cascade. Nevertheless, for many impacts it is the full LMB, starting from Chiang Saen, which needs to be included in the modelling.

4.1.2 Dominant processes to be modelled

The following processes will need to be modelled:

1. Rainfall-runoff in the tributaries
2. Sediment input from the various tributaries
3. Flow routing through the main channels
4. Sediment routing with the flow routing
5. Tonle Sap system, including sediment and water quality issues
6. Flood-plain inundation in the Cambodian and Vietnam delta region
7. Salt-water intrusion in the Mekong delta

An overview of the various processes along the main river is shown in Figure 4.2.

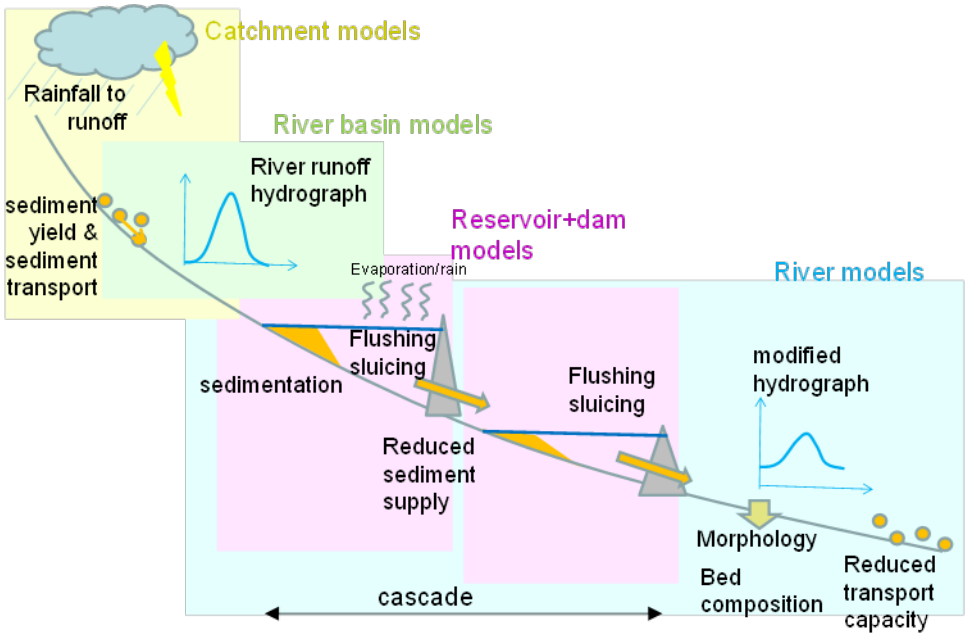


Figure 4.2. *Dominant processes along the Mekong River.*

4.2 Modelling approaches for specific processes and functions

4.2.1 MRC Decision Support Framework (DSF)

The presently available MRC Decision Support Framework (DSF) forms the basis of the modelling studies for the Case Study. For specific modelling of hydropower optimisation and detailed flows and morphology of the reservoirs, additional components have been introduced that connect and agree well with the DSF schematisations. Figure 4.3 shows the components of the presently available DSF, together with new additional components to be used for the cascade modelling. The

eWater component is in fact part of DSF as it is a replacement of the obsolete IQQM module.

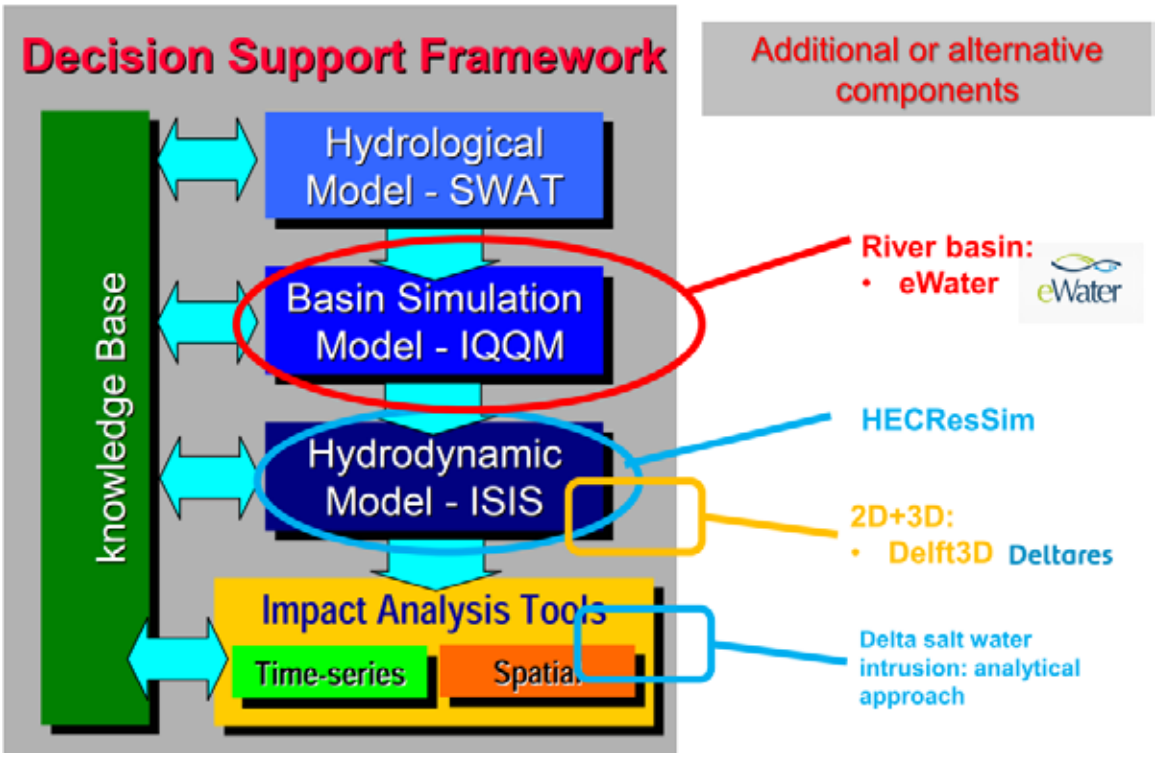


Figure 4.3. *Overview of modelling systems.*

4.2.2 Rainfall-runoff in the tributaries and the UMB (Chinese dams)

The boundary conditions of the cascade models are formed by the inflow from the UMB (Lancang) and the various tributaries up to Vientiane. For the former, use will be made of the discharge and sediment concentrations as provided by the modelling of the UMB by the DSF suite of models. This is specifically necessary to simulate the future scenarios, as the measured records up till present only just start to show the impacts of the Lancang cascade. The existing databases for DSF scenarios (Council Study and BDP) contain results for hydrology with the lower six dams in the cascade (for which the Mitigation Guidelines project study 5, see Chapter 2.1), as well as the eight in Lancang in the UMB. ***The impact of the lower six additional dams is considered relatively small compared to the lower Lancang cascade, as the latter contains significant larger storage reservoirs***.

Also for the tributary flows the simulated discharge series have to be retrieved from the DSF model, derived from a simulation for the BDP 2030 scenario, i.e. the chosen future state of development of tributary dams.

The following future scenarios are considered relevant for the relevant inflows to the cascade in this case study.

Table 4.1. Future scenarios covered by the DSF model runs in Council Study and BDP2.

Type	Comment	Mitigation Guideline Project Phase
Council Study 2008 with BDP 2030-20Y tributary development and UMB	This condition is needed for the base condition of the Case Study. It contains both flow and sediment input from UMB and tributaries. It is used as a base case for the 2nd interim phase.	Case Study 2nd interim phase (Lao cascade)
Council Study development scenario 2040 (tributaries 2040 dam development, main-stream dams and UMB, with climate change) – sub-scenario M3CC (or hydropower sub-scenario H1)	This is the preferred scenario for setting-up the cascade. However, the required conditions from the DSF were not available in time for the Case Study in this project (in the 2nd interim phase). Therefore, they have only be used in the Final phase.	Final Phase
BDP 2 scenario 2030-20Y hydropower development with hydrology 1985 to 2008	The original simulations from 2011 were re-run with the updated (end 2015) DSF model (IQQM and ISIS), but only for hydrodynamics not for sediment. The results from these runs form the base case of the Case Study modelling work.	Case Study 2nd interim phase (Lao cascade)

In the DSF modelling work the time-series of discharges and water levels is based on hydrological conditions for the period 1985-2007. However, the modelling work for the BDP 2 scenarios were completed in 2011, and is only based on conditions for the period 1985-2000.

4.2.3 Sediment input from the various tributaries

In the DSF sediment input to the cascade are proposed to be determined by the amount of catchment erosion, by instream sediment processes in the tributaries and reservoirs, and by sediment supply from the UMB. The DSF models are presently being prepared to calculate the sediment discharge in the Mekong basin (using SWAT and eWater sources). However, the relevant components and the calibration were not completed in time for usage in the 2nd interim phase of the case study (situation middle 2016).

As an alternative, the potential sediment inflow from the tributaries and rivers have been estimated from a combination of results of the MRC's DSMP monitoring (Koehnken, 2015), sediment-balance/ budget studies for the main-river, catchment size and erosion potential, and sediment trap-efficiency of planned tributary dams. These data have partially been obtained from existing EIA's for planned and constructed tributary dams, and updated with the above recent sediment data from the MRC.

4.2.4 Reservoir cascade modelling

In fact the most important part of the modelling for the Case Study is the reservoir simulations of the cascade. In the cascade the reservoirs are assumed to be connected in the sense that the tailwater of each reservoir is connected to the dam of the upper reservoir (with no or hardly any free-flowing river sections). The new detailed models for the cascade therefore need cover the full

cascade reach without gaps that have to be filled in by the DSF. Two types of models are needed for the cascade (see chapter 4.3 for details):

- Hydropower model for hydropower optimisation and joint operation;
- Delft3D model for detailed flow and sediment movement in the reservoirs.

For hydropower modelling HEC-ResSim was used, which is a public-domain software package in the HEC modelling suite. It is not fully resolving the flows in reservoirs and channels, but uses a water-balance approach specifically designed for river systems with multiple hydropower reservoirs. The model makes use of the input series that are produced as part of the scenario simulations of the DSF and the results is then used as input to the Delft3D model. Due to the simplified approach for channel flow, the approach is showing limitations with respect to simulating the tail-water variations of individual reservoirs. This is, however, catered for by running MIKE11 in parallel.

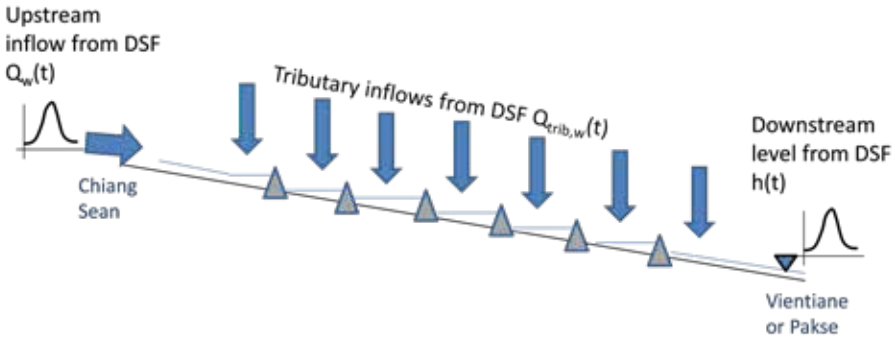


Figure 4.4. *Schematic presentation of the cascade and the required data inputs from the DSF for the hydropower modelling.*

Figure 4.4 shows how the flow-discharge series for each time step at Chiang Sean (Qw(t)) and at tributary mouths (Qtrib,w(t)) are obtained from the DSF model calculations for chosen development scenarios, i.e. BDP2-2030. The figure also shows that at the downstream end, a water level time series from the DSF model runs is prescribed as well. The choice of the location of the downstream boundary will determine at which location the DSF has to generate the data.

For detailed modelling of the flow and sediment processes in the reservoirs, use will be made of the open-source Delft3D software package. This modelling system allows for a 2- and 3-dimensional hydrodynamic simulation of the flow processes in the reservoirs including the erosion, sediment transport and deposition processes. It is also fully dynamic, which means that unsteady flow processes on small time scales (minutes) can be resolved, with bed-level and bed composition update at each computational time step.

For each of the reservoirs in the cascade, a separate model has been built, and the results of the upstream reservoir form the input for the next downstream reservoir. In this way, the flow conditions and impacts are routed through the cascade. Figure 4.5 shows one single model within the series of connected Delft3D models in the cascade, and how data from DSF and hydropower modelling is used as input to the Delf3D model. Note that for this model also sediment loads have to be prescribed as function of time at the upstream boundary and from tributaries. The inflow of water and sediment at the upper boundary follows directly from the output of dam spills and power

releases from the upstream Delft3D model. For the first (upstream) Delft3D model, for Pak Beng, the inflow from Chiang Sean coming from the DSF has to be used.

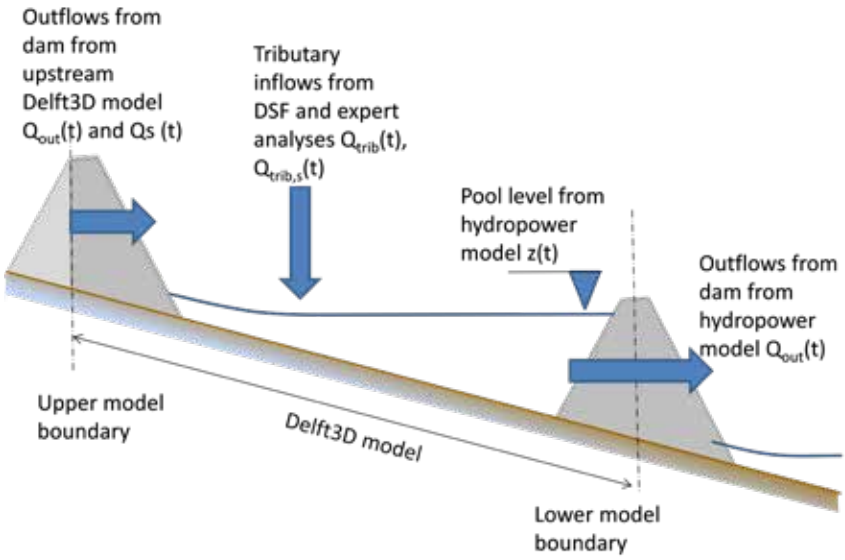


Figure 4.5. *Schematic presentation of a Delft3D model for one reservoir, with indication of data input from the DSF and hydropower modelling.*

The various mitigation options that has been studied, to assess their efficiency for incorporation in the Guidelines, is represented in the 3D model according to their particular characteristics. Operational measures can be simulated mostly by prescription of operation levels of the reservoir pool, and the outflows at different outlets at the dam. The results of the simulation of the most downstream reservoir will form the input for the subsequent simulation of the downstream processes along the mainstream.

4.2.5 Flow routing through the main channels downstream

Modifications in flow conditions in the reach downstream of the cascade can be assessed using the one-dimensional river models. Most of these impacts, such as changes in hydrograph of hydropeaking, will travel down as damped long waves, for which these 1D models are well suited. The input of flow conditions at the lower dam (Sanakham dam) is directly coming from the lower Delft3D model as time series of water discharges and sediment loads. Tributary inflows are taken from the DSF models (similar to the hydropower and reservoir modelling).

Downstream from the lower dam of the cascade, the ISIS one-dimensional modelling module of the DSF can simulate the relevant unsteady-flow processes with very small timescales (ranging from days to hours). The model is therefore suitable to simulate even the effects of variations caused by hour-to-hour operation, such as with power peaking. The model includes both main-channel and floodplain flow, but does not fully resolve the details of the flow variations in the cross-section. Details of higher resolution (e.g., flow in side channels, or inundation depths per cell in floodplains) require the more detailed 2D/3D models in DSF, or can be based on post processing and expert opinions of the 1D model results. The choice for this approach depends on the availability of relevant 3D models and their support for the considered reach. The focus of the modelling has been for the 2nd Interim Phase (assessment of the Northern cascade) on the reach downstream of the

cascade, down until Pakse (zones 2 and 3). This limitation is imposed due to the difficulties that still exist to model the flows through the section of the four-thousand islands, using the 1D modelling approach in the DSF. In this phase the assessments are based primarily on output of the Delft3D model until Paksane. Because of damping of flow impacts from the cascade, and lack of noticeable hydrological impacts further downstream, the assessment of area downstream of Paksane (until Pakse) was not needed. Only for Phase 4, with the lower cascade of main-stream dams in place, it was necessary to include the lower parts as well. For this purpose the model results of the Council Study hydropower scenarios are required (using the full DSF, 30 year modelling runs). For a 'first order' assessment it was found that a more simple conceptual hydraulic modelling approach already provided useful quantitative output to evaluate the possible mitigation approaches.

In line with routing flows through the lower reach, it is best to use the ISIS modelling system to also route the sediments. For this purpose the time series of discharges from the lower dam, as well as sediment loads from this dam (out of the Delft3D model), have to be used. In addition, a simplified ISIS version with a limited number of cross-sections was used.

4.2.6 Downstream Dams

Similar to the upstream cascade, the hydrological impacts and their mitigation are mostly related to discharge and water-level changes. As these features are mostly one-dimensional characteristics (mostly varying along the river and not in transverse direction), the use of a 1D approach is suitable. For instance the basic modelling system for flow in the DSF (section 4.2.1) for the Mekong is a 1D hydraulic model that can be applied very well for this purpose. The assessment of the mitigation measures mostly focusses on propagation and damping of long waves (flood waves and peaking waves) in the reservoirs and rivers.

The most relevant hydraulic impacts in and downstream the cascade are again the water-level fluctuations caused by hydropeaking. Besides using the DSF (for unsteady flow calculation) these can be calculated using an approximate flow-routing approach (e.g., mentioned also in section 4.2.5). Such an approach approximately calculates damping and propagation of the long waves, using a simplified 1D unsteady flow approach based on DSF geometry, or analytical routing functions. In this case study a simplified 1D approach has been used for rapid assessment. Only the condition is considered with the highest difference in off-peak and peak discharge during the year, based on the inflow and maximum turbine discharge.

4.2.7 Flows and sediment in the Mekong Delta

The Mekong delta in Cambodia and Vietnam, downstream of Kratie, and flowing into the East Sea, is affected by upstream hydropower development through changes in hydrology and sediment load. This system can be considered rather complex and unique in its large-scale hydrological behaviour, because of the presence of bifurcating channels, inundating flood plains, and the exchange with Tonle Sap lake through the Tonle Sap River. The following figure schematizes and illustrates the essential components of the system, which are considered relevant for the large-scale impacts of hydropower development.

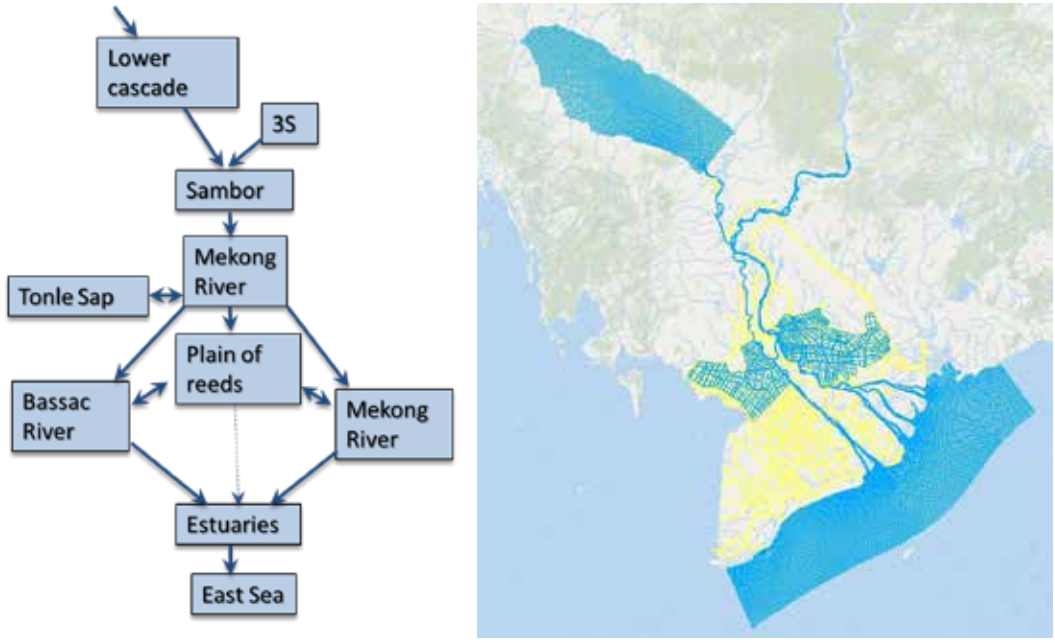


Figure 4.6. *Schematic presentation of the Mekong Delta, with the identified main components that govern the hydrological system (left panel) and model outline (right panel).*

The most relevant seasonal-flow impacts in the hydropower scenarios, as mentioned earlier, are reduced floods, increased low flows, and changed timining of start and end of wet season. These large-scale changes in hydrology, are partially 'absorbed' by the Tonle Sap lake and the flood plains, hence reducing the remaining impacts in the estuarine sections of the delta. In the following figure, Pronker (2017) shows the most relevant processes for the assessment of impacts of hydropower in the Mekong Delta in general (for flows and sediment). A full understanding of the system requires a detailed schematisation of all of these processes, as well as their mutual interactions.

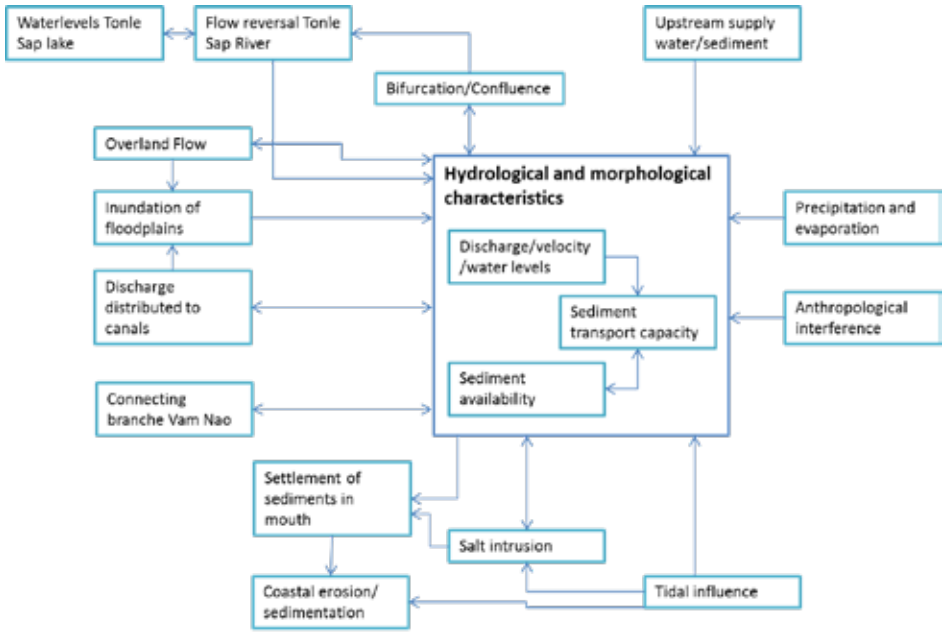


Figure 4.7. *Scheme with the most relevant hydrological and morphological characteristics and relevant processes which are considered relevant for modelling the Mekong delta impacts (Pronker, 2017)*

To assess these impacts, the DSF combines different modules for routing the flow impacts through the rivers (1D) and exchanging with the storage and inundation areas (2D) and tidal reaches with salt intrusion (3D). However, for understanding the actual contribution of the different components of the system, it is better to look at the individual models (per component) and then the interactions between them.

Therefore, and because of limited availability of DSF modelling results for this region during the Final Phase, an alternative but comparable modelling approach has been applied. In this approach the overall unsteady flow for the entire system is solved using a Delft3D model with Flexible Mesh solver (unstructured grid). The model starts at Kratie and includes the full delta, including the Tonle Sap, the flood plains, delta branches and part of the East Sea, as shown in right panel of Figure 4.6. The model has been created by Vo Thanh from UNESCO-IHE, and adapted and applied by Pronker[15] (2017). This type of model is able to combine 1D and 2D grids, which can be more efficient than a complete 2D model. It has also more applications than a 1D model such as a coupling to the DelWAQ water quality model and to model the inundation of floodplains. The main branches, lake and sea are modelled with 2D depth average and the canals and smaller side branches are modelled in 1D. The largest branches are modelled using 8 grid cells per width and smaller branches, such as Tonle Sap river and upper Bassac, with 4 grid cells in the width. The width of the cells depends on local river geometry and the length of the cells is around 650 m, excluding more complicated areas such as bifurcations and confluences. In the lake and sea area the grid cells are large up to 2000 m x 2000 m. The bathymetry is interpolated from the 1D ISIS model cross sections from the year 2000. The 1D canals are modelled with a distance between nodes of 400m, however since little data is available, the width and depth of the canals is uniform in the model (resp. 100m and -5m m.a.s.l.). In the Plain of Reeds and Long Xuyen Quadrangle, simplified floodplains (with uniform floodplain and dike-heights) are modelled that inundate with natural conditions. The upstream boundary is a discharge time series at Kratie and the sea connections are waterlevel boundaries that are composed by the tidal constituents. The tributary inflow in Tonle Sap is an average inflow, schematized in one single inflow point, which is estimated by Kummu et al. (2014)[16] . The model has been calibrated with data available from the year 2002.

Based on this overall complex dynamic model, Pronker (2017) developed a set of simplified conceptual models for all the relevant components, which could be used to understand and predict the contribution of each component to the entire Mekong-Delta system. This could for instance be used to determine the effect of introducing an extra bypass for Mekong flow towards Tonle Sap Lake.

To estimate the impacts on the delta, initially the discharge at Kratie for the BDP 2030 scenarios has been calculated. This has been done by combining the results from the DSF simulations for the BDP2030 and Baseline-MT at Pakse (obtained during the Case Study for the Northern Cascade) with the results of a study by Piman et al (2013) [17], which estimated the changes to dry and wet season flow in the 3S system due to hydropower scenarios. Later, after the full Council Study simulation results became available (end of 2017), the results have been compared. Figures 4.8

15 The influence of hydropower developments on the Mekong delta, Pronker J.S., November 2017

16 Water balance analyses for the Tonle Sap lake – floodplains system, Kummu et al., February 2014

17 Effects of Proposed large dams on water flows and hydropower production in the Se Kong, Se San and Sre Pok rivers of the Mekong Basin – Piman et al., June 2016

and 4.9 shown this comparison for the average discharge hydrographs at Kratie. Although there are differences in the reduction of the mean flood peaks, the overall impacts of the dam-development are found to be in the same order of magnitude. Note that in both approaches the main impacts are between the average 1985-2008 conditions with and without Chinese dams and tributary dams. The impacts of the Lao cascades are negligible on this scale.

Note that In order to calculated the average daily contribution of the system, the difference in daily discharge between Pakse and Kratie from 2001-2006 has been averaged with an estimated travelling time from Pakse to Kratie of 3 days. The resulting hydrographs have been smoothed using a moving average. During the first months of the wet season it is expected that the most water is retained in the reservoirs to increase the water level and hereby the power production. This effect is taken into account for the discharges from the 3S system. The total volume during the year discharged by the 3S system is not changed for the scenarios.

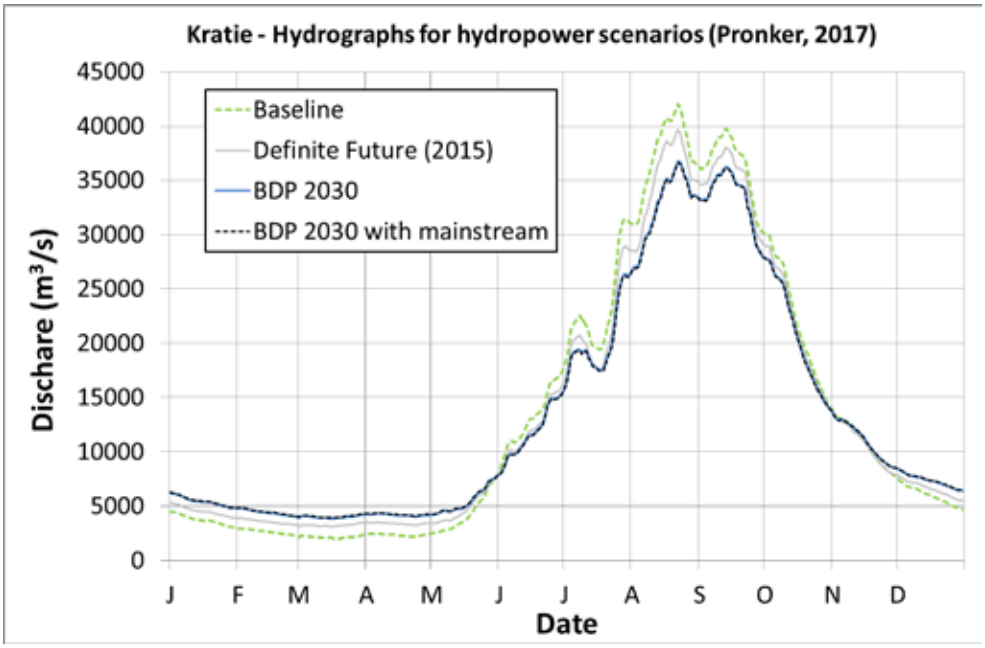


Figure 4.8. *Average hydrograph for Kratie for different hydropower scenarios, following from combining Pakse BDP 2030 DSF output, and estimate for 3S contribution.*

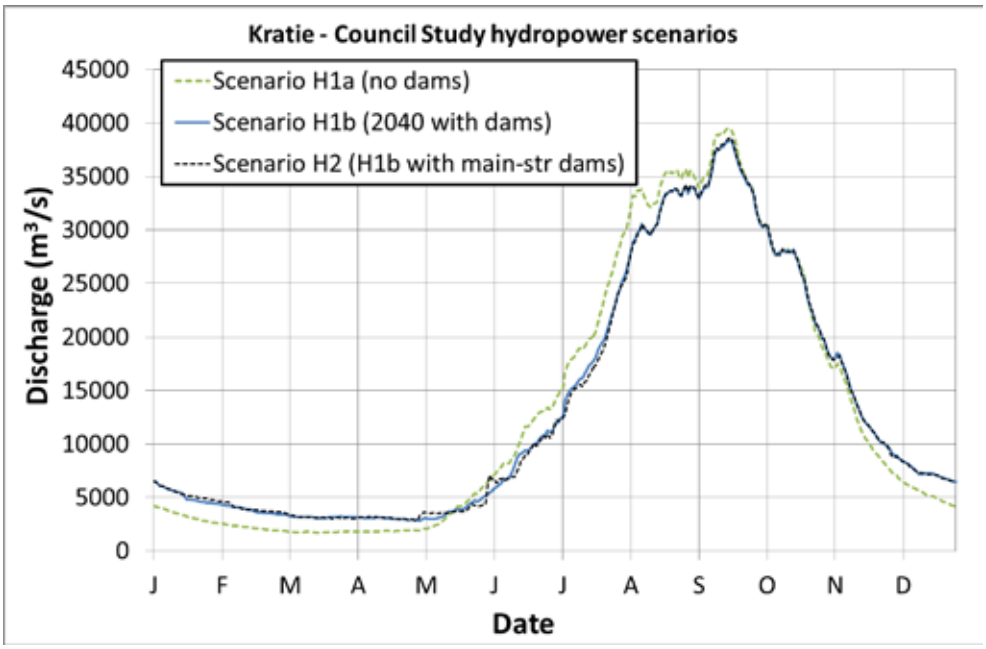


Figure 4.9. *Average hydrograph at Kratie for different hydropower scenarios calculated for 2040 in the Council Study hydropower scenarios.*

4.2.8 Salt-water intrusion in the Mekong delta

The impact of the hydropower dams on the salt water intrusion is caused by the changed hydrograph in the downstream stretches of the delta, as well as by changes in bed level. As mentioned in the previous section, the assessment of impacts of hydropower development on the Mekong delta has been carried out using a Delft3D-FM model instead of the full DSF modelling system. Since salt water intrusion is a very complicated process that cannot be modelled accurately with a 2D depth averaged model, the existing Delft3D-FM model (in depth-averaged mode) is not suitable for an in-depth analyses of this process. However, an indication of the expected changes due to the changes in the flows, particularly during the dry season, can be made, e.g. on the salt-water intrusion that has implications for the irrigated agriculture and fisheries in the delta.

An alternative approach has been considered, i.e. the analytical method that was developed and applied for the Mekong delta by Savenije from Delft University of Technology and Nguyen from UNESCO-IHE (Nguyen and Savenije, 2006)[18]. However, the approach did not provide sufficient insight into the impacts of the hydropower scenarios in different situations in time. A more basic approach, based on evaluating the effect of dispersion under different circumstances has been applied here.

4.3 Details on hydropower and Delft3D reservoir modelling

4.3.1 Introduction and overall setup

As presented in the previous section, to quantitatively design and evaluate the potential mitigation measures of the Lao Cascade, a suite of special models has to be applied. It is important that these models are part of the MRC, and therefore should be freely available for MRC after completion of

18 Salt intrusion, Tides and Mixing in Multi-channel Estuaries – Nguyen and Savenije, February 2008

the present study. It is also important that any new models are well connected (both results and exchange of information) to the existing modelling framework of MRC, i.e. the DSF system.

In Figure 4.10 an overview is given of the various steps of the modelling activities. The input towards the cascade modelling has been based on existing (DSF) modelling efforts, whose results feed into both the HEC-ResSim/MIKE11 hydropower model and the Delft3D hydrodynamic model. The latter also makes use of the results of the hydropower model. The results of the Delft3D modelling forms the basis for the assessment of the impact of the various possible measures in the Lao cascade on sediment, morphology, water quality, fishery, etc. The assessment in the LMB downstream from the Lao cascade starts off from the results of the Delft3D modelling of the lowest reservoir. It will preferably be based (again) on the DSF modelling system for the main river, with the addition of special tools / techniques for the Tonle Sap and Mekong Delta.

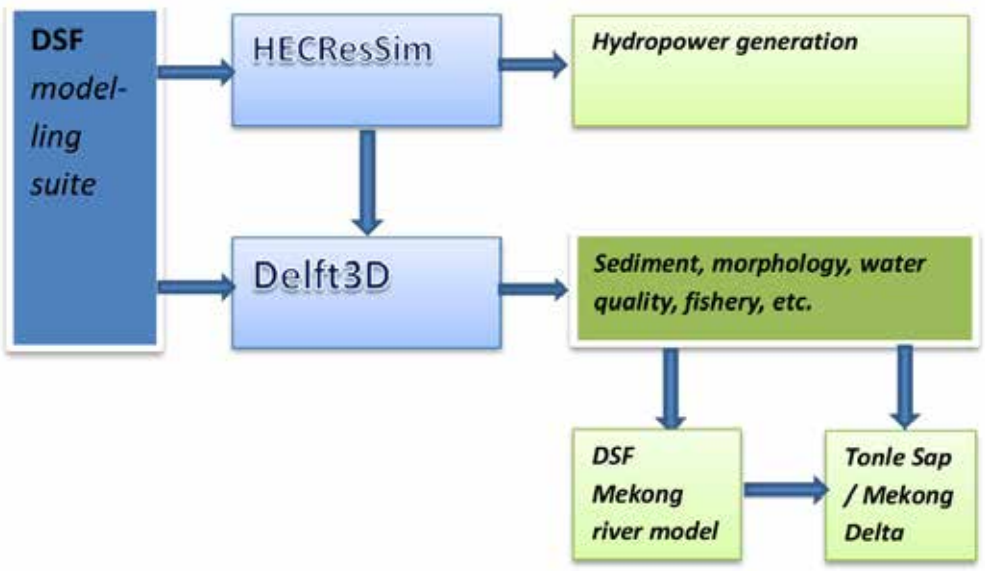


Figure 4.10. *Layout of modelling framework.*

In the following paragraphs, the two main modelling systems will be discussed that will be used for the simulation of the Lao cascade. Firstly, the hydropower model, which produces part of the boundary conditions for the hydrodynamic (3D) model.

For the downstream dams and for Tonle Sap and the delta the results can be drawn from the DSF. In the case study alternative approaches have been used as well to calculate the impacts and mitigation, based on a Delft3D model for the Mekong delta. As the studied indicators are mostly one-dimensional, the effects studied are mostly well reproduced by the DSF.

4.3.2 Hydropower model for the Northern Lao Cascade

4.3.2.1 Modelling system

The main purpose of the hydropower modelling is to establish a relationship between different scenarios for hydropower and water resources management on one side and financial implications on the other. In most cases, this means loss of generation income as a consequence of mitigation

measures or other imposed modifications/limitations to the exploitation of the hydropower potential, as part of the proposed Guidelines. Figure ES.1 in the Executive Summary, illustrates how the Methodological Framework for Hydropower modelling is undertaken. Comparison of modelled scenarios will put a “price tag” on various mitigating options.

The three most important elements in the computation of income from energy generation at any time are 1) the energy tariff at the given time of the day and week; 2) the discharge through the turbines at the given moment, and 3) the hydraulic head at the given moment. The two latter elements are output from the hydropower model.

4.3.2.2 Modelling software

During the Inception phase, a considerable effort was made to examine and compare various commercial software packages for hydropower calculation. Around a dozen packages were considered. The most critical requirement for an adequate software package is the ability to carry out simulation on a short time step, i.e. around hourly basis in order to simulate hydropeaking. Most packages failed to meet this requirement. In the end, the two software selected were MIKE11 and HEC-ResSIM. MIKE11 is not a specialised hydropower or reservoir model but a 1-dimensional hydraulic model. Nevertheless, it is so generalised that also hydropower operation can relatively easily be simulated.

HEC-ResSim is a freeware developed by US Army Corps of Engineers (USACE). The software is a lumped, conceptual model, and calculates the variation of reservoir levels based on water balance calculations. The model is very flexible when it comes to defining operating rules, but has some limitations when it comes to backwater effects on tailwater curves and transport time between the dams.

To overcome these limitations, and provide more robust results, an additional model in MIKE11 has been developed. Output from the MIKE11 model has been used to calibrate the river routing in HEC-ResSim, and tailwater curves for HEC-ResSim are also imported from MIKE11. Most scenarios are calculated in both packages.

4.3.2.3 Model set-up – 2nd Interim Phase

Xayaburi hydropower plant is currently under construction, but the other four dams are at a much less advanced stage of development, and the information about them is sparse. Because of this, it has been chosen to use the Xayaburi design as a “template” for the other hydropower plants when information is incomplete.

Design flow and reservoir water level

The design flow of Xayaburi is 5142 m³/s. Design discharge for the other hydropower plants has been scaled based on the Xayaburi flow, and the median flow in the river at the different dam sites.

Table 4.2. Design flows and supply levels for the 5 mainstream dams.

	Design flow	Full supply level	Minimum supply level
Pak Beng	4110 m³/s	340/335[19] masl	334 masl
Luang Prabang	4110 m³/s	310 masl	305 masl
Xayaburi	5140 m³/s	275 masl	270 masl
Pak Lay	5140 m³/s	240 masl	235 masl
Sanakham	5140 m³/s	220 masl	215 masl

Gates

The capacity curves for the spillway- and flushing gates of the different dams are based on the Xayaburi gate curves presented in "Physical Hydraulic Model Study of Xayaburi Hydroelectric Power Project" (AIT, 2013).

Result comparison between MIKE11 and HEC-ResSim

The calculated power generation from the results of the HEC-ResSim model and MIKE11 are very similar, which strengthens the robustness of the results. In Phase 4, 2017, the HEC-ResSim results is planned to be compared with the updated ISIS options, in the DSF. The table below shows the HEC-ResSim results in % of the MIKE11 results for the different scenarios and power plants.

Table 4.3. Comparison between MIKE11 and HEC-ResSim.

Scenario	Pak Beng	Luang Prabang	Xayaburi	Pak Lay	Sanakham	SUM
1.1.0	100%	100%	100%	100%	101%	100%
1.1.A	101%	100%	105%	100%	102%	102%
1.1.B	101%	99%	105%	100%	98%	101%
1.2.A	97%	100%	98%	98%	100%	99%
1.3.0	99%	98%	98%	97%	96%	98%
1.3.A	100%	99%	104%	96%	100%	100%
1.3.B	100%	100%	104%	96%	100%	100%
1.3.C	100%	100%	104%	96%	100%	100%

Scenarios 1.2B, 1.2.C, 1.3.D and 1.3.E have not been simulated in both models, and are therefore not included in the table.

Modelled Energy Output compared to previous studies

The hydropower plants of the Laos mainstream cascade was first proposed in 1994, and since then, several different layouts and configurations of the projects have been studied. As only the

19 340 in wet season (jun-nov), 335 in dry season (dec-may). In scenario 1.1.0 and 1.3.0, the full supply level is set to 340 all year.

design for the Xayaburi project is finalized, design assumptions based on the most recent available information have been made for the other four projects. These assumptions does not necessary comply with the earlier studies, but even so, the modelled power generation for the total cascade is very close to the generation in the studies (98%).

The table overleaf shows the difference between technical key data and power generation between the 2009 optimisation study (TOR scenario), and modelled generation (scenario 1.1.B).

Table 4.4. Comparison between the case study and previous planning documents

		Pak Beng		Luang Prabang		Xayaburi		Pak Lay		Sanakham	
		Optimisation study	Model (1.1.B)	Optimisation study	Model (1.1.B)	Project presentation	Model (1.1.B)	Optimisation study	Model (1.1.B)	Feasibility study 2015	Model (1.1.B)
HRWL	masl	345	340/	310	310	275	275	240	240	220	220
Design flow	m³/s	4400	4100	5500	4100	5142	5140	6600	5140	5500	5140
Capacity	MW	1230	965	1410	1090	1285	1400	1320	834	660	608
Generation	GWh	5370	4935	5480	6052	7370	7166	4880	4510	3697	3533
Difference	%	92%		110%		97%		92%		96%	

4.3.2.4 Interconnection with other modelling

One basic input to the HP model is runoff from upstream, i.e. inflow from China, as well as tributary inflows along the Cascade reach. These inflows will need to be provided by the DSF modelling team in order to reflect the future basin development. As was discussed already in Chapter 4.2.1, the actual future situation that will be used in this study will depend on the timely availability of the modelling results of DSF.

The final output from the HP modelling is, as mentioned, generated income from power generation. Furthermore, intermediate outputs for pure hydraulic parameters constitute the boundary conditions for the Delft3D hydraulic sediment models that are discussed in the next chapter. In the HP modelling, one integrated model encompasses the entire cascade, whereas this would be impractical for the Delft3D modelling, which instead will establish separate models for each reach between two dams (plus the most upstream reservoir). Consequently, each Delft3D model reach requires a set of boundary conditions; an inflow (time series) at the upstream boundary and; a water level (time series) at the downstream boundary. The upstream boundary flow and sediment flux will come directly from the same Delft3D modelling of the reservoir directly upstream and these results will be compared with those from the HP modelling in order to ensure that these are sufficiently similar.

There will be a larger number of model runs under HP modelling than under Delft3D sediment modelling. Under a given scenario, a number of HP model runs will be carried out to optimise the operation under that scenario, and only the final, optimised result, will be “coupled” with the Delft3D

sediment model. In case the Delft3D sediment models show that the HP-modelled HP operation did not achieve its goal (i.e. with respect to flushing), a trial-and-error approach will be used in the two co-operating modelling systems, until a satisfactory result has been reached.

4.3.3 Detailed Delft3D reservoir modelling for the Northern Lao Cascade

For the detailed hydrodynamic simulations of the reservoirs, the open-source modelling system Delft3D is applied. This software is supported and maintained by Deltares, and its source code is freely available from the Deltares website. This modelling approach can be used to assess the dynamic (time dependent) and spatially varying hydrodynamics and geomorphology of the Mekong and the reservoirs.

The full Northern Lao Cascade and the reach between Sanakham dam and Paksane, have been modelled using the Delft3D software. The purpose of the model is to assess the effect of mitigation measures, and hence it is not used for full impact assessment at this time. Nevertheless, the approach and types of models can in principle also be used for quantifying impacts of the dams and reservoirs as well. The main aims of the detailed model are therefore:

- Quantify the change in transport of sediments through the cascade (pulses) with and without sediment management;
- Quantify the bed-level changes and amount of sedimentation in the reservoirs, for different mitigation approaches;
- Quantify the changes in bed level in the downstream reach;
- Quantify the changes in bed composition in the reservoirs and the downstream reach;
- Quantify the morphological processes (erosion) and additional concentrations during flushing events.

The emphasis of the analysis is on the effects of the mitigation measures relative to the condition with operation on a full supply level, and does not focus on the impacts of the dams itself (although these are assessed as well) and not on mitigation of the impacts of Chinese dams and tributary dams. We can distinguish three phases in reservoir operation that characterise specific sediment processes and sediment management in the reservoirs. The three phases are reservoir filling, sediment sluicing or routing (operation at MOL), and sediment flushing with full water-level drawdown.

Delft 3D software

Delft3D is a world leading 3D modelling suite to investigate hydrodynamics, sediment transport and morphology and water quality for fluvial, estuarine and coastal environments. The FLOW module is the heart of Delft3D and is a multi-dimensional (2D or 3D) hydrodynamic (and transport) simulation programme which calculates non-steady flow and transport phenomena resulting from tidal and meteorological forcing on a curvilinear, boundary fitted grid or spherical coordinates. In 3D simulations, the vertical grid is defined following the so-called sigma coordinate approach or Z-layer approach. The MOR module computes sediment transport (both suspended and bed total load) and morphological changes for an arbitrary number of cohesive and non-cohesive fractions. Both currents and waves act as driving forces and a wide variety of transport formulae have been incorporated. For the suspended load this module connects to the 2D or 3D advection-diffusion solver of the FLOW module; density effects may be taken into account. An essential feature of the MOR module is the dynamic feedback with the FLOW and WAVE modules, which allow the flows and waves to adjust themselves to the local bathymetry and allows for simulations on any time scale from days (storm impact) to centuries (system dynamics). It can keep track of the bed composition to build up a stratigraphic record. The MOR module may be extended to include extensive features to simulate dredging and dumping scenarios.

Models have been set-up to simulate the erosion and sedimentation processes during all these three phases. This means that the models have to include the dynamics of flow (unsteady flow, time-dependent emptying and filling, low-flow and high-flow conditions). In principle, the reservoir models are meant to support the development of an adequate sediment management strategy for the reservoir cascades, considering the three phases of sediment processes and management.

More specifically the reservoir models are used to calculate:

- detailed hydrodynamics: transverse and longitudinal variation in water depth, flow velocity, bed shear stress; horizontal and vertical circulation, and mixing processes;
- suspended-load and wash-load concentration: advection-diffusion process; fall velocity versus turbulent mixing; sand-mud mixtures;
- bed-load transport of sediment mixtures (gravel-sand mixtures);
- bed composition changes of the active layer of the bed; under-layer book-keeping system;
- sedimentation and erosion of the bed;
- non-erodible layers, such as bed rock sections;

Most of the dams are projected on the river section that is considered as the bedrock reach. In this steep river section the bed of the deep channel consists of bed rock or very coarse material (cobbles, rocks). The gravel and sand fractions that constitute the main transport of the river are mainly found in sand bars in lateral eddy zones along banks, and in the wake of rock outcrops in the channel. The model results show that only in these zones, shear stresses are low enough to allow some deposition of sand. The figures below show, for a typical bedrock section of the Pak Beng reservoir reach, how sediment is modelled along the banks.

The details of eddy formation and sediment entrapment in eddies, are not reproduced exactly due to coarseness of the grid and absence of data. Nevertheless, this process is mimicked by the model to some extent, and shows deposition along the banks in areas where deposition is expected and can be observed from other sources, such as Google Earth or from the field visits.

Figure 4.11. *Google Earth image for Pak Beng reservoir, km 2274-2278, showing lateral sediment bars.*

Figure 4.12. *Photograph of typical lateral sand bar in Pak Beng reservoir, around km 2286, field visit Nov 2015.*

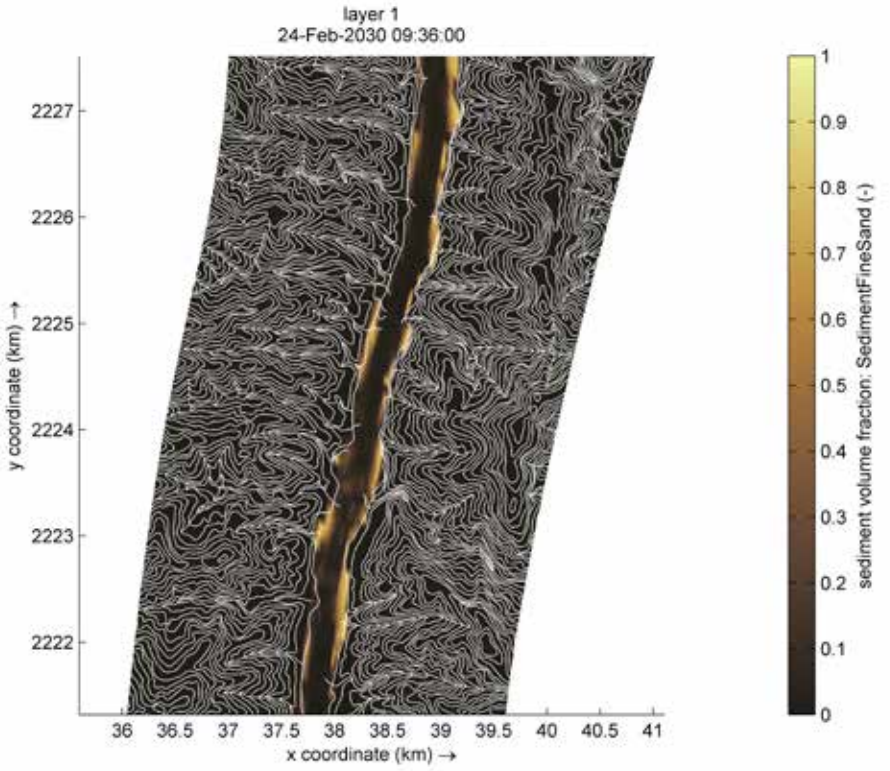


Figure 4.13. *Fine sand fraction in river bed, Pak Beng reservoir without dams (Base Case scenario), km 2274-2278.*

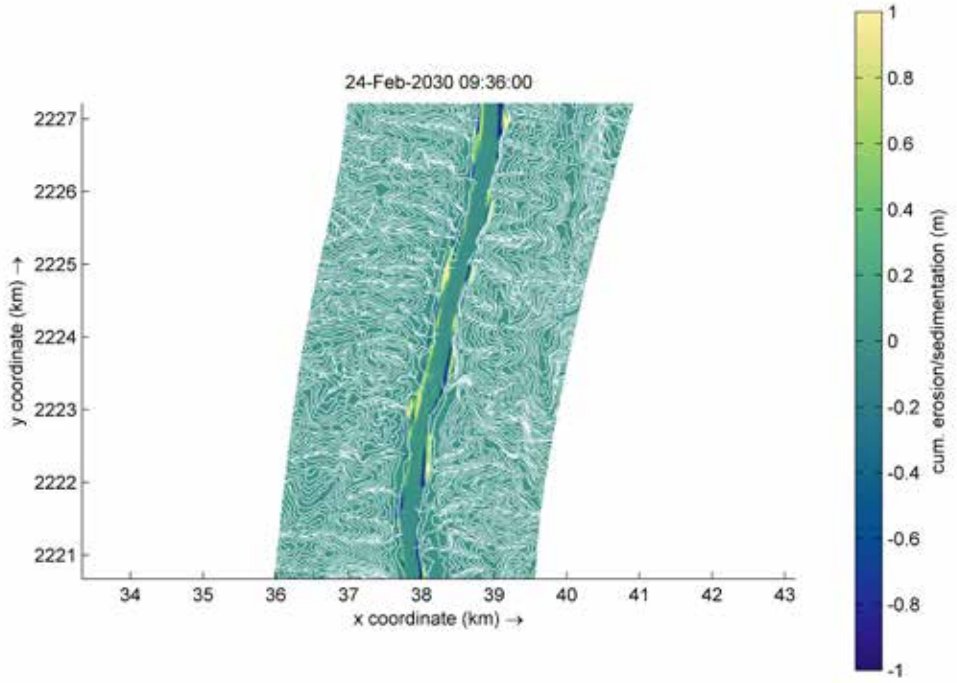


Figure 4.14. *Cumulative erosion and sedimentation in Pak Beng reservoir, km 2274-2278, showing development of lateral sediment bars. Yellow zones along the banks indicate areas with deposition (sand bar growth).*

Scenarios with different operational mitigation strategies requirea full dynamic (unsteady) approach, covering periods of at least one year with the relevant discharge and reservoir-level variations (the full hydrograph).

More details of the approach, and the 2D and 3D modelling characteristics, are presented in the Annex A of this report.

4.3.3.1 Modelling of operational mitigation measures

Flushing and sluicing operations are measures that have to be simulated fully dynamic with reduced reservoir levels and high inflows. When dealing with this kind of operations, it is necessary to consider the following three phase of operation:

Filling

- Discharge is blocked. Flow velocities drop
- Significant sedimentation

Water level at Minimum Operating Level: sluicing

- During flood: maintain high velocity
- Balance erosion and sedimentation

Water level draw down: flushing

- Flow velocities increase in lower reach
- Channel erosion

Figure 4.15 shows which processes determine the sediment balance of the reservoir, and which have to be modelled. Flushing and sluicing can be used to influence the components “transport” and “entrainment/deposition” in this figure (higher velocities cause increased transport etc.).

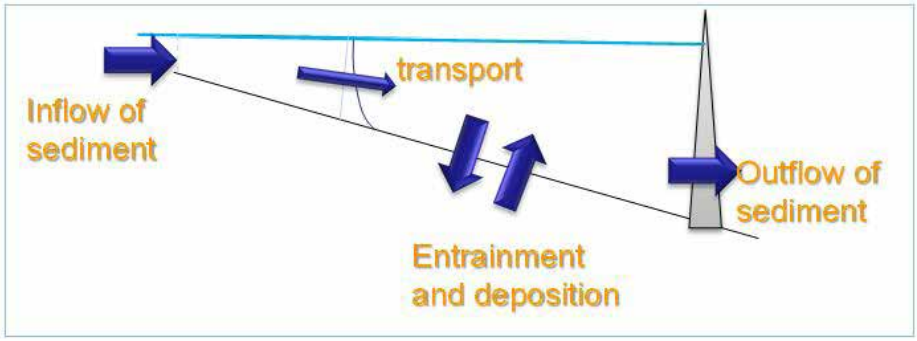


Figure 4.15. *Relevant processes for modelling sediment management operation measures.*

Flushing and sluicing can be modelled simply by lowering the water-levels imposed on the outflow boundary (i.e., the dam), to mimic the release of through gates or spillways. The corresponding outflow is automatically computed, but it can also be imposed as additional extraction near the

dam. Lowering the water levels in the reservoir pool raises the flow velocity, and initiates erosion along the reservoir. During full draw down (especially with a sudden drop of water levels at the dam by using large outlet sluices) the flow velocities temporarily increase significantly in a zone that extends beyond the width of the main channel. But, after the full reservoir is drained, the velocities drop again to moderate values. The slower the down-ramping, the less intensive is this effect of increased erosion.

An example of the computed evolution of bed-shear stresses during draw down is presented in Figure 4.16, after imposing the water-level draw down as shown in figure 4.17. The figures show bed-shear stresses computed with Delft3D for the Pak Beng reservoir for a condition with discharges in the order of 2500 m3/s at Chiang Sean. The bed-shear stress for the full draw down condition is an order of magnitude larger than during the situation with normal pool level. The highest bed shear stresses are found in the deep channel, while banks (with most sediment deposits) are less exposed.

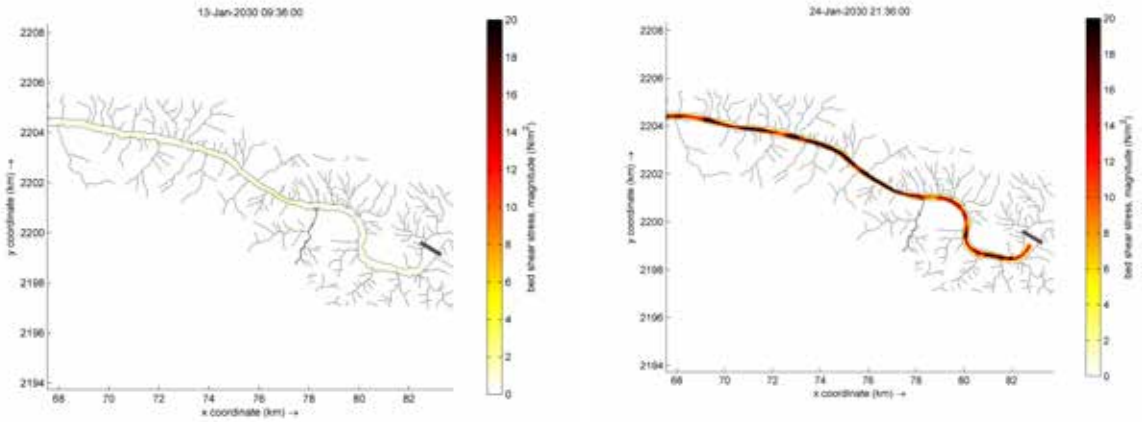


Figure 4.16. *Bed shear stress computed for draw down flushing at Pak Beng reservoir: left, before draw down; right, during full draw down.*

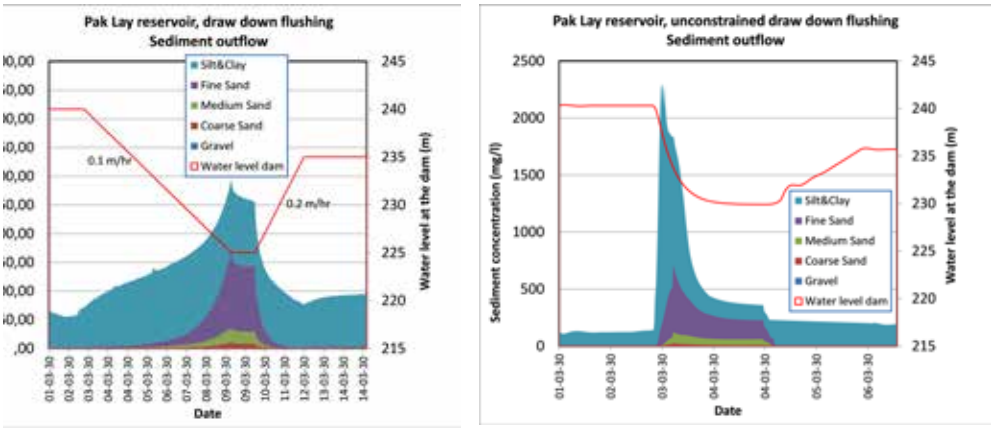


Figure 4.17. *Delft3D result Pak Lay reservoir: outflow of sediment (concentration in mg/l) as function of time, and water level at the dam. Left, draw down with ramping 0.1 m/hr; right, draw down without ramping constraint.*

It should be noted that for both flushing and sluicing, the results are highly dependent on the choice of critical shear stresses for erosion and the fall velocity of the suspended sediment fractions

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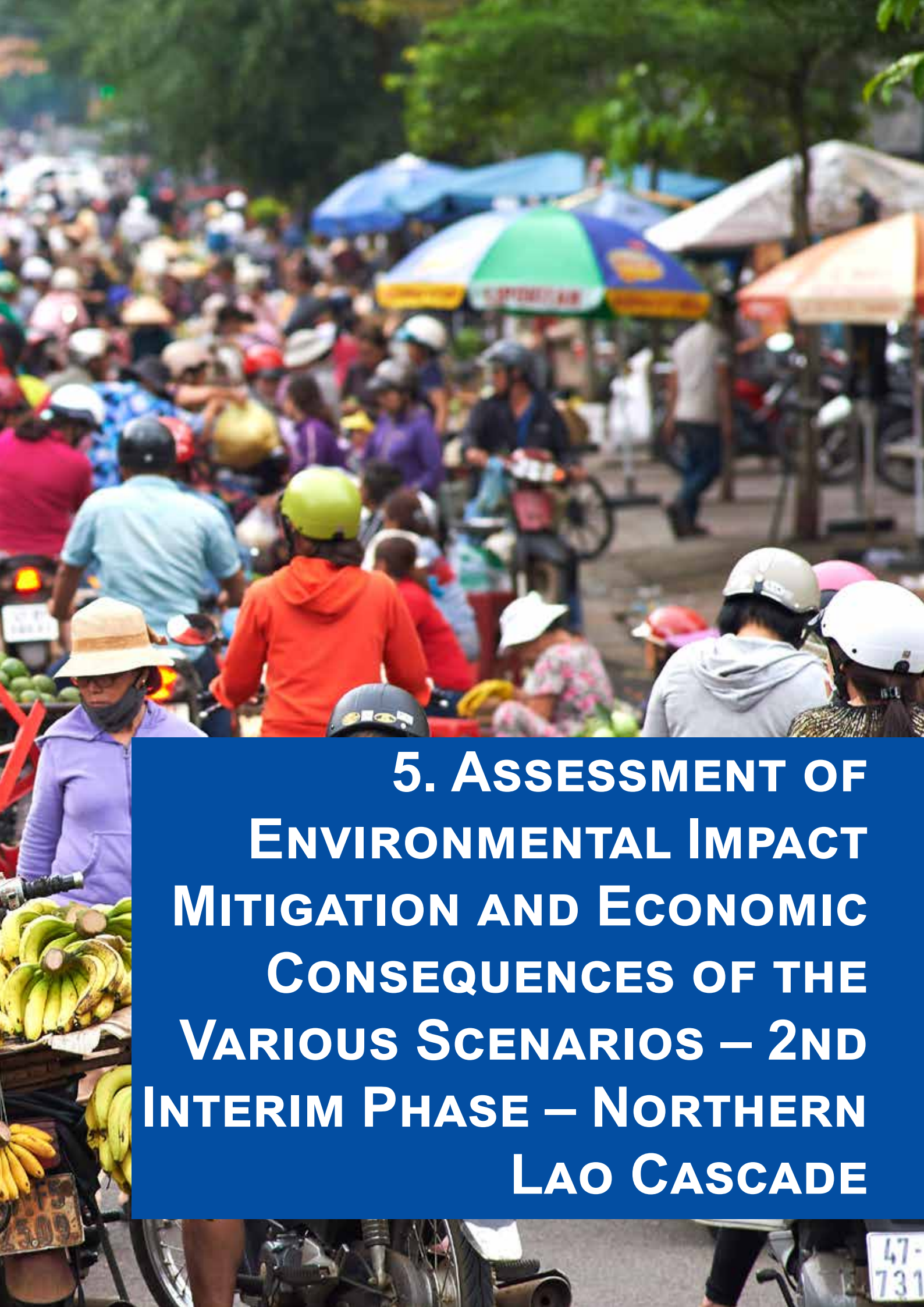
102.13



5. Assessment of Environmental Impact Mitigation and Economic Consequences of the Various Scenarios – 2nd Interim Phase – Northern Lao Cascade

5. Assessment of Environmental Impact Mitigation and Economic Consequences of the Various Scenarios – 2nd Interim Phase – Northern Lao Cascade

5.1 General

Chapter 5 comprises detailed assessment of the scenario modelling and the associated impact mitigation for each theme, based on the indicator framework outlined in Chapter 3.1. At the end of Chapter 5 (Chapter 5.7) a joint evaluation of the scenarios and mitigation measures are outlined, based on the indicator framework. Details of the indicators framework with its associated measures and scenarios are attached to Annex F.

5.2 Overall Hydrology and Flows Impacts

5.2.1 General

The first impact that needs to be assessed is the change in the river regimes due to hydropower development. Most of the other impacts are a function of the change in hydrology, particularly the sediment transport, but also the fish migration. However, it is not necessary to have large changes in the river hydrology to find major changes in the sediment and/or ecological values of a river (see chapters 5.3 to 5.5). Many changes are particularly related to the changes in flow velocity due to the presence of a reservoir, even if the volume is relatively small, and the interruption of the continuity of the water body by a dam on the river. In this chapter, the expected impact of the changes in flow regime on the Lao cascade is described that forms the pilot reach of this study.

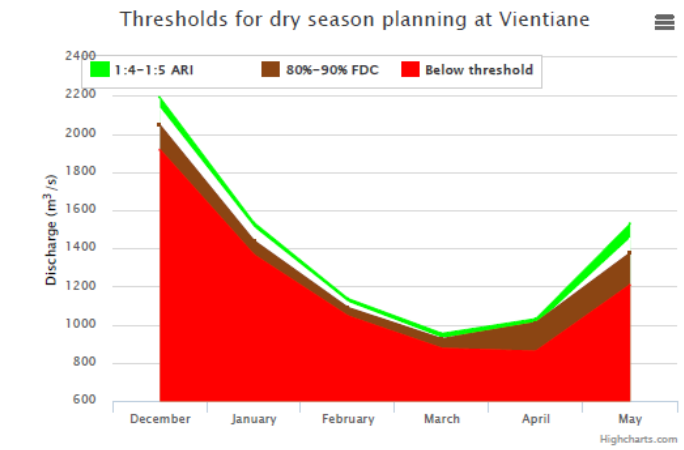
5.2.2 Basin Wide Assessment

5.2.2.1 Compliance with PMFM flow procedures

In order to judge the compliance of the river discharges with the PMFM flow procedures (Procedures for the Maintenance of Flows on the Mainstream), an assessment is made of the discharge series of the various scenarios at a key location at the end of the Lao Cascade. For this purpose, location '1572' is used, which is directly upstream from Vientiane, for which criteria are available in the PMFM. The criteria have been established between the member countries of MRC and summarized in Technical Guidelines [15] that give a description of the procedure and how the guidelines should be applied. For some issues, like the planning purposes in the dry season, no consensus has yet been reached and the guidelines are still in a draft state. Still, it is useful to assess whether the flow series from the model simulations of the Lao cascade for the various scenarios, comply with the criteria.

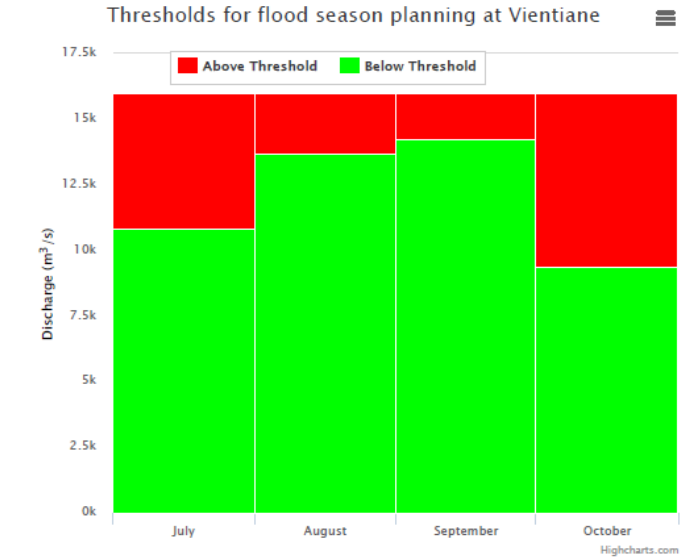
The PMFM makes a distinction between criteria for planning and for monitoring. In this case evidently use should be made of the planning criteria. Criteria exist for both dry seasons flow and for wet season flow, with values per month. The acceptable flows framework for planning purposes during the dry season is based on the monthly average discharge in the dry season (December-May) during 1986-2000, as simulated by the Baseline scenario in the DSF at Vientiane . For the flood season, the flows framework for planning purposes is the daily average peak flow during the flood season (July-October) of the same baseline flow regime (1986-2000) at Vientiane.

The criteria are shown in the following figures.



	December	January	February	March	April	May
1:4 ARI	2193 m³/s	1537 m³/s	1140 m³/s	957 m³/s	1034 m³/s	1532 m³/s
1:5 ARI	2134 m³/s	1506 m³/s	1117 m³/s	928 m³/s	996 m³/s	1451 m³/s
80% FDC	2049 m³/s	1442 m³/s	1093 m³/s	929 m³/s	1013 m³/s	1379 m³/s
90% FDC	1919 m³/s	1368 m³/s	1047 m³/s	878 m³/s	863 m³/s	1211 m³/s

Figure 5.1. *Dry season planning purpose flow criteria (Vientiane).*



	July	August	September	October
Threshold	10799 m³/s	13723 m³/s	14285 m³/s	9415 m³/s

Figure 5.2. *Wet season planning purpose flow criteria (Vientiane).*

An analysis is made of the discharge series for the various scenarios, together with the historical series. For this purpose, a frequency analysis is made of the 24 years daily simulation results and the historical flow series. The following comparisons have been made:

- Dry season planning:
  - 90% FDC versus 90% simulation flows

- 90% FDC versus minimum observed daily flows

- Wet season planning:
  - Threshold values versus 90% simulations flows
  - Threshold values versus maximum observed daily flows.

The results are shown in Figures 5.3 to 5.8.

Dry Season Flow

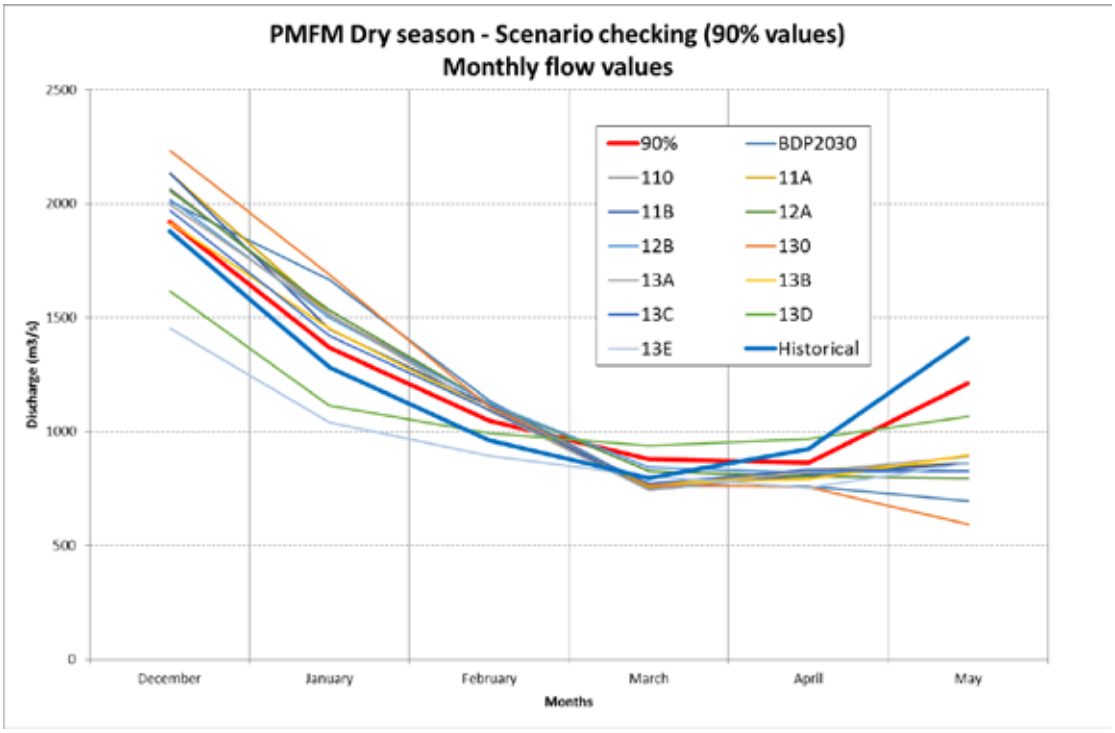


Figure 5.3. *Scenario calculations with PMFM flow criteria (dry season at Vientiane) – 90% values (monthly values).*

For the dry season (December – May) criteria, the 90% monthly historical flows follow rather well the 90% line of the criteria, which indicates that this criterion is valid for the period for which it was derived. This is an important remark, because for the other lines in the graph, starting with BDP2030, the 90% monthly flow values lies significantly higher (with the exception of two of them), about 500 m3/s, at the onset of the dry season, with in general very little variation between the various scenarios. This is probably due to the large increase in average dry season flow since the start of operation of the Chinese dams, which produce significant higher flows in the dry season when turbine flow is at a maximum. ***This implies in fact that the present 90% criterion is obsolete and will need to be adjusted to the new situation. The Lao cascade has hardly any influence on the low flow characteristics, as will be discussed in the following paragraphs on seasonal flow***.

A graph is also shown for the compliance of the 90% daily flow values for the historical and scenarios series. Here most of the flow values are also significantly above the 90% criterion and the large

increase in dry season flow compared to the historical situation is evident.

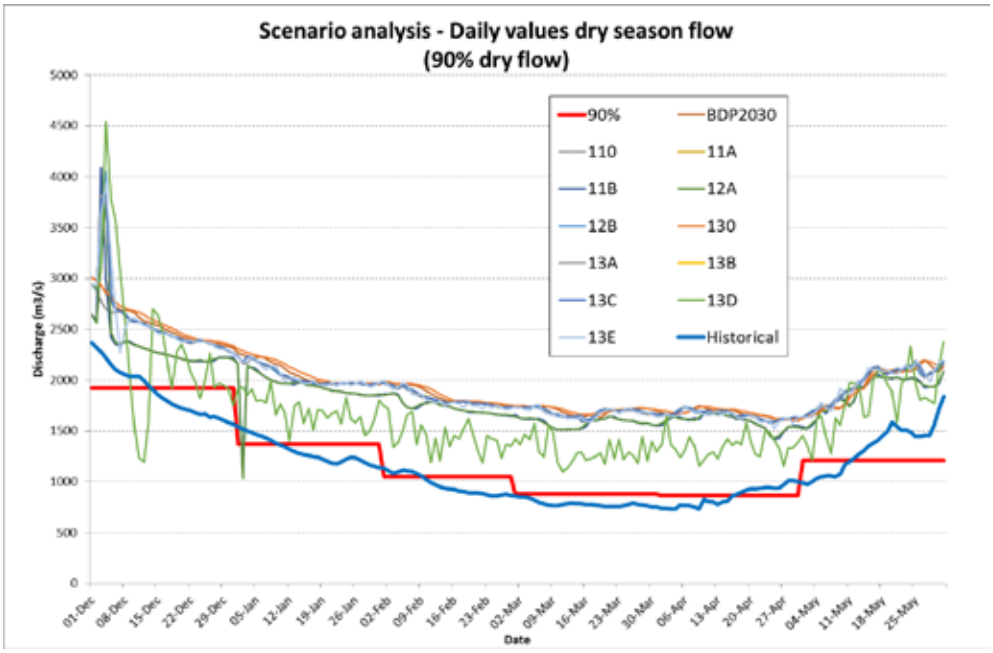


***Figure 5.4**. Scenario calculations with PMFM flow criteria (dry season at Vientiane) – 90% values.*

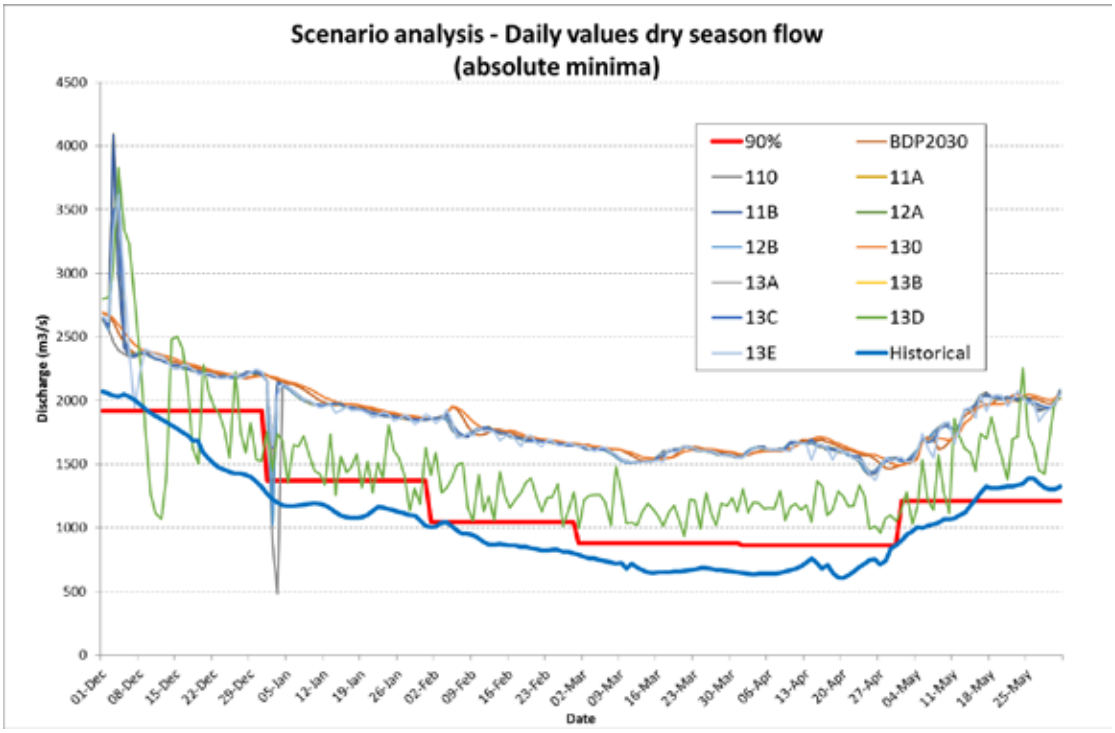


***Figure 5.5.** Scenario calculations with PMFM flow criteria (dry season at Vientiane) – Absolute minima.*

Even for the most severe case, using the absolute minima for each day in the 24 years simulation series for each of the scenarios, the low flows of BDP2030 and the various scenarios do not

underpass the dry season criterion, with the exception of scenario 1.3D, which does violate the criterion in a few cases. Given the fact that this is a very extreme case, using the absolute daily minima in a 24 year series, ***it can be concluded that the introduction of the Lao Cascade, and any of the measures that are represented by the various scenarios, will not lead to violation of the dry season PMFM criterion***.

Wet season flow

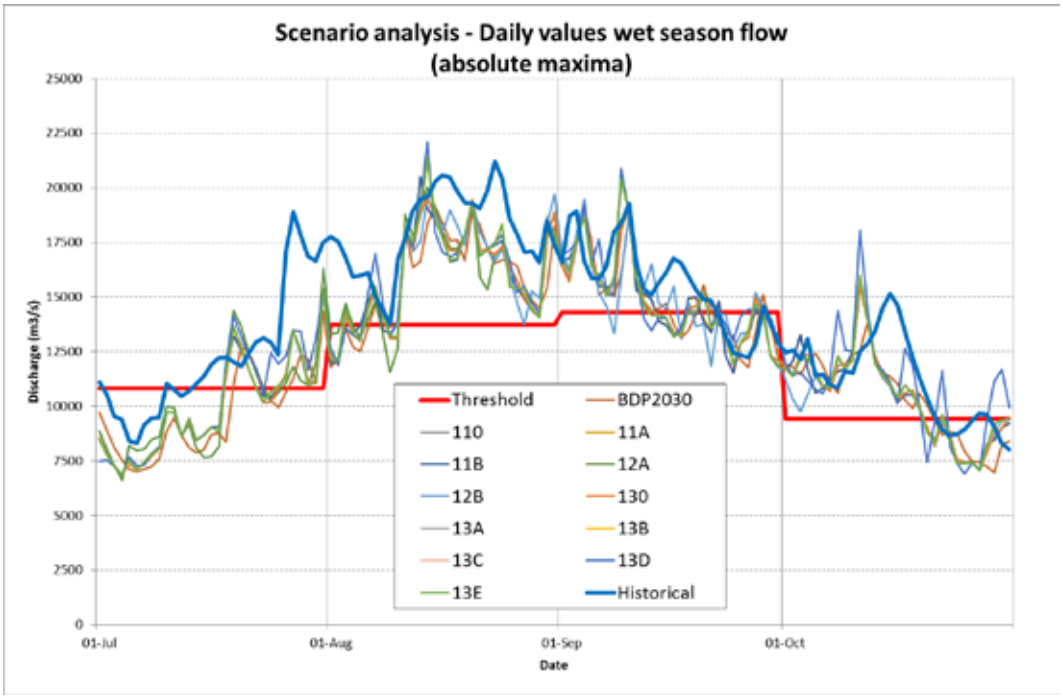


Figure 5.6. *Scenario calculations with PMFM flow criteria (wet season at Vientiane) – Absolute maxima.*

For the wet season (July – October), there is a remarkable difference between the threshold line and the historical series, which implies that the present threshold line is too low and exceeding of the line can be expected. Still, the frequency analysis of the scenario flow series show that these series have lower maxima, particularly in the start of the wet season, which is probably due to the filling of the Chinese dams. Once the wet season is more advanced, there is not much difference with the historical line as most of the reservoirs will be full and the inflow will be close to the outflow. This is even more visible on the graph for the 90% values, which show less variation.

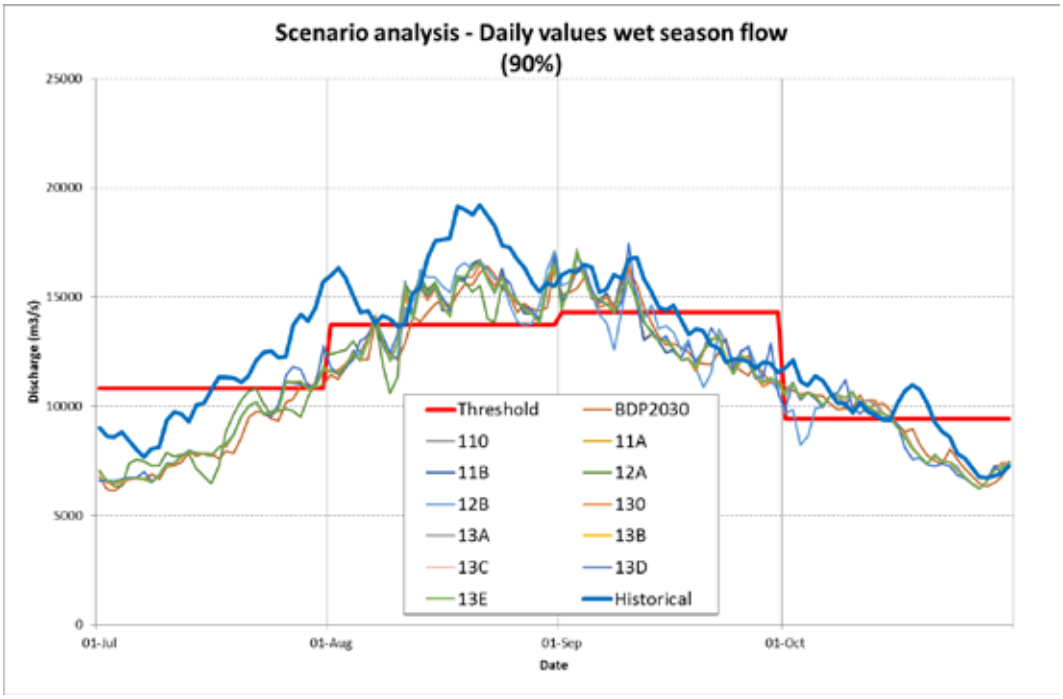


Figure 5.7. *Scenario calculations with PMFM flow criteria (wet season at Vientiane) – 90% values.*

Therefore, although the scenario flows do exceed the PMFM wet season threshold, in our opinion this threshold is placed too low as the historical flows particularly in the start of the wet season are significantly higher than the threshold. As an extreme example, the 50% frequency values are shown in figure 5.8. Only in that case, the flow values remain entirely below the threshold.

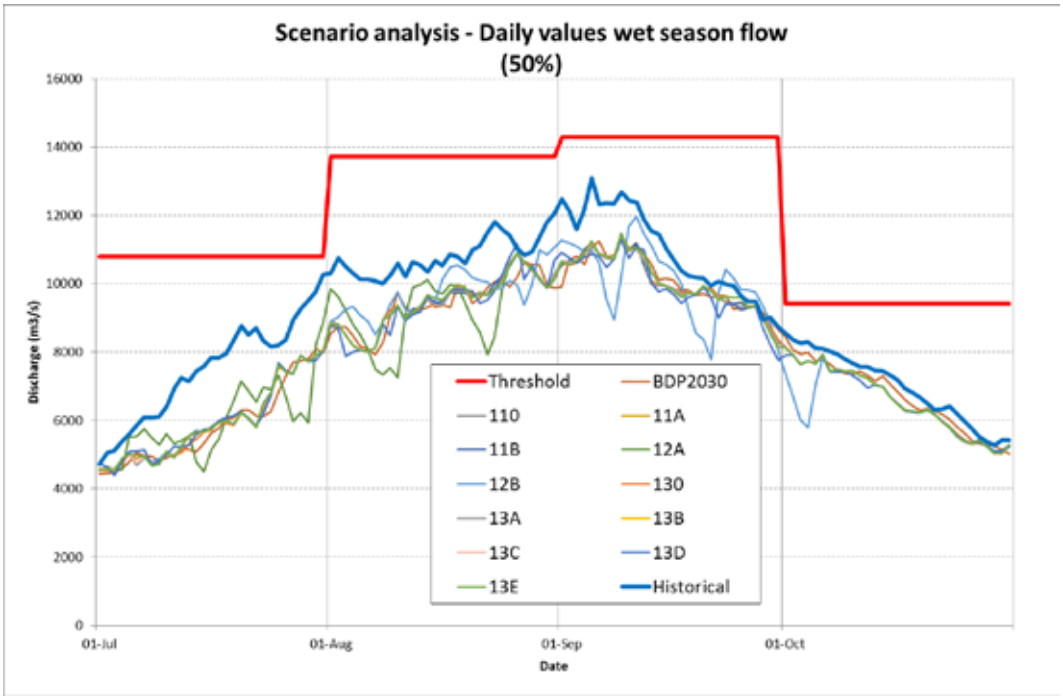


Figure 5.8. *Scenario calculations with PMFM flow criteria (wet season at Vientiane) – 50% values.*

5.2.3 Lao Cascade – Description of Local and Cumulative Impacts

5.2.3.1 Seasonal flow distribution

The impacts of the development of the Lao cascade, both individual and cumulative for the five reservoirs, is limited due to the small volume of the reservoirs (see also Chapter 3.3). In most cases, the residence time of the reservoirs is in the order of days, and even at the onset of the wet season, with the reservoirs filling up, there will be no major change in the river regime. ***In the overall context of the Lao cascade with the major reservoirs in the Lancang River, the impact of the Lao cascade on the hydrology is minor*** (see also previous sub-chapter). This was also illustrated already in Chapter 2.2 of Volume 2 – The Manual – 2nd Interim Phase Report (Figure 2.12) for the Pak Beng dam (MRC, 2015).

The following graphs and tables compare the seasonal flow indicators (see chapter 3.3.1) of all cascade scenarios (i.e., Scenario 1.1.0 to 1.3.E). The results are presented representatively for one location in the cascade (M2020, zone 1) and one location downstream of the cascade (M1572, zone 2).

5.2.3.1.1 Seasonal flow distribution in zone 1

The wet season onset and duration are provided in Table 5.1. Again, the end of the wet season is not given separately, as it is included in the duration of the wet season (for details see Annex D1). It is clearly visible that the onset and duration does not significantly differ between the individual scenarios.

Table 5.1. Onset and duration of the wet season for M2020 (upstream of Luang Prabang town) representatively for zone 1 and for all cascade scenarios.

Scenario	Wet season onset	Wet season duration
Scenario	25 Jun ±39 days	142 days ± 37 days
Sc. 1.1.0	25 Jun ±39 days	142 days ± 37 days
Sc. 1.1.A	25 Jun ±39 days	142 days ± 37 days
Sc. 1.1.B	25 Jun ±39 days	142 days ± 37 days
Sc. 1.2.A	25 Jun ±39 days	142 days ± 37 days
Sc. 1.2.B	25 Jun ±39 days	142 days ± 37 days
Sc. 1.2.C	Not calculated	Not calculated
Sc. 1.2.D	Not calculated	Not calculated
Sc. 1.3.0	25 Jun ±39 days	142 days ± 37 days
Sc. 1.3.A	25 Jun ±39 days	142 days ± 37 days
Sc. 1.3.B	25 Jun ±39 days	142 days ± 37 days
Sc. 1.3.C	25 Jun ±39 days	142 days ± 37 days
Sc. 1.3.D	25 Jun ±39 days	142 days ± 37 days
Sc. 1.3.E	25 Jun ±39 days	142 days ± 37 days

Also the flow volume of the wet season does not differ between the cascade-scenarios.

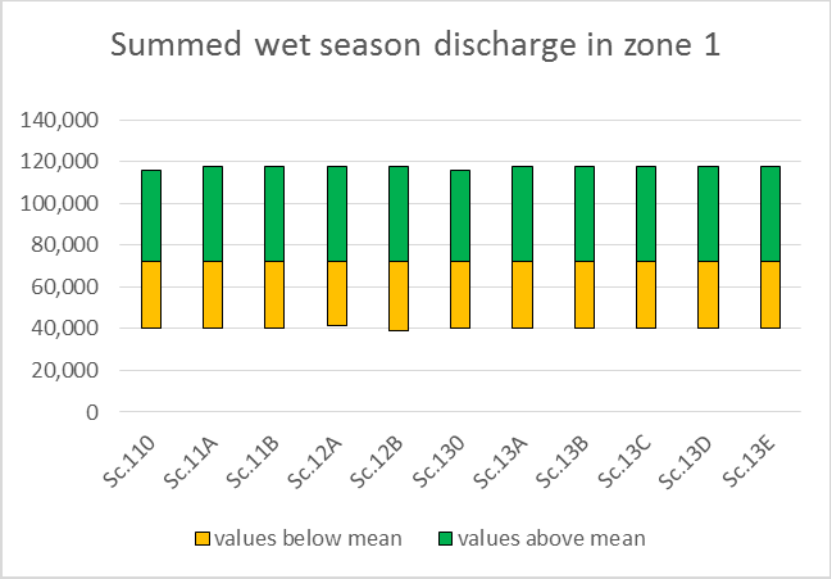


Figure 5.9. *Summed wet season discharge (in Mil. m³) in zone 1 (M2020) and all cascade scenarios.*

5.2.3.1.2 Seasonal flow distribution in zone 2

Also in zone 2, the values do not differ between the Scenarios. However, there are two “outliers” (marked with * in the table) for Scenario 1.3.D. Some short-term fluctuations caused by the modelling of the mitigation measures caused a wrong identification of the season for some years

over the 24-year period. Consequently, it seems legit to state that the scenarios do not differ with regard to their seasonality.

Table 5.2. Onset and duration of the wet season for zone 2 (M1572) and all cascade scenarios.

		Wet season duration
Sc. 1.1.0	21 Jun ±19 days	143 days ± 24 days
Sc. 1.1.A	22 Jun ±18 days	142 days ± 24 days
Sc. 1.1.B	22 Jun ±18 days	142 days ± 24 days
Sc. 1.2.A	21 Jun ±18 days	144 days ± 24 days
Sc. 1.2.B	22 Jun ±18 days	142 days ± 24 days
Sc. 1.2.C	Not calculated	Not calculated
Sc. 1.2.D	Not calculated	Not calculated
Sc. 1.3.0	21 Jun ±19 days	143 days ± 24 days
Sc. 1.3.A	22 Jun ±18 days	142 days ± 24 days
Sc. 1.3.B	22 Jun ±18 days	142 days ± 24 days
Sc. 1.3.C	22 Jun ±18 days	142 days ± 24 days
Sc. 1.3.D	*(12 Jun ±36 days)	*(155 days ± 34 days)
Sc. 1.3.E	22 Jun ±18 days	143 days ± 24 days

* Short-term fluctuations due to modelling caused wrong identification of season. Values are not representable and are not related to the respective scenario.

Also in zone 2, the flow volume of the wet season does not differ between the cascade-scenarios. Only Scenario 1.3.D shows slightly higher values, which is again caused by a wrong delineation of the wet season and is therefore negligible.

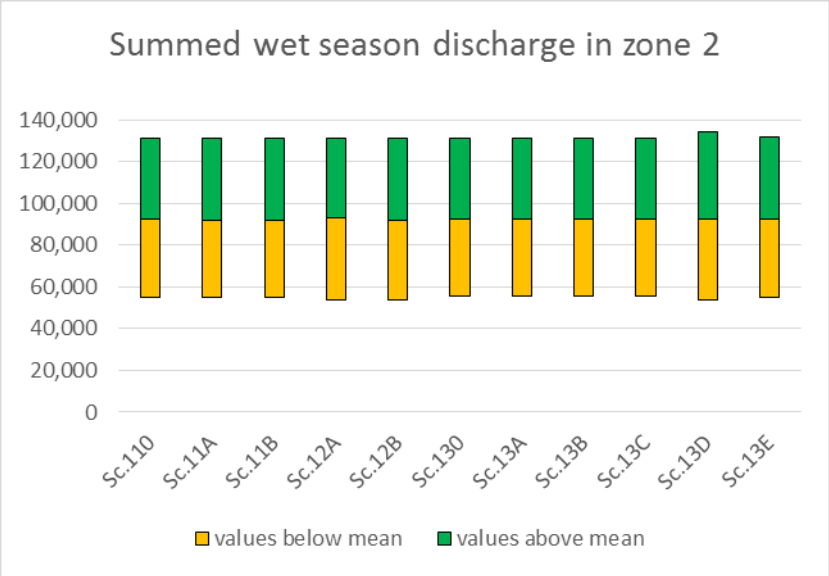


Figure 5.10. *Summed wet season discharge (in Mio. m³) in zone 2 (M1572).*

Finally, also the daily flow characteristics were assessed and compared for the cascade scenarios. It can be seen that the differences are so marginal, that the individual lines cannot be distinguished (Figure 5.11).

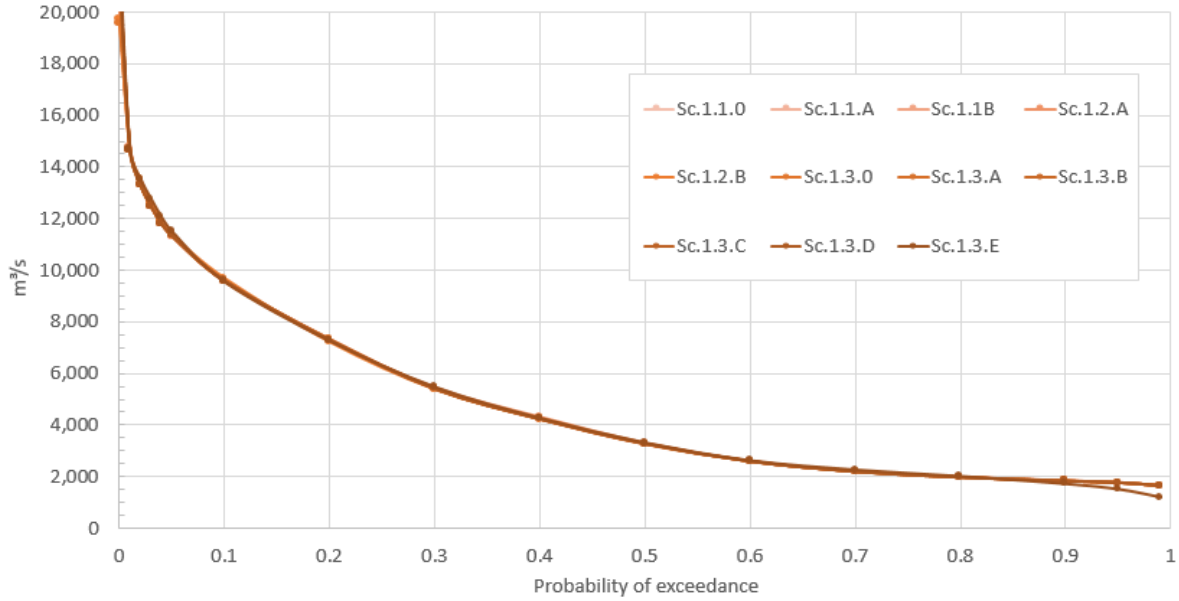


Figure 5.11. *Flow duration curve for zone 2 (M1572) and all cascade-scenarios.*

Again, Violin plots were used to show the difference between all scenarios and zones 2 and 3. Figure 5.12 reveals only slight differences between the scenarios, which are too marginal to reflect a seasonal flow change.

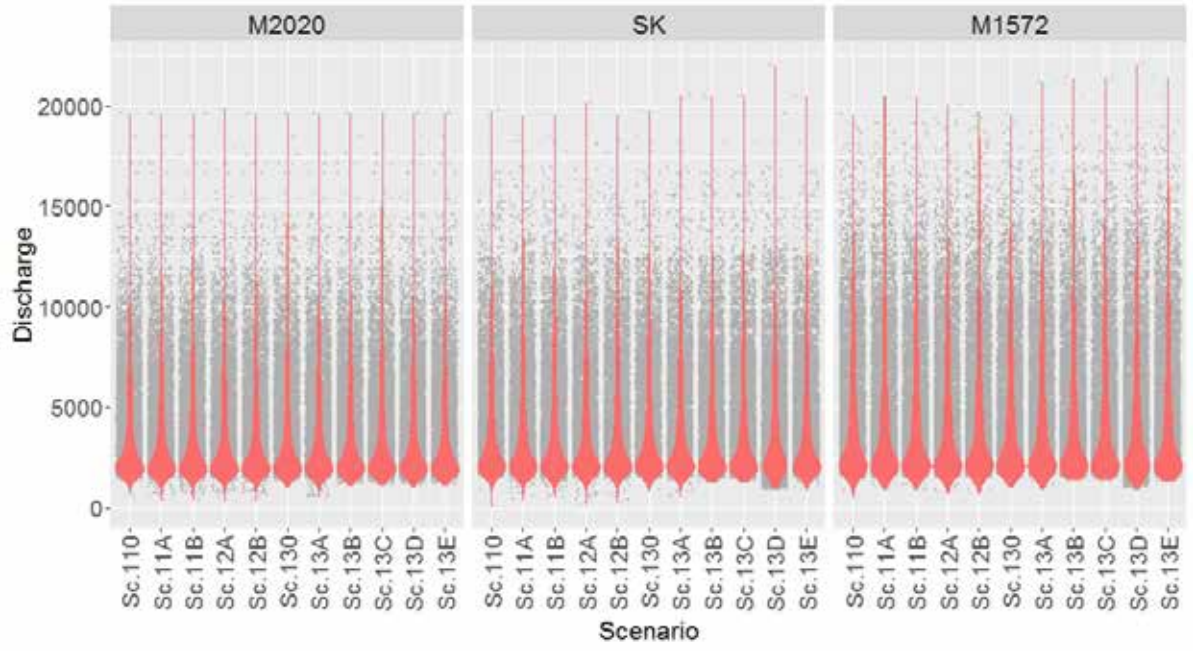


Figure 5.12. *Violin plots showing the daily flow distribution in zone 1 (M2020 and Sanakham dam) and zone 2 (M1572) for all scenarios.*

No assessments were made downstream of Paksane (zone 3), but since no impacts were detected

in zones 1 and 2, seasonal changes in zone 3 are also assumed to be negligible.

5.2.3.2 Sub-daily flow distribution

While seasonal flow changes are negligible for individual cascade-scenarios, changes do occur, though, in the within-day flow fluctuations, which are a function of the operation of the various reservoirs (hydropeaking). These fluctuations can result in major disturbances of the flow velocities and consequently have important consequences for bank stability, sediment transport and fish population. The ecological risks related to sub-daily flow changes was discussed in chapter 2.3.4. As was mentioned in Chapter 2.3 of Volume 2 – The Manual – 1st Interim Report (MRC, 2015), hydropeaking can in principle easily be mitigated by the introduction of re-regulation dams directly downstream from the structure.

Based on the reservoir characteristics short-term water storage is possible to deliver peak energy. Sub-daily flows are shifted from hours with low energy price to hours with high energy prices. The related short-term hydrologic variations cause several impacts on the aquatic ecosystem. Fast flow increases induce considerable drifts of macrointertebrates, small fish and larvae. The consecutive short-term reduction of flow causes a rapid dewatering of the shoreline area and might cause stranding of small fish and larvae. While the presence of peaking will always be related to drifting, the impact related to dewatering is highly dependent on the downramping rate. Scientific studies and natural flow variations in the Mekong suggest that no or minor impacts can be expected if the downramping rate is below 5 cm/hour. Impoundment characteristics (e.g. impounded area) can be calculated for different headwater levels (i.e. a range of 5 m) and linked to the water-level changes (assuming a linear relationship) to assess the dewatered area per event.

5.2.3.2.1 Impact of sub-daily flow changes in zone 1

Peaking event do only occur in Scenarios 1.3.0 to 1.3.E. Nevertheless, some of the plots are also shown for Scenarios 1.2, since the flushing is detected as short-term peaking by the indicators. This can also be seen in Figure 5.13, where especially the headwater level of Xayaburi reacts to the opening of the gates and indicates a fast downramping event in July for Scenario 1.1.A and August/September for Scenario 1.2.B.

Since downramping occurs slower compared to upramping, some months show up to 60 % of hours with peaking, especially in the tailwater of Luang Prabang and for Scenario 1.3.0 (without any mitigation). This has, of course, a high impact on aquatic organisms which are flushed downstream or seek shallow areas with lower flow velocities during the peaks, where they are then at risk of stranding during the downramping events. Similar plots are provided for all impoundments, as well as 4 points downstream of Sanakham in Annex D2.

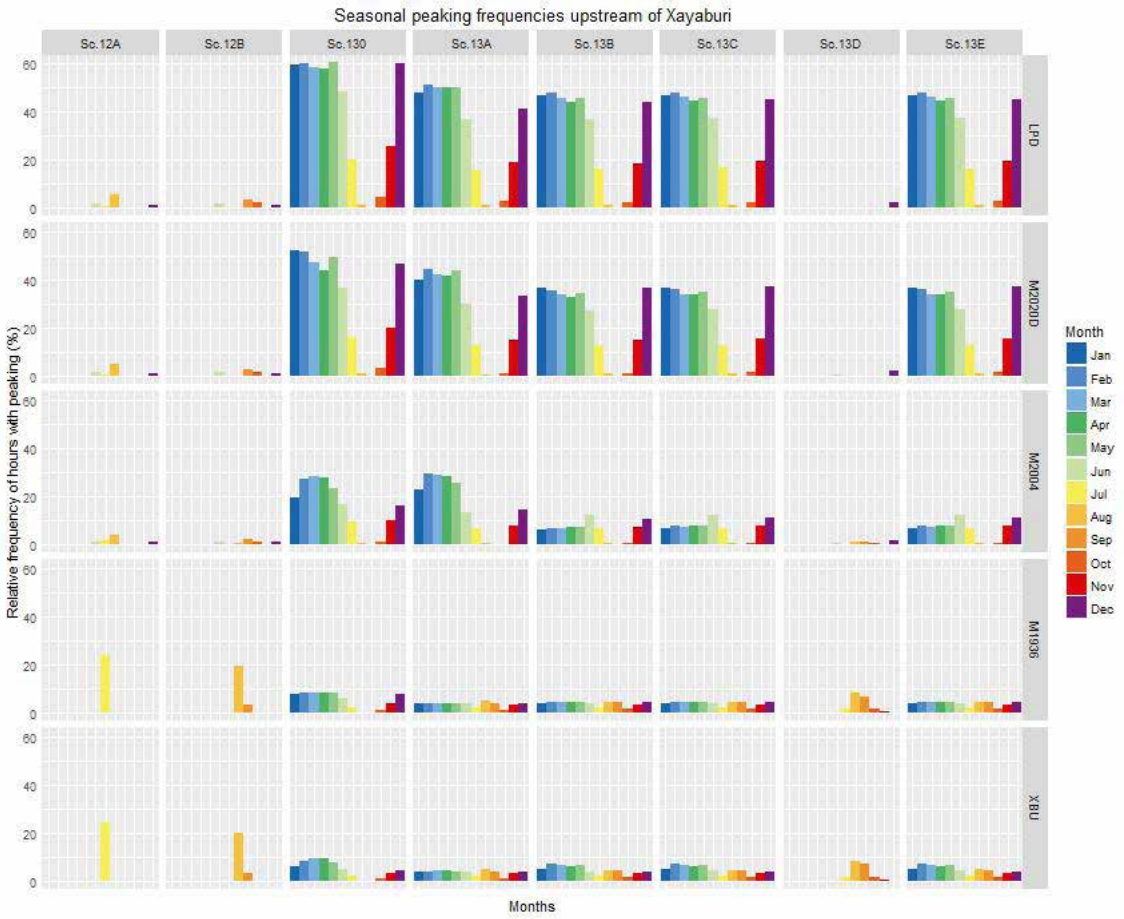


Figure 5.13. *Proportion of hours with downramping events faster than 5 cm/hr for each month in the impoundment of Xayaburi (LPD = tailwater of Luang Prabang dam, M2020D, M2004, M1936, XBU = headwater of Xayaburi).*

For each downramping event, the dewatered area was calculated, following the method described in chapter 3.3.2. By summing up the area which is dewatered during fast downramping (i.e. faster than 5 cm/hr) and by dividing it by the total number of hours, the mean dewatered area per hour was calculated (see Figure 5.14). It clearly shows, that Scenario 1.3.0 has the highest peaking intensities, with scenarios 1.3.A to 1.3.C already decreasing in intensity. The lowest peaking intensities occur in scenario 1.3.D. The two bars for Pak Beng and Xayaburi reflect the downramping events related to the mitigation measures (dry season drawdown at Pak Beng and flood protection of Luang Prabang town) and can therefore be neglected, since they would be much slower in reality. In scenario 1.3.E downramping thresholds are only met by Sanakham. Since the dam cannot peak itself, the impoundment is less effective in processing the waves coming from the upstream dams, which is why the most downstream impoundment shows higher peaking in scenario 1.3.E compared to 1.3.C.

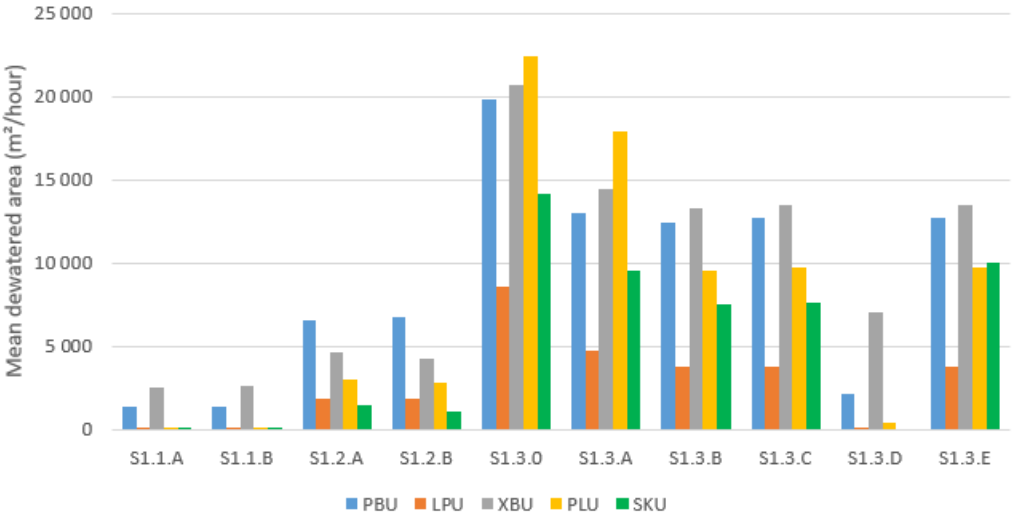


Figure 5.14. *Mean dewatered area in m²/hour (for all hours).*

To assess how the peaking waves behave within the impoundment, model results were assessed at 4 sites for each impoundment. Figure 5.15 illustrates this for the impoundment of Xayaburi and for the dry season. While Luang Prabang Dam releases waves with an amplitude of 3 m (for scenario 1.3.), the range is reduced to less than 1 m at Luang Prabang town (M2004).

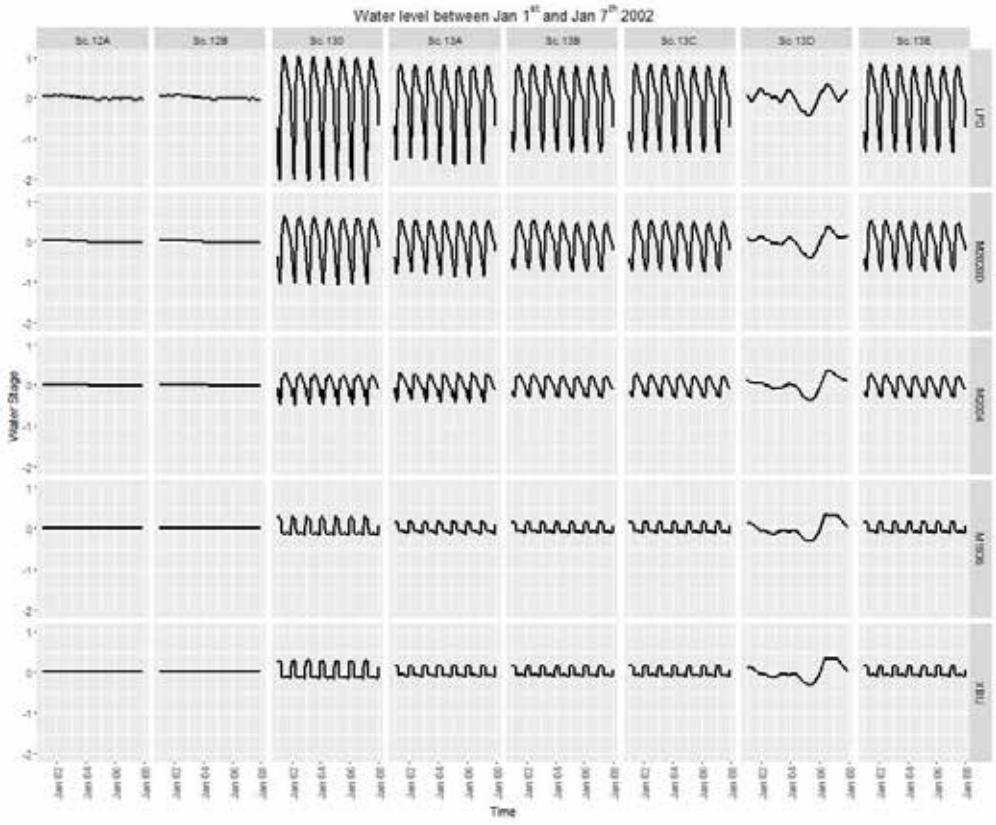


Figure 5.15 *Peaking waves along the Xayaburi impoundment.*

5.2.3.2.2 Impact of sub-daily flow changes in zone 2 and 3

Hydropeaking does not only impact the cascade itself but also acts downstream of the cascade. With regard to the impact assessment, it is of relevance how far downstream the peaking-waves propagate until they are equalized by the flowing wave and tributaries entering the Mekong. To assess the wave's behaviour downstream, two test-waves were extracted from the time series at Sanakham. The data were extracted from 2002, which represents an average year, for the months January (dry season) and June (onset of wet season, since peaking does not take place at higher discharges) and for Scenario 1.3.C. Figure 5.16 shows the peaking waves at Sanakham over each month (January and June). It is clearly visible that the peaking-waves are very homogenous for the dry season, while a greater variability is given at the onset of the wet season. The red bars highlight those waves, which were selected for a more detailed assessment (see overleaf).

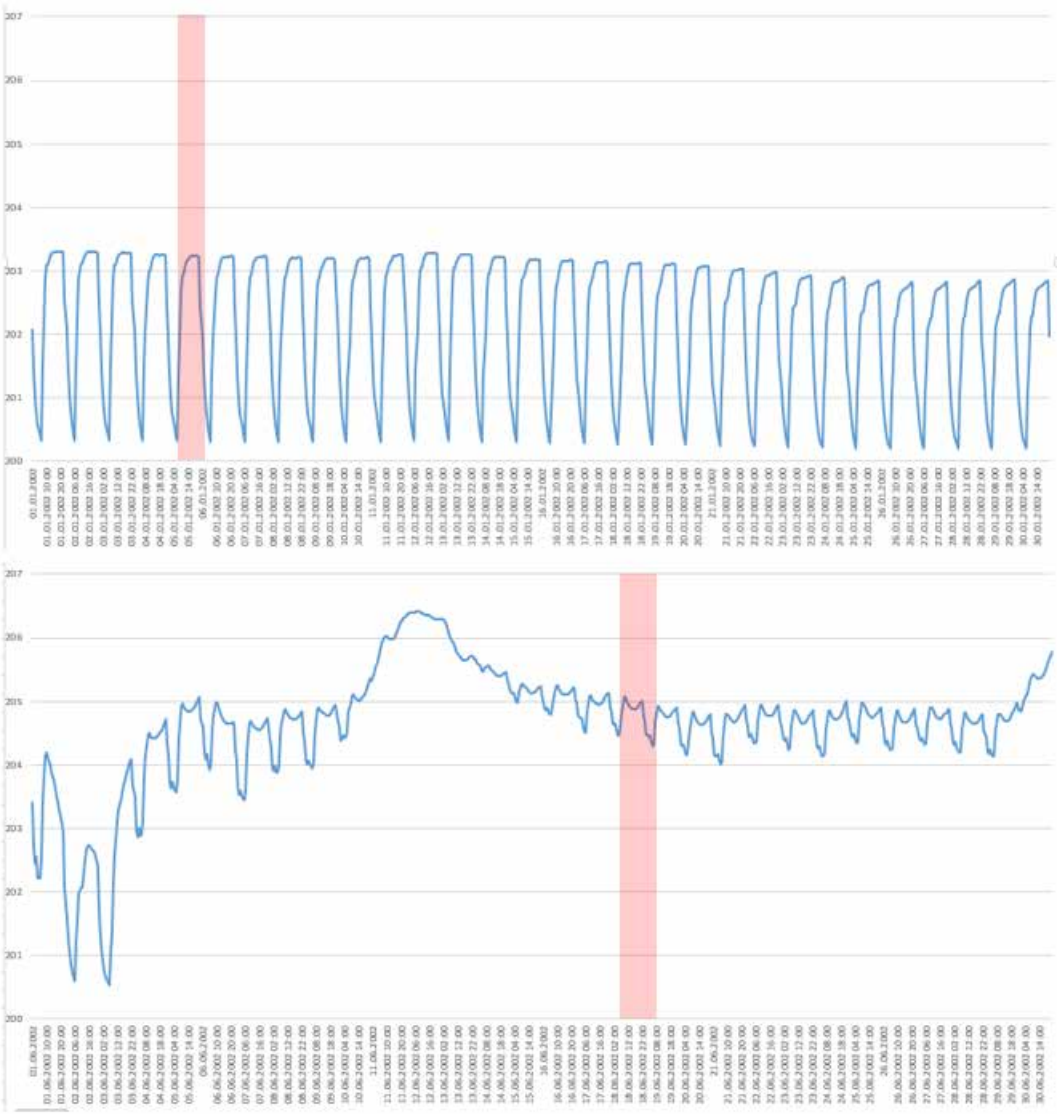


Figure 5.16. *Selected test waves for peaking assessment downstream of cascade (upper graph: January 2002; lower graph: June 2002) (waves in red blocks were selected for detailed assessment, see below).*

To assess how the waves propagate downstream, water level changes were also measured at 10 sites from Sanakham to Paksane. Since the water levels are expressed in meters above sea level and are therefore not directly comparable, the values were standardized by extracting the mean water level of the respective site and days included in the graph. The following figures illustrate well how the waves are attenuated in downstream direction in January (Figure 5.17) and June (Figure 5.18). Not all sites were included to the graph to increase the readability.

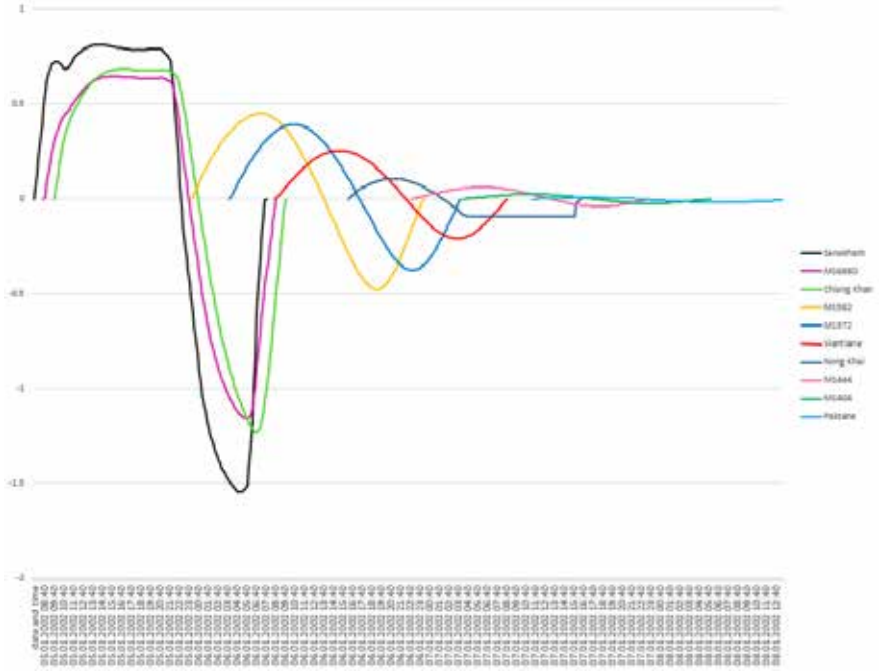


Figure 5.17. *Attenuation of peaking-waves downstream of Sanakham (example January 2002).*

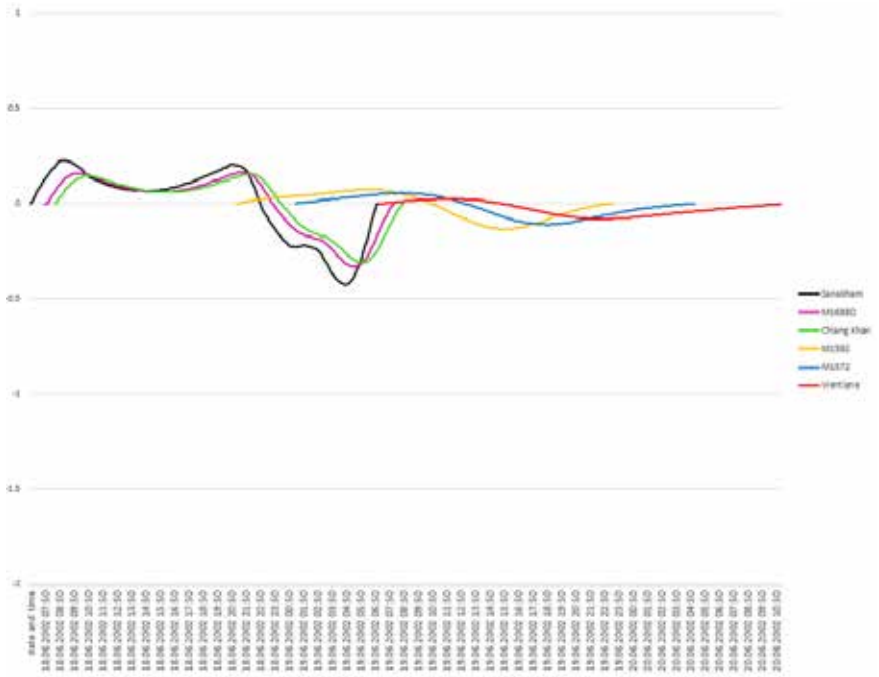


Figure 5.18. *Attenuation of peaking-waves downstream of Sanakham (example June 2002).*

Again, the down ramping rates were used to assess the harmful character of the peaking waves with regard to stranding of juveniles and larvae. The percentage of time where negative water level changes occurred faster than 5 cm/year was recorded and compared for the respective sites. Table 5.3 indicates that severe peaking occurs down to Vientiane in January and down to Chiang Khan around June and is quickly equalized further downstream. Again, also the amplitude decreases in downstream direction and shows values of 25 cm (June) to 45 cm (January) at Vientiane.

Table 5.3. Percentage of time negative water level changes exceed 5 cm/hour.

Percentace of time downramping exceeds 5 cm/hour			Mean daily peaking amplitude in m	
Location	**January**	**June**	**January**	**June**
Sanakham	30.7	21.3	2.27	0.86
M1688D	29.0	16.6	1.73	0.65
Chiang Khan	32.9	16.6	1.85	0.63
M1592	35.8	5.0	0.90	0.36
M1572	33.1	3.2	0.76	0.32
Vientiane	14.8	1.6	0.45	0.25
Nong Khai	1.2	0.8	0.14	0.18
M1444	0.0	0.0	0.11	0.18
M1404	0.0	0.0	0.06	0.15
Paksane	0.0	0.0	0.04	0.14
Nakhon Phanom	0.0	0.0	0.03	0.10
Savannakhet	0.0	0.0	0.02	0.08
Kong Chiam	2.8	2.8	0.03	0.20

The results highlight that the directly related impacts of hydropeaking (i.e. stranding, drift) will not affect zone 3.

5.3 Sediment Impact Mitigation

5.3.1 General

The following sections present the findings of the sediment and geomorphic investigations. The findings are predominantly based on the results of the sediment model, with results and discussion presented by indicator. For the indicator groups 'Sediment loads and composition' and 'Geomorphic changes', each scenario is discussed for the cascade reach, and for the reach between the last dam (Sanakham) and Paksane, which is the downstream extent of the sediment model. Where possible, comments are provided regarding potential changes occurring downstream of Paksane.

5.3.2 Lao Cascade – Local and Cumulative Impacts

5.3.2.1 Indicators: Sediment loads and composition

5.3.2.1.1 Scenario 1.1 –Sediment Loads and Composition-Cascade Reach (Zone 1)

Scenario 1.1.0 – the base-case – includes the implementation of the 5-dam cascade being operated as a run-of-river system without any additional mitigation measures. Sub-scenarios within Scenario 1.1 include mitigation measures addressing water levels in Luang Prabang during flood events, reduction in water levels within the Pak Beng reservoir to limit impoundment water levels during the dry season and the provision of a flow for fish passage.

The Deflt3D sediment model was used to evaluate the changes in the magnitude and composition of sediments transported through the cascade reach for scenario 1.1.0 (cascade without mitigation). No additional sediment model runs were included for sub-scenarios 1.1.A and 1.1.B because the relatively minor changes to the flow regime associated with the mitigation actions included in those sub-scenarios were not considered sufficient to alter the sediment transport regime in the river as compared to Scenario 1.1.0. This is supported by the lack of change in hydrologic indicators such as flow duration or magnitude of the sub-scenarios as compared to Scenario 1.1.0 (see section 5.1).

The sediment transport and grain-size distribution results for Scenario 1.1.0 (and considered applicable to Scenarios 1.1.A and 1.1.B) presented in table 5.4 are based on the average of the five final median flow years in the seven-year model sequence. Results are presented for the upstream extent of the sediment model (Km 2347) to show the initial sediment input to the reach, and at the discharge locations for each of the dam sites in the case study. The discharge from one dam was considered to be the input for the next dam downstream along with additional tributary inputs where appropriate. In Table 5.4 the model results for the BDP2030 scenario which includes the tributary and Chinese dams but not the cascade are provided for comparison. Indicator values for sediment loads used in the multi-criteria assessment were derived from the values presented in the indicator table in Annex F. The median grain-size indicator was also based on these results.

Table 5.4. Summary of sediment transport indicators related to sediment loads and sediment composition for the BDP 2030 scenario, Scenarios 1.1.0, 1.1B and 1.1.C.

Indicator	Scen 0.2 BDP 2030	Scen 1.1.0 Run of Riv	Scen. 1.1.A & 1.1.B
Annual Sediment Load upstream of Cascade (Mt/yr) Km 2347	12.2 Mt/yr Gr: 2% C Sand:8% M Sand: 23% F Sand: 63% Silt+Clay: 5%	12.2 Mt/yr Gr: 2% C Sand:8% M Sand: 22% F Sand:63% Silt+Clay: 5%	**No change compared to 1.1.0**
Annual Sediment Load at Pak Beng Dam site (Mt/yr) Km 2188 Input to Luang Prabang	9.6 Mt/yr Gr: <1% C Sand:7% M Sand 11% F Sand: 60% Silt+Clay: 21%	2.7 Mt/yr Gr: <1% C Sand:<1% M Sand: 1% F Sand: 16% Silt+Clay: 84%	**No change compared to 1.1.0**
Annual Sediment Load at Luang Prabang Dam site Km 2038 Input to Xayaburi	10.7 Mt/yr Gr: <1% C Sand:6% M Sand 11% F Sand: 63% Silt+Clay: 20%	2.4 Mt/yr Gr: <1% C Sand:<1% M Sand: <1% F Sand: 2% Silt+Clay: 98%	**No change compared to 1.1.0**
Annual Sediment Load at Xayaburi Dam siteKm 1931 Input to Pak Lay	13.5 Mt/yr Gr: <1% C Sand:5% M Sand 10% F Sand:57% Silt+Clay: 27%	3.5 Mt/yr Gr: <1% C Sand:<1% M Sand: <1% F Sand: <1% Silt+Clay:100%	**No change compared to 1.1.0**
Annual Sediment Load at Pak Lay Dam site Km 1818 Input to Sanakham	22.5 Mt/yr Gr: 1% C Sand: 6% M Sand 18% F Sand: 59% Silt+Clay: 17%	3.9 Mt/yr Gr: <1% C Sand: 1% M Sand: 2% F Sand: 4% Silt+Clay: 93%	**No change compared to 1.1.0**
Annual Sediment Load at Sanakham Dam site Km 1737	21.3 Mt/yr Gr: 1% C Sand: 5% M Sand 16% F Sand: 59% Silt+Clay: 20%	6.0 Mt/yr Gr: <1% C Sand: 1% M Sand: 3% F Sand: 12% Silt+Clay: 84%	**No change compared to 1.1.0**

Gr= Gravel, C Sand = Coarse Sand, M Sand=Medium Sand, F Sand = Fine Sand

Graphical comparisons of the model results for BDP2030 and Scenario 1.1.0 based on the values in the Table are shown in Figure 5.19 and Figure 5.20. The sediment input into the top of the reach for both scenarios is dominated by sand.

The sediment load in the BDP 2030 scenario shows a small decrease between the input (Km 2347) and the Pak Beng dam site, and progressive increases downstream, with another decrease at the Sanakham dam site. The decrease in sediment load at Pak Beng is attributable to a reduction in gravel and sands being transported by the river, resulting in the sediment load being dominated by fine sand, with silt & clay being the next largest contribution. These changes in sediment grain-size

is consistent with the reduction in slope of the river, with these coarser size fractions only being transported at very high flows. A relatively high sediment load enters between the Xayaburi and Pak Lay dam sites, and gravel and sand is deposited upstream of the Sanakham dam site. The reach between the Pak Beng damsite and Xayaburi dam site shows little sediment deposition, consistent with the reach being a sediment throughput zone.

In comparison, the sediment load results for Scenario 1.1.0, show a substantial reduction in loads relative to the BDP 2030 Reference (Figure 5.20).

Most sediment is lost within the Pak Beng reservoir, with loads decreasing from 12.2 Mt/yr to 2.7 Mt/yr. The sediment input that occurs upstream of the Pak Lay dam site in the BDP 2030 scenario is trapped locally within the Pak Lay reservoir, so does not appear as an additional reduction, but would contribute to a reduction in the volume of the impoundment. ***In comparison to the BDP2030 Reference scenario, there is a reduction in the total sediment load at the Sanakham dam site from 21.3 Mt/yr to 6 Mt/yr***.

There is also a substantial shift in the grain-size distribution of the transported sediment in scenario 1.1.0 with virtually all gravel, coarse and medium sand, and most of the fine sand captured within the impoundments. The contribution of silt and clay to the sediment load increases from 35% of the total sediment load at the Sanakham dam site in the BDP 2030 Reference Scenario to 85% under Scenario 1.1.0, with fine sand contributing an additional 12% of the load. This is a shift from the BDP 2030 scenario in which fine sand comprised the majority of the loads. The coarser sediment fractions (gravel, coarse and medium sand) constitute <4% of the load under Scenario 1.1.0, as compared to ~15% in the BDP 2030 scenario.

These results are in good agreement with the sediment modelling completed for the Mekong Delta Study, which predicted a post-cascade sediment load at Sanakham of 6.2 MT per year, containing 5.5 MT of silt (DHI, 2015).

Figure 5.19. *Sediment inputs and outputs at each of the dam sites under BDP 2030 Reference Scenario (top graphs) and Scenario 1.1 (bottom graphs). PB= Pak Beng dam site LP = Luang Prabang dam site, XB Xayaburi dam site, PL = Pak Lay dam site, SK = Sanakham dam site.*

Figure 5.20. *Comparison of sediment loads and grain-size distribution for the BDP 2030 Reference Scenario (top left) and Scenario 1.1 (top right) upstream of the cascade (PB 'In' Km 2344) and at each of the dam sites. The gravel results are presented in the lower graphs with at a different scale for clarity. Results based on average of 5 median flow years.*

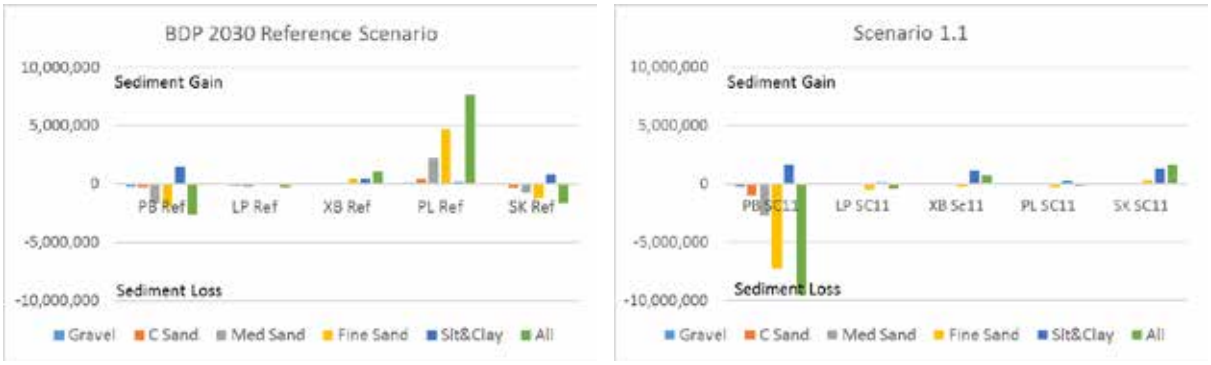


Figure 5.21. *Changes in sediment load by size-fraction in the BDP 2030 Reference scenario (left) and Scenario 1.1 (right). A negative value indicates a reduction in sediment transport relative to the dam site upstream.*

The sediment loads for the BDP 2030 Reference Scenario and Scenario 1.1.0 are compared to the pre-Lancang Cascade sediment loads at Chiang Saen in Figure 5.22, and show that sediment loads associated with the Lao cascade are projected to be ~30% of the BDP 2030 loads, and <10% of the pre-Lancang cascade loads. It also needs to be recognised that over time, the BDP2030 'in' sediment load is likely to decrease due to the depletion of the sediment resident in the mainstream river channel downstream of the Lancang Cascade, and in tributaries downstream of impoundments.

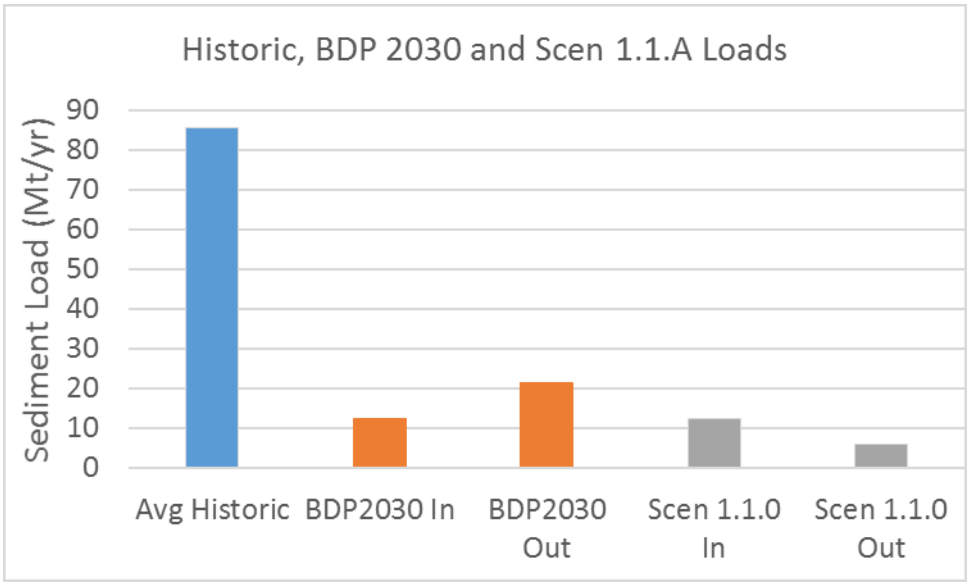


Figure 5.22. *Comparison of average historic sediment loads at Chiang Saen (1968 – 2003) pre-Lancang cascade, BDP2030 Reference scenario (no Lao PDR cascade) and Scenario 1.1.A (5 Hydropower cascade in northern Lao PDR). 'In' is sediment load upstream of Pak Beng, 'Out' is sediment load downstream of Sanakham dam site.*

The flow changes associated with mitigation Scenarios 1.1.A and 1.1.B will not substantially alter the sediment loads or grain-size distribution within the cascade reach. The reduction in water level associated with the reduced dry season normal operating level at Pak Beng will not affect sediment transport as the same volume of water will be discharged at the same rate under the two

scenarios once the lake level change as been adjusted. Similarly, the discharge associated with the fish passage will transport the same quantity of sediment whether it is discharged through the fish pass or the turbines.

Based on the modelling results, drawing down the water level at the Xayaburi dam site during a large flood event will not greatly increase the overall volume of sediment being passed through the system because the reduction of level at the dam site does not control the water level or slope at the upstream end of the impoundment during very high flows. The hydropower modelling found that for this reason, a flood drawdown needed to commence at flows of 7,000-8,000 m3/s rather than 10,000m3/s to have any impact in the upper reservoir. In general, sedimentation of large material will continue to occur in the reservoir during flood events, and fine material will continue to be transported through the impoundment, similar to non-flood conditions.

Opening the low level gates during a high flow event will remove sediment that is deposited near the toe of the dam wall, but will not promote the removal of sediment in areas upstream of the dam due to the low water slopes associated with the flood event. Sediment sluicing using the low level gates without lowering water levels was investigated as part of Scenario 1.2 (sediment flushing) and is discussed in more detail in section 5.3.1.4 and onwards.

5..3.2.1.2 Scenario 1.1 -Sediment loads & Composition downstream of Sanakham to Paksane (Zone 2)

Downstream of the final dam at Sanakham, the sediment loads will be controlled by discharge from the dam, and tributary inflows. A summary of sediment loads at Vientiane and Paksane based on the sediment model results is shown in Table 5.5. The results are based on a model run of 7 years, hence it provides a ‘snap-shot’ of sediment transport within a decade of implementation.

The results indicate that ***sediment loads increase downstream of the Sanakham dam site, with values returning to similar levels to the BDP2030 scenario at Vientiane and Paksane***. This large increase is attributable to the erosion of sediment from the river channel, with additional sediment input from tributaries. The 7-year results also show that the grain-size distribution of the transported sediment changes, with the proportion of sand increasing and silt and clay decreasing. At Paksane the grain-size distributions for the two model runs are similar, with both reflecting the availability of sediment within the model.

The area downstream of Sanakham is characterised by large alluvial deposits occurring as insets within the bedrock controlled channel, and as alluvial deposits in the reach upstream of Vientiane. The model was calibrated using pre-Lancang cascade sediment loads, so it contains a large volume of material that is available for erosion and transport by the low-sediment bearing water discharged from the final dam. Over time, the availability of this sediment for transport will decrease as the deposited material is exhausted, and not replaced, and sediment loads to the downstream river will decrease. Long-term changes such as this erosional trend are discussed in more detail under Geomorphic Changes section 5.3.3.

Table 5.5. Summary of sediment transport indicators related to sediment loads and sediment composition for the BDP 2030 scenario, Scenarios 1.1.0, 1.1B and 1.1.C.

Indicator	Scen 0.2 BDP 2030	Scen 1.1 Run of Riv	Scen. 1.1.A & 1.1.B
Annual Sediment Load at Sanakham Dam site Km 1737	**21.3 Mt/yr** Gr: 1% C Sand: 5% M Sand 16% F Sand: 59% Silt+Clay: 20%	**6.0 Mt/yr** Gr: <1% C Sand: 1% M Sand: 3% F Sand: 12% Silt+Clay: 84%	**No change compared to 1.1.0**
Annual Sediment Load at Vientiane / Nong Khai	**19.3 Mt/yr** Gr: 1% C Sand: 4% M Sand 15% F Sand: 51% Silt+Clay: 30%	**18.7 Mt/yr** Gr: 1% C Sand: 4% M Sand 14% F Sand: 22% Silt+Clay: 60%	**No change compared to 1.1.0**
Annual Sediment Load at Paksane	**18.3 Mt/yr** Gr: 1% C Sand: 4% M Sand 14% F Sand: 22% Silt+Clay: 60%	**18.5 Mt/yr** Gr: 1% C Sand: 4% M Sand 14% F Sand: 22% Silt+, Clay: 60%	**No change compared to 1.1.0**

5.3.2.1.3 Scenario 1.1: Sediment loads & Composition downstream of Paksane to Pakse (Zone 3)

Under Scenario 1.1, the river reach between Paksane and Pakse will not experience an immediate reduction in sediment loads due to the sediment being eroded downstream of Sanakham. Ultimately, the available sediment will be exhausted, and sediment loads derived from upstream of Paksane will decrease. If all of the sediment load at Sanakham in the BDP 2030 Reference Scenario (~20 Mt/yr) reaches Pakse, then the upper LMB is the source of between ~25 % and 40% of the load at Pakse (assuming a load at Pakse of 55 to 80 Mt/yr, Koehnken, 2015), with the remaining load derived from tributaries downstream of Sanakham. If implementation of the cascade (scenario 1.1) reduces the sediment load from upstream of Sanakham by ~15 Mt over the long term, it will eventually translate to a similar reduction in the lower river. This reduction is unlikely to occur rapidly due to the sediment supply resident in the river that is available for transport, similar to the situation in the Sanakham to Paksane reach where the erosional 'wave' is progressing downstream.

Perhaps more important than the overall decrease in the sediment load is the preferential capture of larger grain-sizes in the cascade, as these are the sediment fractions that maintain alluvial habitats and channel stability in the river. The reduction in the concentration of different grain-size classes discharged to the Mekong River from Sanakham between the BDP 2030 Reference Scenario and Scenario 1.1 shows an almost complete removal of sands and gravels, with little change to silt a& clay. Based on recent MRC monitoring results, the sediment load at Pakse is comprised of ~80% fine sand and coarser material, equivalent to ~37 Mt/yr (based on 64 Mt/yr). Sediment trapping by the cascade in Scenario 1.1 is projected to decrease sand and gravel delivery to the lower river from 17 Mt/yr to < 1 Mt/yr. Once a new equilibrium is established, this reduction could eventually translate into a ~45% reduction in sand delivery to the lower river. There is potential for a further reduction in sediment inputs due to additional damming on tributaries downstream of Sanakham.

Other activities that directly or indirectly affect the sand balance within the system (e.g. sand mining, or bank armouring) also need to be considered when projecting into the future with respect to the sediment budget of the river.

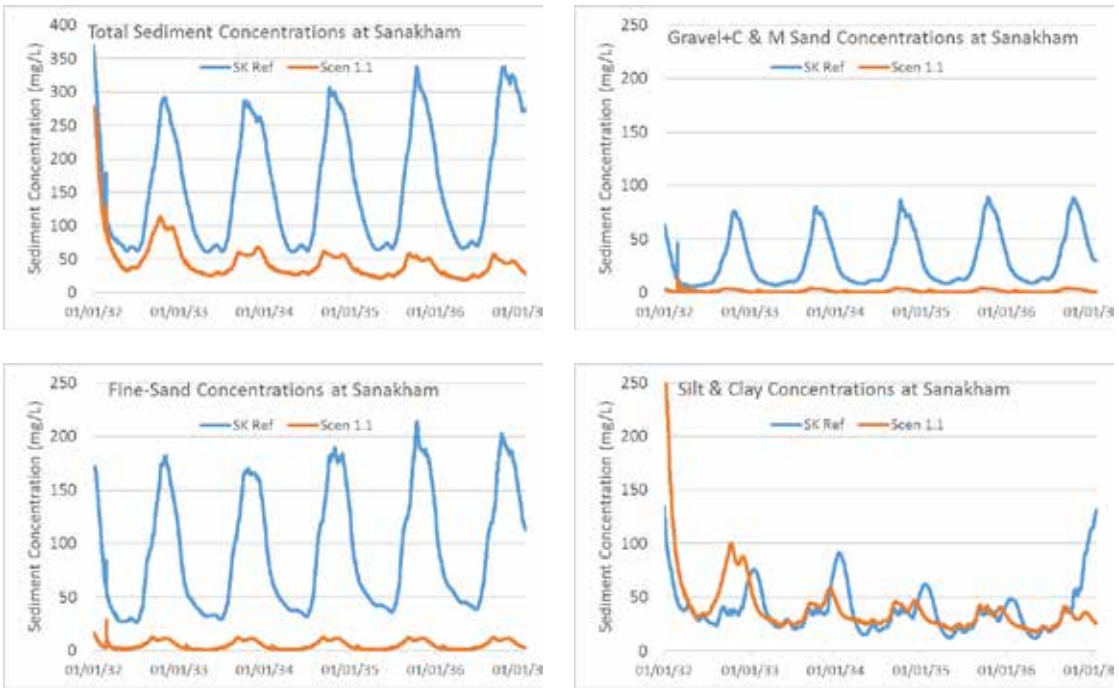


Figure 5.23. *Comparison of sediment concentrations at Sanakham in the BDP 2030 Reference Scenario and Scenario 1.1 for all sediment fractions, and for Gravel+Coarse+Med Sand, Fine-sand and silty+clay.*

5.3.2.1.4 Scenario 1.2 – Sediment Loads and Composition Cascade Reach (Zone 1)

Sediment flushing in the cascade is a complicated and long-term management challenge that will require optimisation and adaptive management over a number of years. The analysis and assessment presented here provides insights into how flushing could be implemented, and the factors that need to be considered. Ongoing monitoring will be required to guide the actual implementation and coordination between the various hydropower projects.

Sediment flushing (Scenario 1.2), has been investigated in detail in the Case Study. The number of model runs completed exceeds the number of scenarios described in Section 2.5 (Description of Scenarios) or contained in the final indicator table (Annex F) because numerous additional runs have been included to investigate how various conditions (e.g. inflows or season) or parameters (rates of drawdown, duration of low water level, rate of filling) alter the efficiency of flushing. Only the results that directly pertain to the scenarios for which hydropower modelling is available (1.2.A, 1.2.B&C, 1.2.D) are summarised in the indicator table in Annex F. For the modelling exercise, each dam was run as an independent model, and assumed that low level gates are present at each dam. A detailed description of the sediment model is provided in Annex A.

The evaluation of flushing as a mitigation measure primarily focusses on the Mekong downstream of the cascade within the context of sediment transport continuity. The sediment flushing results

are also useful for understanding how sediment management can maintain storage space within impoundments and how sediment can be transported downstream through the cascade.

Flushing runs were completed for Pak Beng, Xayaburi, Pak Lay and Sanakham, with sediment sluicing investigated for Sanakham. For each site, a 'no flushing' model run was completed to determine the discharge of sediments from each impoundment under run of river operations for the same time period as used in the flushing runs. The assessment was based on a 12-day flushing period, with the sediment load discharged from the dam compared to the amount of sediment discharged in the absence of flushing. Draw down rates in the dam, associated with flushing, ranged from 0.1 m/s to 'unconstrained', that is, there was no limit put on the rate at which water level could decrease. All scenarios included a reservoir filling rate of 0.2 m/hr.

Key Results for Flushing of Sediments: The results from all of the flushing runs and the sluicing run at Sanakham are summarised in Table 5.6, and presented graphically in Figures 5.24 to 5.27, and show the following characteristics and trends:

- ***The amount of sediment discharged during a flushing event at the bottom of the cascade (Sanakham) is small compared to the annual load of sediment entering the cascade.*** In most scenarios, the volume of sediment entering the impoundment exceeds the volume discharged during the flushing event. This is especially relevant to gravels and medium and coarse sand, as shown in Figure 5.24. The low sediment discharge from the impoundments is attributable to the overall low sediment loads entering the impoundments, combined with the short duration of the model runs; the flushing scenarios were completed using the sediment accumulation in the reservoirs after 7-years of cascade operation. The overall volume of sediment deposited in the impoundments during the 7-year period is very small compared to the volume of the impoundments, and sediment 'deltas' have not reached anywhere near the toe of the dam. It is expected that sediment accumulation will increase after a period of several decades that will lead to a larger volume of sediment being mobilised during an individual flushing event. The rate of sediment accumulation is discussed in more detail in the Geomorphology section 5.3.3;
- *The reservoir geometry affects sediment movement during flushing.* The cascade is characterised by long, narrow impoundments, punctuated by sharp bends within each of the reservoirs. These 'choke' points reduce the transport of sediment due to reductions and changes in velocities caused by the channel morphology. These features affect sediment transport during 'normal' operations as well as during flushing;
- ***Silt and clay are relatively insensitive to sediment flushing.*** Silt and clay are generally transported through the impoundments under the non-flushing flow regime, so only limited volumes of this grain-size accumulate in impoundments. During flushing, the quantity of silt and clay tends to be uniform throughout the event, and similar to the magnitude of the load entering the impoundment. An exception occurred at Pak Lay when draw down rates during flushing were 'unconstrained', and water levels decreased at rates greater than 1 m/hr. During this event large quantities of silt and clay were mobilised. This is consistent with silt and clay accumulating in quiet areas of the reservoir that require a large change in the flow dynamics to re-mobilise;
- ***The timing and initial conditions of flushing affect the efficiency of flushing. In general, the higher the sediment loads entering the impoundment at the initiation of flushing, the more successful the results.*** This is due to a larger proportion of the sediment remaining in suspension and being transported through the impoundment under the higher shear stress conditions created by flushing.

- Flushing during periods of high flows will promote the movement of sediment delivered by tributaries through the reservoir. ***Sediment flushing coinciding with the end of the dry season will remove a larger silt and clay load as compared to at other times of year, due to the accumulation of fine-sediment during the dry season.*** This is a minor consideration when planning sediment flushing as most of this material would be re-mobilised during the wet season, with or without flushing.
- The rate of reservoir drawdown is important. ***In general, the faster the drawdown rate, the higher the resulting shear stress and the higher the sediment load entrained and discharged from the impoundment.*** This is clearly shown in Figures 5.24 and 5.25, where faster draw down rates are associated with higher sediment loads, and in Figure 5.26 where the timing of sediment delivery by grain-size is shown for two flushing events at Pak Lay. The 'slow' drawdown maintains low discharge volumes and sediment concentrations, but moves less material as compared to the 'fast' drawdown;
- Based on this, ***the coordinated flushing of the cascade, involving the coordinated timing of water level decrease in successive reservoirs to promote movement of a sediment 'plug' through multiple impoundment, is a possibility and likely to improve the overall success rate as compared to the flushing of individual impoundments*** independently (joint cascade operation is also discussed in chapter 3.1.3).
- The duration that low water levels are maintained affect sediment flushing. In almost all of the flushing model runs, water levels were decreased to the targeted minimum level and held at the minimum for 1-day before increasing at the rate of 0.2 m/hr up to the minimum operating level. In one of the Pak Beng runs, the water level was maintained at the lowest point for 2-days. The flushing results are shown as discrete data points in the August results for Pak Beng in Figure 5.24. The longer 'hold' period increased the quantity of sediment discharged in all size fractions, with the largest increase occurring in the fine sand fraction. The quantity of fine-sand mobilised during the1 m/hr flush with the extended 'hold' at low water exceeded the quantity of fine-sand mobilised using a higher flushing rate of 2 m/hr;
- The maximum volume of water discharged during sediment flushing is controlled by the rate of drawdown and the rate of water entering from upstream. High drawdown rates provide the greatest 'return' with respect to sediment discharge, but also produce large flood peaks. The size of these peaks needs to be considered with respect to human safety and downstream impacts. This finding is consistent with previous investigations into flushing that found approximately twice the annual average flow is required to promote successful flushing (Pitt and Thompson, 1984).

Table 5.6. Summary of sediment flushing results from Delft 3D model runs for Pak Beng and Sanakham.

Location	Draw Down Rate (m/hr)	Max Flow Out	Sediment Loads (X 1000 tonnes)			Net Increase in Sediment Net Inc. In Sediment Outflow attributable to Flushing (x 1000 tonnes)		
			Gravel +C& M Sand	Fine Sand	Silt & Clay	Gravel +C& M Sand	Fine Sand	Silt & Clay
Pak Beng*			Sediment Inflow					
June: Inflow = 2374 m3/s			113.3	216.0	17.1			

Location	Draw Down Rate (m/hr)	Max Flow Out	Sediment Loads (X 1000 tonnes)			Net Increase in Sediment Net Inc. In Sediment Outflow attributable to Flushing (x 1000 tonnes)		
Normal Oper.	0	2,369	0.0	0.1	37.3	0	0	0
Flush	0.1	3,506	9.1	45.2	88.5	9.1	45.1	51.2
Flush*	0.5	7,303	10.5	53.6	83.7	10.5	53.4	46.3
Flush	1	10,557	26.6	123.3	86.5	26.6	123.1	49.2
Flush	2	14,592	92.2	285.1	92.3	92.1	284.9	54.9
			Sediment Inflow					
August: Inflow = 5,106			282.2	528.3	40.9			
			Sediment Outflow			Increase in sediment Outflow		
Normal Oper.	0	5,337	0.8	8.4	296.5	0	0	0
Flush	0.1	6,402	146.6	552.5	348.3	145.8	544.1	51.8
Flush*	0.5	9,661	123.5	426.6	339.2	122.7	418.2	42.7
Flush	1	12,429	144.9	464.9	334.6	144.1	456.5	38.0
Flush	2	16,095	192.8	553.2	333.7	192.0	544.8	37.2
			Sediment Inflow					
November: Inflow = 3,184			156.1	295.1	23.0			
			Sediment Outflow			Increase in sediment Outflow		
Normal Oper.	0	3299	0.0	0.6	94.9	0	0	0
Flush*	1	11,149	47.0	204.4	142.4	47.0	203.8	47.6
Xayaburi								
			Sediment Inflow					
November: Inflow = 3,184			13.7	28.0	521.1			
			Sediment Outflow			Increase in sediment Outflow		
Normal Oper.	0	8244	0.3	6.6	763.5	0	0	0
Flush	0.1	9262	16.3	117.1	1,057.8	16.0	110.5	294.3
Flush	0.5	14029	31.3	154.1	1,016.0	31.0	147.5	252.5
Flush	1	18665	33.8	193.9	992.0	33.5	187.3	228.5
Flush	2	25,808	105.6	426.4	985.9	105.3	419.8	222.4
Pak Lay								
			Sediment Inflow					
March: Inflow = 4880			35.7	76.3	499.3			
			Sediment Outflow			Increase in sediment Outflow		
Normal Oper.	0	5,055	1.4	3.6	463	0	0	0
Flush	0.1	6,072	36.2	126.2	607.9	34.8	122.6	144.9
Flush	0.5	9,744	39.1	132.1	457.0	37.7	128.5	-6.0
Flush	Unconstrained	18,520	66.4	280.8	1575.9	65	277.2	1112.9

Location	Draw Down Rate (m/hr)	Max Flow Out	Sediment Loads (X 1000 tonnes)			Net Increase in Sediment Net Inc. In Sediment Outflow attributable to Flushing (x 1000 tonnes)		
Sanakham								
			Sediment Inflow					
June: Inflow = 1,961 m3/s			0.9	1.3	17.8	0	0	0
Normal Oper.	0	1975	0.0	0.2	23.6	0	0	0
Flush	0.1	3,127.0	6.7	25.7	57.5	6.7	25.5	33.8
Flush	0.5	6,536.0	10.2	43.6	56.9	10.2	43.4	33.3
Flush	1	9,092.0	37.3	170.5	59.5	37.3	170.3	35.8
Flush	2	12,237	159.4	598.2	64.2	159.4	598.0	40.6
			Sediment Inflow					
March: Inflow = 4,880 m3/s			77.4	154.5	1,119.4			
			Sediment Outflow			Increase in sediment Outflow		
Normal Oper.	0	4887	4.7	22.9	1,125.5	0	0	0
Sluice	0	5228	4.7	18.9	1,136.5	0.0	-4.1	11.0

*Indicates results used in Indicator Table

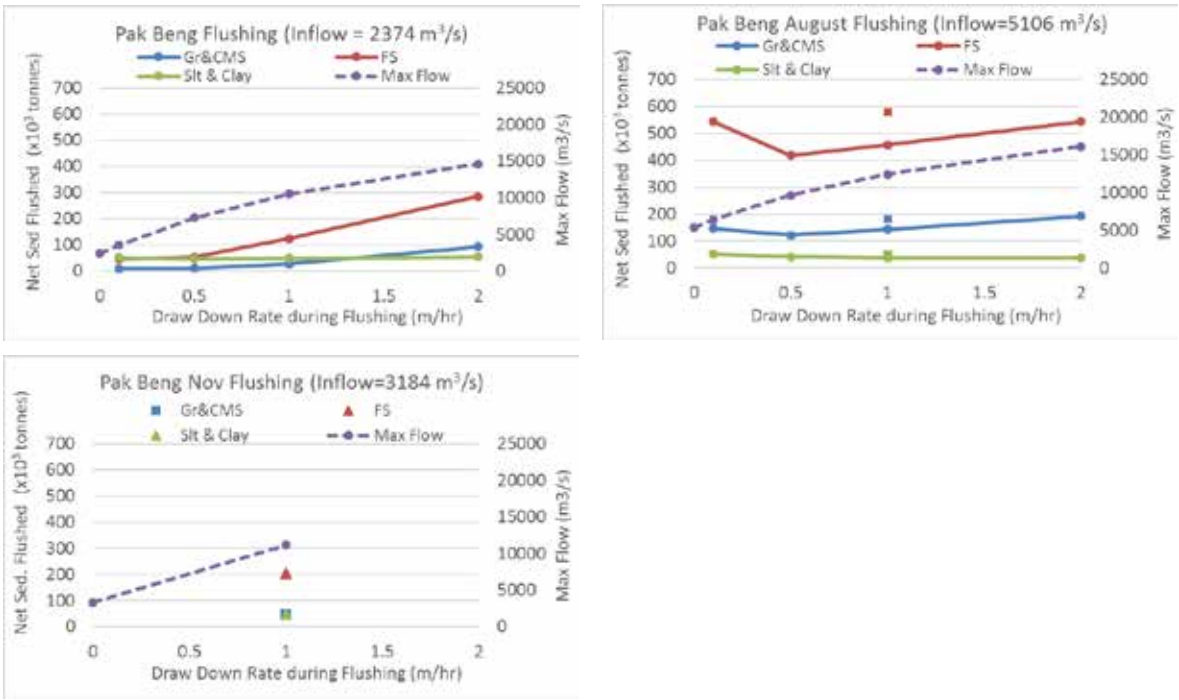


Figure 5.24. *Flushing results at Pak Beng. Graphs show the increase in sediment discharge from the dam compared to a non-flushing period. Model run is for 12 days, including draw down and refilling of reservoir. In the August results, additional data points are shown for a run in which the reservoir was maintained at the lowest level for 2-days.*

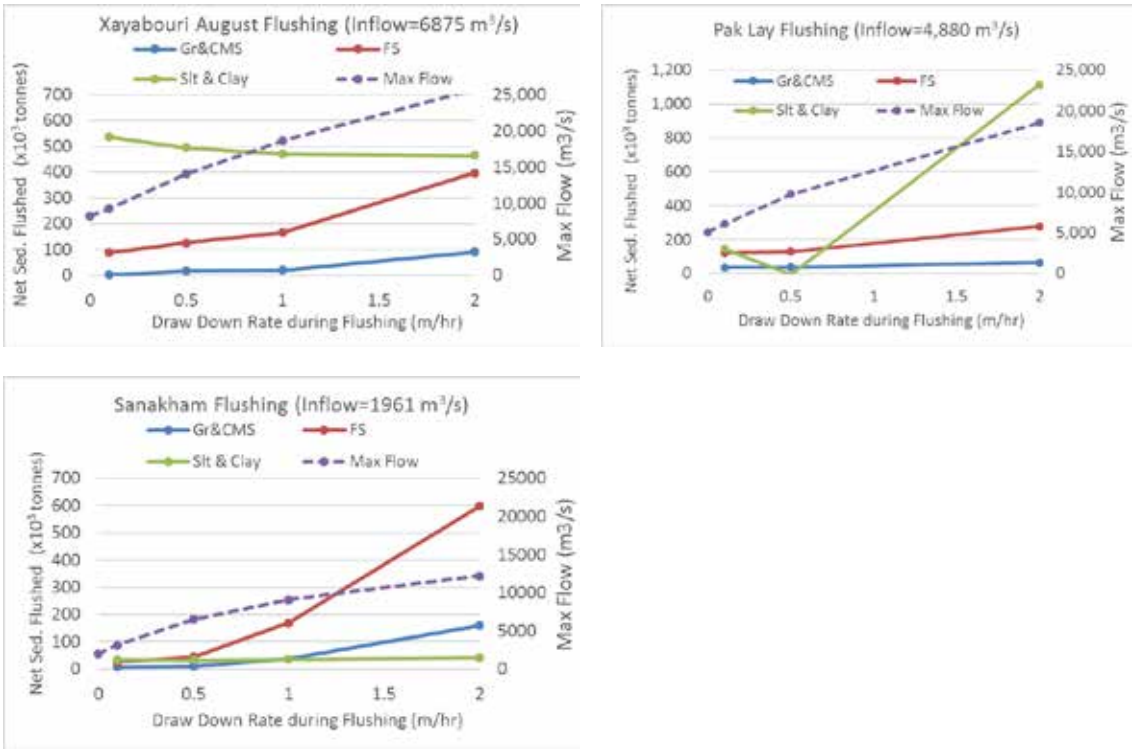


Figure 5.25. *Sediment flushing results for Xayaburi, Pak Lay and Sanakham. In Pak Lay graph the 'unconstrained' draw down results are graphed as a 2 m/hr draw down. Note change of sediment scale in Pak Lay.*

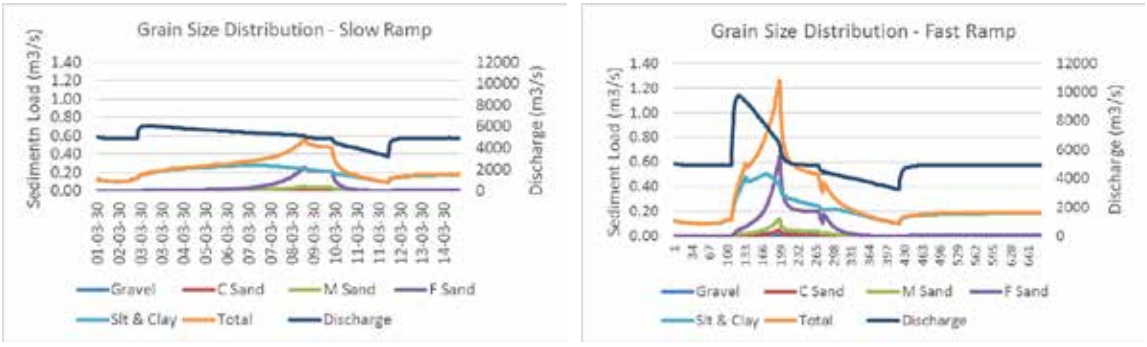


Figure 5.26. *Grain-size distributions in discharge during 'slow' (left) and 'fast' (right) sediment flushing mitigation runs at Pak Lay. Discharge also shown.*

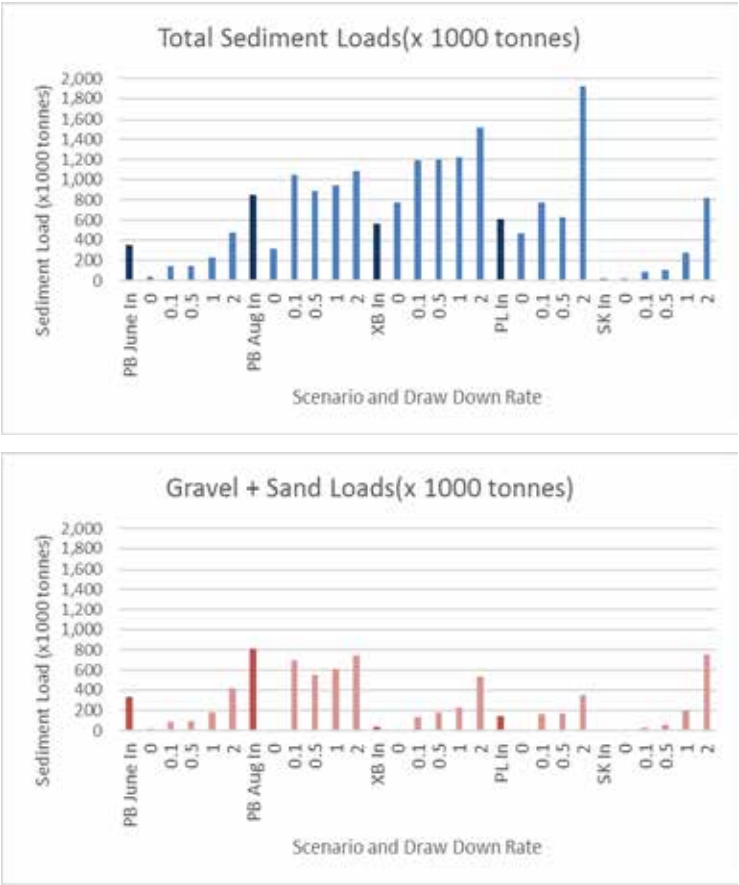


Figure 5.27. *Sediment loads associated with flushing runs. Top – Total sediment load entering the impoundment (dark blue bars) is compared to the total sediment discharged from the impoundment during the flushing event. Bottom – Same graph except only gravel and sand (Coarse, medium and fine) included. The '0' draw down rate indicates sediment discharge over the same time-period without flushing.*

The overall impact of sediment flushing on the sediment loads discharged from each of the impoundments is summarised in Table 5.7. The net sediment loads are provided, representing the difference between the sediment load discharged from the dam without flushing and the quantity discharged during flushing. This quantity indicates the sediment load that has been discharged directly as a result of flushing. The flushed sediment loads range from 1% and 37% of the annual sediment load at the dam sites. The variability of the results is attributable to the range of flow, draw down and low-flow conditions, and flushing results can probably be improved through optimization. The quantity of sediment mobilised and the percentage of the annual sediment load that can be flushed will likely increase in the future as larger volumes of sediment are trapped within the impoundment and deposited closer to the toe of the dam.

Table 5.7. Comparison of net sediment discharged during flushing with annual sediment loads.

Location	Sediment Load without Flushing (Scenario 1.1.0) Mt/yr	Range of Sediment Loads Discharged during Flushing Event (Mt)	Flushed Load as a percentage of Annual Sediment Load without Flushing
Entering Pak Beng	12.2		
Pak Beng Dam	2.7	0.07 – 0.47	3% - 17%
Luang Prabang dam	2.4	No model runs	
Xayaburi	3.5	0.42 – 0.75	12% - 21%
Pak Lay	3.9	0.16 – 1.46	4% - 37%
Sanakham	6.0	0.07 – 0.80	1% - 13%

5.3.2.1.5 Sediment Loads – Scenario 1.2. Sanakham to Paksane Reach (Zone 2)

The volume of sediment transported through the cascade reach is greatly reduced compared to 'natural' conditions. Of the sediment that is entering the cascade and being trapped, only a small proportion is mobilised during sediment flushing events with sand and gravel contributing only a minor proportion of the total sediment load. Based on this, it is unlikely that the relatively low quantities of sand being delivered downstream through flushing could prevent channel erosion from occurring downstream of the final dam, even if flushing occurred on an annual basis. Pulses of sand might reduce the rate of erosion very locally, and could assist in the maintenance of some habitats characterised by fine sand that would otherwise be lost in the absence of flushing. To achieve these benefits, the timing of flushing activities needs to coincide with a period when sand would provide the most geomorphic and ecological benefit. If flushing is completed at the beginning or middle of the wet season, the released sediment is likely to be transported through the river and any benefit would be limited. If flushing is completed towards the end of the wet season or beginning of the dry season, there is an increased likelihood that sediment would be deposited in the river channel, where it could maintain habitats through the next dry season.

5.3.2.1.6 Sediment Loads-Scenario 1.2 Paksane to Pakse Reach (Zone 3)

The impact of sediment trapping and flushing, on overall sediment loads, is likely to be limited downstream of Paksane, at least in the short term. The modelled sediment flushing events produce 'pulses' of water and sediment that increased the concentration of sediment discharged from the dam for a duration of up to several days. Sediment concentrations at the Pak Lay dam site for each of the flushing events (Figure 5.28) show the more rapid draw down rate produced substantially higher suspended sediment concentrations. Although the concentrations are elevated compared to the BDP 2030 scenario or 'typical' Scenario 1.1 (Run-of-River) operation, they are well within the historically experienced range of suspended sediment concentrations measured in the Mekong. The modelling results show that by the time a 'flush' event is measured downstream of Paksane, it is likely that concentrations will decrease compared to the dam site values due to deposition of coarser material and additional inflows from other tributaries.

The total volume of sediment mobilised during the flushing events (~200,000 tonnes) is small compared to the sediment load in this portion of the river, and is unlikely to create issues associated with increased sedimentation, such as coating or infilling of habitats. Similarly, a relatively low sediment load released episodically from the cascade is unlikely to be able to 'maintain' the geomorphology similar to pre-cascade and tributary impoundment conditions. Over decades as more sediment accumulates in the impoundments, the risk of unacceptably high suspended sediment concentrations during flushing events will increase. For this reason ongoing monitoring of sediment accumulation within the reservoirs, and sediment concentrations during flushing events is required.

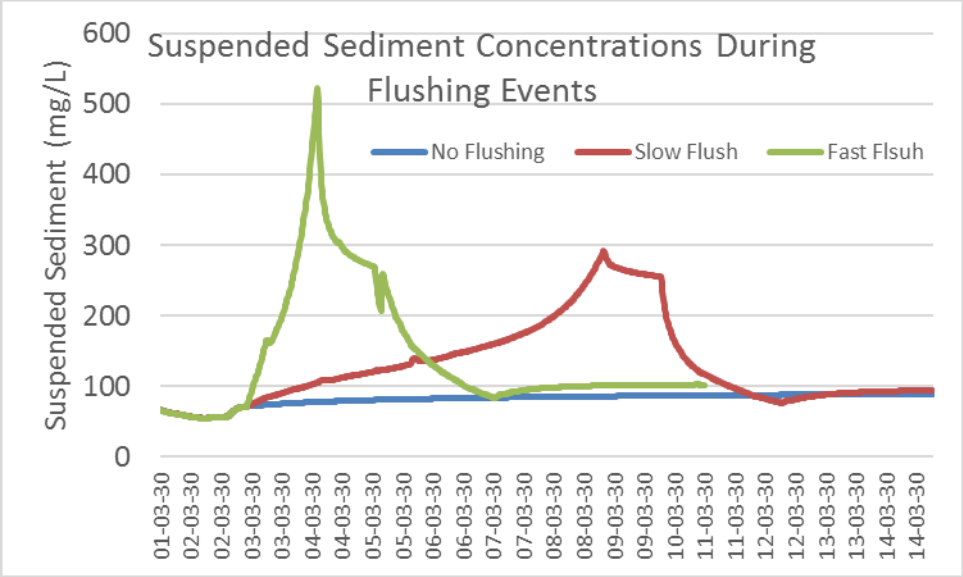


Figure 5.28. *Sediment concentrations in the discharge from Pak Lay dam during two sediment flushing events.*

More discussion regarding sediment concentrations in the water discharged during the flushing event is contained in Water Quality Section 5.4.

5.3.2.1.7 Summary of Sediment Yields from Flushing – Scenario 1.2

The sediment flushing indicators included in the final indicator table (Annex F) are based on the June, August and November flushing results at Pak Beng. Pak Beng was chosen because the reservoir has the highest sediment input and so provides the best indication of sediment flushing within the 7-year time frame of the model. These runs do not provide the highest sediment yields of all of the modelled runs, but are consistent with the conditions included in the energy modelling flushing scenarios to provide an indication of the power costs associated with sediment flushing. The same results are provided for Scenarios 1.2.B and 1.2.C, because the flow changes between the two scenarios are small and do not affect sediment flushing. The summary of the runs and the results are in table 5.8.

Table 5.8. Summary of sediment flushing indicators included in the final indicator table.

Scenario	Start Time	Drawdown Rate	Gravel & Sand X 103 tonnes	Fine-Sand X 103 tonnes	Silt & Clay x 103 tonnes
1.2.A	June	0.5 m/hr	10.5	53.4	46.3
1.2.B & C	August	0.5 m/hr	122.7	418.2	42.7
1.2.D	November	1.0 m/hr	47.0	203.8	47.6

5.3.2.1.8 Scenario 1.3 (Peaking) – Sediment Loads and Composition- Cascade Reach and downstream (Zone 1-3)

Hydropeaking can enhance revenues associated with power generation by increasing production during periods of 'peak' energy demand. Hydropeaking can affect the geomorphology and channel stability of a river through the following processes:

- The shear stress of a river (sediment carrying capacity) is directly proportional to the depth and slope of the water. Rapidly increasing water levels will increase both of these parameters leading to an increase in erosion;
- Rapidly decreasing water levels can destabilise river banks if they are saturated leading to draw-down failure or seepage erosion;

Downstream of power stations, erosion promoted by rapid water level changes can exacerbate erosion attributable to a reduction in sediment supply due to trapping in impoundments. Common mitigation measures include controlling the ramping rate and frequency of water level fluctuations, and linking bank saturation levels to power station drawdown rates.

Hourly water level results associated with unregulated flows (BDP 2030 scenario) and hydropeaking scenarios without and with mitigation (1.3.0, 1.3.D, respectively) were analysed for the sites show in Table 5.9. A threshold of 0.05 m/hr water level change was adopted for the analysis as this is the value associated with minimising fish stranding.

The results from the 24-year period show that power station controlled water level changes were greatest during the dry months, so all results from each site in January were grouped and analysed for hourly changes (Figure 5.29). The analysis reveals that under the BDP 2030 Reference Scenario, there were no water level changes that exceeded ±0.05 m/hr at any of the sites. Without operating constraints, hydropeaking increased the proportion of water level changes exceeding ±0.05 m/hr to 88% of the time at the Luang Prabang dam site, decreasing to 34% of hourly events at the city of Luang Prabang. Further downstream, at Sanakham, 56% of the hourly events exceeded the threshold value.

Implementation of the water level change constraint removed these large water level fluctuations, and returned the number of events exceeding the 0.05 m/hr threshold to near 'reference' condition at the Luang Prabang dam site and Luang Prabang town. At Sanakham, 4% of the events exceeded the target threshold, representing a large decrease as compared to hydropeaking without mitigation.

Table 5.9. Water level fluctuations associated with hydro-peaking scenario 1.3. Results based on hourly water level results from MIKE-11.

	Relevance of site	BDP 2030	1.3.0 No Mitigation	1.3.D With Ramping limited to 0.05m/hr
Hourly water level fluctuations at Luang Prabang Dam site >±0.05 m/hr in January (85 - 08)	Upstream major tourist area	0%	88%	<1%
Hourly water level fluctuations at Luang Prabang Town >±0.05 m/hr in January (85 - 08)	At major town	0%	34%	<1%
Water level fluctuations at Sanakham >±0.05 m/hr in January (85 - 08)	Downstream final dam in cascade	0%	56%	4%

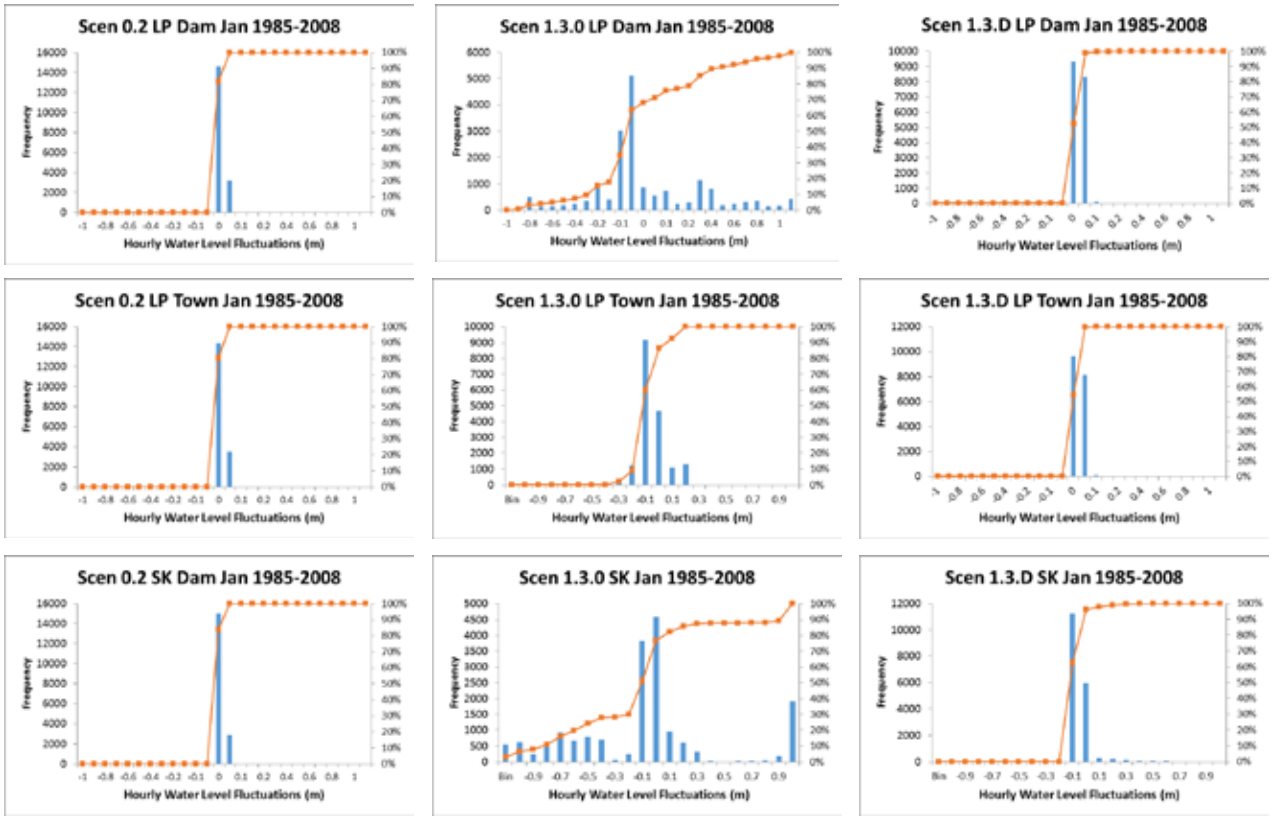


Figure 5.29. Histogram of hourly water level changes at the Luang Prabang Damsite, Luang Prabang Town and Sanakham under scenario 1.3.A (hydropeaking without water level constraints), and under scenario 1.3.C, (hydropeaking with water level constraints).

The impacts of hydropeaking at sites downstream of the cascade were investigated using a simplified ISIS model for the river downstream of the cascade, and flow results from Scenario 1.3.0 for January 2002 (Figure 5.30). Water level fluctuations at Vientiane show impacts associated with the hydropower operations, with 16% of the hourly water level changes exceeding 0.05 m/yr. At Paksane, the impact is negligible, with all hourly water level changes below the target of 0.05 m/yr.

Interestingly, much farther downstream at Kong Chiam, the percentage of flow changes that exceed the 0.05 m/hr threshold increases, suggesting that other inflows or hydropower operations contained within the BDP 2030 flow model are affecting water levels downstream.

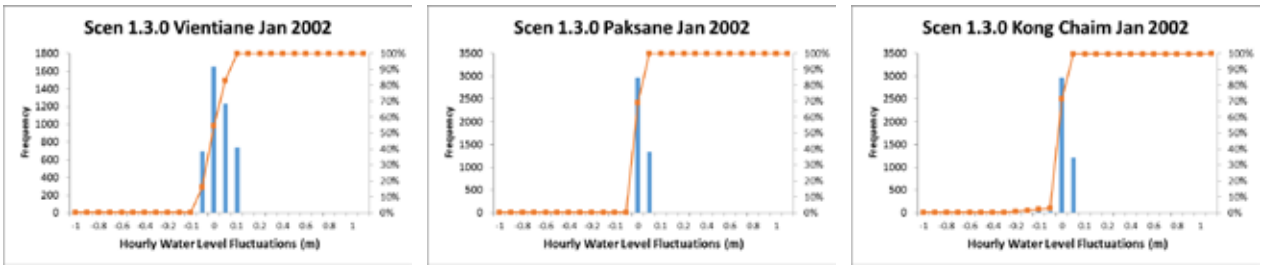


Figure 5.30. *Water level analysis for Vientiane, Paksane and Kong Chaim.*

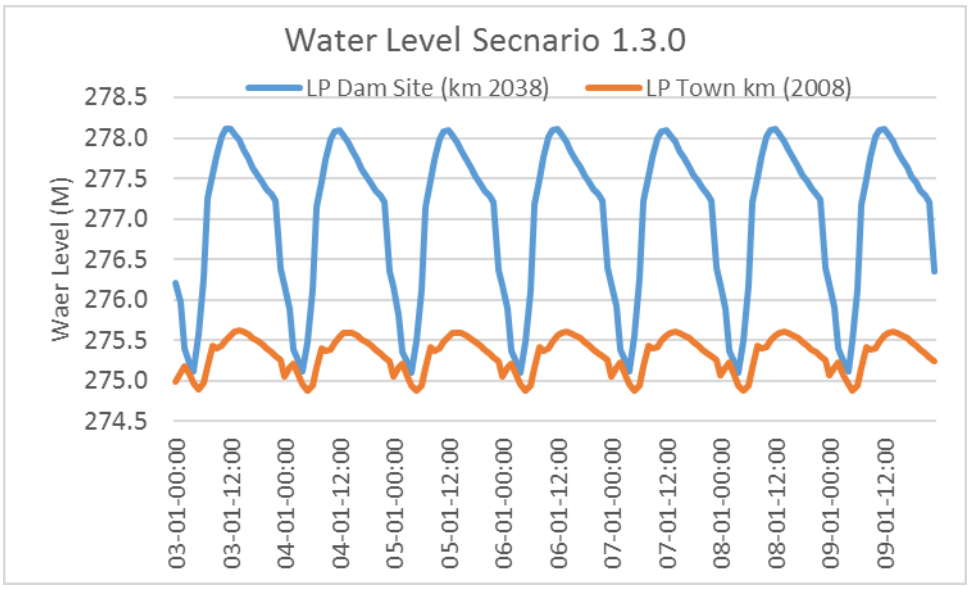


Figure 5.31. *Comparison of water level fluctuations at Luang Prabang dam and Luang Prabang town, 30 km downstream showing attenuation between the sites.*

A comparison of shear stresses associated with a peaking and a run-of-river flow regime was completed for the reach downstream of Sanakham, with results shown in Table 5.10 and Figure 5.32. For all sites except Nong Khai the peaking regime has a higher net sediment transport capacity due to higher maximum shear stress and / or longer periods under which the maximum shear stresses occur. The increase is most pronounced close to the dam site where water level fluctuations are greatest. The relative decrease in sediment transport capacity at Nong Khai under the peaking regime is attributable to the attenuation of 'peaks' with distance downstream, resulting in higher minimum shear stress values under the run-of-river regime, with similar maximum values under both regimes. There is also a small increase in the volume of water (~3%) discharged under the non-peaking regime as compared to the peaking regime in the model run which contributes to these differences.

Table 5.10. Summary of shear stress and sediment transport associated with a peaking regime (without mitigation) and a non-peaking regime.

		PEAKING (no mitigation)			RUN OF RIVER			
		Min/Max	Transport	Min/Max	Transport			
	Nav	Shear Stress	Med Sand	Fine Sand	Shear Stress	Med. Sand	Fine Sand	Change in load
Name	KM	N/m2	m2/s	m2/s	N/m2	m2/s	m2/s	(+=inc)
Sanakham	1734	0.3/2.7	0.32	26.92	1.4/2.0	0.22	18.51	45.5%
Bedrock sect	1724	2.2/8.7	0.68	57.29	5.5/7.8	0.58	48.46	18.2%
Alluvial start	1692	5.0/11.7	1.40	117.68	8.7/11.7	1.37	115.15	2.2%
Upstr Vient.	1604	5.0/7.2	4.30	361.47	5.9/6.9	4.29	360.09	0.4%
Nong Khia	1550	3.4/5.5	2.39	200.77	4.0/5.5	2.62	220.17	-8.8%

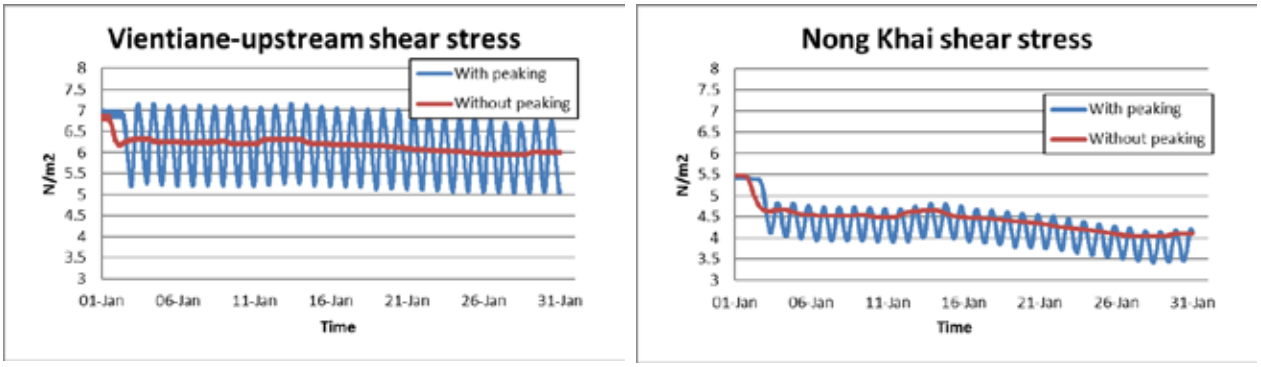


Figure 5.32. *Comparison of shear stress at Vientiane and Nong Khai under a peaking regime without mitigation and a non-peaking power station operations at Sanakham. Shear stress pressure is expressed as Newton/m2.*

The model results suggest that limited hydropeaking may be feasible if appropriate operating constraints are adopted. For the purposes of geomorphology, a slightly higher ramping rate may be able to be implemented, depending on the nature of the downstream channel, and the rate at which the 'peak' dissipates downstream. As shown in Figure 5.31, the magnitude of the 'peak' dissipates in the 30 km between the Luang Prabang dam site and the town, with fluctuations at the town limited to ~0.5 m even in the absence of ramping constraints. ***It is probable that adaptive management on a site by site basis will be required to identify whether and to what degree hydropeaking may be implemented. In addition to geomorphic and ecological considerations, navigation, infrastructure safety and human safety must also be considered.***

In summary, hydropeaking without constraints on water level changes is likely to increase the rate of erosion immediately downstream of the power station, with the impact decreasing as the wave attenuates downstream. This area is projected to record increased rates of erosion even in the absence of hydropeaking due to the lack of sediment discharge from the impoundments, but peaking would accelerate the rate. With operating constraints, erosion rates downstream of the power station are likely to be similar to rates of change under a non-peaking regime.

The indicators associated with hydropeaking in the multi-criteria assessment include flow variability as hourly changes, and are based on the hydrologic analysis of the flow regime.

5.3.2.2 Indicator: Timing of sediment delivery

5.3.2.2.1 Scenario 1.1 Downstream of Cascade (Zone 2 and 3)

The timing of sediment delivery in the LMB is of importance for the maintenance of the river channel and ecological habitats, and the timing of nutrient delivery to the river, floodplains, Tonle Sap and Delta. The Mekong River is naturally a flood pulse and sediment pulse system, with ~80% of sediments transported within a 4-month period under unregulated, natural conditions.

The timing of sediment delivery is considered only in the context of Scenario 1.1 because the changes to the timing of sediment delivery are considered to be negligible in Scenario 1.3, and able to be managed in Scenario 1.2 (e.g., the timing of sediment flushing can be targeted). To provide a context for evaluating Scenario 1.1., historic and BDP2030 conditions are also considered.

The distribution of sediment delivery at Chiang Saen prior to the Lancang Cascade is shown in Figure 5.33 for three years prior to major water management infrastructure in the basin (1970 – 1972). Also included in the graph is the distribution of sediment delivery based on the BDP 2030 Reference scenario at Km 2347, the upstream extent of the sediment model. The sediment load at Km 2344 shows a more even distribution of loads throughout the year, and higher sediment loads during the dry season. This is attributable to the alteration of the flow regime associated with the Lancang Cascade, and to the smoothed flow regimes used in the model.

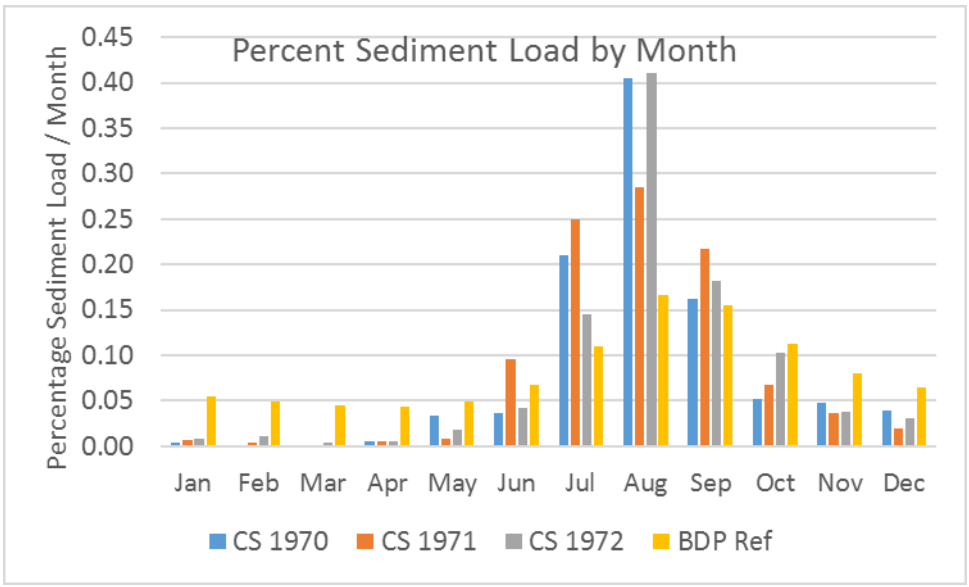


Figure 5.33. *The monthly distribution of sediment loads (percent) for the pre-Lancang Dam conditions at Chiang Saen and upstream of the Pak Beng dam site in the Delft 3D sediment model for the BDP 2030 Reference scenario.*

The distribution of sediment loads through the year is shown for each dam location for the BDP 2030 Reference Scenario and Scenario 1.1 in Figure 5.34. Under the BDP 2030 Reference Scenario sediment loads are delivered proportionately earlier at the upstream sites as compared to the downstream sites. In contrast, the Scenario 1.1 results show variable output. The changes are attributable to several mechanisms:

- Sediment trapping of the coarser fractions leads to the sediment load being dominated by fine sand, silt and clay. These fractions require lower flow velocities to be carried in suspension and are able to be transported throughout the year;
- The residence time of sediment within reservoirs can lead to 'lag' periods in sediment delivery;

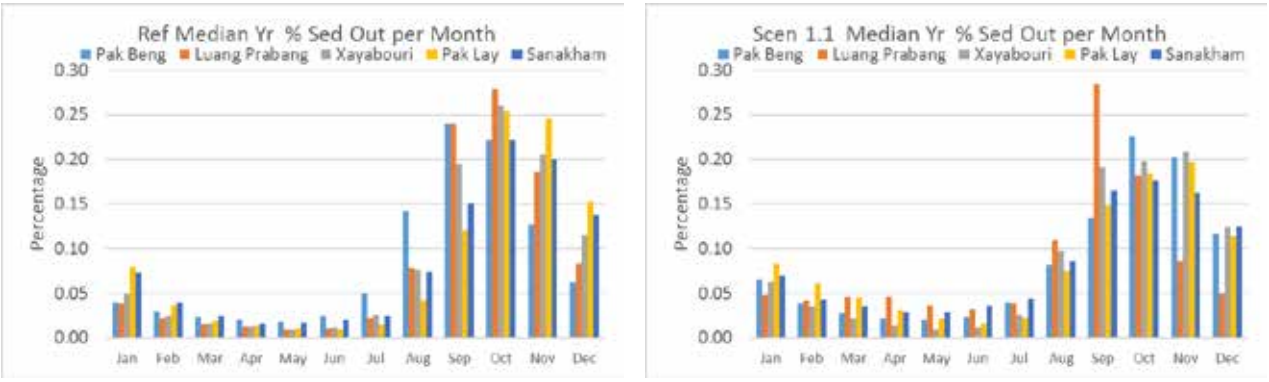


Figure 5.34. *Distribution of sediment delivery at dam locations for the BDP Reference scenario (left) and Scenario 1.1 (right).*

Time-series of the model results, showing the sediment input and output at each dam site for the BDP 2030 Reference Scenario, and the output for Scenario 1.1 (Figure 5.35) demonstrate that the sediment 'peaks' become less pronounced with distance down the cascade, but are similar in magnitude at the discharge of each of the dams. This similarity in Scenario 1.1 is due to the majority of the sediment load being comprised of fine-sands, silts and clay, which are passing directly through the system, with all other size fractions being captured. In contrast, the BDP 2030 Reference 'In' and 'Out' results show variability with respect to inflows and outflows due to tributary inputs and variable degrees of sand and gravel deposition, as discussed in the previous section.

Figure 5.35. *Time-series of BDP 2030 Ref input, output and Scenario 1.1 output at the 5 dam sites based on Delft 3D sediment model results.*

Due to the smoothed hydrographs producing a more uniform pattern of sediment delivery, and the lag of sediment delivery through the cascade reach, the percentage of sediment delivered over the period August to December has been used as the indicator for sediment timing, with the results provided in table 5.11. The results show that the majority of the sediment load is being transported through the system during the wet season and early dry season for the BDP 2030 Reference Scenario and Scenario 1.1. There is a small reduction in the percentage of the load being delivered in Scenario 1.1 as compared to the BDP Reference.

5.3.2.2.2 Summary of Timing of Sediment Delivery

The percentages contained in table 5.11 are used as the indicators for the timing of sediment delivery in the multi-criteria analysis. ***Overall the operation of the cascade is considered to have a discernible but minor effect on the timing of sediment transport.*** The changes to timing

are likely less of a change to the system as compared to the large reduction in the magnitude of sediment delivery related to the operation of the Lancang Cascade, tributary dams and potentially the Northern Laos Cascade.

Table 5.11. Timing of sediment delivery based on the average percentage of sediment delivered in the months August to December during the 5-median flow years in the smoothed flow sequence. The 'historic' values are based on the period July to October.

Indicator	Historic Pre-Lancang Cascade	0.2 BDP 2030 Median Year (Avg 5 yrs)	1.1 Run of Riv Median Year (Avg 5 yrs)
% Sediment Load Aug to Dec upstream cascade	66 – 88% July to Oct (based on historical results at CS)	55%	59%
% Sediment Load Aug to Dec Pak Beng Dam site		77% 7.4 Mt	77% 2.1 Mt
% Sediment Load Aug to Dec at Luang Prabang Dam site		87% 9.2 Mt	69% 1.7 Mt
% Sediment Load Aug to Dec at Xayaburi Dam site		76% 10.3 Mt	72% 2.6 Mt
% Sediment Load Aug to Dec at Pak Lay Dam site		75% 15.6 Mt	66% 2.6 Mt
% Sediment Load Aug to Dec at Sanakham Dam site	~58 - 89% July to Oct (Nong Khai historical)	68% 14.5 Mt	61% 3.6 Mt

5.3.2.3 Geomorphic Indicators: Channel Changes

The sediment budgets and balances presented in the previous sections are based on the sediment inflows and outflows to each of the impoundment areas, but do not provide a quantitative assessment of the amount of deposition or erosion occurring within or downstream of the cascade reach. To understand the distribution of sedimentation and erosion, changes to reservoir volumes have been determined in each of the impoundments, and downstream of the cascade using the Delft 3D sediment model for Scenario 1.1.

5.3.2.3.1 Scenario 1.1 Channel changes in the Cascade Reach (Zone 1)

The topography of the cascade reach with and without the development of the cascade was investigated over the 7-year time frame of the sediment model. For each impoundment, the bed topography at the start of the model run is compared to changes to the bed elevation after 3, 5 and 7 years (Figure 5.36).

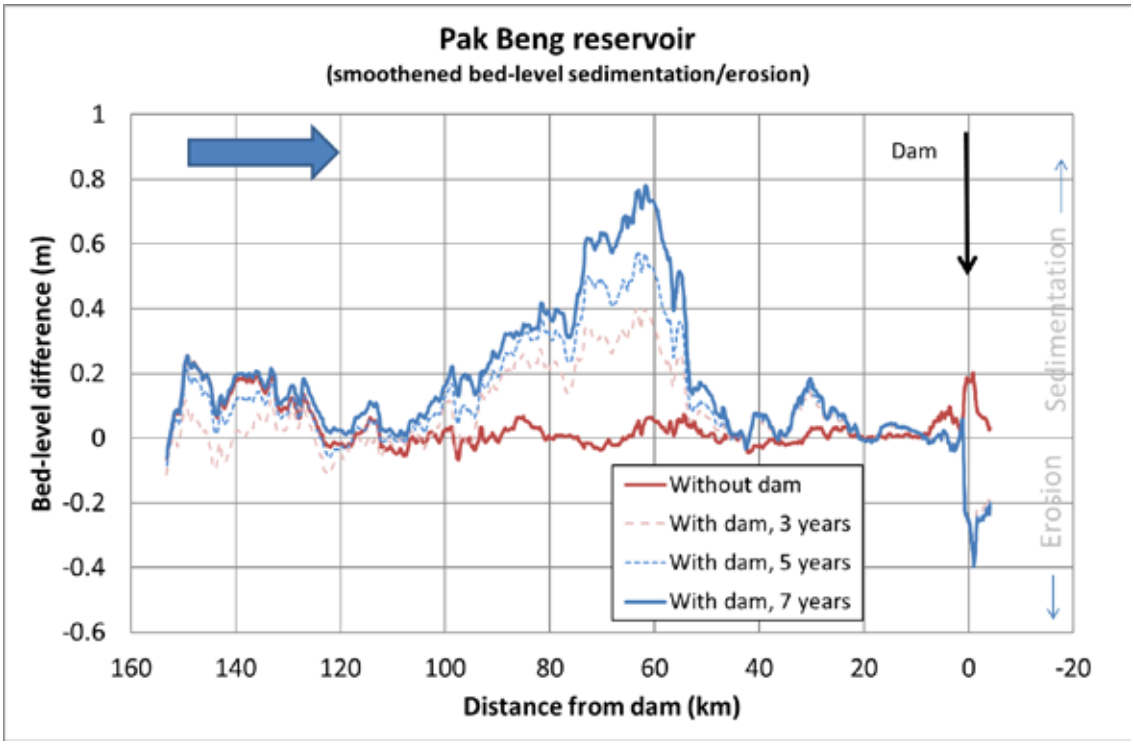
The results show that there is a high degree of variability, with both erosion and deposition recorded. ***With the exception of the most upstream reservoir, Pak Beng, which receives the highest sediment loads, erosion is recorded in the upstream area of each impoundment and also immediately downstream of each dam site.*** This is attributable to large volumes of sediment

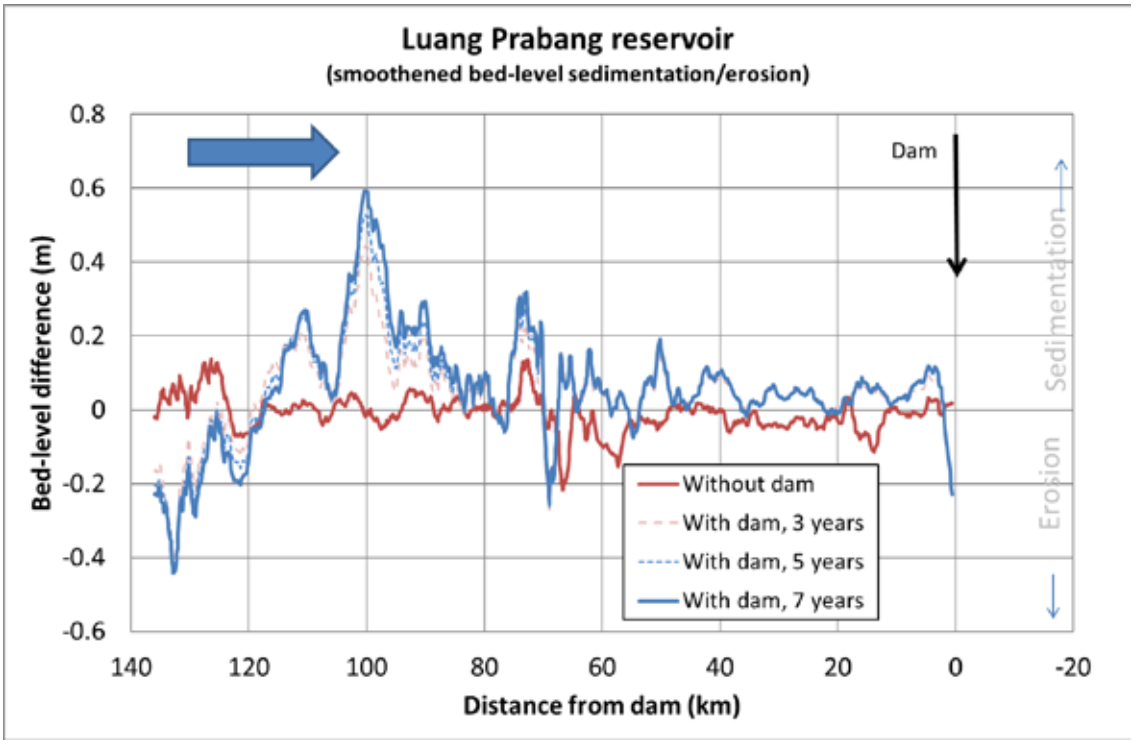
poor water being discharged from the upstream impoundment into the tail water section of the reservoir. The water continues to have sufficient velocity and energy to transport sediments, leading to increased erosion and the decrease in bed level elevation shown in the plots. Some of the initial erosion (e.g. year 3) might be attributable to the model containing a large volume of sediment at the initial start-up which could be readily transported, but the on-going degree of erosion at the end of the 7-year period suggests that erosion and bed incision is likely to prevail in these areas.

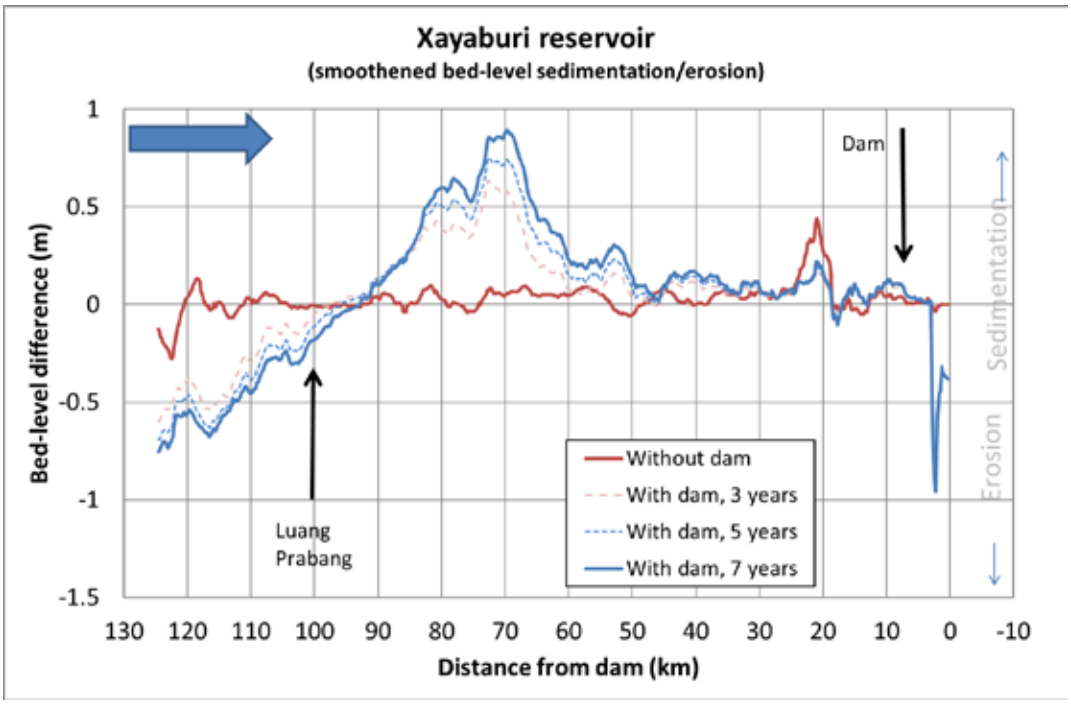
Downstream of these erosive areas in each reservoir, sediment deposition increases. These areas coincide with areas of reduced velocity within the impoundments and also reflect the presence of tight bends or river constrictions which affect flow velocities and sediment transport capacity. ***The deposition of material is shown to progress in a downstream direction, with most deposition limited to the mid-reaches of the waterways after 7-years.*** Over time, the sediment 'delta' will progress downstream and approach the toe of the dam. The time required for this process to occur is likely to be on the order of decades based on modelling results.

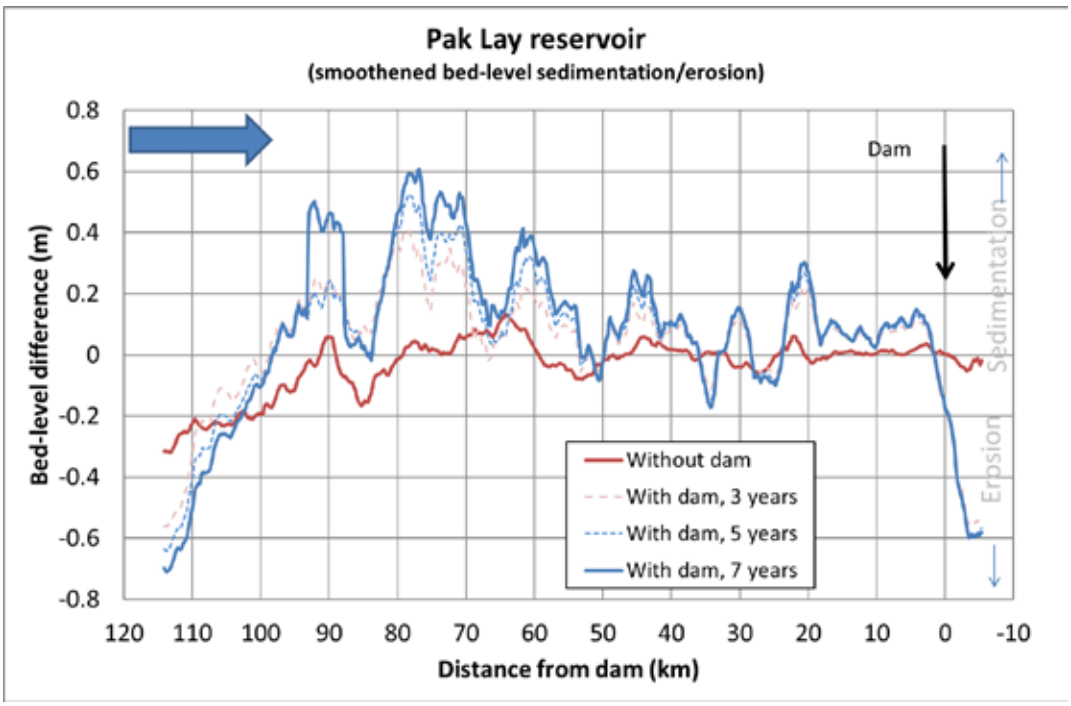
Observations related to channel changes in individual reservoirs include:

- The river channel upstream of Pak Beng shows geomorphic changes over the 7-year time period that are not directly related to the impoundment. This is consistent with the channel being in a state of change associated with the upstream mainstream HP developments and other catchment activities;
- The Xayaburi model suggests that erosion will be the predominant process from downstream of the Luang Prabang dam site to approximately the confluence of the Mekong River with the Nam Ou or Nam Suong. Downstream of the Luang Prabang township, deposition becomes the dominant processes;
- The lower 4 impoundments all show a 'nick' point where channel erosion shifts to channel deposition. Over time, the location of this point will migrate, moving upstream if sediment supply increases, or downstream if sediment supply decreases. Eventually an equilibrium with the 'new' sediment regime should be reached, but this is likely to require a long time, and is sensitive to future changes in flow or sediment inflows;
- The model results are consistent with the sediment flushing results, with little sediment available for transport near the dam wall. Pak Lay had the highest sediment load associated with flushing, and also shows the highest deposition of sediment in the lower downstream area of the impoundment (note, no flushing run was completed for Luang Prabang reservoir).


Pak Beng reservoir
(smoothened bed-level sedimentation/erosion)
Bed-level difference (m)
1
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
160
140
120
100
80
60
40
20
0
-20
Distance from dam (km)
Dam
Sedimentation
Erosion
Without dam
With dam, 3 years
With dam, 5 years
With dam, 7 years


Luang Prabang reservoir
(smoothened bed-level sedimentation/erosion)
Bed-level difference (m)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
140
120
100
80
60
40
20
0
-20
Distance from dam (km)
Dam
Sedimentation
Erosion
Without dam
With dam, 3 years
With dam, 5 years
With dam, 7 years


Xayaburi reservoir
(smoothened bed-level sedimentation/erosion)
Bed-level difference (m)
1
0.5
0
-0.5
-1
-1.5
130 120 110 100 90 80 70 60 50 40 30 20 10 0 -10
Distance from dam (km)
Dam
Luang Prabang
Without dam
With dam, 3 years
With dam, 5 years
With dam, 7 years
Sedimentation
Erosion


Pak Lay reservoir
(smoothened bed-level sedimentation/erosion)
Bed-level difference (m)
0.8
0.6
0.4
0.2
0
-0.2
-0.4
-0.6
-0.8
120 110 100 90 80 70 60 50 40 30 20 10 0 -10
Distance from dam (km)
Dam
Without dam
With dam, 3 years
With dam, 5 years
With dam, 7 years
Sedimentation
Erpsion

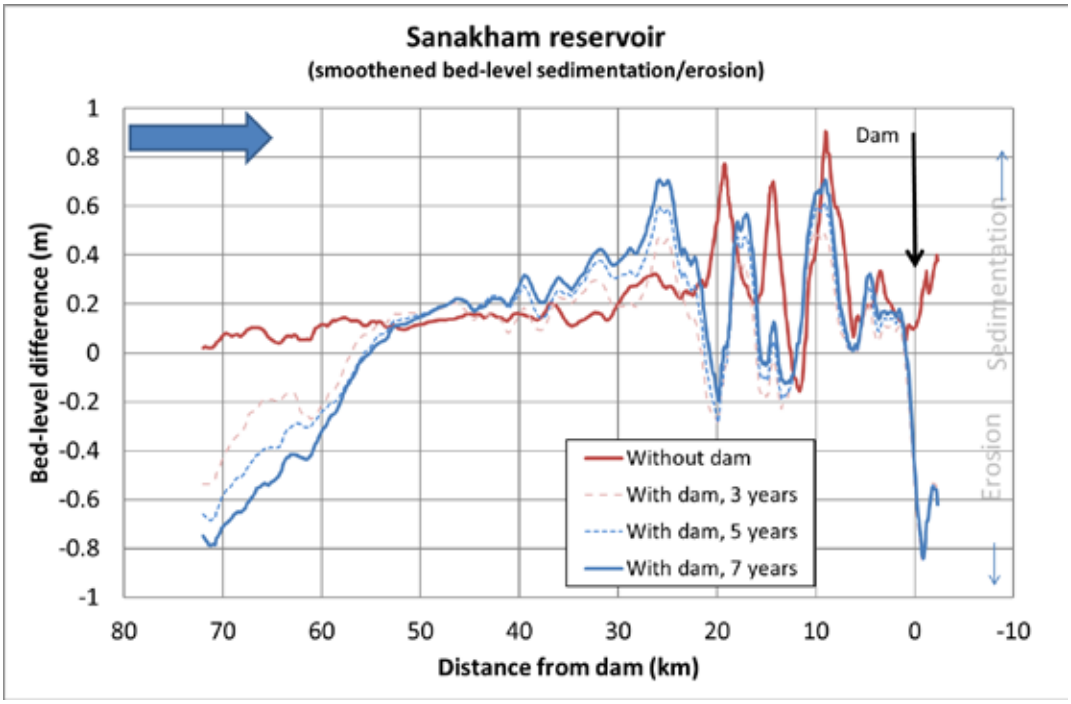


Figure 5.36. *Changes to bed elevation in the five reservoirs under Scenario 1.1. X axis=distance upstream from dam wall with the dam located at '0', y axis = change to bed level. Model results are smoothed over a distance of ~0.7 km.*

The model has also been used to examine the distribution of sediment deposition and erosion within the river channel, and shows that the distribution of sediments in the reservoirs is not uniform, with deposits commonly forming lateral bars along the original river channel. Similarly, downstream of dams, erosion is concentrated on outside bends, consistent with higher channel shear stress and low sediment concentrations in these locations.

The longitudinal distribution of coarse, medium and fine sand within the Pak Beng reservoir (Figure 5.37) demonstrates that finer material is deposited farther downstream as compared to coarse sediment, but most material is trapped in the upper half of the reservoir over the 7-years of the model run.

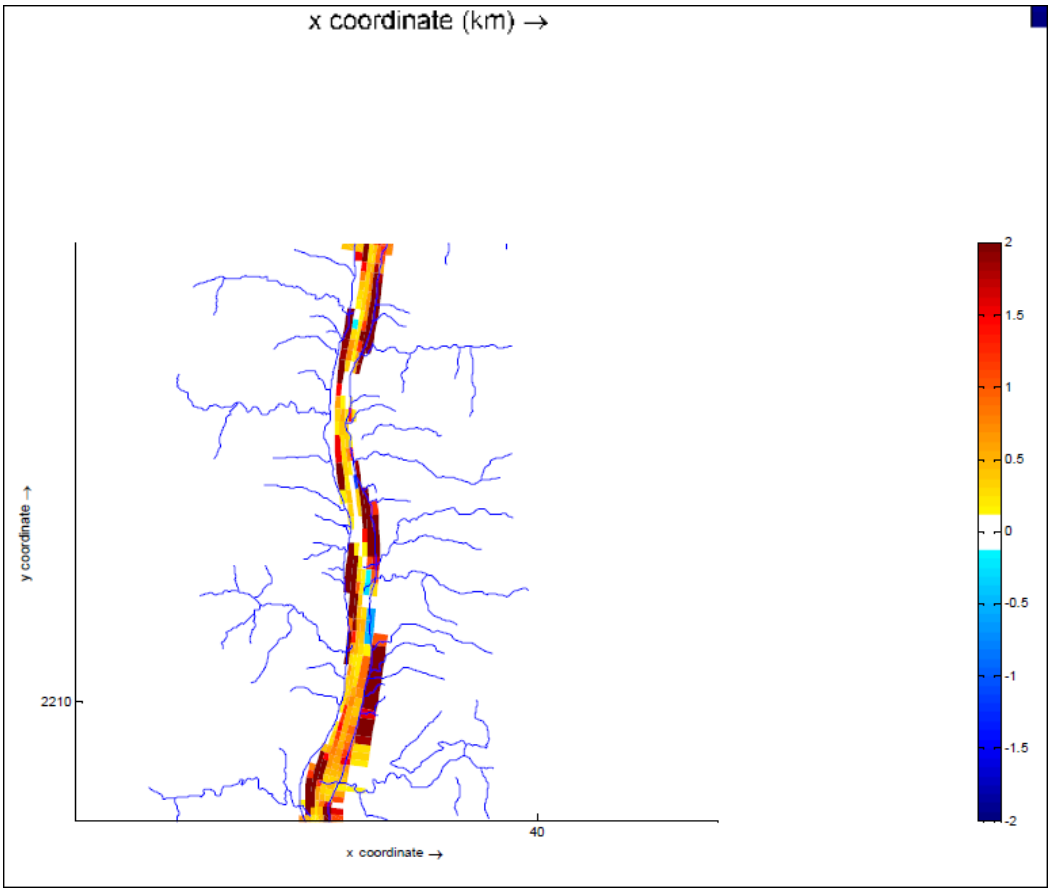


Figure 5.37. *Distribution of sediment deposition within the Pak Beng reservoir. Colour bar shows deposition (red) and erosion (blue) in m.*

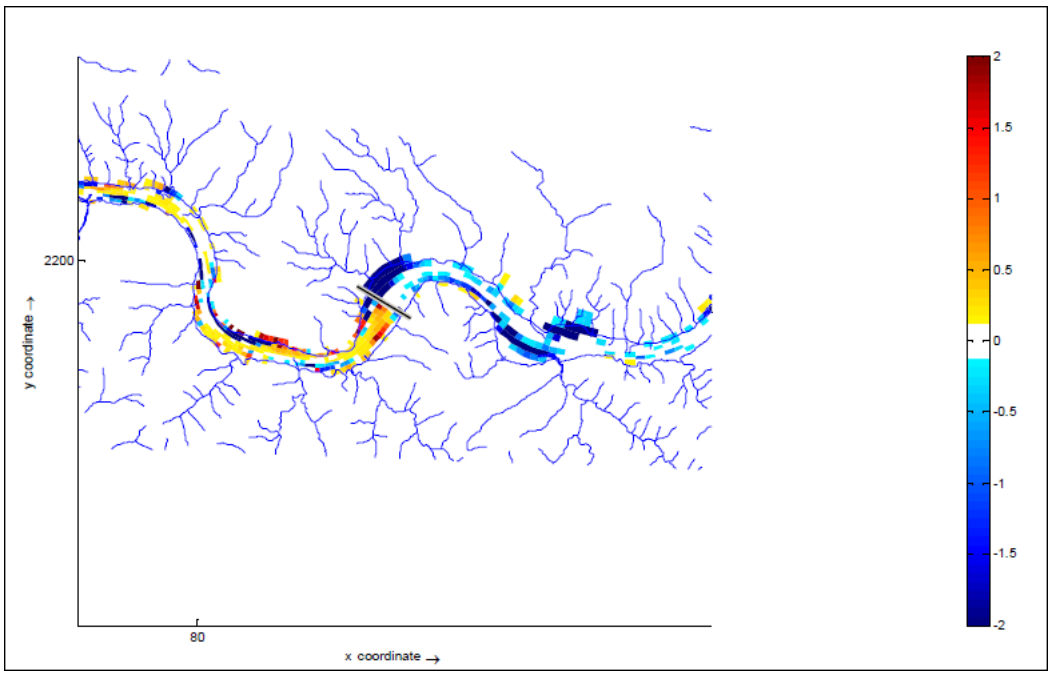


Figure 5.38. *Bed elevation changes in the vicinity of Pak Beng dam, showing deposition upstream of the dam and erosion on outside bends downstream.*

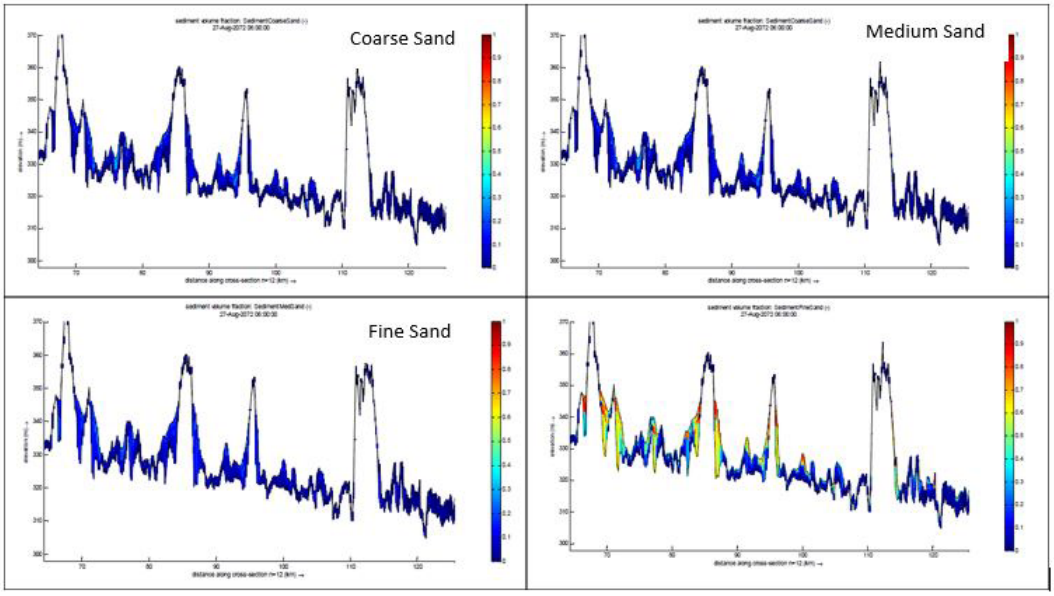


Figure 5.39. *Distribution of coarse, medium and fine sand deposited in Pak Beng reservoir under scenario 1.1. Colour scale indicates depth of deposition.*

Rates of channel changes

The annualised rate of reservoir sedimentation is shown in table 5.12 for the BDP 2030 Reference Scenario and Scenario 1.1 for each of the impoundments. Net deposition occurs within the top three impoundments under both of the Scenarios, but rates are higher with the cascade in place, especially in the Pak Beng reservoir due to the larger influx of sediments from upstream. In the Pak Lay reservoir, erosion is recorded under the BDP scenario, likely due to the large reduction in sediment associated with the Lancang cascade and increased trapping of sediments in tributary dams, but deposition is recorded in Scenario 1.1. In Sanakham, sedimentation decreases in Scenario 1.1 relative to the BDP 2030 reference case, presumably because the sediment trapping upstream is diminishing the input of sediments to the final impoundment.

Table 5.12. Changes to reservoir volumes based on bed elevation differences associated with sedimentation and erosion.

Volume changes based on bed elevation changes	BDP 2030	Scenario 1.1	Net Change
Changes to bed elevation within Pakbeng + = deposition -= erosion	+2.1 Mm3/yr	+6.6 Mm3 /yr	+4.5 Mm3/yr
Changes to bed elevation within Luang Prabang	+0.24 Mm3/yr	+0.36 Mm3 /yr	+0.12 Mm3/yr
Changes to bed elevation within Xayaburi	+0.16 Mm3/yr	+0.60 Mm3/yr	+0.45 Mm3/yr
Changes to bed elevation within Paklay	-0.45 Mm3/yr	+0.63 Mm3/yr	+0.98 Mm3/yr
Changes to bed elevation within Sanakham	+1.9 Mm3/yr	+0.32 Mm3/yr	-1.58 Mm3/yr

5.3.2.3.2 Scenario 1.2 Effect of sediment flushing on channel changes

Sediment flushing is an effective mitigation measure for retaining reservoir volume as well as providing a pulse of sediment to the downstream environment. Sediment flushing affects reservoir volume through the progressive removal of material starting at the upstream end of the impoundment (Figure 5.40). As water levels decrease in the upstream area, shear stress increases and scours material. The changes to the reservoir volume are completed within the first half of the sediment flushing event. As the draw down progresses, the increase in shear stress moves downstream, and more material is eroded and transported. In the example in figure 5.40, there is an increase in sediment deposition near the dam wall at the end of the simulation, which is derived from upstream and will be available for transport during the next flushing event.

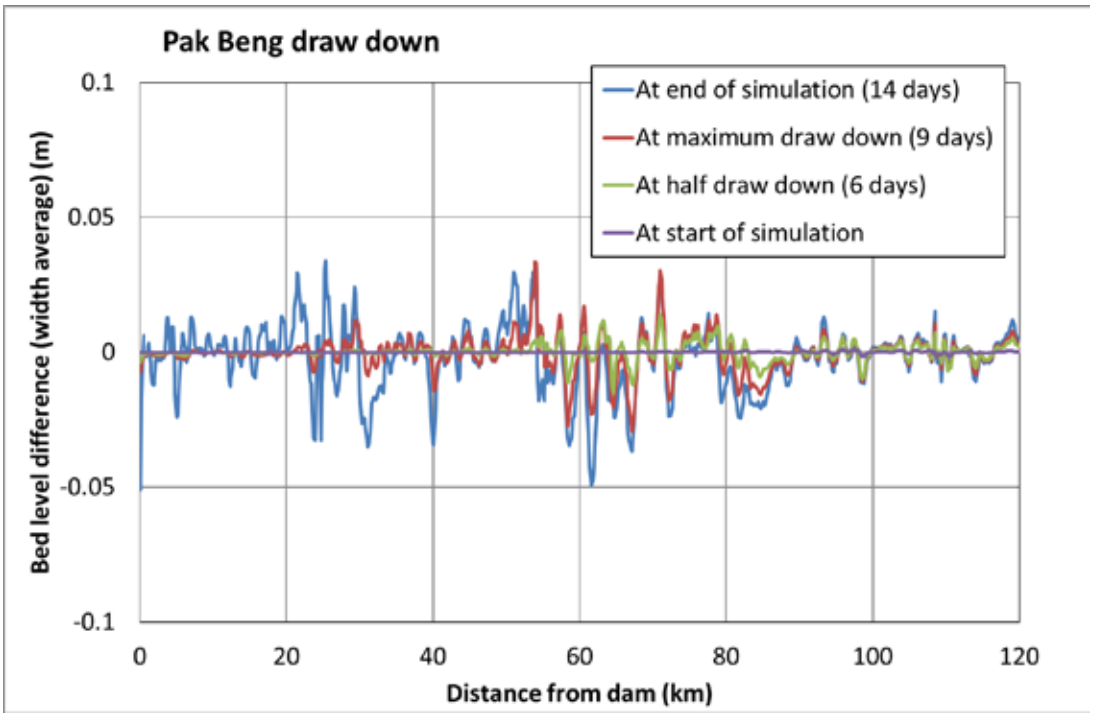


Figure 5.40. *Reservoir volume changes during a 14 day flushing event at Pak Beng.*

The potential effect of sediment flushing (Scenario 1.2) on reservoir volume is summarised in table 5.13. The volume balance is in good agreement at the upstream end of the cascade, with the volume of sediment entering Pak Beng and Luang Prabang, being about equivalent to what is retained in the impoundment, and being discharged. In the lower three impoundments, tributary inflows increase sediment outflow volumes relative to the inflows and what is being retained. In this 'volume balance' the sediment mobilised during flushing ***at Pak Beng is small compared to the sediment being trapped in the reservoir, but at the downstream impoundments, where sediment inflows are very low, the maximum flushed volumes are similar in magnitude to the volume that is being trapped on an annual basis.*** It must be recognised that much of the sediment that is being trapped is coarse grained, whereas sediment that is readily flushed is fine grained, so not all material will be flushed with the same efficiency.

Table 5.13. Comparison of sediment volumes entering each reservoir, changes to sediment volume within the reservoir, and volumes associated with flushing events.

Location	Sediment Load Mm3/yr	Change to Reservoir Volume Mm3/yr	Range of Sediment Loads Discharged during Flushing Event (Mm3)
Entering Pak Beng	7.32		
Pak Beng Dam-Out	1.62	+6.6	0.04 – 0.29
Luang Prabang Dam-Out	1.4	+0.36	No Flushing Runs
Xayabouri-Out	2.1	+0.60	0.26 – 0.47
Pak Lay-Out	2.3	+0.63	0.10 – 0.91
Sanakham-Out	3.6	+0.32	0.04 – 0.50

5.3.2.3.3 Channel changes downstream of the Cascade Reach (Zone 2 and 3)

Changes to channel fill from the Sanakham dam site to Paksane were modelled for the BDP 2030 Reference Scenario and Scenario 1.1. Each scenario was run from the same starting condition with respect to channel fill for a period 7 years. The results are presented as changes in channel fill for each scenario (Figure 5.41), and as relative changes in bed level between the scenarios (Figure 5.42). The results are presented as a longitudinal profile from the Sanakham dam site (km 0) to upstream of Paksane. Both scenarios recorded areas of erosion in the 100 km of river channel downstream of the cascade, with changes decreasing with distance downstream. The results are consistent with sediment starvation associated with the BDP 2030 Reference Scenario causing an erosional 'wave' moving downstream. The higher erosion associated with Scenario 1.1 is attributable to the additional sediment capture associated with the cascade, including the trapping of tributary sediments entering downstream of the Lancang cascade and Sanakham.

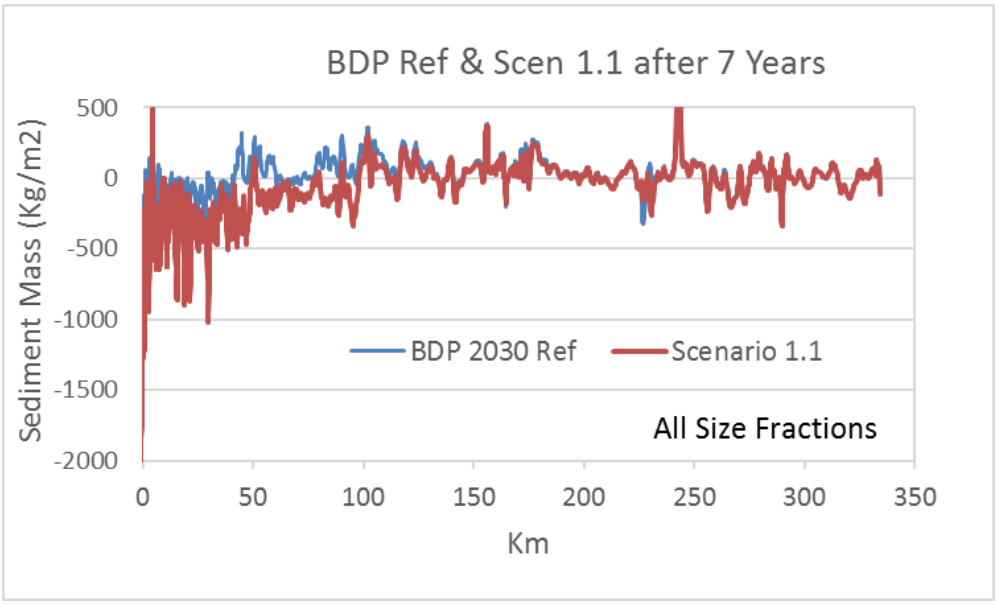


Figure 5.41. *Changes in channel fill for the reach downstream of Sanakham and upstream of Paksane.*

The net change after 7 years between the two scenarios (Figure 5.42) shows that erosion is increasing the channel depth in the upstream reach over time, and progressing downstream. After 7 years the difference between the two scenarios is restricted to upstream of Vientiane, suggesting the 'erosional wave' has yet to progress that far downstream.

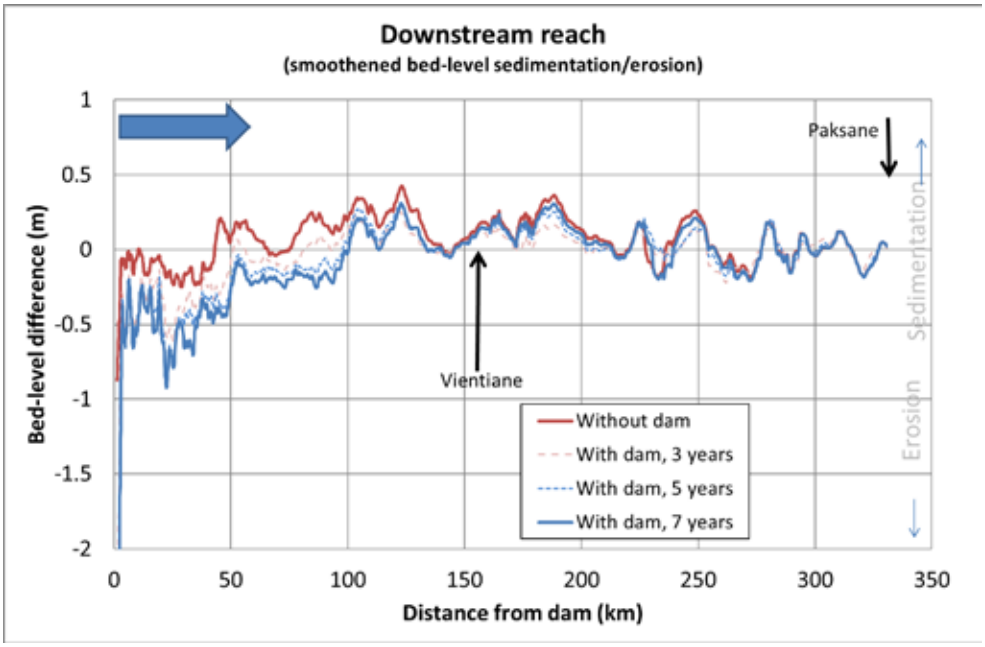


Figure 5.42. *Output of sediment model showing bed level changes without the dam, and at 3, 5 and 7 years after implementation.*

The differences between the two runs with respect to changes in channel fill are summarised in Table 5.14 in the same format as provided in Table 5.12 for the impoundments and shows the magnitude of increased erosion over the reach between the two scenarios.

Table 5.14. Summary of bed level changes between Sanakham and Paksane.

Volume changes based on bed elevation changes	BDP 2030	Scenario 1.1	Net Change
Changes to bed elevation between Sanakham and Paksane	+6.2 Mm3/yr	-2.8m3/yr	-9.0 Mm3/yr

In figure 5.43, the changes in channel fill are shown for all sediment fractions, and for coarser material (gravel + coarse sand + medium sand), fine-sand and silt and clay. The greatest differences between the scenarios occur in the upstream 100 km of the reach, where overall sediment removal is the greatest as well. With respect to changes in the grain-size distribution of sediment present in the channel, ***the coarser fractions and fine sand size-fractions show the largest decrease in Scenario 1.1 compared to the BDP 2030 Reference, with silt and clay showing virtually no change between the two scenarios.*** This is consistent with the coarser sediment fractions being trapped in the cascade, as previously presented and discussed.

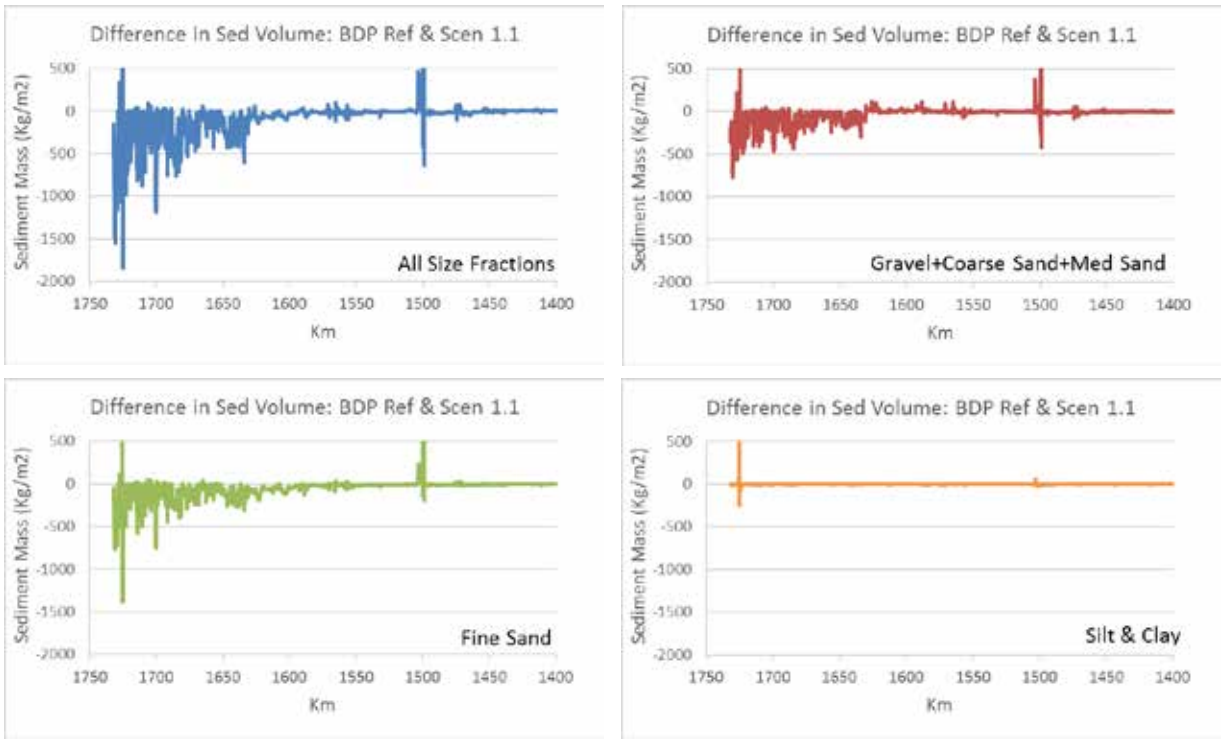


Figure 5.43. *Changes to sediment volumes in the river channel downstream of Sanakham dam site (km 1737) and upstream of Paksane (km 1395). Vientiane at km 1583 and Nong Khai at km 1550.*

The average change in sediment over the reach by 100 km intervals is summarised in Figure 5.44 and Table 5.15, and demonstrates that the direction of change is similar in both the BDP 2030 Reference and Scenario 1.1, however, the magnitude of erosion is greater, and magnitude of deposition is less in Scenario 1.1 as compared to the BDP 2030. Under either scenario, it is highly likely that the erosional 'wave' will continue to progress downstream, with the largest difference between the scenarios likely to be the rate of movement of the 'wave'.

These trends demonstrate that implementation of the Lao cascade will increase the rate of erosion in the downstream river channel. The cascade will hasten the impact of the Lancang cascade by effectively removing the buffering potential of the sediment located within the cascade reach. That is, in the absence of the cascade, the erosion the sediment within the cascade will increase sediment loads downstream, and reduce the impact of the Lancang Cascade whilst sediments remain available for transport. Once the cascade is established, the potential for the sediments in the river channel to be transported downstream is greatly reduced, thus reducing the time until the (cumulative) impacts of the Lancang and northern Laos cascades extend downstream. Whether the ultimate 'end point' on the scale of decades to centuries will be different between the two scenarios (with and without the Laos cascade) is difficult to assess.

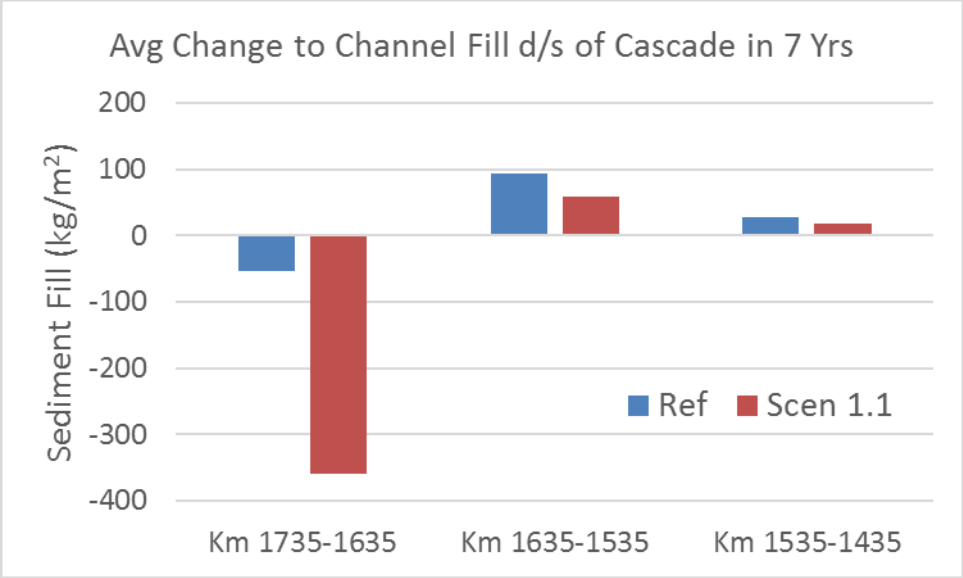


Figure 5.44. *Average change to channel fill downstream of Sanakham dam site over 7 years. Results grouped by 100 km section of river channel.*

Table 5.15. Annualised changes to sediment mass/m2/yr in three sections of the river downstream of Sanakham.

Changes to sediment mass downstream of cascade to Paksane		BDP 2030	Scenario 1.1	Net Change
Changes to volume of sediment downstream of cascade to Paksane	Km 1735 - 1635 Km1635 - 1535 Km 1535 - 1435	-7.7 kg/m2/yr +13.4 kg/m2/yr +4.0 kg/m2/yr	-51.0 kg/m2/yr +8.3kg/m2/yr +2.5kg/m2/yr	-43.3 kg/m2/yr -5.1 kg/m2/yr -1.5 kg/m2/yr

5.3.2.4 Geomorphic Indicator – Deep Pools

Deep pools provide important habitat and refuge for aquatic systems (see also chapter 5.5), and are maintained by the balance between the timing and magnitude of sediment delivery and the timing and magnitude of flow (shear stress). Based on the hydrologic and sediment model results, the following is projected to occur to deep pools in the various reaches of the river:

- **Cascade reach (Zone 1):** Within most of the cascade reach, sedimentation increases and water velocity decreases after development of the cascade. ***These changes will promote sedimentation and eventual filling of the deep pools.*** Examples of sedimentation within reservoirs showing in-filling of deep pools are portrayed in figure 5.45. The rate of filling will depend on the sediment load entering each impoundment, and the location of the deep pool within the impoundment, for example, pools located within the Pak Beng reservoir would be expected to fill more rapidly as compared to pools in the Luang Prabang impoundment due to higher sediment loads in the upstream impoundment. There are some limited areas, notably the river reach between the Luang Prabang Dam and the head of the Xayaburi reservoir where the river will not be impounded and pools in these areas are likely to be maintained, especially as sediment loads from tributaries decrease due to capture in tributary dams. The upper reaches of the Sanakham reservoir is another area that is projected to experience erosion, which may maintain pools;

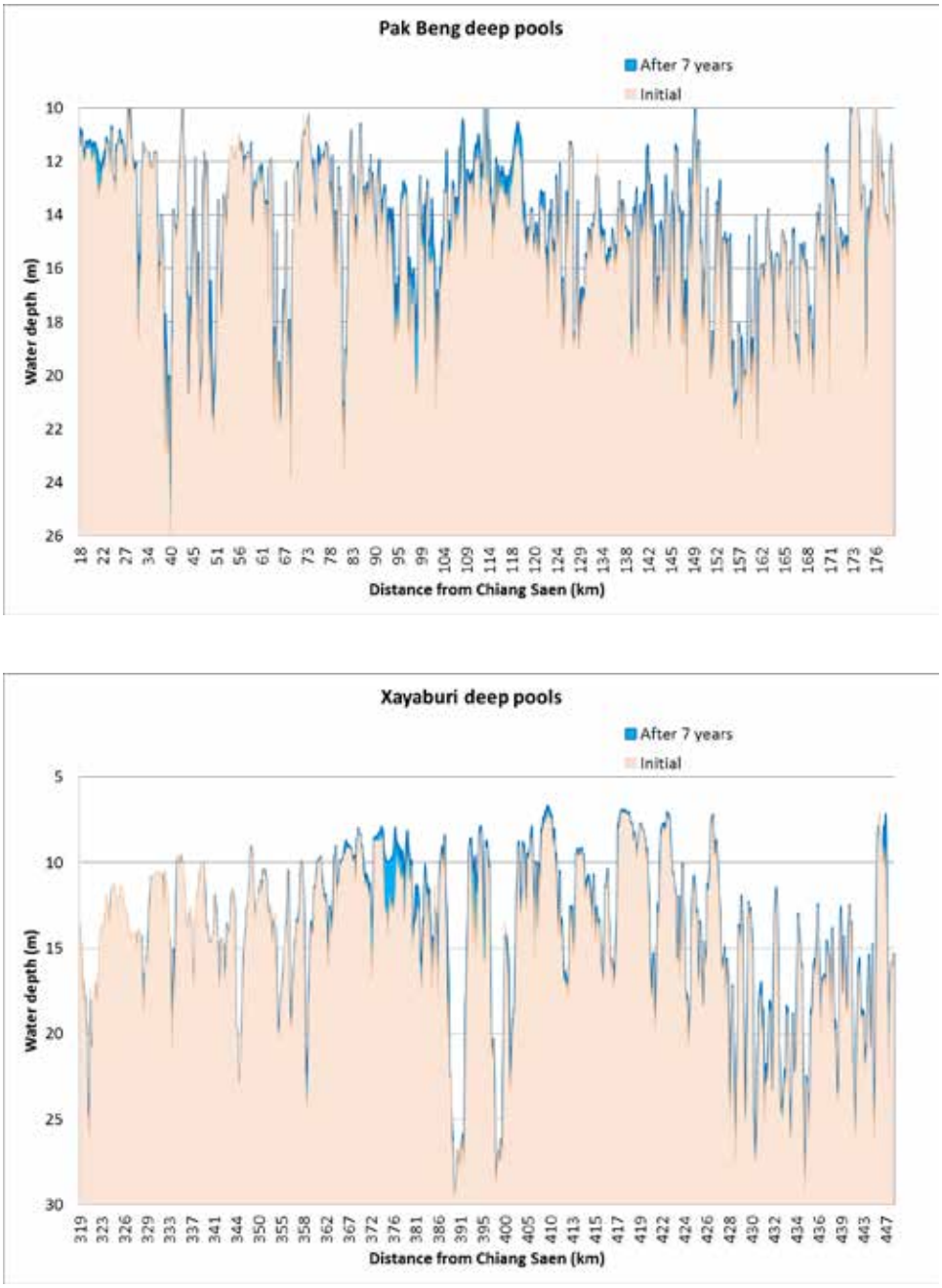


Figure 5.45. *Examples of deposition in impoundments after 7-years, showing in-filling of deep pools.*

- **Sanakham to Paksane reach (Zone 2):** Model results within this reach suggest that deep pools will be maintained (Figure 5.46). This is based on a reduction in sediment loads entering from the cascade reach, but little change in the seasonal hydrology of the river. The high shear stress associated with flood flows will maintain existing pools, and promote the erosional wave progressing downstream. ***Overtime, pools in this reach may deepen (if not constrained by bedrock) owing to the long-term reduction in sediment loads;***

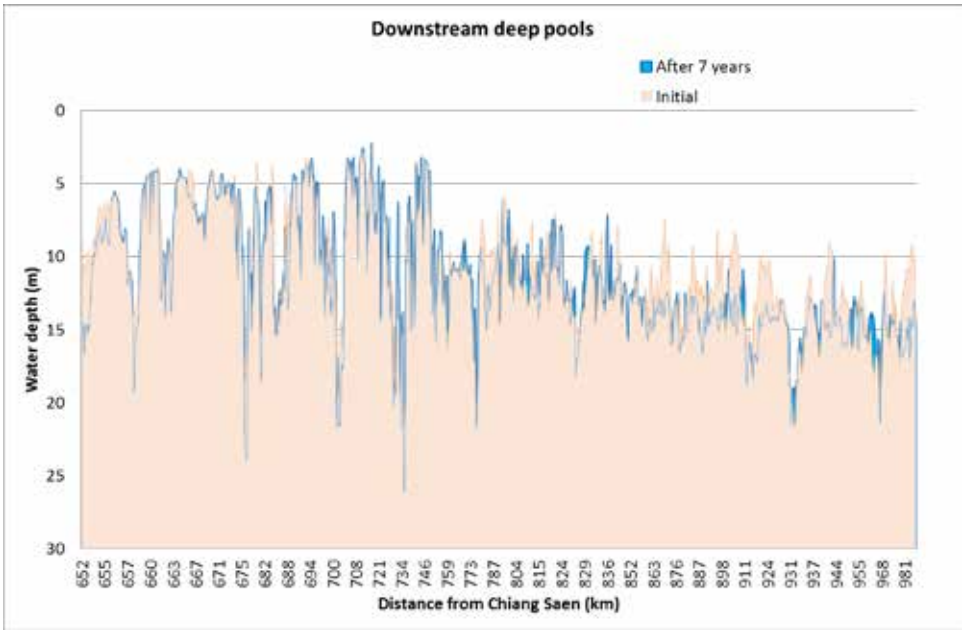


Figure 5.46. *Deposition and erosion downstream of Sanakham after 7-years of cascade operations.*

- **Downstream of Paksane (Zone 3):** Over the long term, deep pools downstream of Paksane will experience a decrease in sediment supply but little change to the timing or magnitude of peak flood flows that are required for maintenance of the pools. ***This could promote a deepening of pools that are not constrained by bedrock, and / or reduce the quantity of sediment that accumulates in pools during the dry season.*** Pools in this reach will also be affected by tributary dams and other water resource developments, such as irrigation and sand mining.

The indicators for deep pools are based on the modelling results, but considered qualitative as no magnitude of the degree of deposition or erosion in the deep pools has been extracted from the model results. In the final indicator table in Annex F, arrows indicating an increase (↑) or decrease (↓) in depth of pools have been assigned to the scenarios. ***There is no difference in the indicator score for deep pools between the three mains scenarios.***

5.3.2.5 Geomorphic Indicator – Rapids

Rapids are important for fish, providing areas for spawning and feeding (see also Chapter 5.5). They also contain a mosaic of hydraulic conditions that support a huge range of vegetation types. The implementation of the cascade will alter the distribution and quality of rapids in the following ways:

- ***Cascade reach (Zone 1):*** In the cascade reach, ***the great majority of rapids will be inundated, and cease to exist.*** Short bedrock reaches downstream of dams may continue to be covered by shallow, rapidly moving water and remain as rapid-habitat. In these areas, some additional bedrock may be exposed due to erosion of overlying sediments and also provide rapid-habitat. Rapids present within the reach downstream of the Luang Prabang dam and upstream of the tail water of the Xayaburi impoundment will also remain;
- ***Sanakham to Paksane (Zone 2): Rapids in this reach are projected to remain, and may increase in occurrence as sediment is removed from the channel.*** As the sediment is removed, vegetation communities that are associated with rapids may decrease, which would alter the overall characteristics of the habitat;
- ***Downstream of Paksane (Zone 3):*** In the short term, rapids downstream of Paksane are unlikely to be affected by the operation of the cascade. Over the long term, as sediment supply decreases, exposed bedrock and rapids may increase, but this is dependent on other land use and catchment activities as well as the upstream cascade.

5.3.2.6 Long-term trends in Channel Changes and Sediment Loads

Sediment transport in the LMB is in a state of change, and will continue to change into the future with or without the development of the norther Laos Cascade due to the operation of the Lancang Cascade, tributary dams and other land use and catchment activities. The sediment modelling results have provided information about a wide range of sediment processes over a 7-year time frame. The model has also been used to investigate changes over longer time frames with respect to bed level changes within the Pak Beng reservoir and in the downstream reach between Sanakham and Paksane.

The continued deposition of material and the progressive deposition of material closer to the dam wall is evident in the Pak Beng model results (Figure 5.47). Between years 10 and 28, the delta 'front' progresses approximately 30 km downstream, where as it only moved about 10 km in the first 10 years of the impoundment's life. The profiles also suggest that the upstream extent of the reservoir alters from an area of erosion to deposition in years 20 to 28. Under these conditions of sediment deposition, it is likely that sediment flushing could mobilise a higher sediment load as compared to the scenario after only 7 years. The transect suggests that there is a constriction or other feature that is affecting the hydraulics of the system and preventing the movement of sediment downstream at about 20 km upstream of the dam. In this location, the channel is narrow and characterised by numerous deep pools and bends. These features may be creating a localised backwater that is trapping sediment.

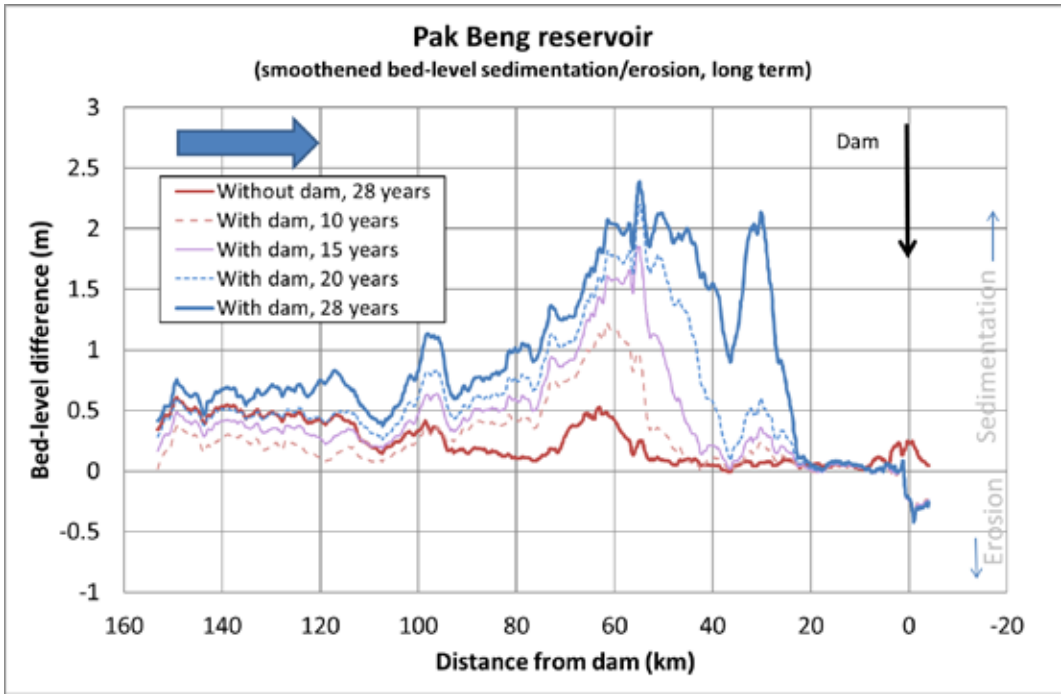


Figure 5.47. *Bed level changes in the Pak Beng reservoir from years 10 to 28 of the cascade.*

The longer model runs for the reach between Sanakham and Paksane show similar processes as captured in the 7-year run, and demonstrate the downstream progression of the sediment wave. Differences in bed level changes now extend well downstream of Vientiane, but have yet to reach Paksane. Net changes between the scenarios range up to 1 m, attributable to deposition BDP 2030 scenario and erosion in Scenario 1.1.

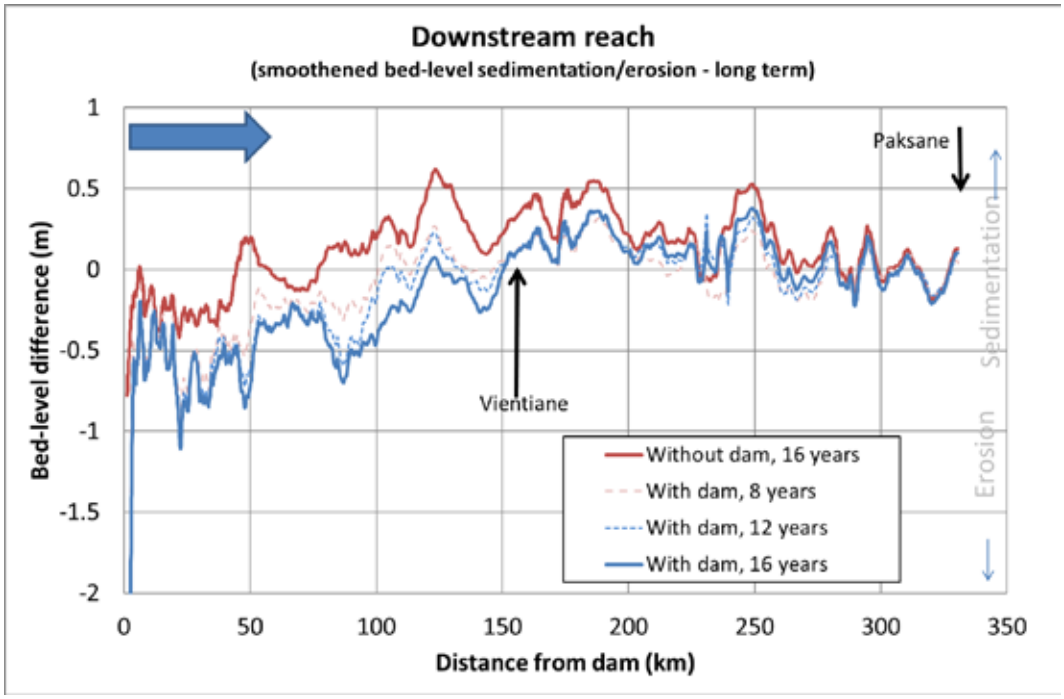


Figure 5.48. *Differences in bed level changes in the downstream reach.*

The sediment output from the model after 7 and 16 years is compared for sediment load and grain-size distribution in Table 5.16, and shows that there is overall little change in the output from the Sanakham dam or sediment discharge at Paksane between the two time periods. The lack of change at Paksane is attributable to sediment still being available for transport in the upstream reach as the erosional wave has yet to reach Paksane. If the same rate of progression between years 7 and 16 is assumed, the sediment load at Paksane would be expected to decrease in the following 10 years as the sediment supply becomes exhausted.

Table 5.16. Sediment loads and grain-size distribution at Sanakham and Paksane after 7 and 16 years based on model output.

Indicator	Scen 0.2 BDP 2030	Scen 1.1 Run of Riv
Annual Sediment Load at Sanakham Dam site Km 1737 **AFTER 7 YEARS**	**21.3 Mt/yr** Gr: 1% C Sand: 5% M Sand 16% F Sand: 59% Silt+Clay: 20%	**6.0 Mt/yr** Gr: <1% C Sand: 1% M Sand: 3% F Sand: 12% Silt+Clay: 84%
Annual Sediment Load at Sanakham Dam site Km 1737 AFTER 16 YEARS	**22.9 Mt/yr** Gr: <1% C Sand: 5% M Sand 16% F Sand: 59% Silt+Clay: 29%	**6.0 Mt/yr** Gr: <1% C Sand: 1% M Sand: 3% F Sand: 14% Silt+Clay: 82%
Annual Sediment Load at Paksane **AFTER 7 YEARS**	**18.3 Mt/yr** Gr: 1% C Sand: 4% M Sand 14% F Sand: 22% Silt+Clay: 60%	**18.5 Mt/yr** Gr: 1% C Sand: 4% M Sand 14% F Sand: 22% Silt+, Clay: 60%
Annual Sediment Load at Paksane **AFTER 16 YEARS**	**15.6 Mt/yr** Gr: 1% C Sand: 5% M Sand 16% F Sand: 34% Silt+Clay: 45%	**15.1 Mt/yr** Gr: 1% C Sand: 5% M Sand 17% F Sand: 31% Silt+, Clay: 47%

The indicators in the main indicator table (Annex F) reflect conditions after the first 7 years of cascade operation. Indicators that are likely to change over the longer term include:

- Sediment load entering the Pak Beng reservoir: This is expected to decrease due to increased trapping in reservoirs and the depletion of the in channel sediment source downstream of the Lancang cascade;
- Sediment trapping in reservoirs will change as the sediment load diminishes and changes composition;
- Erosion in the Sanakham to Paksane reach will increase over time as the sediment supply is depleted.

5.3.2.6.1 Value of sediment in multi-criteria assessment

The 'value' of the sediment trapped within the cascade and / or mobilised during sediment flushing is included as an indicator in the multi-criteria analysis. This value is restricted to a monetary value in the analysis, and is based on the price of gravel, sand and clay as construction materials. This approach is consistent with the ISH02 economic evaluation methodology that limits the 'value' to quantifiable economic commodities.

This approach may not capture the true value of sediment due to the long time frames associated with geomorphic change. For example, sediment removal is likely to increase bank instability and collapse over long periods, and the costs associated with bank stabilisation works or loss of infrastructure is not captured or reflected in the 'value' of the sediment being removed on an annual basis. Some of the other economic values of sediment that need to be considered include:

- Maintenance of channel stability which is important for navigation and other infra structure;
- Maintenance of floodplains and river banks which are used for agriculture, including the provision of 'free' nutrients;
- Maintenance of the quality and distribution of ecological habitats and food webs;

5.4 Water Quality Impact Mitigation

5.4.1 General

The ISH0306 investigations have not included specific water quality mitigation measures or water quality modelling e. Instead, a risk based approach has been adopted to identify potential water quality issues associated with each of the scenarios based on the physical changes identified through the modelling work. Where appropriate the potential to mitigate any identified changes based on the infrastructure and operating pattern of the cascade have also been evaluated.

As noted in the Methodology section of this report, there are many other indicators that are relevant to water quality within and downstream of hydropower impoundments, including nutrients, dissolved oxygen, and metals. These have not been considered in the Case Study due to a lack of input data for the model, and the relatively short time available for the Case Study exercise.

The water quality risks arising from the physical changes associated with implementation of the cascade include the following:

- Increased residence time in the river reach promoting increased water temperatures during the dry season and promoting algal blooms (Indicator = Residence time);
- Reduction in water velocities through the reach promoting deposition of sediments and promoting algal blooms (Indicator = water velocity <0.4 m/s);
- Reduction in suspended material and increased light penetration promoting algal growth (Indicator = Water clarity);
- Changes to nutrient discharge due to sediment trapping within the impoundment (Indicator = suspended sediment surface area);
- Thermal stratification leading to low levels of dissolved oxygen in bottom water and discharge waters (Indicator = Residence time);

- Nutrient and metal release from sediments under changing oxygen regimes (Indicator = risk of stratification).

The first three indicators are associated with the risk of algal bloom and are considered collectively. It is also important to recognise the water quality changes and trends that are inherent in the BDP 2030 reference condition and directly affect future changes to water quality in the cascade.

5.4.2 Changes to water quality in absence of cascade

Water quality changes associated with the BDP 2030 Reference Scenario without a mainstream cascade have already included or are likely to include the following:

Increased water clarity due to the large reduction in suspended sediment concentrations from sediment trapping in the Lancang Cascade and tributary dams. The large reduction in suspended sediment concentrations (Figure 5.49) associated with development in the UMB has reduced median suspended sediment concentrations to <100 mg/L for 6-months of the year (2009 – 2013) as compared to 2-3 months of the year prior to 1993. This decrease allows greater light penetration into the water column, and could contribute to increased algal activity during periods of low river flow.

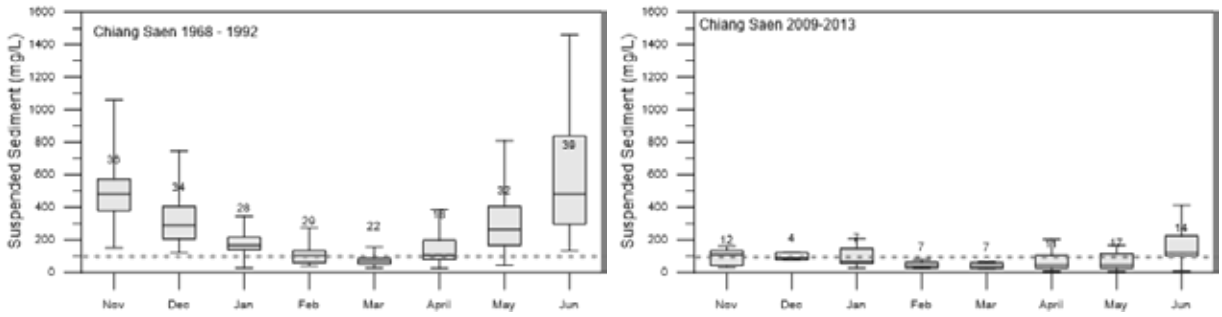


Figure 5.49. *Comparison of suspend sediment concentrations at Chiang Saen during the dry season in 1968 to 1992, and in 2009 to 2013.*

Changes to water temperature due to storage in the mainstream UMB dams and the tributary dams. Water temperatures are altered during storage in dams. Large impoundments that can store water on an inter-seasonal basis have the potential to alter water quality downstream through the release seasonally warmer or colder water. Even small impoundments can alter water temperature through increased warming during storage in the dry season.

Other changes to water quality during storage. The large number of tributary dams included in the BDP 2030 Reference scenario has the potential to alter water quality through chemical changes associated with impoundments. Decreased oxygen concentrations leading to metal release from sediments or, increased nutrients associated with the decomposition of organic matter in inundation areas are examples of potential changes. Because many of the tributary dams included in the BDP 2030 Scenario are located in close proximity to the mainstream Mekong, there is a high potential for these water quality changes to impact on mainstream water quality.

Increased run-off of nutrients, pesticides and herbicides from increased and changing agricultural and other land use practices in the UMB and LMB as activities expands and intensify. As an example, in northern Lao PDR there has been a large expansion in banana plantations near the Mekong River over the past decade. The establishment and management of these and other agricultural activities have the potential to increase run off into river systems. The expansion of irrigation schemes that enable intensification of agriculture can also contribute to the run-off of nutrients and chemicals into water ways.

Figure 5.50. *Photo of banana plantations near the Mekong River upstream of Xayaburi. Photo obtained in November 2015.*

Increased municipal discharge and runoff from urban areas as populations increase. The LMB region in general is experiencing increases in urban populations that will increase the discharge of sewage and urban run-off into waterways.

5.4.3 Lao Cascade – Local and Cumulative Impacts

5.4.3.1 Increased risk of algal bloom-Cascade Reach (Zone 1) – Scenarios 1.1 and 1.3

The risk of algal blooms is directly related to the physical attributes and hydrology of the cascade. The hydrologic investigations have demonstrated that there is little difference in the hydrology between Scenarios 1.1 and 1.3 so these are considered collectively in the following discussion. Scenario 1.2, sediment flushing, has a low risk of algal blooms due to the high velocity of water moving through the impoundments.

Table 5.17 summarises the physical characteristics of the impoundments in the cascade, and provides ***estimates*** of the pre- and post- dam residence time of water in each river reach. The pre-dam estimates are based on the length of the river channel and the average flow velocity associated with dry (April) and wet (August) seasons derived from MRC discharge monitoring. The post-dam residence times are based on dividing the volume of each impoundment by the average monthly inflows for a dry (April) and a wet (August) month. The 'total' and 'active' volumes for each impoundment are presented in Table 5.17. If an impoundment is completely mixed, then using the total volume for the calculation provides an estimate of the residence time of water. If an impoundment is stratified, and water flows only through the active volume with 'dead' water remaining stationary at depth, then using the active volume is a more accurate determination.

Because the cascade hydropower stations are assumed to have low level intakes, it is likely that there will be a reasonable degree of mixing in the lakes, so the actual residence time of water in the impoundments is likely closer to the total volume calculation rather than the 'active' volume.

In the dry season, the pre-dam residence time of water in the cascade reach is estimated to range from ~1 to ~3 days in each of the impoundments, and about 9 days in the entire reach. After development of the cascade, the dry season residence time is estimated to range from ~9 to ~35 days. In the wet season, the pre-dam residence time ranges from ~0.5 days to ~1.5 days in each reservoir, with a total time of ~5 days. The estimated residence time post-dam ranges from 2 to 7 days. The lower residence time in the wet season for the 'active' volume as compared to the pre-dam scenario is because the 'active' storage only has a depth of 5 m in each reservoir, whereas the depth of the river during the wet season is greater than 5 m (on average). ***These comparisons suggest that during the dry season, there will be a sizeable increase in residence time of water within the cascade reach as compared to the pre-dam scenario, and only a small change during the wet season.***

Table 5.17. Summary of physical characteristics of the northern Lao PDR cascade, and estimated changes to residence time of water in the river reach.

Lake	Total Vol	Active Vol	Length	Residence time pre-dam (Days)		Residence time Post-dam (Days)		Residence time Post dam (Days)	
	Mm3	Mm3	km	Dry	Wet	Dry - Tot Vol	Dry-Active Vol	Wet-Tot Vol	Wet-Active Vol
PB	665	209	183.2	3.1	1.6	5.1	1.6	1.3	0.4
LP	1211	226	137.4	2.3	1.2	9.3	1.7	2.1	0.4
XB	1107	312	127.5	1.6	1.0	7.3	2.1	1.5	0.4
PL	1312	324	117	1.4	0.9	8.4	2.1	1.7	0.4
SK	750	264	75	0.9	0.6	4.8	1.7	1.0	0.3
Total	**5044**	**1335**	**640**	**9.3**	**5.2**	**34.8**	**9.1**	**7.6**	**2.0**

During storage in the dams, water temperatures are likely to increase, due to the increase in surface area of the impoundments, and the increased residence time. This is not only applicable to the mainstream cascade, but to tributary dams as well. An example of increased surface area associated with damming is shown in a Google Earth image (Figure 5.51) that captures an impoundment on the Nam Khan both before and after impoundment, and demonstrates the much larger surface area following damming. Not all impoundments increase surface area by such a large extent; the impoundments in the cascade are projected to individually increase surface areas by between 4% and 60%, with an overall increase over the cascade of ~35%.

An estimate of the potential warming of water whilst in storage is provided by comparing the degree of warming presently occurring within the river in the reach between Chian Saen and Vientiane (Figure 5.51). During the dry months, it is estimated that it takes ~13 days to transit the distance between the sites, and temperatures increase by 4°C to 5°C during that period. It is plausible

that a similar magnitude of warming will occur during storage in the impoundments, with slow moving surface waters potentially increasing by larger amounts locally. This would increase water temperatures earlier in the dry season as compared to the BDP2030 Reference Scenario, and could contribute to increased algal growth.

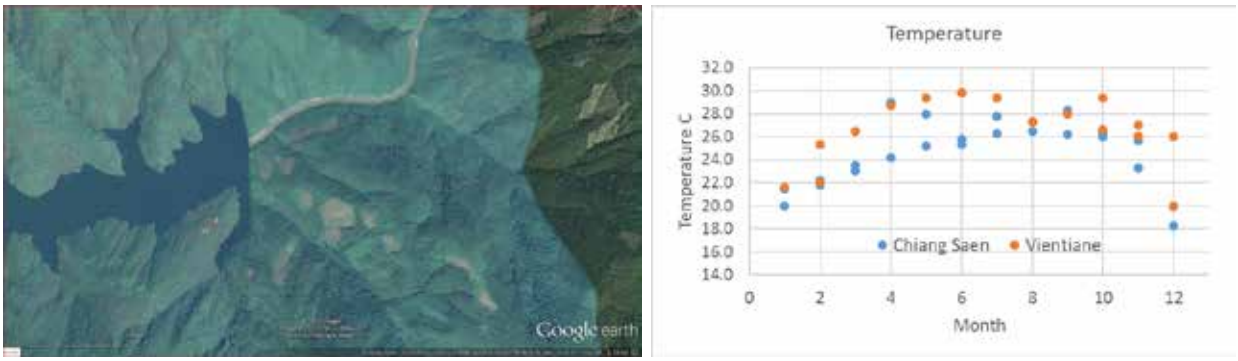
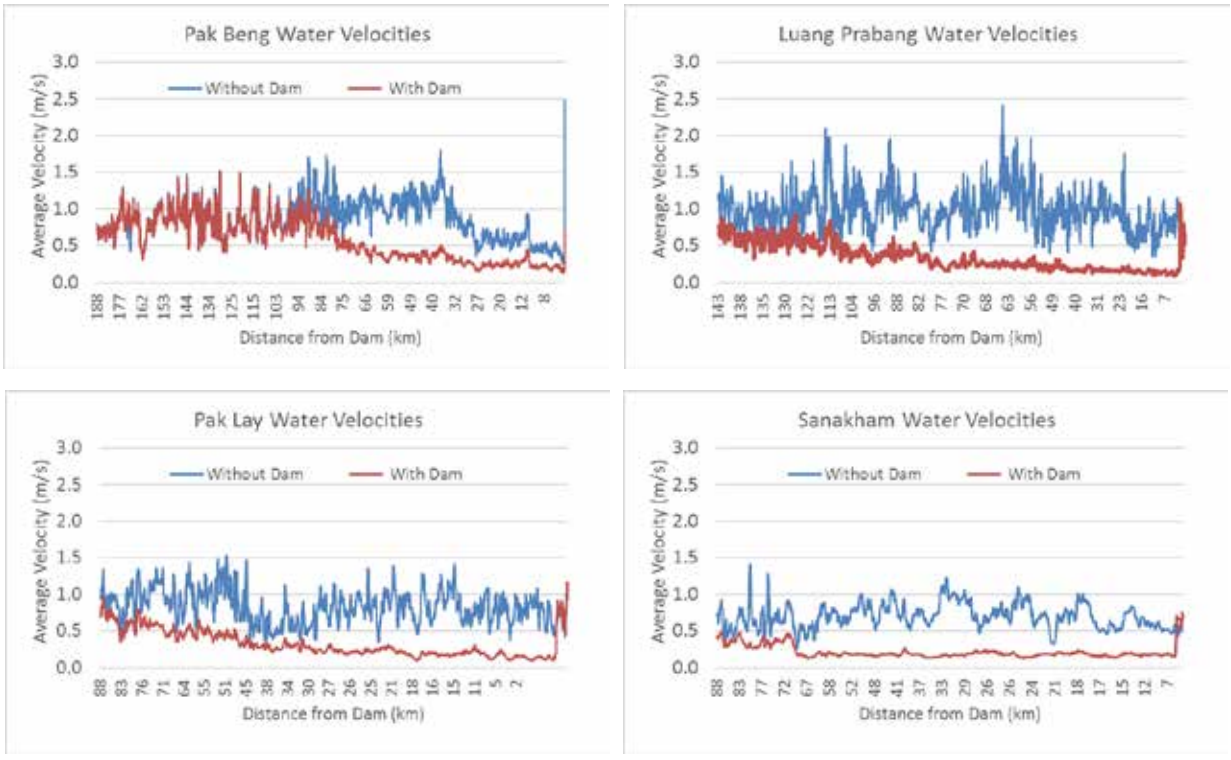


Figure 5.51. *(left) Google Earth image of the Nam Kham river showing increase in water surface area following creation of an impoundment. (right) Monthly water temperature readings from Chiang Saen and Vientiane 2012-2013.*

Water velocities in each of the impoundment reaches will decrease relative to the BDP 2030 pre-dam conditions, with velocities reducing to well below 0.5 m/s during the dry season (Figure 5.52). Modelling investigations into the hydraulic conditions that promote algal blooms have found that the risk of growth increases when water velocities decrease below 0.4 m/s (Huang, 2008). The velocity graphs show that these conditions extend for tens of kilometres with in each of the impoundment. Within the Pak Lay and Sanakham reservoirs, velocities below 0.5 m/s persist for a combined length of >120 km, with the exception of increased velocities at the Pak Lay dam site. As these lakes are the last in the cascade, these low velocities combined with warmer water temperatures could increase the risk blooms and of high algal concentrations being discharged downstream.



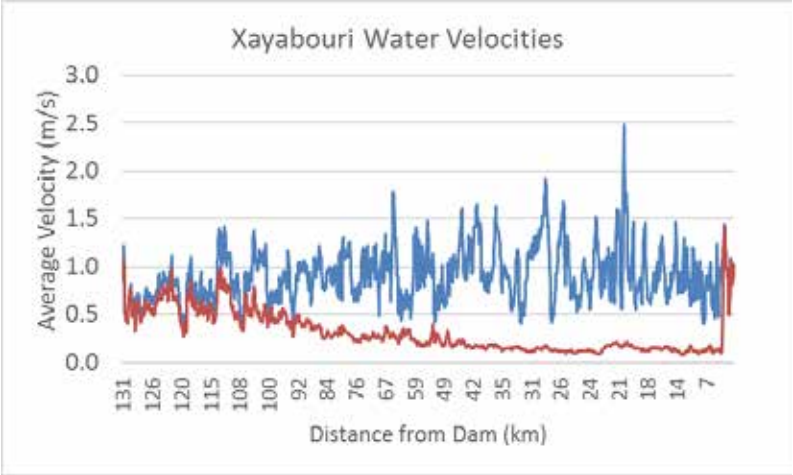


Figure 5.52. *Average velocities in each of the impoundments for the months of Dec - April. Based on cross-sectional averaged velocities from Delft 3D model.*

Light penetration in the cascade will increase due to the reduction in suspended sediments driven by the decrease in flow velocity. The sediment modelling results have shown that silts and clays will be retained in the water column. These size fractions have the largest surface area per unit mass of any sediment fraction and exert the greatest influence on water clarity, so the increase in light penetration will not be directly proportional to the decrease in sediment concentrations. Investigations in northern Thailand by Zeigler et al. (2014) found that turbidity values of 20 to 50 NTU roughly equated to suspended solids concentrations of about 30 to 80 mg/L in rivers in the region. Ecological health monitoring by the MRC has recorded light penetration depths (Secchi) of 0.5 m at turbidity levels of 20 NTU.

Based on this information, it is assumed that light penetration will extend into the water column on days when the average daily suspended sediment concentration falls below 50 mg/L. The number of days this condition is met was determined for each dam site using the daily averaged sediment model results (Figure 5.53). In the BDP2030 Reference scenario, low concentrations occur upstream of Pak Lay 10% to 45% of the time. In the post-dam Scenario 1.1, the low sediment concentrations occur between 68% and 92% of the time. The largest changes are projected to occur in the Pak Lay and Sanakham impoundments, where 'pre-dam' model results suggest sediment concentrations below 50 mg/L will occur ~10% of the time in Pak Lay, and <1% of the time at Sanakham, but increase to ~85 and ~65% of the time under Scenario 1.1.

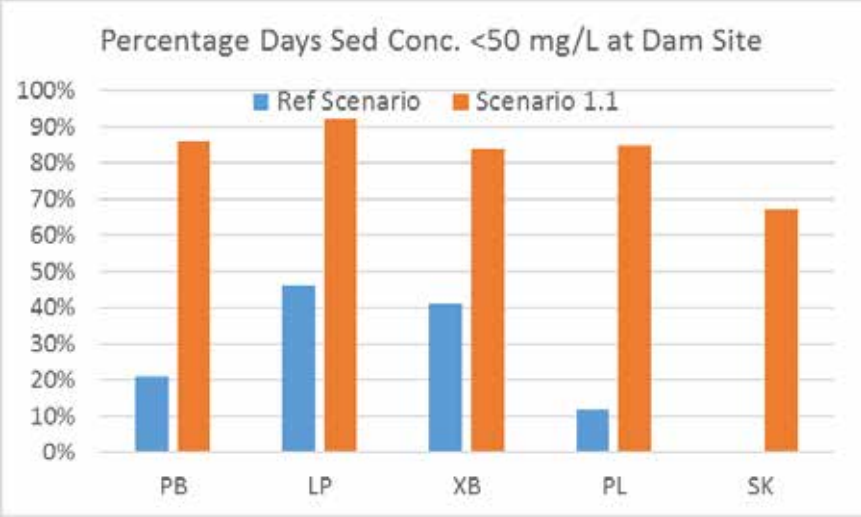


Figure 5.53. *Percentage of days the suspended sediment concentration in the average daily discharge at each of the dam sites was below 50 mg/L based on the results of the sediment model.*

It must be recognised, that in addition to warm, slow moving and relatively clear water, a nutrient supply is required for algal blooms to occur. As discussed in the 'no cascade' scenario, nutrient inputs to the river from agricultural activities are likely increasing due to the expansion and intensification of agricultural activities in the cascade catchment. In addition, hydropower impoundments frequently enable additional water related development (agriculture, aquaculture, industry) that can increase nutrient inputs into impoundments through runoff or discharges.

There is evidence that sufficient nutrients are present in the Mekong to promote algal growth given the right physical conditions based on the presence of an algal bloom 'pond' upstream of the Xayaburi dam in March 2015. This bloom was present even though residence times were low relative to the future operating conditions of the impoundment (water level was 18 m below full supply level), and the water had not been subjected to storage upstream.

Mitigation measures to address algal blooms are largely dependent on catchment management approaches that limit nutrient input to impoundments. In some instances, operating procedures can be used to lessen the severity of bloom events. For example, in the Three Gorges project, algal blooms commonly occur at tributary confluences due to hydraulic changes and elevated nutrient loads. Numerical modelling has found that operating the station under a daily hydropeaking regime can increase mixing in these high risk zones, and reduce the severity of algal blooms (Lian et al., 2014). Whether this approach is applicable to the Mekong cascade would require additional investigation.

Figure 5.54. *Algal bloom on surface water in backwater pond upstream of Xayaburi dam. Photo obtained in March 2016.*

In summary, the development of the norther Lao PDR cascade will alter the physical attributes of the Mekong River valley. The free-flowing river will be divided into five separate impoundments. This change will affect water quality through altering the residence time and flow velocity of water within the cascade reach and reducing suspended sediment concentrations. Collectively, these changes have the potential to increase the risk of algal blooms in the impoundment areas.

Algal blooms and the poor water quality that can result from algal blooms can impact on the multi-use 'benefits' provided by Hydropower Projects. For example, very poor water quality could preclude the use of the waterway for aquaculture, or as a source of irrigation water, or prevent the migration of fish due to chemical or low dissolved oxygen 'barriers'.

The water quality indicators included in the final Indicator Table are derived from the residence time, water clarity and velocity results presented in this section.

5.4.3.2 Increased risk of algal bloom-Sanakham to Paksane (Zones 2 and 3) – Scenarios 1.1 and 1.3

Water quality changes occurring within the cascade will impact the river system downstream of the final dam, with impacts generally proportional to the distance from the discharge point of the dam, and the number and volume of tributary inflows entering downstream.

Potential impacts could include an increase in water temperature during the dry season, and lower turbidity throughout the year as compared to pre-dam conditions. There is potential for nutrient fluxes to decrease, however, because nutrients are typically carried by fine-sediments and the the

vast majority of the silt and clay passes through the dams, nutrients fluxes are unlikely to decrease as much as sediment loads.

This has been the case at Chian Saen, where in spite of large decreases in sediment concentrations associated with development of the Lancang Cascade, nutrient levels have not decreased. In addition to the maintenance of silt and clay transport through the river, nutrient transport has also likely been affected by the development of new industries linked to the water supply provided by the cascade, such as paper mills. It is also possible that the degradation of organic matter within the reservoirs has provided an additional source of nutrients downstream.

If algal blooms are prevalent in the impoundments, then higher concentrations of algae are likely to be discharged to the river system, which may promote additional growth downstream under conditions of low flow.

The potential differences to risks of algal blooms between Scenario 1.1 and Scenario 1.3 are considered small. Hydropeaking is unlikely to alter water quality conditions in the impoundments or downstream of the final impoundment to a large degree. If discharge from the final dam were shut off completely and then re-initiated, there would likely be a pulse of higher sediment (and nutrient) water at the beginning of each hydropeaking cycle, but this mode of operation is not likely as it is not practicable to turn off the Mekong River.

Similarly, temperature variations in the river may occur over short time periods if there is a large difference in temperature between the tributaries and the impoundment. During periods of power generation, the temperature in the downstream river will be controlled by the power station discharge, however, during periods of lower power station discharge, inflow from the tributaries could dominate, resulting in frequent temperature fluctuations.

As referenced in the water quality section on algal blooms, there is potential for hydropeaking to alter localised hydraulics in an impoundment, which could enhance mixing at tributary confluences, as has been identified for the Three Rivers hydropower impoundment. Whether this is feasible or desirable within the context of the northern Lao PDR cascade is unknown.

5.4.3.3 Risk of water column stratification

Lake stratification is controlled by the hydrology, bathymetry, orientation and solar radiation of an impoundment. In turn, the solar radiation is a function of latitude, longitude and elevation. The potential for a water body to stratify c, and elevation, indicating how many times per year a lake may stratify and subsequently mix. The lakes in the cascade are located between approximately 17°N and 20°N which places them in the classification between oligomictic (permanently stratified) and monomictic (stratify and mix once per year). This suggests there is a risk of lake stratification, but does not reflect the specific flow and bathymetric characteristics of the cascade.

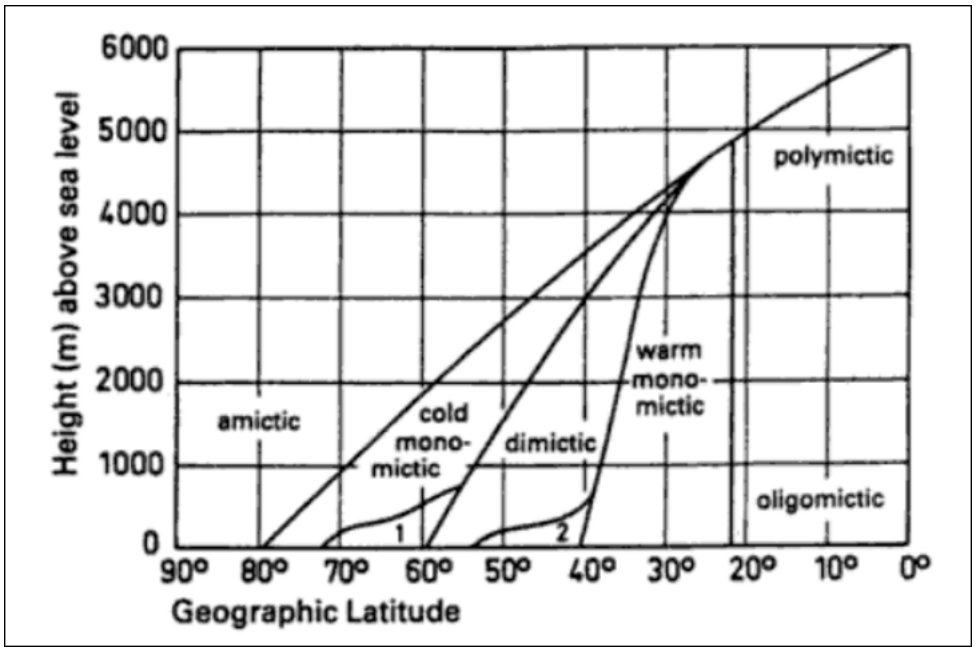


Figure 5.55. *General classification of lakes with respect to stratification (Wetzel, 1975).*

A second approach to evaluate the potential for stratification is the derivation of the Densiometric Froude number (Fd) which uses the following relationship based on the volume (V), length (L), gravity (g) and a constant (e), (Norton et al., 1968 in Martin and McCutcheon, 1998):

$$Fd = \sqrt{(1/ge)}\ LQ/VD$$

Values of Fd < ~0.32 indicate the potential for stratification. Values much higher are considered to indicate well mixed water bodies.

Using this approach and the appropriate parameters for each impoundment, the potential for stratification within the cascade is suggested to be low with all Fd values > 4. The order for potential stratification decreased as follows (e.g. Luang Prabang had the lowest Fd value and Sanakham the highest): Luang Prabang > Pak Lay > Xayabouri > Pak Beng > Sanakham.

These results suggest there is a low risk of stratification occurring on a lake wide basis in the cascade, but there may be a risk of localised stratification due to the low level inlets included in the power station and dam design (assuming all hydropower projects have a similar design to Xayaburi). The drawing of water from low in the reservoir can create a 'dead' zone in the surface waters near the dam, which can increase in temperature and lead to local stratification (Figure 5.56). Because this is a hydraulically controlled phenomenon rather than a thermal or morphological controlled process, it is possible that this zone could persist except during periods of high flows when the power station was spilling and the surface waters near the dam were discharged.

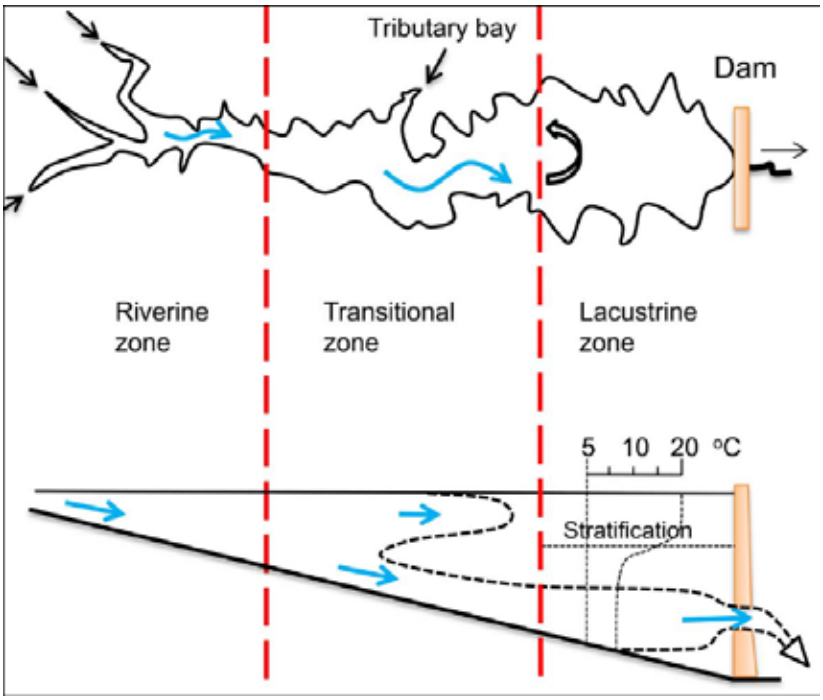


Figure 5.56. *Schematic of dam with low-level intake showing potential area of water column stratification (Dai et al, 2013).*

This risk of localised stratification may increase in successive impoundments; if the water entering from the upstream reservoir is cooler than the resident water in the downstream impoundment, it could form a density current and 'flow' along the bottom of the impoundment to the power station inlet, thus isolating the surface waters. Monitoring will be required to determine the thermal changes within each reservoir.

5.4.3.4 Risk of nutrient or metal release from sediments in impoundments

The release or cycling of nutrients, metals or other compounds such as mercury within impoundments is closely related to thermal stratification and oxygen levels. Under conditions of low oxygen, iron and manganese compounds, which are commonly present in the sediment load of rivers, can dissolve and release other metals or nutrients that were adsorbed onto the sediment surface. The decomposition of organic matter following inundation can be a major contributor to this process during the first few years following inundation, and can release compounds stored within the underlying soils.

The large volume of organic material that will be inundated during creation of each reservoir will increase the risk of low oxygen conditions within the impoundments even in the absence of thermal stratification. Unless the entire water column can 'ventilate' and be re-oxygenated or replenished by 'new' water at a rate that exceeds the rate of organic decay, then dissolved oxygen levels will decrease. The extent and duration of the decrease will be dependent on rate of water level movement through the impoundment and the quantity of organic material undergoing decay. It is unknown whether the rate of movement of water through the impoundments, especially in the dry season, will be sufficient to prevent oxygen depletion. Monitoring and additional investigations are required to address this question.

5.4.3.5 Risk to water quality from sediment-flushing downstream of cascade (Zone 2 and 3)

Sediment flushing of reservoirs has the potential to affect water quality in the following ways:

- A 'pulse' of sediment-laden water can be discharged to the downstream environment. The concentration of sediment may directly affect the quality of water for extractive uses and impact downstream ecological processes;
- The release of water at depth from an impoundment can result in water containing low concentrations of dissolved oxygen entering the downstream river;
- The pore water released during sediment flushing can have water quality characteristics which differ considerably, and may increase nutrient / metal or other concentrations in the discharge;
- The draining of an impoundment can expose partially decomposed dead vegetation that can produce unpleasant odours.

Each of these risks is assessed based on the results of the sediment modelling and water quality risk analysis.

The model results for sediment flushing runs are presented and discussed in detail in Section 5.3.1.4., and should be consulted for information. This analysis focuses on flushing events at Pak Beng that vary in draw down rates between 0.1 and 1.0 m/hr.

The concentrations and grain size distribution in the discharge associated with no flushing, and 'slow' and 'fast' flushing runs are shown in Figure 5.57, and demonstrate that anticipated sediment concentrations are in the range of ~100 mg/L to 1100 mg/L, with the maximum concentrations during the 1 m/hr drawdown limited to only a few hours. ***These concentrations are well within the range of sediment concentrations previously present in the river, and should not present a wide-spread water quality issue.***

The extent to which the sediment would settle or be transported downstream is somewhat dependent on when the flushing operation is completed (e.g. dry v wet season), although because of the 'flushed' material being composed of predominantly fine sand and silt& clay, most is likely to be transported large distances downstream.

The discharge of a large plume of sediments could also be accompanied by a pulse of nutrients and other constituents (iron, manganese and other pollutants) that are bound to the sediments, or were present in interstitial water within the reservoir. Sediment bound nutrients may increase by about 20% during the flushing operations, based on the 20% increase in the discharge of fine sand, silt & clay during this period. It is not possible to estimate the magnitude of nutrients or other parameters that may be mobilised during sediment disturbance. Early in the life of the reservoir nutrient loads may be relatively high related to the degradation of organic matter in the inundated soils. The short duration of the sediment flushing event, especially in the case of the 'fast' pulse will limit the duration of these discharges.

Mitigation measures that can reduce risks associated with increased sediment and nutrient concentrations include completing flushing operations during periods of moderate tributary inflow such that there are other lower sediment and nutrient sources entering the river,

releasing additional 'clean' water downstream through higher level intakes (or the turbines) and informing downstream water users about the timing of any flushing events such that water intakes can be managed accordingly.

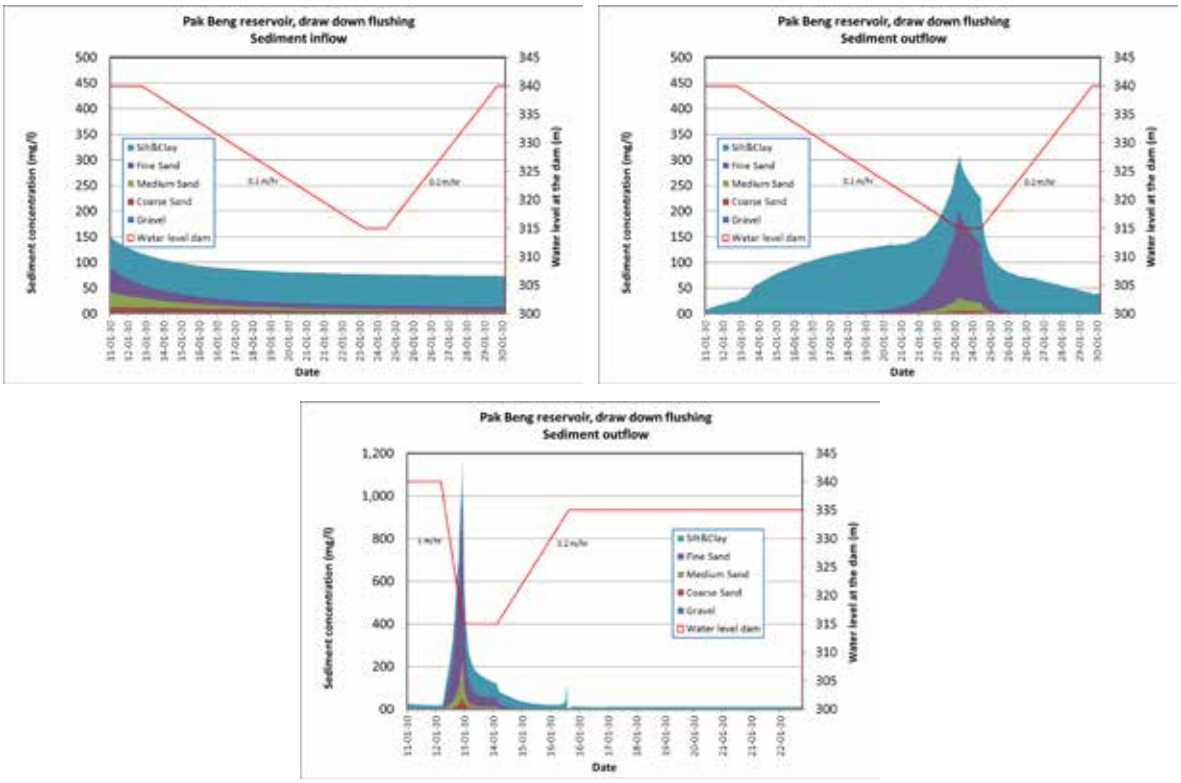


Figure 5.57. *Suspended sediment concentrations associated with flushing events at Pak Beng. Top graphs shows no flushing, middle graph shows flushing with a drawdown rate of 0.1 m/hr and the bottom graphs shows an event with 1.0 m/hr drawdown. The distribution of sediment grain sizes is also shown.*

The risk of releasing low oxygen bearing water during sediment flushing is considered low due to the low risk of water column stratification. The risk might temporarily increase during the first years following impoundment due to the consumption of oxygen through the degradation of organic matter. Due to the large volume of water from higher in the water column that would be released during a flushing event it is unlikely that low dissolved oxygen levels would persist downstream. The flushing event would also generate high water flows and increase turbulence in the river that would assist with re-oxygenation of water.

5.5 Fisheries and Aquatic Ecology Impact Mitigation

5.5.1 General

Most of the previously discussed indicators are also of high relevance for assessing the efficiency of the mitigation measures for the diverse scenarios on fisheries and aquatic ecology. In this chapter, only indicators, which were not yet covered by previous chapters, are included.

5.5.2 Lao Cascade – Local and Cumulative Impacts

5.5.2.1 River connectivity

The disruption of river continuity is considered as one of the main cause of impact to aquatic organisms, especially migratory fish. Aquatic organisms rely on connectivity on four dimensions: lateral, longitudinal, vertical and seasonal (Stanford & Ward, 2001; Ward, 1989). Connectivity affects both ecosystems (functions, habitats and community structures) and population dynamics (migration, dispersal). Connectivity indicators were either calculated for the entire catchment or for zone 1. However, negative impacts of the cascade and improvements by mitigation options will also effect downstream reaches (i.e. zone 2 and 3).

5.5.2.1.1 Overall connectivity (catchment and zone 1)

As already described in chapter 3.6.1.1, different connectivity indices were calculated for the Mekong basin. Scenario 1.1.0 results in a $DCI_{Strahler}$ of 28 % and a DCIMigr of 74 % (see also Figure 5.58). For the diverse cascade-scenarios (1.1.0 to 1.3.E) the DCIs stays the same for all scenarios without fish pass facilities (see table 5.18). This means, that only the connected-river network downstream of the cascade is reachable for migratory species, while the cascade is no longer accessible. If a species relies on spawning grounds located in or upstream of the cascade, the population can no longer sustain and will most likely become extinct in near future.

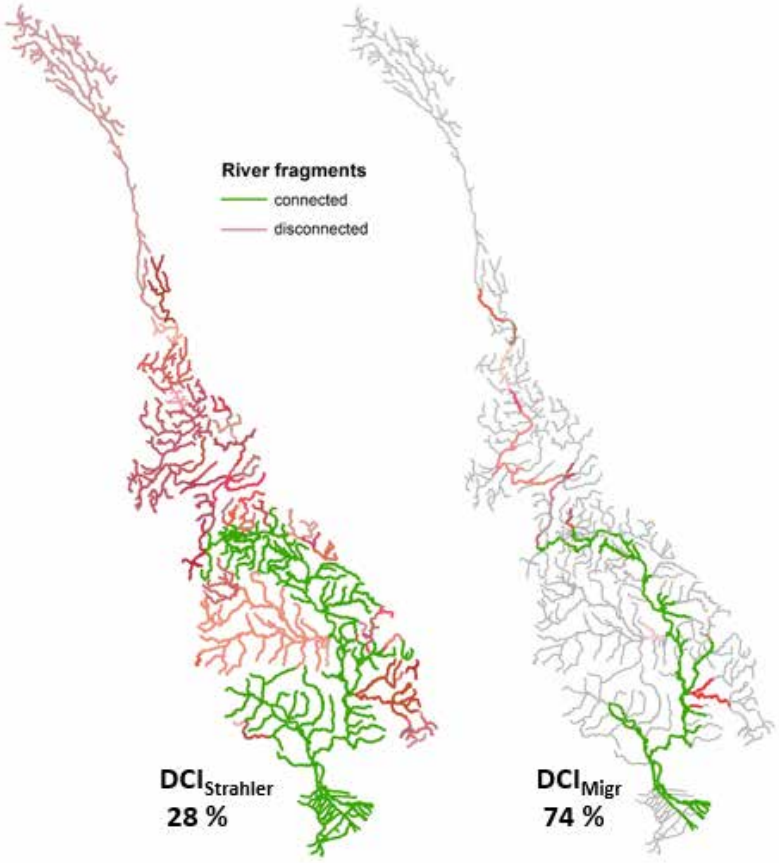


Figure 5.58. *DCIs for scenarios without a fish pass (green = still connected river section).*

Once the connectivity loss is mitigated by fish passes, it is assumed that the DCIs again correspond to the BDP 2030 conditions. Of course, this is not entirely true, since selected species and age classes might still be limited in their up- and downstream migration efficiency or subject to the risk of turbine passage. To take this into consideration, additional indicators are assessed for these scenarios (see below).

Table 5.18. Scenarios with (FP) and without fish pass (x).

Scenario	Fish pass	DCI Strahler	DCI Migr
1.1.0	no	28	74
1.1.A	no	28	74
1.1.B	yes	37	81
1.2.A	no	28	74
1.2.B	no	28	74
1.2.C	yes	37	81
1.2.D	yes	37	81
1.3.0	no	28	74
1.3.A	no	28	74
1.3.B	no	28	74
1.3.C	yes	37	81
1.3.D	yes	37	81
1.3.E	yes	37	81

5.5.2.1.2 Upstream migrating adults

For those scenarios, where fish pass solutions are in place (see table 5.18 above), the upstream migration efficiency for adults is assessed. Upstream migration is mostly supported by the technical fish pass with consecutive fish lift (see chapter 3.1.3). Also the navigation locks might provide a passage route, which is, however, only operated occasionally and only in the wet season and is therefore not considered in the assessment. One of the indicators assesses the upstream passage efficiency via the whole cascade (i.e. 5 dams).

Although the dimension and flow velocities in the fish pass seem suitable for most species, it yet needs to be tested if all species can find the entrance. Although a collection gallery provides several entries, the galleries position (i.e. above the turbines) might not be suitable for bottom-dwelling fish. It also has to be proven if the fish pass can cope with high biomass peaks at the onset of the wet season. Even by assuming an optimistic 90 % passage efficiency in upstream direction (see also table 5.19) a starting population of 100 % is reduced to 90 % by the first dam, 81 % by the second and ends up with 59 % upstream of the fifth dam. Fish that have to spawn upstream of the cascade are affected by the cumulated passage efficiency (see Figure 5.59 for different passage efficiencies). Some few individuals (which are less specialized) might manage to spawn in the impoundment or adjacent tributaries. However, considering the habitat alteration within the impoundment, spawning grounds might be scarce.

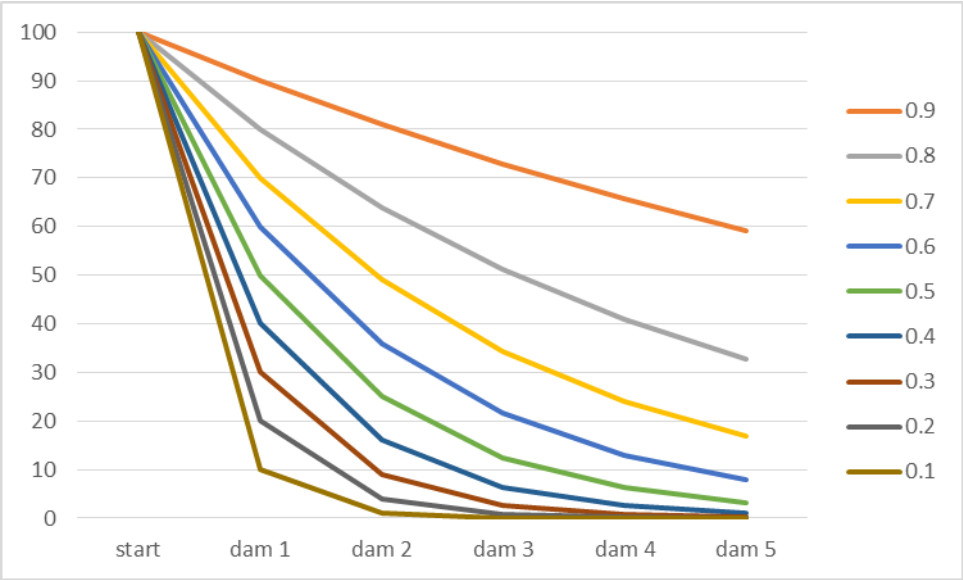


Figure 5.59. *Cumulative passage efficiencies for five dams assuming individual passage efficiencies of 10-90 %.*

Table 5.19. Scheme for cumulative upstream migration efficiency.

Upstream migrating adults

Passage efficiency of 90 %	Passage efficiency of 50 %	Length of section
59 %	3 %	431 km
↑ Pak Beng Dam ↑		
66 %	6 %	137 km
↑ Luang Prabang Dam ↑		
73 %	13 %	128 km
↑ Xayaburi Dam ↑		
81 %	25 %	117 km
↑ Pak Lay Dam ↑		
90 %	50 %	75 km
↑ Sanakham Dam ↑		
START: 100 % of all upstream migrating fish		

Nevertheless, spawning of migratory species in and upstream of the cascade is again assumed only to take place in scenarios with fish pass. For these cases, the adult fish and their offspring migrate downstream after spawning. Hereby, mortality has to be assessed for two different age classes:

- adults returning after spawning (see chapter 5.5.1.4) and
- eggs and larvae passively transported by flow (see chapter 5.5.1.3).

5.5.2.1.3 Downstream migrating eggs and larvae

Very little is known concerning downstream migration of adults and larvae. A recent study by Hortle et al. (2015) assessed larval and juvenile fish drift up- and downstream of Xayaburi (i.e. within the planned cascade) between May and August and showed that ten species made up about 95 % of all sampled larvae (Hortle et al. 2015).

Another study by Cowx et al. (2015) observed higher diversities around Luang Prabang between February and May. Although reproduction periods were assumed to be highly linked to rising water levels, Cowx et al. (2015) suggests that spawning and larvae drift occurs throughout the year, including the dry season.

Impacts of impoundments on drifting larvae in large tropical rivers are largely unexplored but the few studies available raise the problem of ecological traps (Pelicice & Agostinho, 2008). The impoundment can alter the local conditions and make spawning sites unsuitable. Furthermore, it can act as a sink for passively downstream drifting eggs and larvae. If they, nevertheless, manage to reach the dam, turbine and spillway passage may cause injuries or death (Cowx et al. 2015). These impacts can offset recruitment and jeopardize the entire populations.

To assess this impact, the mean flow velocity was extracted for all cross sections and representatively one day per month. The following figure shows, that the flow velocities in the impoundment highly depend on the respective flow conditions, with very low flow velocities during March and higher velocities during August. The results show clearly, that in March the minimum flow velocity for passive transport falls below critical level (< 0.2 m/s) for several kilometres per impoundment. Under these conditions, it is very likely that the drift of ichthyoplankton is interrupted.

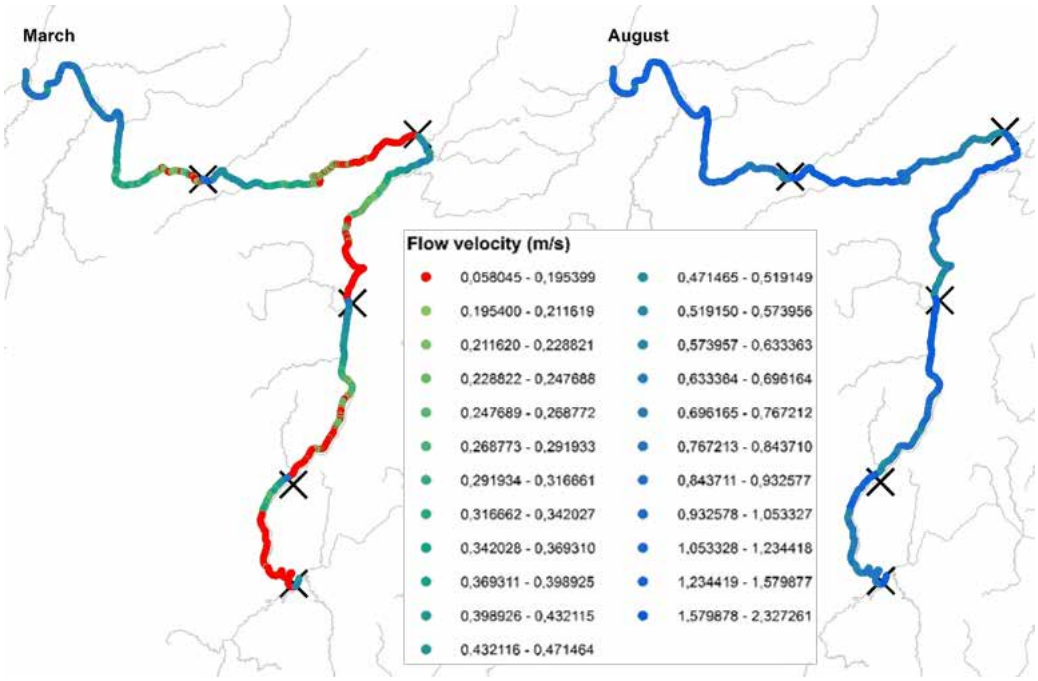


Figure 5.60. *Comparison of the mean flow velocity in March (left) and August (right) in the cascade (red sections indicate flow velocities of <0.2 m/s).*

The data were assessed for each month and cascade and the respective distances, where the flow velocity drops below 0.2 m/s are provided in figure 5.61. ***The data show, that passive downstream drift is only supported for four months during the wet season.*** A blocked larvae drift at the onset of the wet season can diminish the reproduction success and cause long-term stock declines. This negative impact cannot be mitigated without changing the overall characteristics of the impoundment (height of dam).

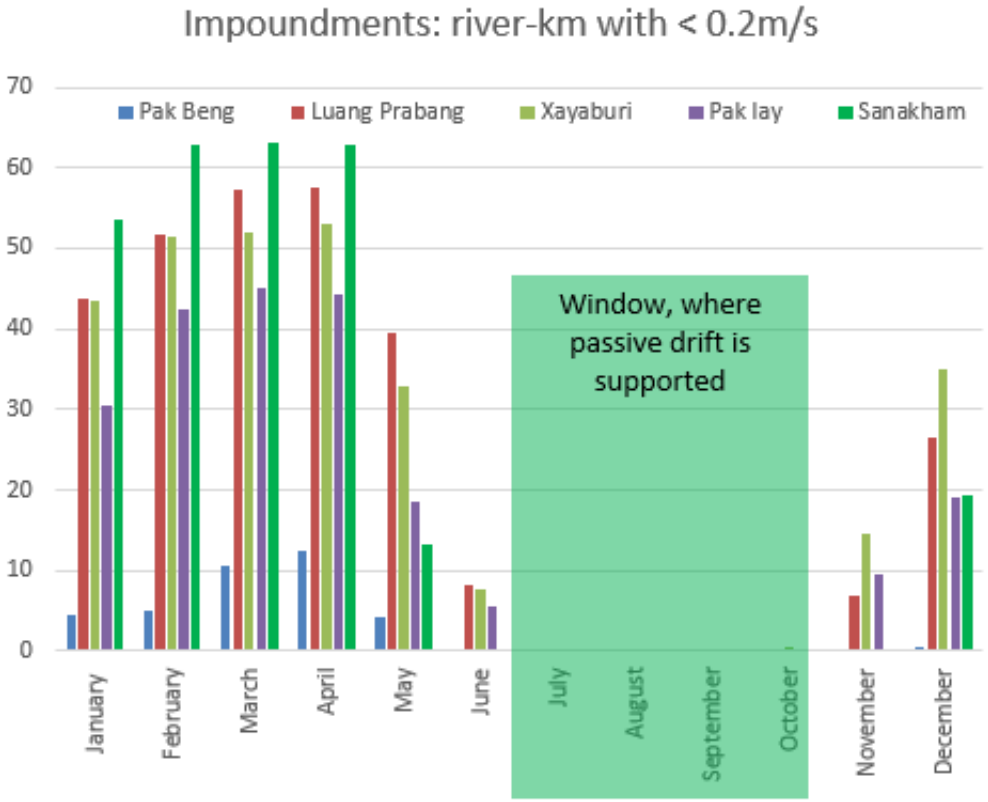


Figure 5.61. *Reservoir length (km) with flow velocities <0.2 m/s per month and dam.*

However, as the flow velocities within this “window” are still lower compared to historic conditions, drift delays might occur which can be assessed by calculating the time for passively drifting through each impoundment under impounded conditions in comparison to natural conditions (i.e. historic). The results are shown in Figure 5.62 and Table 5.20 and indicate that the overall delay for the entire cascade sums up to 3-5 days (depending on the month of drift). While delays of several weeks and months could cause a delayed arrival at feeding grounds and reduced time for feeding, ***a delay of up to 5 days is assumed to have no or only a minor impact on the growth and fitness of the young-of-the-year drifting from July to October.***

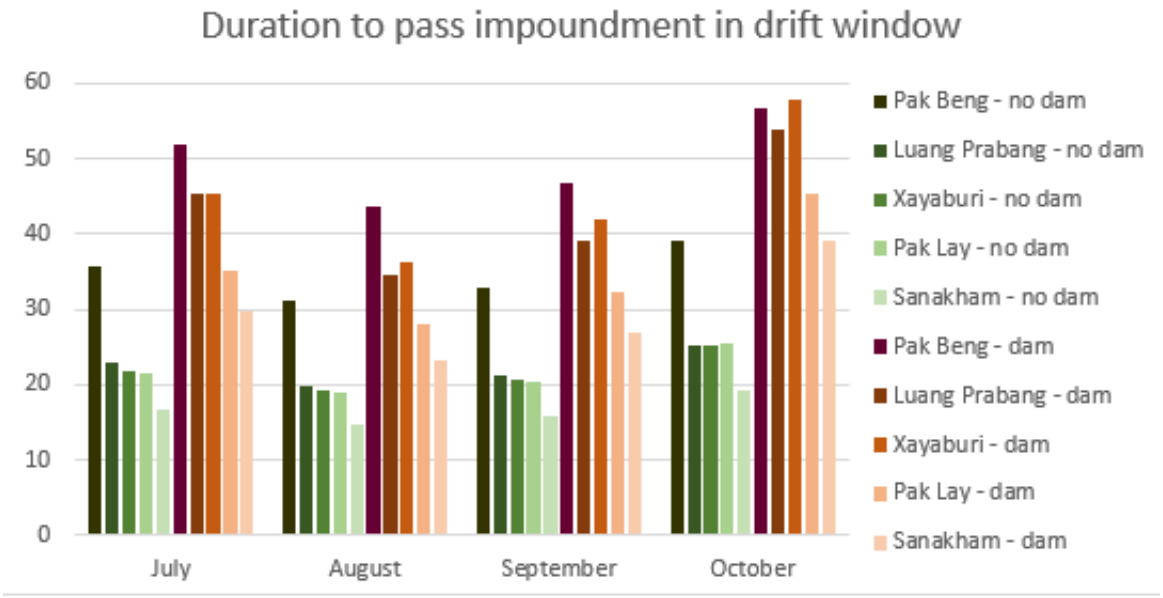


Figure 5.62. *Duration (h) to pass impoundments in drift window (i.e. flow velocities >0.2 m/s).*

Table 5.20. Comparison of duration to pass cascade and total delay per month.

Drift-delay in hours per impoundment				
	July	**August**	**September**	**October**
Pak Beng	16.28	12.64	13.78	17.76
Luang Prabang	22.33	14.77	17.84	28.68
Xayaburi	23.66	17.14	21.15	32.73
Pak Lay	13.50	9.10	11.78	19.98
Sanakham	13.07	8.41	10.94	19.91
total delay (days)	**3.70**	**2.59**	**3.15**	**4.96**

5.5.2.1.4 Downstream migrating adults

Downstream migrating adults swim downstream actively and may pass the dam by one of the following corridors. Fish can either pass the dam by the downstream migration facility (i.e. chute), the turbine or, if spillflow is released, over the spill gates. If the ship lock is in operation, individual fish might be able to pass through the lock, but as the ship lock is not operating continuously, the proportion of fish passing trough the lock is assumed to be negligible.

Halls & Kshatriya (2009) identified 58 highly migratory species threatened by Mekong mainstream dams, which contribute 38.5 % to the total weight of all recorded species in the catch surveys (see Annex E, Table E1). On the basis of passage success and mortality rates of 10 selected species, they modelled the cumulative barrier and passage effect for migratory species at the LMB with a detailed projection matrix. The assessment, however, neglected the aspect of passive downstream drift of larvae, which is very important for fulfilling the life cycles and sustaining the populations (see chapter 5.5.1.3)

Table 5.21. Summary and characteristics of species considered in the impact assessment.

Species	Max length (cm)	Size class	Guild	Turbine mort. (Halls & Kshatriya 2009)	Cumulative mortality for 5 dams
Henicorhynchus siamensis & lobatus	20	small	3	2-15	12-62
Gyrinocheilus pennockii	28	small	2	2-15	12-62
Paralaubuca typus	20.5	small	3	2-15	12-62
Hypsibarbus malcolmi	50	large	2	35	92.5
Cosmochilus harmandi	100	large	3	70	99.9
Pangasius conchophilus	120	large	2	80	99.9
Pangasius macronema	40	medium	2	30	88.2

Table 5.22. Scheme for cumulative downstream passage efficiency for different mortality rates.

Downstream migrating adults

Mortality of 2 %	Mortality of 70 %	Length of section
START: 100 % of all upstream migrating fish		
↓ Pak Beng Dam ↓		
98 %	30 %	137 km
↓ Luang Prabang Dam ↓		
96 %	9 %	128 km
↓ Xayaburi Dam ↓		
94 %	2,7 %	117 km
↓ Pak Lay Dam ↓		
92 %	0.81 %	75 km
↓ Sanakham Dam ↓		
90 %	0.24 %	

Halls & Kshatriya (2009) assessed the minimum mitigation targets to maintain viable populations assuming that all migratory species have their spawning habitats upstream of the cascade and their feeding/ nursing habitats downstream of the cascade. This means that adults have to successfully pass the cascade of five dams in upstream direction and adults and larvae have to return in sufficient numbers downstream of the cascade to sustain the population on the long run.

Adults of small species are considered to show low mortality rates (i.e. 2-15 % for turbines and 5 % for spillway passage) during downstream migration. For those small species, upstream passage success rates of 88-96 % are required (for 3 dams) to maintain viable populations (Halls & Kshatriya, 2009). Adults of large species, however, may show high mortality rates through turbines (see Table 5.21) and the maintenance of viable populations might even be problematic for a 100 % upstream migration success rate (which is not the case, see chapter 5.5.1.2). According to Halls & Kshatriya, these species would only sustain if they could be successfully redirected from harmful passage routes (e.g. turbines and spillway). However, the rack at Xayaburi (10 cm bar distance)

is only suitable to prevent fish larger than 100 cm from entering the turbines while smaller species and individuals will be entrained into the turbines. Although the two largest species assessed here, Consmochilus harmandi and Pangasius conchophilus, grow up to 100 or 120 cm in length, a large proportion of migrating individuals will be smaller than 100 cm and can, therefore, pass the turbines. Due to the high mortality rates, they will dramatically decrease in density over the next years or decades and might finally become extinct (at least within the cascade). The density of giant catfish (Pangasius gigas) is already very low in the entire Mekong catchment, thus, extinction of this species within and upstream of the cascade is very likely.

5.5.2.2 River channel habitats

A detailed assessment of the individual indicators related to river channel habitats were already discussed in other chapters. Only some few indicators, which were not already covered in those chapters, will be added here. However, the biomass assessment incorporates most of the previously discussed indicators to assess the overall biomass changes. Therefore, a more detailed interpretation of changes related to each topic can be found in chapter 5.5.3.

5.5.2.2.1 Hydrology

As already shown in chapter 5.2.1.2, the ***seasonality and distribution of seasonal flows is not impacted by the cascade.*** Therefore, negative impacts on aquatic organisms are not expected with regard to this pressure indicator. However, as already discussed in chapter 5.2.1.3., ***sub-daily flow fluctuations related to peaking operation will clearly affect aquatic organisms.***

Peaking effects within the cascade (zone 1)

The dewatered area for each impoundment and scenario were already shown in chapter 5.2.1.3 and provide a rough estimation of potential effects on aquatic organisms and clearly demonstrate differences between the scenarios.

In scenario 1.2.A and 1.2.B the dewatered area is caused by the flushing events, which occur only over a short time span and not on a daily basis. Especially, if these flushing events coincide with natural high flow events (e.g. at the onset or during the wet season) less impact is expected. It is assumed that the related losses caused by stranding can be compensated within the populations and show no long-term effect.

Especially in scenario 1.3.0, high losses are expected with regard to catastrophic drift of fish (juveniles and ichthyoplankton) as well as benthic invertebrates. With juvenile age classes and larvae seeking shelter at shoreline areas, especially during the peak, it was clearly shown that there is a high risk of stranding due to too fast downramping (i.e. faster than 5 cm/hour). While the negative impact is already slightly reduced in scenarios 1.3.A to 1.3.C ***a clear improvement is visible in scenario 1.3.D, which includes the ramping restrictions.*** As already discussed, the detected events in the Pak Beng and Xayaburi reservoir stem from the dry season environmental drawdown at Pak Beng and the flood protection drawdown at Xayaburi, which was modelled without complying to the defined thresholds. Also in reality, these event would (and should) occur much slower and would therefore cause no or only minor environmental problems. With regard to scenario 1.3.E, it is interesting to observe that this scenario is similar to 1.3.C for all impoundments

but Sanakham. With Sanakham itself restricted by the 5 cm/hour threshold but still receiving peaks from upstream dams, the dewatered area is higher compared to scenario 1.3.C.

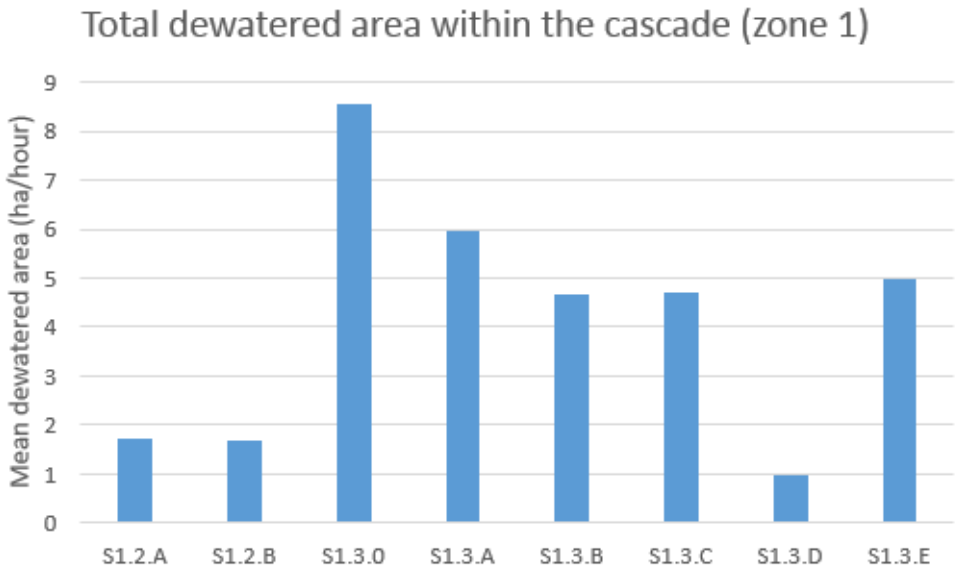


Figure 5.63. *Summed dewatered area in ha/hour for zone 1 (note: the dewatered area in scenario 1.3.D is caused by dry season drawdown at Pak Beng and flood protection at Luang Prabang and can be considered as not relevant).*

Consequently, it can be said that ***ramping limitations represent a suitable measure for mitigating negative effects caused by peaking operations.*** The options of using the lowermost dam as a re-regulation weir can offset negative impacts downstream of the cascade, but can possibly cause a slight increase of negative impacts within the cascade.

Peaking effect downstream of the cascade (zone 2 and 3)

It was clearly shown in chapter 5.2.1.2 that the peaking wave is equalized in downstream direction. In the dry season, significant downramping occurs until Vientiane (~200 km downstream) while the waves are levelled out at a shorter distance at intermediate water levels (e.g. at the onset of the wet season in June). Still, the observed amplitude exceeds 10 cm per day – even downstream of Vientiane. During high flows, when peaking is not required, the same flow conditions as for run-of-river operations can be expected.

Downstream of Paksane (in zone 3) no negative impacts are expected with regard to peaking operations. Indirect effects, due to morphological changes related to the peaking event may however, occur. ***Although scenarios 1.3.D and 1.3.E were not modelled in detail in this zone, it is assumed that ramping rates eliminate any negative impacts in this zone.***

5.5.2.2.2 Morphology

The most important morphological indicators were already described in chapters 5.3.3 to 5.3.6. The most important aspects for aquatic organisms and used for the assessment of biomass changes are, however, reconsidered and discussed here.

Morphological alterations in zone 1

Both sedimentation and erosion processes occur within the impoundments, however, deposition occurs at higher extent in each impoundment, with most material trapped in the upper half of the reservoir and finer material deposited further downstream.

The sedimentation can also promote the filling-up of deep pools, with pools in the Pak Beng impoundment expected to fill more quickly due to the higher sediment load entering this reach compared to downstream impoundments. Not all pools within the cascade will be degraded since erosion processes dominate in the upper section of each impoundment. However, even without filling of pools the habitat characteristics of the pools will change in relation to water depth, riverbed sediments and flow velocity.

Also for other aquatic organisms, as e.g. benthic invertebrate, the deposition of fine sediments, which cover coarser material, can cause a dramatic loss in suitable habitats and may consequently also impact fish and other animals feeding on benthic invertebrates.

For the flushing scenarios (1.2), ***at least some of the deposited sediments can be transported downstream,*** although not all grain sizes are transported with equal proportion and especially coarse substrate remains trapped in the impoundments. ***The flushing event itself causes a total reallocation of sediments within the impoundment and causes habitat destruction,*** which goes hand in hand with the loss of food sources for fish and other aquatic organisms. Furthermore, the flushing itself can cause a catastrophic drift of fish and benthic invertebrates which seek to escape those unliveable conditions. Consequently, the flushing itself does not improve but rather deteriorate habitat conditions within the cascade (zone 1).

Although the water surface area increases from BDP 2030 to Scenario 1.1.0, an increase in fish biomass related to the area and volume increase of the water body seems very unlikely, as potential positive effects are offset by other impacts related to the cascade. The increase in water depth causes the ***inundation of most rapids*** currently existing within the cascade (except some rapids located close to the dams). As many species highly depend on these rapids as spawning and feeding habitats, a loss of fish diversity and biomass is very likely.

Within the different cascade scenarios, no significant changes are expected. ***The negative impacts related to higher water depths (e.g. inundation of rapids) cannot be mitigated*** without changing the general layout of the hydropower plant and their operation.

Morphological alterations in zone 2 and 3

In zone 2, erosion dominates the first 100 km downstream of the cascade but decreases further downstream. As already mentioned in scenario 5.3.3 this ***erosional wave is likely to migrate downstream in the long run.*** The related changes in substrate composition will also alter the diversity and biomass of benthic invertebrates, serving as a food source for fish. However, fish might be also impacted by direct habitat alteration and loss of sand bar habitats and instream structures. Sand bars are important habitats for juvenile fish and their reduction or elimination would result in significant fish stock declines.

The model runs indicate that deep pools in zone 2 will be maintained. However, erosion processes can alter the conditions within the deep pools and cause a qualitative degradation of related habitats. In the long run river bed incision is expected to occur with the risk of decoupling the floodplains from the mainstem of the river. Incised river bed would result in less frequent flooding and reduced inundated area. As a consequence, the fish production in the floodplains would decline. The same effects are expected in zone 3, but at a later stage and a smaller extent. Rapids in zone 2 are assumed to remain or even increase.

Zone 2 and 3 will experience benefits from the flushing events. Although the flushing event itself is also associated with risks (e.g. high turbidity, deposition of large amount of material) it will also show positive effects on the river morphology. Nevertheless, it was shown that flushing cannot completely mitigate negative effects caused by the impoundment and, especially, negative impacts already caused by the Chinese and tributary dams. Although large proportions of silt and clay might be transported through the cascade, a decrease of attached nutrients in zones 2 and 3 and especially further downstream in the delta and Tonle Sap system has to be examined critically.

5.5.2.2.3 Water quality

With regard to increased water clarity and nutrient input (due to agriculture, aquaculture and industry), algae blooms and macrophyte development during the dry season are more likely to occur. However, as during the wet season the flow velocity is increased again, algal and macrophyte development might be cease periodically. Ultimately, during reservoir flushing biomass of algae is more or less eliminated and macrophytes flushed out. Furthermore, water temperature changes might occur, especially in the dry season with sizeable increases in residence time in the impoundments. Species sensitive to temperature increases may suffer from this impact.

As silt and clay was shown to pass through the cascade, a decrease in nutrient transport is unlikely, which is especially relevant for downstream floodplain habitats. However, the results have to be examined critically since already a minor decrease might be related to production losses, which might be even more dramatic downstream of zone 3.

Sediment concentrations during flushing operations are assumed not to exceed values of historic (natural) events and will only occur for a short period (chapter 5.3). Consequently, only marginal impacts on aquatic organisms are expected downstream of the cascade (in zone 2).

There is a risk of localised stratification in the impoundments, but monitoring is required to clarify the related impacts. Due to the inundation of organic material within the impoundment, there is a risk of oxygen depletion due to decomposition of organic material. Furthermore, algae blooms can drastically influence the oxygen-cycle within the impoundments.

Although most of the above discussed impacts were only assessed in a qualitative way, it is most likely that the water quality within the impoundment (zone 1) and also downstream of the impoundment (zone 2) will be degraded to some degree, compared to conditions without the cascade. However, the individual cascade scenarios will not significantly differ with regard to water quality indicators, except for scenarios 1.2 including flushing events (see also chapter 5.4).

5.5.2.3 Estimated fish biomass trends

The fish biomass trends of each guild were estimated with regard to the different scenarios and impact zones. This was done by groups of indicators, as already described in chapter 3.6.3. The mean values served as starting values for scenario 1.1.0 and are presented in table 5.23.

Table 5.23. Estimated biomass values for Scenario 1.1.0 (serving as baseline for other scenarios) in kt/yr.

	Zone 1	Zone 2	Zone 3
Migr. L	0.0*	0.0*	40.9
Migr. S	0.0*	0.0*	81.7
Floodplain	7.2	21.3	303.2
Generalists	22.7	26.8	107.8
Others	4.3	7.2	48.3
OAAs	19.6	26.6	162.3
sum total	53.9	81.9	744.3

*ratings (i.e. biomass increase/decrease) cannot be applied to a starting value of 0. Specific rules were defined (see text)

The effect of impacts and mitigation measures of each scenario and each indicator groups is compared to scenario 1.1.0, which serves as reference condition without any mitigation. As already described in chapter 3.6.3, the assessment has been undertaken by application of ratings from +3 to -3 (see table 5.24).

Table 5.24. Ratings for the assessment of impacts and mitigation measures.

Rating	Estimated effect on fish	Estimated biomass change (% change)
3	High increase	+66 - +100
2	Medium increase	+33 - +66
1	Low increase	>0 - +33
0	No change	+/- 0
-1	Low decrease	<0 - -33
-2	Medium decrease	-33 - -66
-3	High decrease	-66 - -100
-	No effect	-

To combine the individual ratings to an overall status (i.e. combining the ratings of all five indicator groups) the following rules were applied:

- Significant impacts overrule positive effects
- Long-term effects overrule short-term effects
- For impacts, the worst impact overrules other impacts
- For improvements: low increases overrule medium increases and if some impacts are not changed (i.e. 0) the best possible outcome is a low increase (1).
- In zone 3, the assessment is limited to connectivity indicators and migratory species, since all other indicator groups and related impacts seem not to reach zone 3 (within years to decades), which is why also no positive effect from mitigation can be expected.

Table 5.25 shows the estimated effects of the mitigation measures on the fish biomass trends. The results show that within all scenarios low or medium change of the biomass is expected, while high increases or decreases are unlikely. This is associated with the fact that the cascade itself causes the main alteration for the fish community and biomass and, hence, all mitigation measures are confined in their efficiency by overall cascade effect. Overall, the same amount of positive and negative effects can be seen within the scenarios. The reason for that is that positive mitigation effects on one ecosystem component are counteracted by negative effects on other ecosystem components. For example, the flushing of the reservoir is beneficial for zone 2 in terms of sediment transport, but detrimental due to flushing of the reservoirs. In general, fish passes always produce an improvement but their effect is counteracted by flushing or hydropeaking impacts in scenarios 1.2.C/D and 1.3.C. Due to the high mortality of large migratory species and the pending question on the functionality of passive drift as well the efficiency of the fish pass, it is assumed that large migratory species will become extinct in zones 1 and 2, irrespective of the fact that a fish pass is in place in some scenarios.

Table 5.25. Estimated effects of mitigation measures on fish biomass trends for each scenario and guild compared to scenario 1.1.0. and for all impact zones.

		Run-of-river						Sediment flushing												Peaking																	
Indicator groups	Fish groups	S1.1.A			S1.1.B			S1.2.A			S1.2.B			S1.2.C			S1.2.D			S1.3.0			S1.3.A			S1.3.B			S1.3.C			S1.3.D			S1.3.E		
		1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3	1	2	3
Seasonal flow	Migr. L	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Migr. S	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Floodplain	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Generalists	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
	Others	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Sub-daily flow	Migr. L	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	0	0	0	0	-2	0	0
	Migr. S	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	0	0	0	0	-2	0	0
	Floodplain	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	0	0	0	0	-2	0	0
	Generalists	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	0	0	0	0	-2	0	0
	Others	-	-	-	-	-	-	0	0	0	0	0	0	0	0	0	0	0	0	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	0	0	0	0	-2	0	0
Connectivity	Migr. L	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	Migr. S	0	0	0	2	2	2	0	0	0	0	0	0	2	2	2	2	2	2	0	0	0	0	0	0	0	0	0	2	2	2	2	2	2	2	2	2
	Floodplain	0	0	-	1	1	-	0	0	-	0	0	-	1	1	-	1	1	-	0	0	-	0	0	-	0	0	-	1	1	-	1	1	-	1	1	-
	Generalists	0	0	-	1	1	-	0	0	-	0	0	-	1	1	-	1	1	-	0	0	-	0	0	-	0	0	-	1	1	-	1	1	-	1	1	-
	Others	0	0	-	1	1	-	0	0	-	0	0	-	1	1	-	1	1	-	0	0	-	0	0	-	0	0	-	1	1	-	1	1	-	1	1	-
Habitats (Morphology)	Migr. L	0	0	-	0	0	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	0	0	-	-2	0	-
	Migr. S	0	0	-	0	0	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	0	0	-	-2	0	-
	Floodplain	0	0	-	0	0	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	0	0	-	-2	0	-
	Generalists	0	0	-	0	0	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	0	0	-	-2	0	-
	Others	0	0	-	0	0	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	0	0	-	-2	0	-
Water quality	Migr. L	0	0	-	0	0	-	-1	-1	-	-1	-1	-	-1	-1	-	-1	-1	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
	Migr. S	0	0	-	0	0	-	-1	-1	-	-1	-1	-	-1	-1	-	-1	-1	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
	Floodplain	0	0	-	0	0	-	-1	-1	-	-1	-1	-	-1	-1	-	-1	-1	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
	Generalists	0	0	-	0	0	-	-1	-1	-	-1	-1	-	-1	-1	-	-1	-1	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
	Others	0	0	-	0	0	-	-1	-1	-	-1	-1	-	-1	-1	-	-1	-1	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-	0	0	-
Overall status	Migr. L	0	0	0	0	0	0	-2	0	0	-2	0	0	-2	0	0	-2	0	0	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	0	0	0	0	-2	0	0
	Migr. S	0	0	0	1	1	2	-2	1	0	-2	1	0	-2	1	2	-2	1	2	-2	-1	0	-2	-1	0	-2	-1	0	-2	-1	2	1	1	2	-2	1	2
	Floodplain	0	0	-	1	1	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	1	1	-	-2	1	-
	Generalists	0	0	-	1	1	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	1	1	-	-2	1	-
	Others	0	0	-	1	1	-	-2	1	-	-2	1	-	-2	1	-	-2	1	-	-2	-1	-	-2	-1	-	-2	-1	-	-2	-1	-	1	1	-	-2	1	-

Note: due to the unknown functionality of the fish pass, the rating of +2 for small migratory species in scenarios with a fish pass was transferred into an increase of 0-66 % (instead of 34-66 %) causing a higher range within the results.

As already described in chapter, the impact ratings of table 5.25 are not directly transposed to the biomass, but by considering adaptation factors ranging from 0.17 to 0.50, depending on the impact zone and group of guilds (see table 5.26). Special conditions apply to large and small migratory species (see below).

Table 5.26. Assumptions for transferring the Mekong mainstream impacts to the biomass of the entire zone for individual groups of fish guilds.

	Migratory species			Floodplain species			Generalists/others species		
	zone 1	zone 2	zone 3	zone 1	zone 2	zone 3	zone 1	zone 2	zone 3
Factor for transferring the impacts of the Mekong mainstream to the entire impact zone	(see text)	(see text)	0.5	0.5	0.33	0.17	0.5	0.5	0.3

Since large and small migratory species start with a biomass of zero (consequence of interrupted continuum), relative biomass changes as used for the classification in table 5.24 cannot be applied. Overall status improvements (i.e. for zones 1 & 2) are only expected in scenario 1.1.B and 1.3.D and only for small migratory species. Here, the BDP 2030 scenario was used as starting value and the following procedure was applied:

- Small migratory species: Assuming a 100 % decrease to scenario 1.1.0 and a 0-33 % increase to scenario 1.1.B, the values were added up (i.e. -100+33 = -66) before applying them to the BDP 2030 scenario data.
- Large migratory species: Despite the presence of a fish pass, it is assumed that the high mortality through turbines and the interrupted larval drift will cause high losses and population declines. It might be the case that a few individuals sporadically re-enter the cascade via the upstream fish pass. However, due to the high mortality in downstream direction (via the turbines) it is assumed that stocks will decline and eventually become extinct in the long run.

Table 5.27. Grouping of scenarios for mitigation assessment.

Grouped scenarios	Type	Fish pass	Flushing	Peaking restrictions	Re-regulation
Scenario 1.1.A	Run-of-river				
Scenario 1.1.B	Run-of-river	x			
Scenario 1.2.A and 1.2.B	Run-of-river		x		
Scenario 1.2.C and 1.2.D	Run-of-river	x	x		
Scenario 1.3.0 to 1.3.B	Peaking				

Grouped scenarios	Type	Fish pass	Flushing	Peaking restrictions	Re-regulation
Scenario 1.3.C	Peaking	x			
Scenario 1.3.D	Peaking	x		x	
Scenario 1.3.E	Peaking	x			x

The trends in fish biomass development within the different scenarios are presented for the three impact zones and split into the response of the various fish guilds and OAAs. ***In general, most distinct differences among the scenarios can be detected in zone 1 and 2, while the effects in zone 3 are less pronounced.*** Considering all effects (over all three impacts zones) scenarios 1.1.B and 1.3.D are expected to be most beneficial (i.e. highest biomass trends).

5.5.2.3.1 Estimated fish biomass trends in impact zone 1

For the run-of-river scenarios, the fish pass has a significant positive effect on the expected fish biomass trend, especially in scenarios 1.1.B and 1.3.D. Although scenarios 1.2.C/D and 1.3.C also include a fish pass, the positive effects are diminished by impacts related to flushing and peaking. Compared to run-of-river scenarios, the flushing (1.2) and peaking (1.3) scenarios cause additional stress on aquatic organisms, which is why lower biomasses are expected. An exception is 1.3.D, where peaking is limited to environmentally acceptable ramping rates. Here, the biomass is comparable to scenario 1.1.B (without hydropeaking).

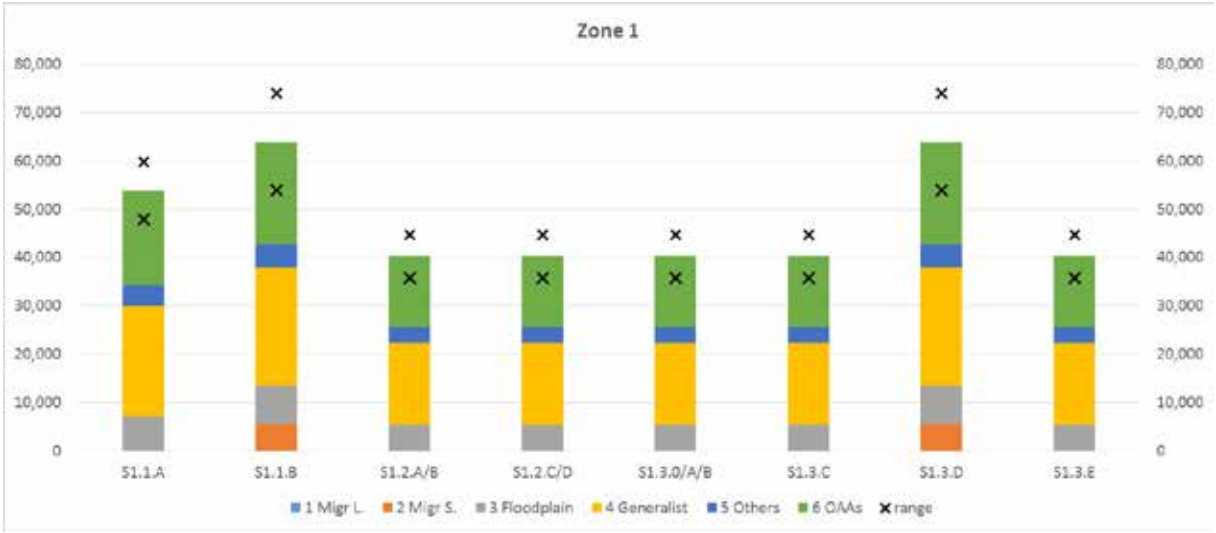


Figure 5.64. *Estimated fish biomass trends in impact zone 1 for combined scenarios.*

5.5.2.3.2 Estimated fish biomass trends in impact zone 2

In zone 2, the positive effect of the fish pass is clearly visible for all scenarios equipped with a fish pass as the effect of continuity restoration is less counteracted by other pressures. Although scenarios 1.2.C/D are equipped with a fish pass they receive the same overall rating as Scenarios 1.2.A/B due to the overriding positive effect of the sediment transport to zone 2.Hydropeaking result in the worst situation among analysed scenarios, but can be mitigated by environmentally acceptable ramping rates. Unlike the situation in zone 1, using Sanakham as re-regulation dam results here in increased biomasses, comparable with the situation without hydropeaking.

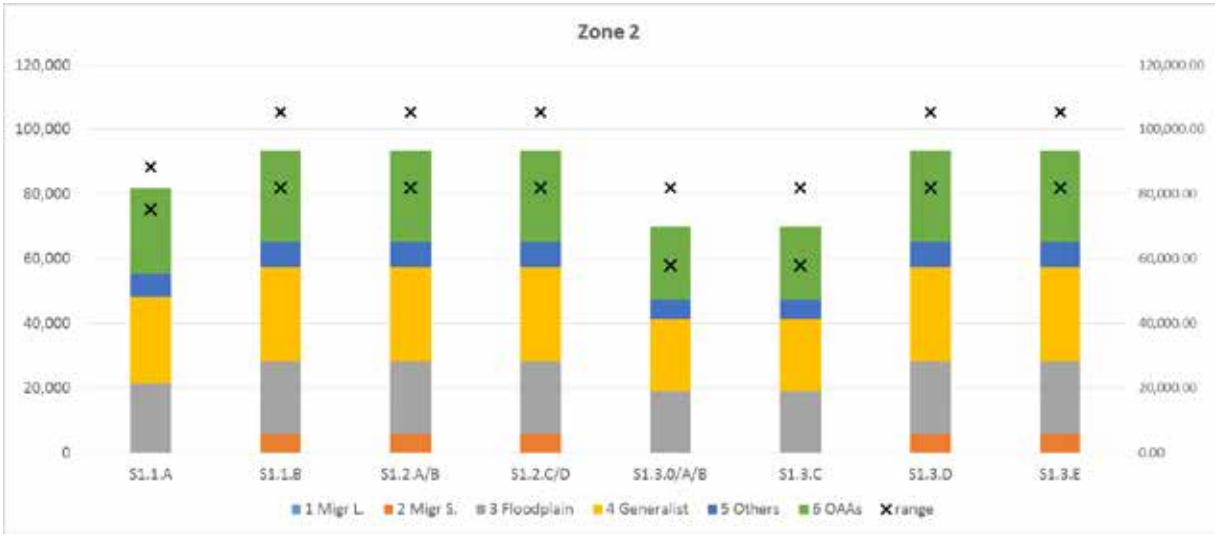


Figure 5.65. *Estimated fish biomass trends in impact zone 2 for combined scenarios.*

5.5.2.3.3 Estimated fish biomass trends in impact zone 3

Zone 3 is the least impacted zone, where biomass increases and decreases are comparable low. Here, the lowest biomass is expected for the unlimited peaking scenario while the other scenarios are a little bit higher. In general, scenarios with a fish pass show the highest biomass values in zone 3.

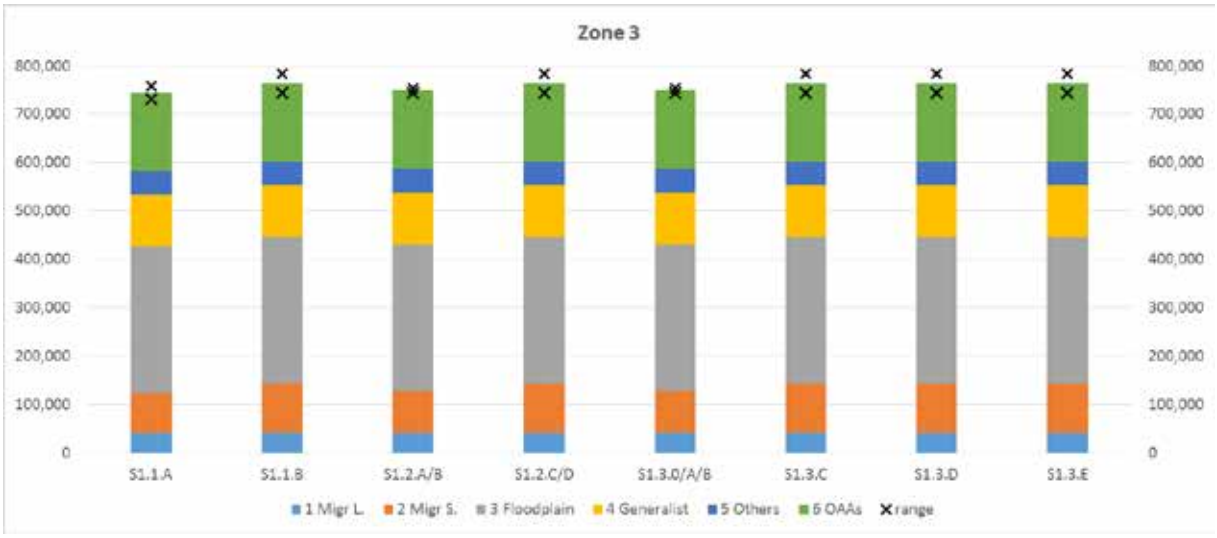
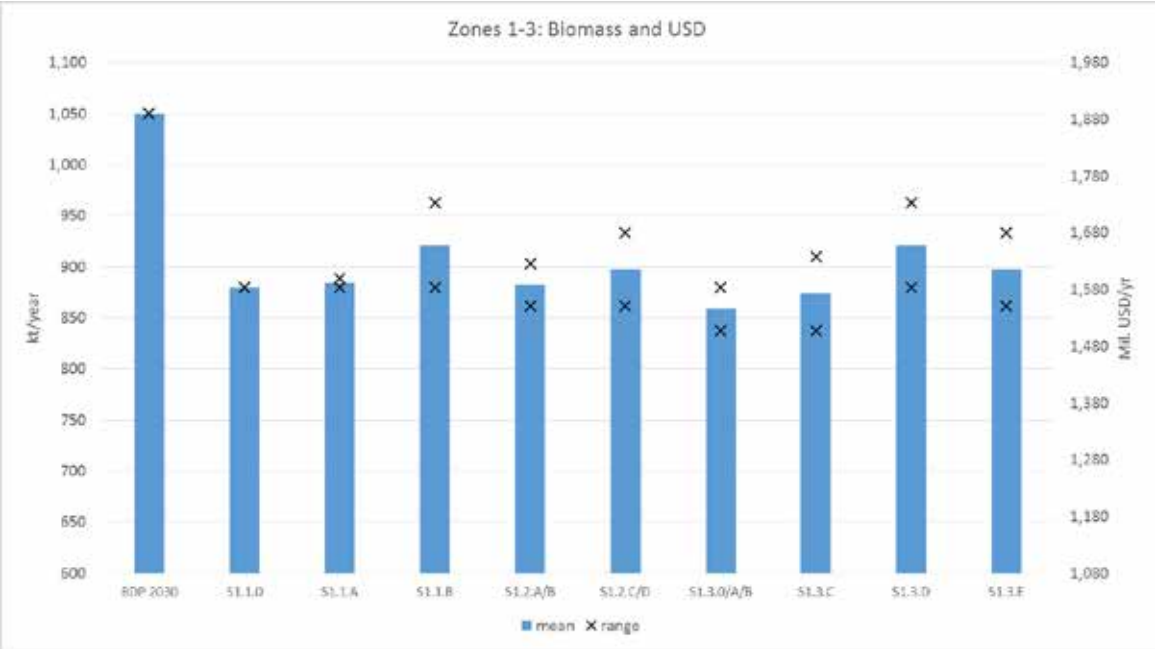


Figure 5.66. *Estimated (short-term) fish biomass trends in impact zone 3 for combined scenarios.*

5.5.2.4 ***Comparison of fisheries values between mitigation scenarios***

The following Figure shows the biomass trends for all scenarios as well as the economic valuation of the related fisheries products. The integrated table provides an overview of the included mitigation measures as well as the changes compared to Scenario 1.1.0 (in Mil. USD and in %). The scenarios with the highest biomass gain (compared to scenario 1.1.0) are scenarios 1.1.B and 1.3.D. Although both scenarios show a clear increase of biomass, it is clearly visible that the mitigation measures compensate a rather small share (compared to BDP 2030). With regard to

the economic valuation, it has to be highlighted that a rather conservative price of 1.8 USD/kg was applied, while much higher prices were stated by So Nam et al. (2015).



Grouped scenarios		1.1.0	1.1.A	1.1.B	1.2.A/B	1.2.C/D	1.3.0/A/B	1.3.C	1.3.D	1.3.E
Type		Run-of-river					Peaking			
Fish pass				x		x		x	x	x
Sed. flush.					x	x				
Peak. limit									x	
Re-reg.										x
Change compared to S.1.1.0	Mil. USD	0 to 16	0 to 148	-32 to 42	-32 to 96	-76 to 0	-76 to 54	0 to 148	-32 to 96	
	%	0 to 1	0 to 9	-2 to 3	-2 to 6	-5 to 0	-5 to 3	0 to 9	-2 to 6	

Figure 5.67. *Grouped scenarios and the related fish biomass and market values (for S1.1.0 only the mean value, which served as a baseline for evaluating the other scenarios, is shown).*

5.5.2.5 Biodiversity

A detailed biodiversity assessment of the different scenarios is not possible at this stage, since too little in known on the habitat requirements and life cycles of individual species. In general it is assumed, that all mitigation measures contribute to biodiversity conservation – at least for some species. However, as discussed in previous chapters, large migratory species might become also

extinct in zones 1 and 2 in scenarios including fish pass solutions. While reservoir flushing is mostly related to negative impacts within the cascade, it can show a clear positive effect further downstream and lead to the revitalisation of habitats for fish and benthic invertebrates. However, as shown in other chapters, flushing can only re-mobilize a small share of the deposited sediments. Therefore, while mitigation measures might be able to preserve some species, their efficiency might not be sufficient to sustain sensitive and highly specialized species, which is why a biodiversity decrease seems unavoidable for all cascade scenarios.

5.6 Impacts on Power Production and Revenues

5.6.1 Lao Cascade

5.6.1.1 Overall Assessment

The average annual energy output for each power plant and mitigation scenario obtained from the HEC-ResSim/MIKE11 energy modelling is presented in table 5.28. Full details of energy model outputs for all scenarios are presented in Appendix A. These details comprise duration curves together with power, energy, water level and discharge data for the average year (2002), a typical wet year (1991) and a typical dry year (1989).

Table 5.28. Average annual energy generation for all scenarios (GWh/yr).

	Pak Beng	Luang Prabang	Xayaburi	Pak Lay	Sanakham	SUM
Scenario 1.1.0	5,371	6,114	7,700	4,543	3,586	27,329
Scenario 1.1.A	5,000	6,129	7,229	4,543	3,557	26,471
Scenario 1.1.B	4,929	6,057	7,171	4,514	3,529	26,200
Scenario 1.2.A	4,786	5,829	7,400	4,343	3,386	25,743
Scenario 1.2.B	4,757	5,843	7,371	4,300	3,386	25,671
Scenario 1.2.C	4,747	5,757	7,325	4,301	3,349	25,478
Scenario 1.2.D	4,841	5,807	7,497	4,434	3,381	25,959
Scenario 1.3.0	5,303	6,080	7,685	4,524	3,507	27,100
Scenario 1.3.A	4,983	6,093	7,143	4,521	3,517	26,258
Scenario 1.3.B	4,987	6,092	7,203	4,535	3,533	26,351
Scenario 1.3.C	4,928	6,019	7,122	4,492	3,496	26,056
Scenario 1.3.D	4,905	5,976	7,022	4,384	3,331	25,617
Scenario 1.3.E	4,928	6,019	7,122	4,492	3,482	26,049

The energy output figures in table 5.28 has been converted to average annual revenue using the assumed tariff rates in table 3.34, in chapter 3.7.3. The results are listed in table 5.29.

Table 5.29. Average Annual Revenue (USD M).

	Pak Beng	Luang Prabang	Xayaburi	Pak Lay	Sanakham	SUM
Scenario 1.1. 0	376	428	539	318	251	1913
Scenario 1.1. A	350	429	506	318	249	1853
Scenario 1.1. B	345	424	502	316	247	1834
Scenario 1.2.A	335	408	518	304	237	1802
Scenario 1.2.B	333	409	516	301	237	1797
Scenario 1.2.C	332	403	513	301	234	1783
Scenario 1.2.D	339	406	525	310	237	1817
Scenario 1.3. 0	383	443	552	325	252	1955
Scenario 1.3. A	353	441	512	325	253	1884
Scenario 1.3. B	353	437	514	323	252	1879
Scenario 1.3. C	349	432	508	320	250	1859
Scenario 1.3. D	343	418	491	307	233	1792
Scenario 1.3. E	349	432	508	321	243	1853

5.6.1.2 Discussions on Hydropeaking

Concerning the additional revenue from hydropeaking, the two tables illustrate the following: With scenarios 1.1.0 and 1.3.0 we can compare unmitigated Run-of-the-River (RoR) with unmitigated hydropeaking. The table shows that hydro peaking reduces the generated energy by 1% but increases the income to developers by 2%. Furthermore, if we compare Scenarios 1.1.B and 1.3.E, i.e. comparing mitigated RoR with mitigated peaking, we see that peaking still reduces the overall generation by 1%, while peaking increases the revenue by only 1%. ***In scenario 1.3.E, a number of mitigation measures have been implemented, but ramping rates only at Sanakham. The evaluation is that such a scenario is relative harsh on the Cascade reach, although re-regulated further downstream by Sanakham. In the light of this, one can question whether a (only) 1% increase of the revenue justifies the environmental - and to some degree social - stress by peaking, thus possibly 1.3.D should be considered instead.***

The finding that peaking operation gives a rather modest increase of revenue to dams owners, reflects the fact that the two tariffs do not differ very much (5 resp. to 8 USc/kWh). It is tempting to say that a larger difference could have increased the gain from peaking, but then there is a need to ask what would have been the “flat” tariff in a RoR operation case. For modelling this question was answered by making some plausible assumptions, but in the real world this hypothetical question cannot be answered. Consequently, there is a significant uncertainty associated with assessing the benefit of peaking operation compared to RoR.

While difference between peak and off-peak tariffs is not large, it could also be argued that the word “peaking” is in fact not very descriptive of the tariff system that has been applied in the Case Study. The term peaking is normally used about a regime with a few hours, typically one or two periods per day, namely when the load indeed peaks. In such cases, the tariffs would reflect this by being much larger than the off-peak tariffs. On this background, it could be argued that the peaking

regime considered is a rather “gentle” form of peaking. Nevertheless, on has to ask whether the modest increase of revenue justifies the stress from a sudden flow change twice a day at four of the five dams (in Scenario 1.3.E).

5.6.1.3 Economic Cost of Mitigation Options

The commercial impact of each mitigation measure can be calculated by evaluating the difference in generation and revenue between the scenarios. In order to gain an understanding of the relative magnitudes of the average annual energy and revenue impact of each mitigation measure the difference between selected scenarios is presented in table 5.30.

Table 5.30. Energy and revenue impact of each mitigation type.

	Energy loss GWh/year	Revenue change MUSD/year	% change of total revenue	Comment
Flood draw down Xayaburi and lower dry-season water level at Pak Beng (Scenario 1.1.0 - 1.1.A)	857	-60	-3.2	30% of loss at Xayaburi and 70% of loss at Pak Beng
Fish passage (Scenario 1.1.A - 1.1.B)	271	-19	-1.0	
Annual sediment flushing (Scenario 1.1.B – 1.2.C)	722	-51	-2.8	
Peaking (Scenario 1.1.B - 1.3.C)	144	+25	+1.4	
Peaking with ramping limit of 5 cm/hr at Sanakham (Scenario 1.3.C – 1.3.E)	7	-6	-0.3	

From the results in table 5.29 it may appear that the requirement for flood draw down at Xayaburi and lower dry season levels at Pak Beng is introducing an annual energy loss on the cascade of approximately 857 GWh/yr representing a reduction in cascade revenue of 3.2%. This loss is almost entirely occurring at Pak Beng and Xayaburi and will require additional generation elsewhere on the Thai power system, most probably from thermal plant that will release approximately 0.8 M tonnes of CO2 equivalent into the atmosphere per year per GWh.

The introduction of the sediment flushing and sluicing programme in Scenario group 1.2 will introduce an additional energy loss of 722 GWh/yr. This loss may be additional to the draw down losses at Pak Beng and Xayaburi bringing the overall revenue loss to approximately 6%. ***This is substantial and would need to be offset by an upward tariff adjustment, when the PPA is negotiated.***

The provision of a fish passage system on each project with a similar design to that adopted at Xayaburi introduces an energy and revenue loss of approximately 1% per year. ***It is possible that this figure can be further reduced by optimisation of the pumping station and auxiliary turbine systems.*** Continued monitoring of fish migration patterns through completed projects should lead to a better understanding of attraction flow requirements and the ability to adjust flow rates to suit migration patterns at particular times of year.

The introduction of limited peaking at each project causes a minor energy loss as would be expected, but provides a useful revenue gain of approximately 1.5% (1.1.B versus 1.3.D). ***This would more than offset the revenue loss due to fish passage discharges.*** The introduction of tailwater limitations at Sanakham makes very little difference to the overall revenue gain from daily peaking.

5.7 Combined Evaluation of Mitigation Measures

5.7.1 General

Details of the impacts of the various mitigation measures on each indicator/measure is given in Annex F. The following is a summary of the latter and the assessment of the previous sub-chapters of Chapter 5. Furthermore, the methodology for the combines scoring and evaluation has been given in Chapter 3.1.1, including the selection of the most promising indicators for the multicriteria assessment

5.7.2 Northern Lao Cascade – Local and Cumulative Impacts

With regard to hydrology and flows there is minor differences between the scenarios on seasonal and intra-seasonal changes to flow as the cascade has minor impact on this anyway. With regard to sub-daily changes to flow this becomes prominent in the peaking scenarios. This scores -2 across the scenarios for Zone 1 with regard to the indicator on hourly dewatered area, while in Scenario 1.3.D (ramping rate limitation on all dams) this is mitigated for and scoring is set to zero.

Related to sediments and geomorphology scenarios 1.1 (Run-of-River) and 1.3 (Peaking) have minor impacts (see also section 5.4). All scenarios in 1.2 have a positive effect in the cascade zone and the zone from Sanakham to Paksane for most of the indicators with a uniform score of +1.

When considering fisheries and aquatic ecology solely scenario 1.1.B and 1.3.D are the most promising for impact zone 1, whilst for zone 2, scenario 1.2.C and D also indicates benefits for the aquatic habitats due to replenishment of sediments via flushing.

Related to hydropower production all scenarios with its associated mitigation measures shows a negative impact on the energy revenues compared to scenario 1.1.0, except 1.3.0 (peaking with no mitigation) which has a positive score of 1. The most negative effects are within the 1.2A to D scenarios (flushing) (see also section 5.2), all with a ranking score of -2. Scenario 1.3.D with restrictions on ramping rate for all dams also gets a negative score of -2.

Overall when the environmental mitigation for the cascade is considered jointly, the following findings are relevant:

- Draw down of the Xayaburi operating level during floods was found to be only marginally beneficial in reducing flood level at Luang Prabang, with the models used. Further work is needed to optimise this rule to maintain operational flexibility and to ensure no effect on flood levels at Luang Prabang; (Scenario 1.1B)
- Water level draw down at Pak Beng as proposed by CNR (2009) allows for reduced dry season flooding of areas upstream on the Thailand border area. Again, this operation and the benefits need to be re-assessed. (Scenario 1.1B)
- The analysis found that the drawdown approach at the above two structures reduced revenue from the two schemes (Pak Beng and Xayaburi) by an average of 3.2% per year ($60m).

- The installation of advanced fish passage facilities for upstream and down stream migration was beneficial. However, certain larger migratory species would be significantly affected and potentially be driven to extinction. Even with mitigation a 60% reduction in biomass within the cascade reach could be expected. Residual loss in biomass and biodiversity is also expected, even with the mitigation, in the reaches downstream. (Scenario 1.1B). Fish passage operations were estimated to reduce annual revenues by approximately 1% per year ($19m).
- The cascade will trap approximately 14 MT of the 20 MT entering the impoundment, with only silt and clay readily transmitted through the cascade as part of normal operations. Coordinated sediment flushing of each cascade dam over a period of about 60 days was found to mobilise fine sand from the impoundments and increased sediment discharge by up to ~2 MT/yr. Flushing operations initiated in August produced the highest sediment discharge due to the higher sediment concentrations entering the impoundments and being maintained in suspension during the flushing events. Only minimal quantities of coarse sands and gravels were mobilised by the flushing operations, however, the effectiveness of flushing coarser material is likely to increase as sediment deposition within the impoundment progresses closer to the dam wall and low level outlets. These flushing operations reduced revenue in the cascade by approximately 2.8% ($51 M/year).
- Within the downstream reaches (zone 2 and zone 3) flushing of sediments was found to benefit the aquatic habitats due to replenishment of sediments (Scenario 1.2.C and D) and the associated nutrients.
- Geomorphological changes both within and downstream of the cascade were shown to occur over longer time frames (decades). A clear “erosion wave”, was observed to move downstream of Sanakham at a rate of approximately 20 km per year, affecting Vientiane after approximately 8 years. The ‘wave’ removes available sediment, resulting in a deepening and / or widening of the channel and an increased exposure of bedrock. The actual rate of channel erosion following implementation of the cascade will depend on the quantity of sediment available for transport in the channel, and the hydrologic variability (e.g. large floods will remove more sediment as compared to dry years). Within the impoundments, sediment deposition created a ‘delta’ that increased in size from the upstream end of the impoundment towards the dam wall over time.
- The introduction of peaking operations, to take advantage of higher daytime tariffs, has significant impact on all indicators downstream and within the cascade. These impacts were found to be mitigated by the introduction of ramping restrictions on all dams (Scenario 1.3.D) or only Sanakam (Scenario 1.3.E) and the introduction of a minimum flow in the cascade reach and downstream. However, the introduction of these ramping restriction and minimum flow almost negated the peaking revenue benefits. (Net across the cascade of $xm per year). Further work is required to optimise and mitigate this operation if peaking operations are envisaged.
- In general scenarios which include a combination of fish passes, minimum flows, provisions of flushing/sluicing and for hydropeaking limitations on ramping rates will benefit the widest array of indicators as shown in the Figure 5.68 overleaf.

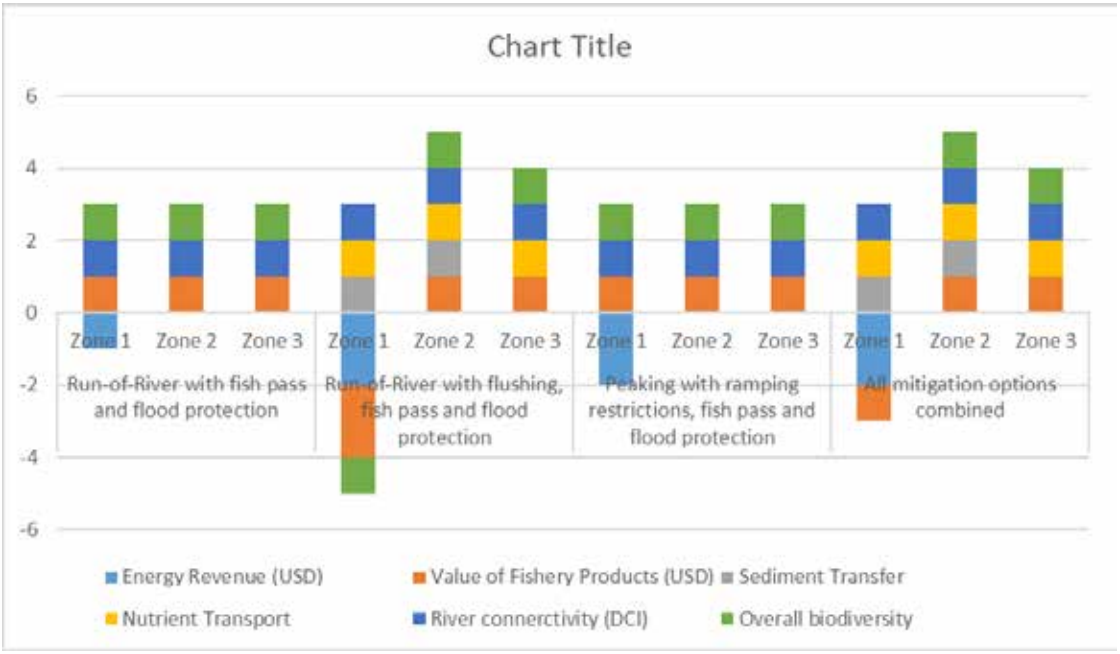


Figure 5.68. *Change in Key Selected Indicators relative to the "no mitigation" Option.*

For each indicator in Figure 5.68 above the scoring indicate as follows:
+3 = high increase
+2 = medium increase
+1 = low increase
0 = no change
-1 = low decrease
-2 = medium decrease
-3 = high decrease
Most indicators scores in the range of +1 to -1 (low increase to low decrease). The scenarios with the lowest energy revenues (flushing and ramping rate restrictions on all dams) scores -2 for this indicator.

Recommended Management Strategy for the Northern Lao Cascade

Given the results from the combined assessment above the strategies that benefits the widest array of themes, issues and users will be those of a combination of all mitigation measures. Peaking with limitations on ramping rates will need to be studied further in order to optimize environmental benefits and economic impacts. To cater for the revenue loss due to sluicing a central authority for dispatching optimal cascade performance should be considered. Tariff adjustment would need to be negotiated within the Power Purchase Agreement after consideration of the ESIA and prior to the signing of the concession agreement to cover the required operational changes (see also last section in the Executive Summary).

When considering the most promising management strategies, optimization of design for the cascade projects should be considered. Allowance should also be made for coordinated operations. This could include, among other options, optimization and flexible designs for pumping stations and auxiliary turbines connected to the fish passages as well as a combination of low and high level sluices, throughout the cascade, for optimal and coordinated flushing and sluicing.

6. Phase 4 Assessment

6. Phase 4 Assessment

6.1 Alternative Schemes Layouts for the Northern Lao Cascade – Good Practise, Practicality and Relevance for LMB

6.1.1 Engineering Design and Operation

6.1.1.1 Potential engineering solutions

Smaller reservoirs

The mainstream schemes do not require active reservoir storage. Analysis of peaking options indicates that storage provides very limited commercial benefit. The reservoirs on the mainstream schemes, as currently envisaged, are created to provide generating head, not storage. The creation of reservoirs obstructs downstream fish migration, traps sediment, reduces water quality and increases environmental footprint. Reduction of reservoir size would therefore be beneficial.

The creation of a series of fully gated low head barrages could replace a single mainstream dam and would capture a similar amount of energy if the cumulative head was the same. These structures would impound smaller volumes of water and keep the river closer to its natural regime. At critical times of year (or on a regular basis such as weekends) the gates could be opened and the river returned to entirely natural conditions to allow sediment transport and fish migration in either direction. This form of structure is adopted for tidal barrages and the principles are described in the Manual.

Low head turbines

There are various forms of low head turbine commercially available. These are described in the Manual. Conventional low head horizontal axis bulb turbines can function efficiently at differential heads as low as 5 m. This type of machine currently provides the only practical alternative to pass the high volumetric flow rates required for the Mekong.

Low speed machines with a low number of blades present a reduced hazard to downstream fish passage. This hazard can be removed almost entirely by shutting down generation and placing the turbines in sluicing mode. Under this sluicing condition, there is almost no pressure gradient and the blades will rotate slowly.

The hazard created by horizontal axis bulb turbines can be further reduced by increasing the submergence of the centre line. There are two requirements for the submergence of a horizontal axis turbine:

- ***Intake submergence:*** The centre line at the intake must be sufficiently submerged to prevent the formation of detrimental vortices. Minor circulation can usually be accepted but air or trash entraining vortices must be avoided.
- ***Draft Tube submergence:*** The centre line of the draft tube must be sufficiently submerged to provide a back pressure on the turbine runner to prevent the formation of vapour pressures and damaging cavitation.

The turbine centre line elevation must be selected to satisfy both these criteria. However, the proportional pressure gradient through the machine can be reduced by setting the centreline lower than the minimum requirement. The concept is shown in Figure 6.1.

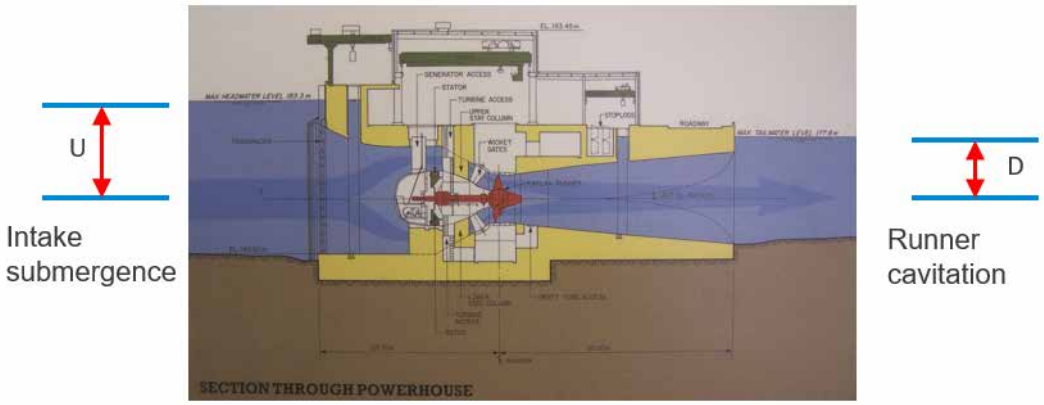


Figure 6.1. *Bulb Turbine Submergence.*

Lowering the turbine centre line results in additional cost for the structure and the excavation. A lower centre line does not alter the generating head (U-D) or the energy delivered, but the relative pressure gradient (U/D) for fish passing through the machine is reduced and a lower centre line improves the opportunity to return the river to its natural regime by sluicing.

Fish friendly spillways

Gated spillways will be required for the mainstream Mekong projects because of the high flow rates that must be discharged. The most economic form of gated spillway is likely to be a gated crest as shown in Figure 6.2.

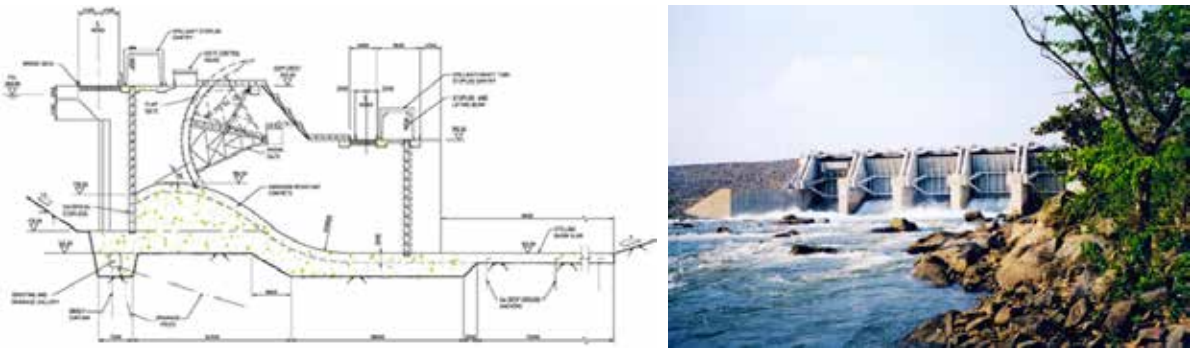


Figure 6.2. *Gated Crest Spillway.*

The gated crest spillway shown in Figure 6.2 is a barrier to upstream fish migration because the water velocity flowing down the weir face will be too high when the gates are fully open. The gated crest is also unsuitable for downstream migration when the gate is partially open (as shown) because of the rapid pressure drop when the water passes under the gate seal. The weir is also a fixed barrier to downstream sediment transport until material has accumulated to the level of the crest.

When the gate is in the fully open position downstream fish migration may be feasible but a hydraulic jump may form on the apron downstream that may cause injury to fish through impact or high pressure gradients. For this reason, end sills and baffle blocks should be avoided on the downstream apron if fish migration is required.

Lower head barrages will relieve some of these issues and undershot gates may provide a satisfactory arrangement if the gate sill is set at riverbed level. The Nam Ou 2 project in Laos shown in Figure 6.3 comprises three horizontal axis bulb turbines and seven vertical lift gates. Once all seven gates are fully open, the river returns to its natural regime and the project is not a barrier to fish migration or sediment transport. However, when the gates are partially open the scheme remains a complete barrier to fish migration in either direction, and coarse sands and gravels are deposited in the reservoir upstream.

Figure 6.3. *Nam Ou 2.*

An alternative approach is to avoid undershot gates where possible and adopt overshot gates. These could be either flap gates or sector gates. Figure 6.4 shows the Nakdong Dalseong and Yeoju rising sector gate barrages in South Korea. These structures can generate a differential head of approximately 10 m and comprise rising sector gates 45 m long. The gates can be lowered to allow the river to be returned to a fully natural condition to allow fish migration, sediment transport and navigation. The gates can be operated in an undershot or overshot condition and can be fully withdrawn from the water for maintenance.

Figure 6.4. *Rising Sector Gate Barrages (South Korea).*

Bottom Outlet Gates

If bottom outlet gates are adopted for draw down or sediment management it may still be possible to use these facilities for downstream fish migration if the pressure gradient can be made sufficiently gradual. One option to create a gentler gradient would be to provide a submerged conduit downstream of the gate so that the pressure drop is distributed along the entire length of the conduit.

Temporary Shut Down

The objective of Option 1.4 in the Case Study was to examine the implications of stopping generation and drawing the reservoirs down at critical times of year. It was envisaged this strategy would facilitate fish migration and sediment transport at selected periods when natural river conditions would be most beneficial. The value of energy lost during these shut down periods could be assessed against the improved environmental performance of the cascade.

However preliminary assessment of Option 1.4 indicated that the adopted spillway geometry at Xayaburi will not support this mode of operation. Flow velocities through the spillway gates were found to be in the range 7 – 10 m/s making upstream fish migration impossible and downstream migration hazardous.

The concept of shut down can therefore only be contemplated for projects downstream of Xayaburi.

The adoption of a shut down mode of operation has been studied on other projects in the region. For example, the Xe Bang Fai 1 Hydroelectric Project (Lamson Geotechnical Co Ltd & Viet Ha Consultant – June 2016) is planned to be shut down for approximately 3 months each year when high tail water levels reduce the generating head to less than 2 m. Under these conditions, the spillway gates will be opened and the river will return to its natural condition. This strategy restores the connectivity of the river and has the additional benefit of reducing the risk of flooding upstream.

6.1.1.2 Alternative Layouts

Concept

In order to assess the feasibility of sub dividing mainstream projects, an examination has been undertaken into the implications of replacing a typical 30 m gross head mainstream project, with two 15 m gross head projects. The overall river reach of the two lower head projects would be the same as the full height scheme. In this manner, the extent of river reach concessions would remain unchanged.

The lower head projects would provide the following environmental advantages:

- Substantial reduction in impounded water volume, potentially resulting in improved water quality, reduced temperature change and lower sediment retention;
- Lower head dams, making fish passage in either direction more feasible and survivable;
- Lower gross heads suitable for fully gated barrages;
- Lower gross heads suitable for horizontal axis low speed bulb turbines;

- Creation of impounded depths much closer to natural flood surcharge levels; and
- Making it feasible to draw down reservoirs to natural river conditions during flood periods without large changes in water level and corresponding ecological stress.

The reduced gross heads would permit the adoption of rising sector gates designed for gross head differences of up to 15 m. Figure 6.5 shows the operating positions for these gates.

All river flow is diverted through the turbines when the gates are in the fully raised position. This configuration would be adopted throughout the dry season when the river discharge is lower than the capacity of the generating plant.

When the river discharge exceeds the generating plant capacity, spilling will commence. This will typically occur for at least 4 months each year. Spill flows will pass over the crest of the gates and down the downstream face. This configuration avoids rapid pressure gradients and fish can pass without injury. The correct discharge can be achieved by adjusting the angle of the gate. The head pond level can be permitted to rise, thereby maintaining the generating head.

Local accumulation of sediment can scoured by rotating the gate in the opposite direction to release an undershot flow. Continued rotation in this direction will raise the gate out of the water for maintenance.

At critical times of the year, the generating plant can be shut down and the gates lowered so that the river is returned to entirely natural conditions. This configuration will facilitate unimpeded fish migration in either direction and sediment transport in a downstream direction.

Figure 6.5. *Rising Sector Gate – Operating Positions.*

Layout

To compare the alternative layout of two 15 m gross head projects replacing the typical 30 m gross head mainstream project, basic concept drawings of the two projects have been produced and a costing exercise completed for both schemes.

The layout drawings have been based on a typical, but non-specific, location on the Mekong. The direct civil engineering quantities and costs have been compared on a percentage of cost basis rather than an actual monetary value.

The full height, 30 m gross head scheme includes a powerhouse located on the left side of the river channel (viewed downstream), an intermediate 'island', and a gated crest spillway in a new channel excavated on the right side of the existing river channel. A navigation lock is positioned on the right side of the river and a fish pass/ladder is on the downstream left side of the river.

The general plan layout is shown in Figure 6.6.

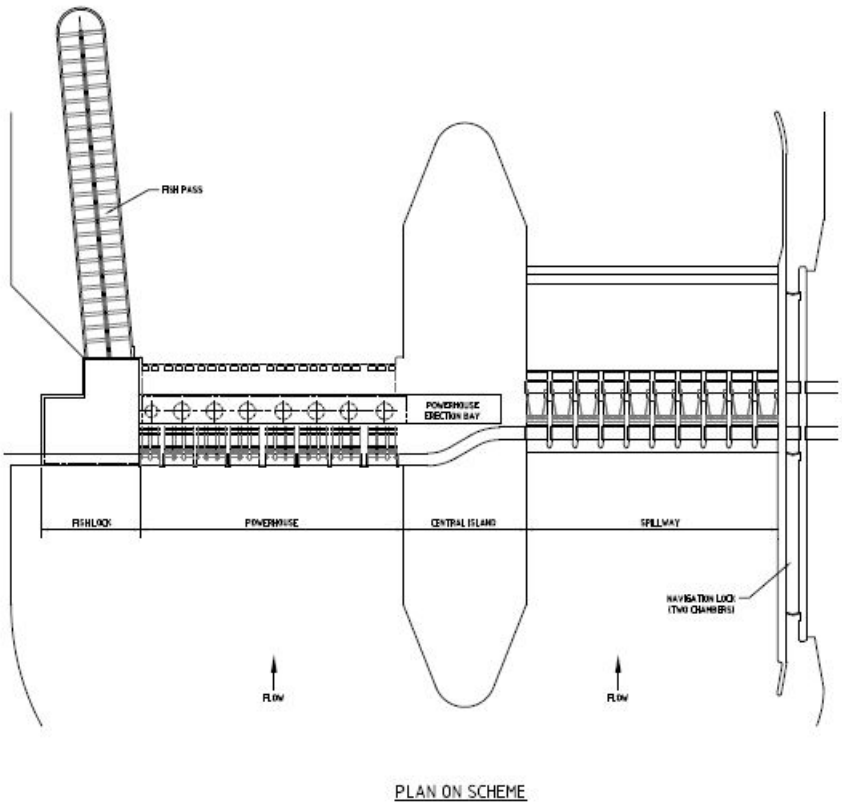


Figure 6.6. *30 m Gross Head Scheme – Plan View.*

To facilitate construction it has been assumed that the initial civil works comprising the spillway, navigation lock and central island, would be constructed in the right channel, outside the main river channel. The river would remain in its original channel during this phase of the works. Upon completion of this first phase, the river would be diverted through the completed spillway and upstream and downstream cofferdams would be installed across the river channel to allow the powerhouse and fish pass to be constructed.

The powerhouse is assumed to consist of 7 no. main export units and 1 no. smaller domestic unit across the full width of the original river channel. The units are all assumed to be vertical axis Kaplan with a combined rated discharge of 5,400 m3/s. The upstream section of the powerhouse structure houses the intake channels with trash rack screens, intake screen gates, stop log slots and gantry cranes. A vehicular road bridge spans across the upstream intake channel walls and allows traffic to cross the full width of the river channel. The central section of the powerhouse houses the Kaplan units and the machine hall. The downstream section contains the control rooms, draft tubes and stop logs. The cross section is shown in Figure 6.7.

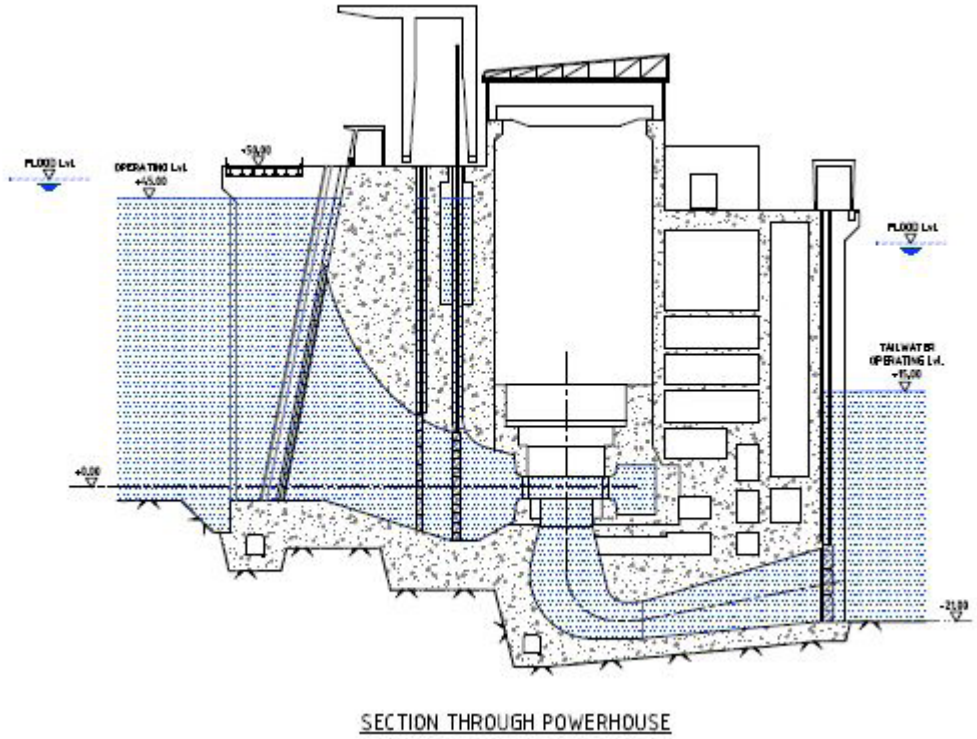


Figure 6.7. *30 m Gross Head Scheme – Powerhouse.*

The spillway is assumed to consist of a gated crest section with 10 no. gates and water passageway channels across the width of the excavated channel. The combined capacity under PMF conditions is assumed to be 45,000 m3/s. Each gate pivots from trunnions set above maximum tailwater level. Upstream and downstream stop log slots are provided. Upstream of the gates a vehicular road bridge spans each channel and continues to the powerhouse bridge section. A second similar road bridge also spans between the channels downstream of the gates. The spillway crest is a gravity structure discharging into a concrete stilling basin. A cross section is shown in Figure 6.8.

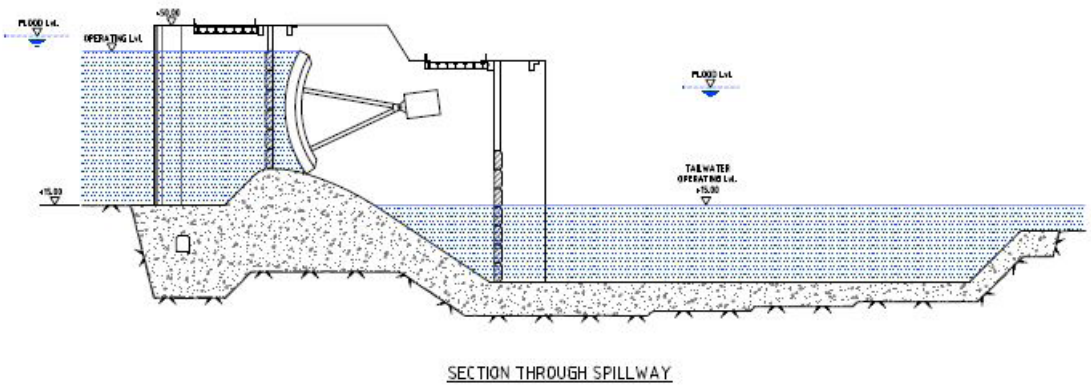


Figure 6.8. *30 m Gross Head Scheme – Spillway.*

The central island connects the powerhouse and spillway structures and is constructed at the edge of the original river channel. The island is assumed to be a concrete structure constructed behind a steel sheet piled cofferdam adjacent to the river channel. It is assumed that the island will house

the erection bay as a continuation of the powerhouse superstructure. Equipment rooms and fish migration passageways are also located in the island structure.

The navigation lock is assumed to consist of a concrete channel section with two gated chambers running the full length of the central island. Concrete training and retaining walls will direct the river traffic through the lock system.

The fish pass is located on the downstream side of the powerhouse and consists of a concrete fish ladder that allows the fish to migrate up approximately half the height of the powerhouse structure. The fish will then enter a double lock system and moved up to the final discharge point into the upstream reservoir.

The alternative half height, 15 m gross head scheme (of which 2 no. will replace the 30 m gross head scheme) also includes a powerhouse located on the left side of the river channel, an intermediate island and a gated spillway constructed in a new channel excavated on the right side of the river. A navigation lock is positioned on the right side of the river and a fish pass on the downstream left side of the existing river channel. However, the reduced gross head of the scheme allows the use of low head horizontal axis turbines and the adoption of rising sector gates for the spillway. The discharge capacity of the turbines and spillway gates will be the same as the full height scheme.

The general plan layout is shown in Figure 6.9.

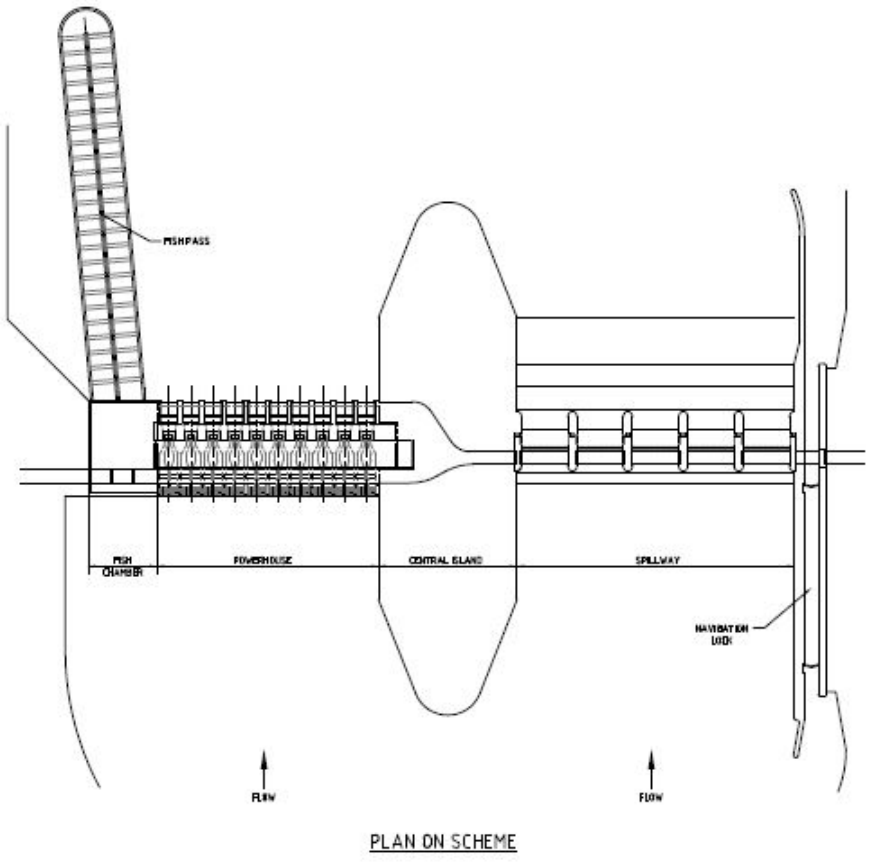


Figure 6.9. *15 m Gross Head Scheme – Plan View.*

The construction sequence will be similar to the full height scheme. It is assumed that the initial civil works will be in the right channel with the river remaining in the main channel. The second phase would again involve the river being diverted using cofferdams through the completed spillway structure and past the central island to allow the powerhouse and fish pass to be constructed offline.

The powerhouse for the alternative scheme is assumed to consist of 10 no. bulb units across the width of the main river channel. The upstream section of the powerhouse will house the intake channels, trash rack screens, intake gates and gantry cranes. The central section of the powerhouse will house the bulb turbines with the machine hall above. The downstream section is assumed to house control and equipment rooms above the draft tubes. A stop log slot is provided in each downstream channel with a high-level vehicular road bridge spanning across the water passageways.

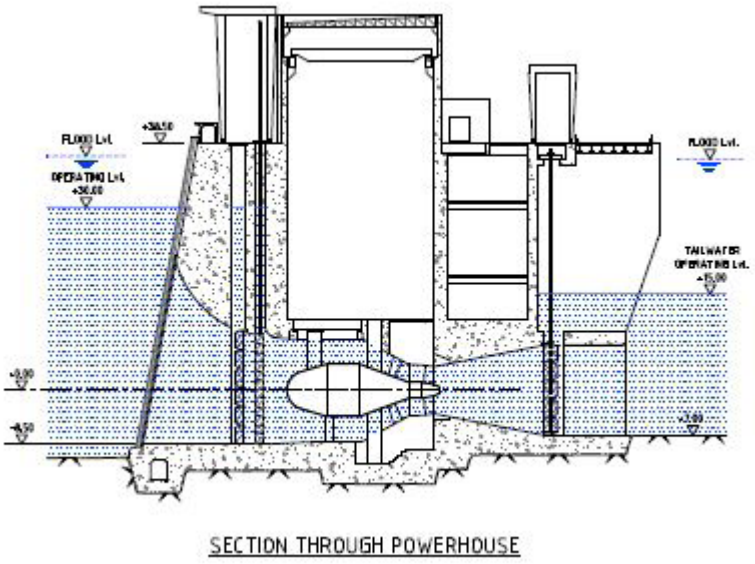


Figure 6.10. *15 m Gross Head Scheme – Powerhouse.*

The spillway is assumed to consist of 5 no. rising sector gates supported by hollow piers. The sector gates are rotated by equipment located within the piers. A scalloped bottom slab allows the gate to be laid flat during shut down and to return the river to natural conditions. Upstream of the gates a vehicular road bridge spans between the waterways and across the full width of the excavated channel. A section through the spillway is shown in figure 6.11.

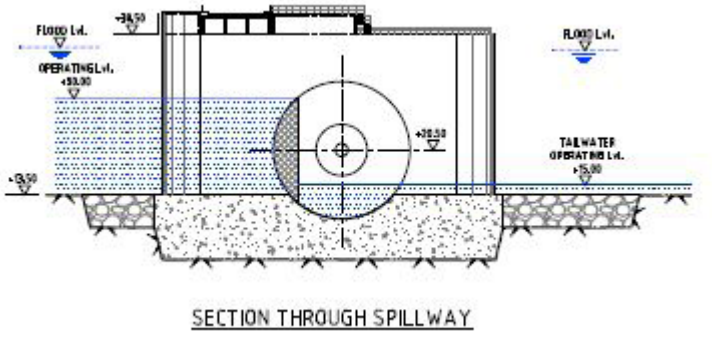


Figure 6.11. *15 m Gross Head Scheme – Spillway.*

The central island will connect the powerhouse and spillway structures. The island for the low head scheme is assumed to be a simple backfilled structure constructed behind a steel sheet piled cofferdam at the edge of the original river channel. The island will not require an erection bay and will not require passageways for the downstream migration of fish. The island will instead be topped with a concrete slab to allow space to support the various items of equipment.

The navigation lock is again assumed to consist of a concrete channel section running the full length of the central island. Concrete training and retaining walls will direct the river traffic through the lock system. Only a single chamber lock is required for the half height scheme.

The fish pass for the half height scheme will be of a similar size to the full height scheme but will deliver the fish to the required discharge height into the upstream reservoir. Therefore, the fish pass will not require additional fish lock and fish lift systems.

The existing river profile is assumed to be similar for both schemes to provide a consistent basis for comparison.

The existing riverbed level is assumed to be at +0.00 m, with a right hand flood channel at +18.00 m.

The dimensions and levels of the main component structures of the alternative schemes are as follows:

Full Height (30 m Gross head) Scheme

Powerhouse

The intake level is assumed to be just below the existing riverbed level with the centreline of the Kaplan units at + 0.00 m. The foundations of the powerhouse are assumed to be founded on rock below the riverbed, with the draft tube outlets at -21.00 m. The operating level of the upstream reservoir is assumed at c. +45.00 m with the deck level at +50.00 m.

Spillway

The upstream intake level is set at +15.00 m i.e. below the assumed existing flood channel level. The spillway is assumed to be founded on rock with the downstream stilling basin set at +0.00 m and the outfall at +10.00 m. The deck level is also set at +50.00 m to tie-in with the road bridge and central island.

Island

The island deck level is assumed to be +50.00 m with the foundations at approximately 3 m below the existing riverbed and flood channel levels.

Navigation Lock

The lock is assumed to be 12 m wide and 25 m deep to allow river traffic to pass through. Two lock chambers are required to command the total head difference of 30 m.

Fish Pass

The fish pass is founded at the level of the powerhouse draft tubes. The ladder structure extends half height up the powerhouse structure and the fish lock chambers are assumed to be founded at this level.

An upstream elevation of the 30 m head scheme is shown in Figure 6.12.

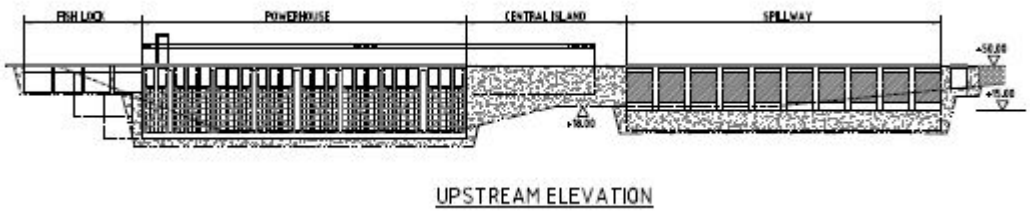


Figure 6.12. *30 m Gross Head Scheme – Elevation.*

Half Height (15 m Gross head) Scheme

Powerhouse

The centreline of the bulb turbines is taken to be lower than the minimum requirement to reduce the pressure gradient for fish. The centreline of the turbine is assumed at +0.00 m (the riverbed level) which will increase excavation depths with the intake level at -8.50 m. The bulb turbine water passageway is horizontal with the downstream outlet level at -7.00 m. The foundations of the powerhouse are assumed to be founded on rock below the riverbed. The operating level of the upstream reservoir is assumed at c. +30.00 m with the deck level at +38.50 m. This large flood surcharge provision is necessary because the selected operating level is lower than the natural extreme flood level.

Spillway

The upstream intake level is set at +13.50 m i.e. below the assumed existing flood channel level. The spillway is assumed to be founded on rock with the downstream outlet also set at +13.50 m to facilitate the shutdown operation and the river being returned to its natural regime. The deck level is also set at +38.50 m to tie-in with the road bridge and central island.

Island

The island deck level is assumed to be +38.50 m with the foundations at approximately 3 m below the existing riverbed and flood channel levels.

Navigation Lock

The lock is assumed to be 12 m wide and 25 m deep to allow river traffic to pass through. A single lock chamber is sufficient for the gross head difference of 15 m.

Fish Pass

The fish pass is founded at the level of the powerhouse draft tubes. The ladder structure extends up the full height up the powerhouse structure.

An upstream elevation of the 15 m gross head scheme is shown in Figure 6.13.

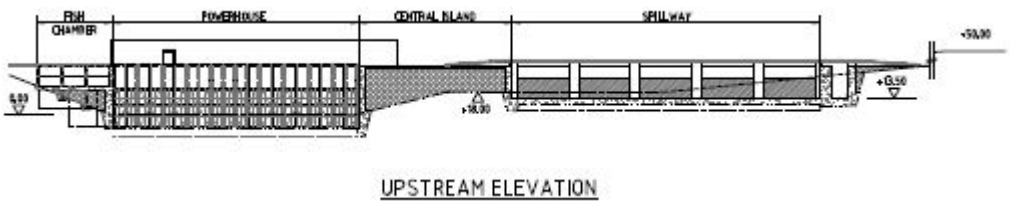


Figure 6.13. *15 m Gross Head Scheme – Elevation.*

The overall stability of the powerhouse and spillway structures for both schemes was assessed using standard methods for gravity structures assuming standard uplift distributions and factors of safety.

Turbine selection and sizing

The half-height (15m gross head) scheme is suited for the incorporation of bulb turbines. Bulb turbines have the same efficiency as Kaplan units but are smaller and more compact. This generally means that the powerhouse is also smaller and results in a shallower excavation as a vertical draft tube is not required. Other advantages include shortened erection times and improved access for maintenance and repair.

To match the assumed output of the full height scheme (c. 1,280 MW) the unit size was selected as 64 MW, which is close to the largest bulb turbines currently installed in the world (75 MW units installed at Jirau, Brazil).

The typical water passageways are shown in Figure 6.14 for the bulb type turbine on the left and a Kaplan type turbine on the right. It can be seen that in general the cross section of a powerhouse incorporating bulb type turbines will be smaller than that of the Kaplan units and require less excavation.

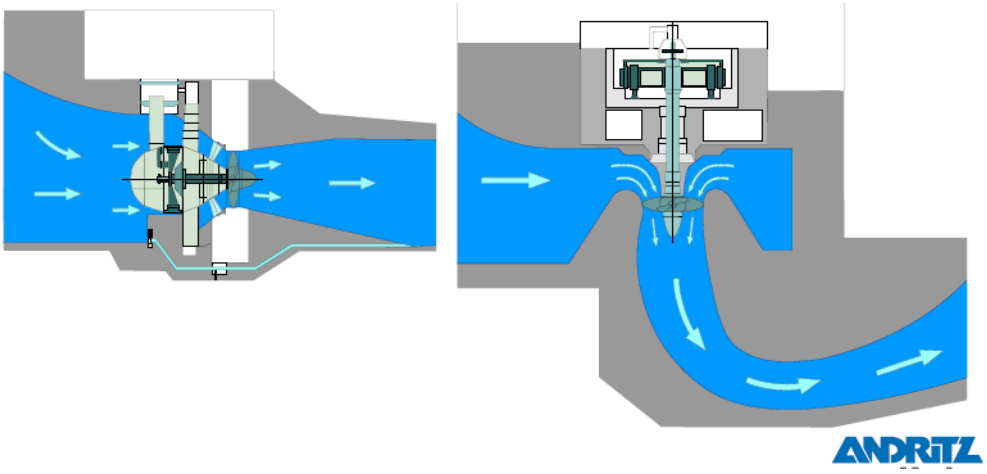


Figure 6.14. *Bulb v Kaplan turbines.*

Similarly, the plan dimensions for the equivalent units can be smaller as shown in Figure 6.15.

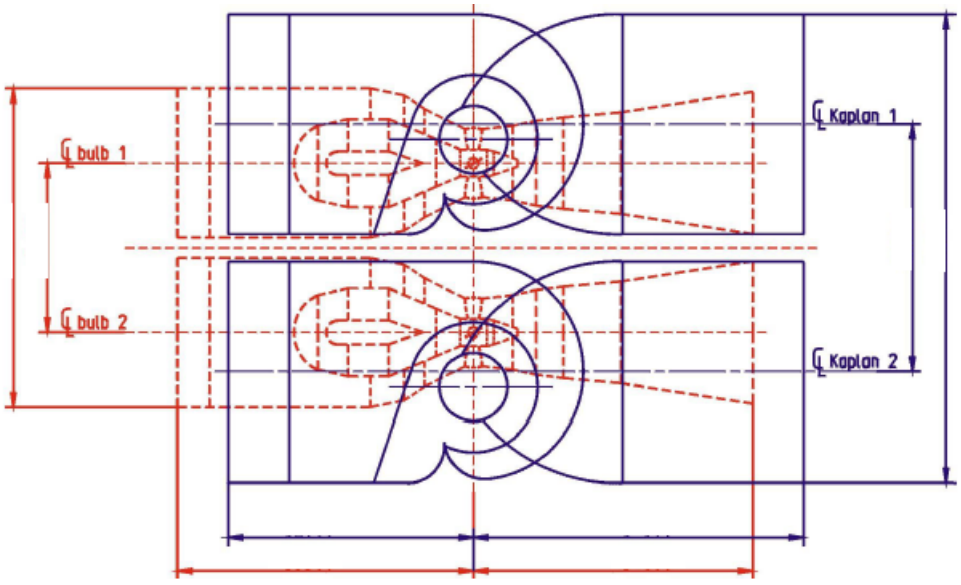


Figure 6.15. *Kaplan vs Bulb sizes turbines – Plan view.*

Construction Cost

Civil works

To compare the alternatives of a 30 m gross head scheme with two 15 m gross head schemes a costing exercise has been undertaken. The main civil works quantities for the two alternatives were calculated and US Dollar rates applied to determine comparative costs.

The alternative schemes were each costed by assessing by following components:

- Powerhouse structure
- Spillway structure

- Central Island
- River Diversion
- Navigation Lock
- Fish Pass structure
- Switchyards
- Access Roads

The main civil works items assumed in the take-off of quantities included excavation, concrete, reinforcement, structural steelwork, grouting, sheet piles, fill, cofferdams and erosion protection.

Quantities of all the above civil works items were based on the typical outlines for the alternative schemes. The rates used to calculate the costs for the schemes were based on a database of unit rates compiled from previous similar projects throughout the world. The rates in the database include figures from feasibility studies and from construction projects with actual contract rates. The most appropriate rate for each work item was established and used to compile and overall costing for each alternative. The rates were escalated where necessary to Q4, 2017.

M&E works

Equipment costs for the powerhouse, spillway and fish pass were calculated together with the switchyard equipment costs and the transmission line. The equipment costs were based on the work completed by the NVE (Norwegian Water Resources and Energy Directorate) – 'Cost base for hydropower plants 2016 version'. The report is based on a large sample of historical prices of installed hydropower plants and the most appropriate equipment costs were used and modified accordingly for the assumptions made for the two alternatives.

Typically, the cost of turbines is calculated as a function of type, power, head and discharge. This approach was also used to calculate costs for the following equipment items; generators, transformers, switchgear, E&M axillaries, control systems, and cooling and drainage systems.

Cost Comparison

Based on the assumptions for the existing riverbed profile and the levels of the different structures, a 'comparative cost' for each alternative was calculated. Additional assumptions for the civil and M&E works were included to provide 'like for like' costs. These included the following:

<u>30 m gross head scheme</u>

- Access roads approximately 25 km;
- Sheet piled cofferdam required to construct the central islands – river channel side only;
- Gantry cranes required for all gates and stop logs;
- The vehicular road bridge is a composite steel beam and concrete deck slab;
- Powerhouse spiral casings are steel lined;
- Powerhouse draft tubes are part steel lined;

- Powerhouse roof is structural steel, walls and slabs are reinforced concrete;
- River diversion cofferdams crest level = +40.00 m, upstream slope = 1:1.5, downstream slope = 1:2;
- A single switchyard serves the power station;
- Transmission line = 40 km;
- 1280 MW total output.

15 m gross head scheme

- Access roads approximately 50 km;
- Sheet piled cofferdam required to construct the central islands – river channel side only;
- Gantry cranes required for all gates and stop logs;
- The vehicular road bridge is a composite steel beam and concrete deck slab;
- Powerhouse draft tubes are steel lined;
- Powerhouse roof is structural steel, walls and slabs are reinforced concrete;
- River diversion cofferdams crest level = +30.00 m, upstream slope = 1:1.5, downstream slope = 1:2;
- Two switchyards serve the two power stations;
- Transmission line = 40 km plus 10 km to connect two power stations;
- 1280 MW total output for the two Power Stations.

It will be noted that more bulb units are shown than Kaplan units on the typical layout drawings. Generally, bulb units have a smaller capacity than Kaplan units and as such more are required for the same power output.

Preliminaries are added to the direct civil and M&E costs to include environmental surveys, topographical and geotechnical surveys, laboratory testing and mobilisation costs. These are taken as a percentage of the direct costs. Also included in the final 'comparison costs' for each alternative are indirect costs to include contractor M&E management and co-ordination costs, design support costs during construction works, client management and support costs, and contractor profit.

The costing exercise produced the following results when comparing a single 30 m gross head scheme with two 15 m gross head schemes. The cost of the single 30 m gross head scheme was assumed to be the baseline cost of 100% and the table below shows the percentage cost contribution of the main components to this baseline final cost.

To compare this baseline cost with the two 15 m gross head schemes, the percentage costs of the equivalent main components were calculated and are also shown in the table below.

Table 6.1. Cost comparison – Alternative schemes.

Cost Comparison – Alternative Schemes			
Scheme Component	**30 m Gross Head Scheme**	**15 m Gross Head Scheme**	**2 No. 15 m Gross Head Schemes**
Powerhouse Structure	26.9%	13.7%	27.5%
Spillway structure	7.7%	4.3%	8.6%
Central Island	8.9%	2.2%	4.3%
River Diversion	8.2%	4.4%	8.8%
Navigation Lock	2.1%	1.6%	3.2%
Fish Pass Structure	4.8%	4.1%	8.2%
Switchyard(s)	0.2%	0.3%	0.6%
Transmission line(s)	0.6%	0.4%	0.8%
Access Roads	0.2%	0.2%	0.3%
Preliminaries	10.2%	8.5%	17.0%
Indirect Costs	30.2%	17.2%	34.4%
Total	100%	56.9%	113.7%

The percentage cost of a single 15m head scheme has been calculated as c. 57% of the full height 30m head scheme. The cost of the alternative two 15 m gross head schemes has been calculated as c. 114% of the single 30m head scheme.

It is noted that the percentage costs of the powerhouse structure(s), spillway structure(s) and the river diversion works are similar for both alternatives. The central island for the 30 m head scheme is proportionally more expensive than for the two 15 m head alternative schemes. This is as a result of the assumption that for a 15 m head scheme the island will be significantly smaller and also not require the construction of fish migration water passageways within the island structure.

The fish pass structure is similar in size for both the 30 m head and the 15 m head schemes. The chambers required for the fish lock system do not add significantly to the costings assumed.

The remaining component structures (navigation lock, switchyard, transmission lines and access roads) all make up a relatively small percentage of the costs and are similar in scope.

The assumed preliminaries and indirect costs both increase as an overall percentage of the costs for the two 15 m gross head scheme alternative, mainly due to the assumption that the two works sites will potentially increase the complexity of working and that issues including environmental, topographical and geotechnical may involve different solutions at the different sites.

Financial Cost

A full height mainstream project will require a construction period of approximately 8 years. Substantial debt service costs will be incurred during this period. By comparison, the lower head

alternative project will require less civil works and a fully gated barrage will incorporate more off site fabrication. A 4-year construction period would be required for the lower head alternative. If the lower head projects were constructed sequentially, the overall period would remain 8 years but revenue would commence after 4 years. There would also be a higher probability of all available energy being absorbed into the system.

A financial model has been developed to assess the reduction in debt finance cost that can be achieved by adopting two lower head projects. The following basic project finance parameters have been adopted:

OPEX	1.5% of CAPEX
Corporate Tax	30%
Discount rate	10%
Debt term	15 years
Debt/equity	70/30
Target FIRR	20%
Concession	30 years

The results are shown in Figure 6.16. In order to provide comparable financial cost results, the capital cost and energy output of the lower head scheme is 50% of the full height scheme. This comparison indicates that the cost of energy from the higher head scheme is 30% greater than the two lower head schemes.

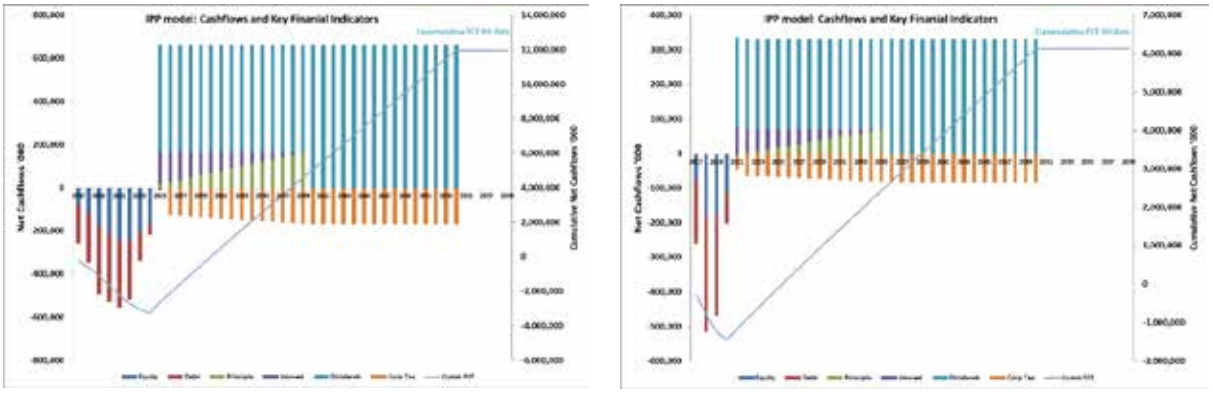


Figure 6.16. *Financial Model Results.*

Conclusion

The comparison between a typical full height mainstream project and the equivalent two half height schemes indicates that the combined construction cost of the two half height schemes will be approximately 15% greater. Conversely, the project finance cost for the two half height schemes is lower because energy and revenue is available approximately four years earlier. The overall implication is that the cost of energy from the half height schemes is approximately the same, and possibly lower, than the single full height scheme. This conclusion is based on river discharges, foundation conditions and cross sections being typical of the Low Cascade reach of the Mekong.

Some aspects of the two half height schemes are likely to be attractive to potential investors. These include:

- Lower initial capital requirement;
- Shorter investment period;
- Higher probability that all scheme output will be absorbed into the grid; and
- Option to adjust timing of the second project.

The impact on energy output has been examined in Section 6.2.5 of this report by considering sub division of the Pak Lay and Samakham projects. The average energy of the sub-divided projects is approximately 7% lower than the full height alternative. The reduction is mostly attributable to the increased impact of raised tailwater levels.

A three month wet season shut down results in an energy reduction of approximately 30%. This energy reduction is not a product of sub diving the projects, it is a result of shut down. This loss would need to be assessed against the advantage of mainstream hydropower development on the Mekong that has the potential to preserve the ecology of one of the world's most important rivers.

6.1.2 Hydrology and Flows

Hydrological impacts of the considered run-of-the river schemes have been found to be very limited. Except for peaking operations, the normal operation of these reservoirs does not lead to increased hydrological risks, as all 'natural' flows pass the dams without modification.

For the choice of smaller reservoirs, any remaining operational influence on the water-level and discharge, will be even smaller than the regular sized reservoirs. Particularly during hydropeaking operations, the amplitude of water-level fluctuations will be less severe than for the original active storage.

More technical solutions for mitigation of sediment-risks or fish connectivity, such as low head turbines and fish friendly spillways, will have only relevance for the local conditions around the dam, but not for the hydrological risks upstream of downstream.

Temporary shutdown of the cascade for environmental purposed means that during this period all flows can pass without noticeable modifications by the operation of the scheme. Only temporary, if the reservoir is lowered before, or refilled after shutdown, the discharges in the downstream reach will be affected, and reservoir levels may drop or rise quickly. For these periods, it is relevant to define appropriate ramping rates. Note that these conditions are only occurring once a year, and may therefore allow a slightly higher ramping rate than more frequent water-level fluctuations.

It should be remarked again that hydrology is intertwined with the sediment and fisheries assessment. Changes in flow conditions and connectivity of the flow have a direct relevant impact on the other themes. Also mitigation measures for dealing with sediment- and fisheries risks may generate hydrological impacts on itself. For instance, drawdown flushing operations will release a temporary flood wave travelling downstream. The following sub-sections and sediment and fisheries therefore also reflect on these indirect connections to the hydrology and flows.

6.1.3 Sediments and Geomorphology

6.1.3.1 The Northern Laos Cascade in a catchment perspective

The Council Study modelled sediment trapping in the tributary and mainstream dams in China and the LMB, with the results showing that collectively, the mainstream and tributary dams trap 157million tonnes (~97%) of sediment per year, with 28 impoundments accounting for 80% of the captured sediment. In Figure 6.17, all projects are divided by geographic location, and demonstrates that the largest capture of sediment occurs in China. If the Chinese dams are removed from the calculation, then the Northern Laos Cascade and the Lao PDR tributary dams are the largest contributors to sediment capture, reducing sediment fluxes by 23 Mt/yr in the Cascade and 28 Mt/yr in the tributary projects. Within the Laos tributaries, Nam Ou accounts for over 20% of the sediment trapping. These northern Lao PDR dams have low impacts in the context of flow changes, but with respect to sediment, they exert an impact that is significant at a catchment scale, and maximising sediment passage is warranted.

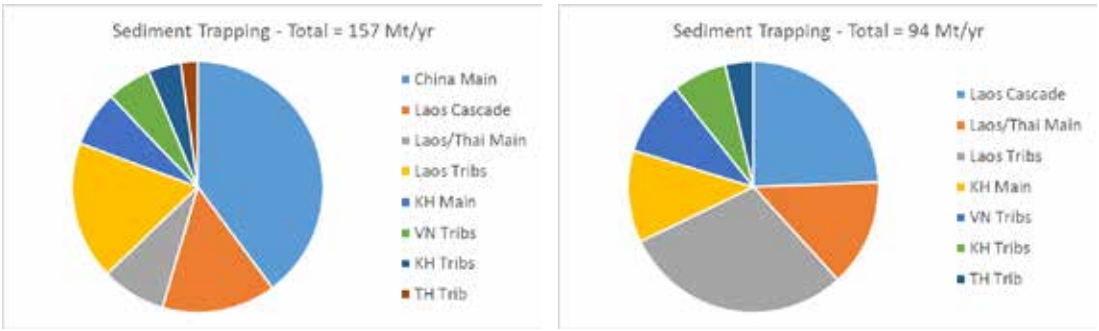


Figure 6.17. *Sediment trapping in the Lancang and Mekong Rivers (left) and in the Lower Mekong Basin (right) based on the results of the Council Study (MRC, 2017).*

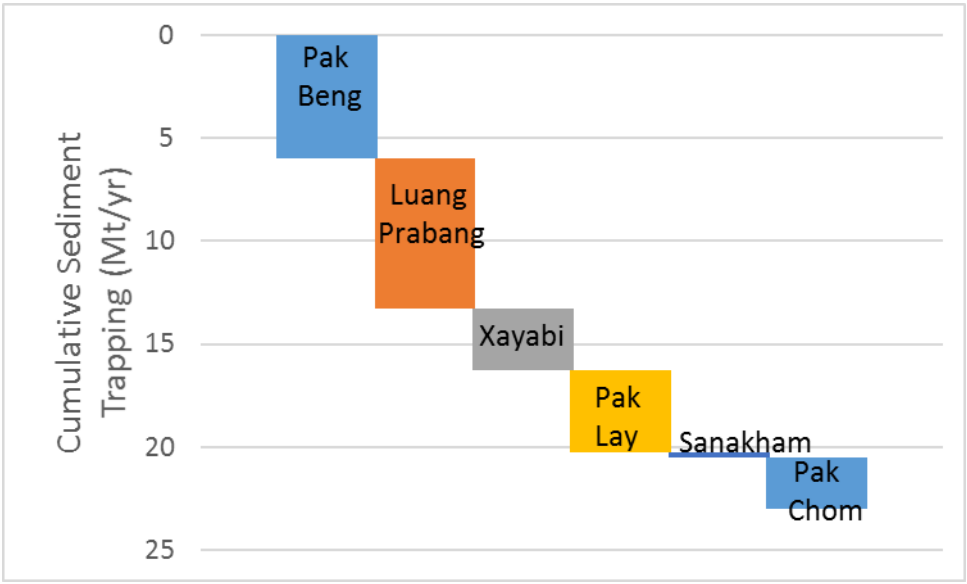


Figure 6.18. *Progressive sediment trapping in the Northern Laos Cascade (reflects conditions after construction of the UMB dams).*

The detailed modelling results of the Northern Laos Cascade Case Study (Chapter 5) showed that the potential to transport sediment through the HPPs was dependent on grain-size and the characteristics of the projects. Fine-grained sediment is maintained in suspension and transported through the impoundment during moderate and high flow events. Fine sediment was found to settle during periods of low flow, but was re-mobilised and transported downstream when flows increased during the following flood season.

Sand and coarser grained material showed a very different behaviour with these grain-sizes being deposited in the impoundments. Deposition was greatest at the upstream end of the reservoirs, where water velocities decreased from riverine to lake conditions. During flushing events, some of the fine-sand was re-suspended and discharged from the impoundment, but very little of the medium or coarse sand or gravel sized material was transported through the long-reservoirs. This is partly attributable to the low volumes of sediment entering the impoundments due to trapping in the upstream Lancang Cascade and in the tributary dams, and partly attributable to the long distances over which the material must be transported through the elongated reservoirs. Flushing events were successful at transporting coarser material along the axis of the dam, and thus were decreasing the amount of time required until discharge via low-level outlets at the dam wall might be viable.

These constraints to allowing sediment to be transported downstream through the cascade could potentially be reduced through the following planning, operational and engineering actions.

6.1.3.2 Planning – identifying and maintaining important sediment pathways

Sediment mitigation in hydropower projects is best identified and integrated at the catchment level energy planning stage. This has not occurred within the LMB, with projects developed with little consideration of the inter-relationship with other hydropower activities. However, catchment planning approaches can be used retro-actively to identify potential sediment 'pathways' which could be used to guide and prioritise HP mitigation approaches for projects yet to be built, and to raise awareness of how the existing projects might coordinate operations to improve sediment passage.

Figure 6.19 shows a Basson and Rooseboom (1997) diagram where the ratio between sediment inflow and sediment storage volumes and water inflow and water storage volumes are compared for a range of projects in the Mekong. The graph provides a general indication of whether sediment flushing, or sediment sluicing might be applicable to an impoundment based these parameters, or whether permanent sediment 'storage' or removal by mechanical means is likely to be the only long-term sediment management option. Other factors, such as the morphology of the impoundment, and suitability of infrastructure to discharge sediments are also critical to sediment mitigation and this graph should be considered as a general overview for illustrative purposes only.

HPPs in the LMB for which there is information about sediment inflows are plotted on the graph, including the Northern Laos Cascade. The sediment data used reflect the post-Lancang Cascade sediment fluxes, which accounts for the very high sediment storage to sediment inflow ratios. The graph suggests that the HPPs on the mainstream Mekong in northern Laos are suitable for sediment flushing and sediment sluicing due to the high-water inflow and low storage capacity. This is reflected in the mitigation measures identified by the study team and the sediment mitigation

measures proposed by the developers of Xayaburi and Pak Beng. However, the very long lengths of the reservoirs in the northern Lao PDR cascade are serious impediments to the success of sediment flushing over the first several decades of operations even though the water inflow to storage volume ratio is very high. This is because the 'delta' of course sediment must prograde to near the toe of the dam before sediment flushing can successfully mobilise the material. To optimise the potential for successful sediment flushing, understanding the potential sources and magnitude of sediment inputs to the cascade on a larger scale is required.

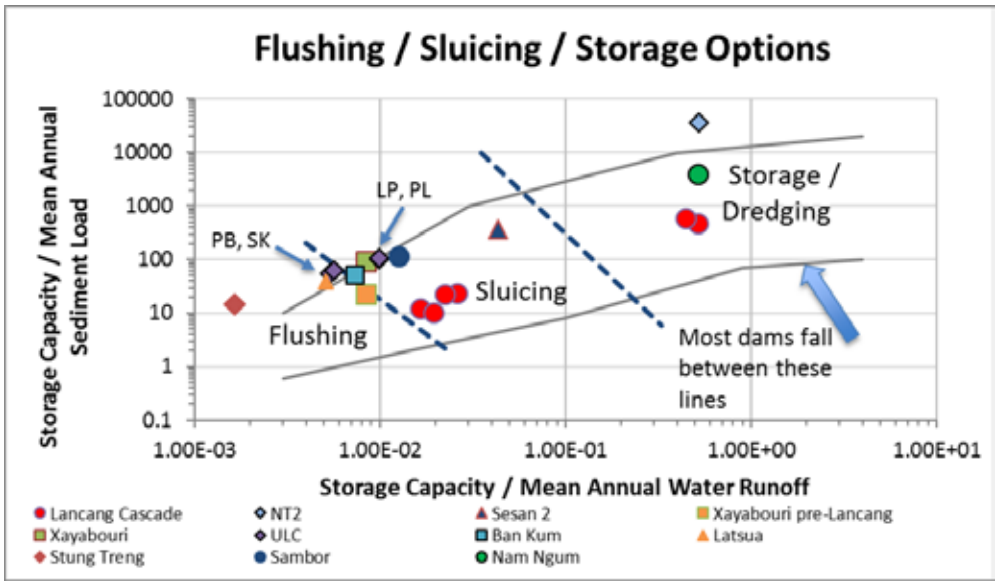


Figure 6.19. *Modified Basson and Rooseboom (1997) diagram showing potential for sediment flushing or sediment sluicing to different dams in the UMB and LMB.*

There is insufficient sediment information to plot the tributary projects in the LMB on a similar graph, but information about dam volumes and water inflows is available, and can be used to provide a high - level assessment of whether sediment flushing or sluicing might be applicable to the projects based on the water storage to inflow ratios. This ratio has been determined for all HPPs in the LMB for which storage volume and inflow information is available. The data has been sourced from the MRC Hydropower Database, and it is recognised that projects change and evolve over time, so the data likely contains some inaccuracies. The results are shown graphically in Figure 6.20 and spatially in Figure 6.21, and suggest that there are many tributary projects that have large storage to inflow volumes and are unlikely to be suitable for sediment passage.

The inflow to volume ratio can also be compared to the installed capacity (or annual generation) of hydropower projects to evaluate the potential for sediment mitigation compared to energy production (Figure 6.22). The graph is divided into four regions, denoting whether a project falling within that area would provide high or low energy, and have high or low sediment mitigation potential. The second graph shows the same hydropower projects as presented in Figures 6.20 and 6.21, and shows that there are some projects that have high installed capacity and high mitigation potential, and many that have high energy potential, but low mitigation potential.

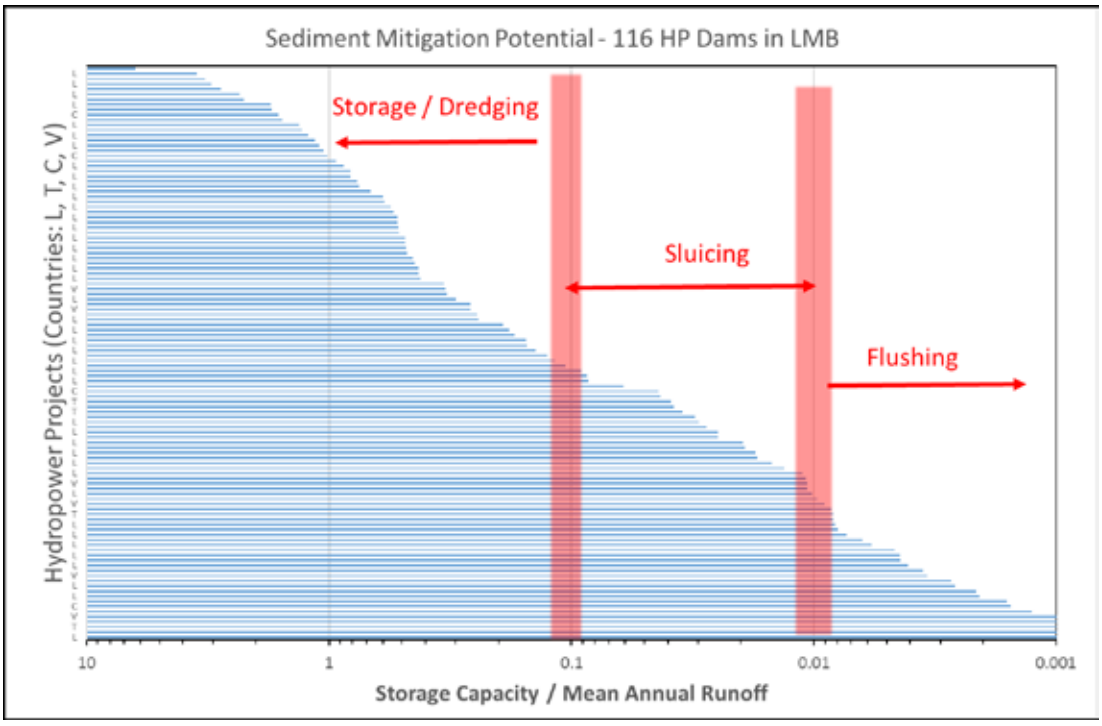


Figure 6.20. *The ratio of water storage capacity to the Mean Annual Runoff for 116 HPPs in the LMB. Not all projects are included due to a lack of information about one of the required parameters.*

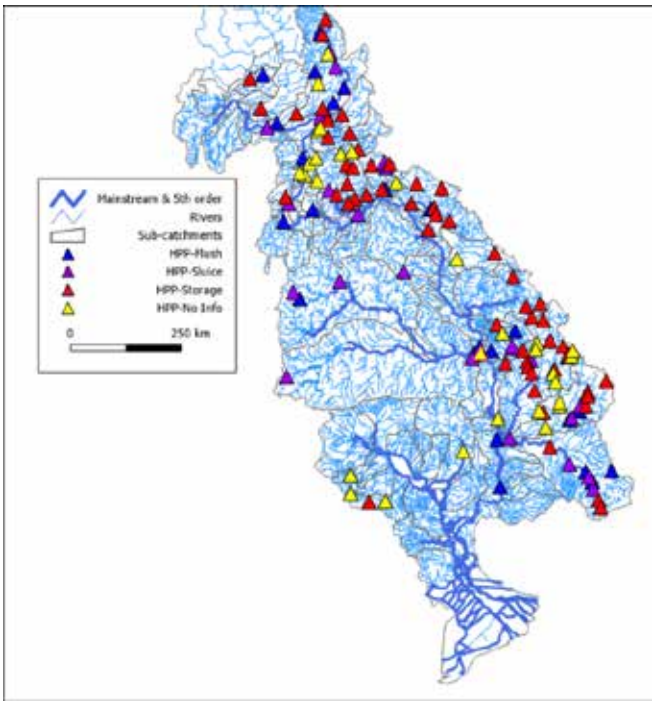


Figure 6.21. *HPPs in the LMB based on the results shown in Figure 6.20. HPPs potentially suitable for sediment flushing are indicated in blue, those potentially suitable for sediment sluicing are indicated in purple and those for which long-term storage is likely the only sediment management option are shown in red. HPPs for which there is insufficient information to complete the analysis are shown in yellow.*

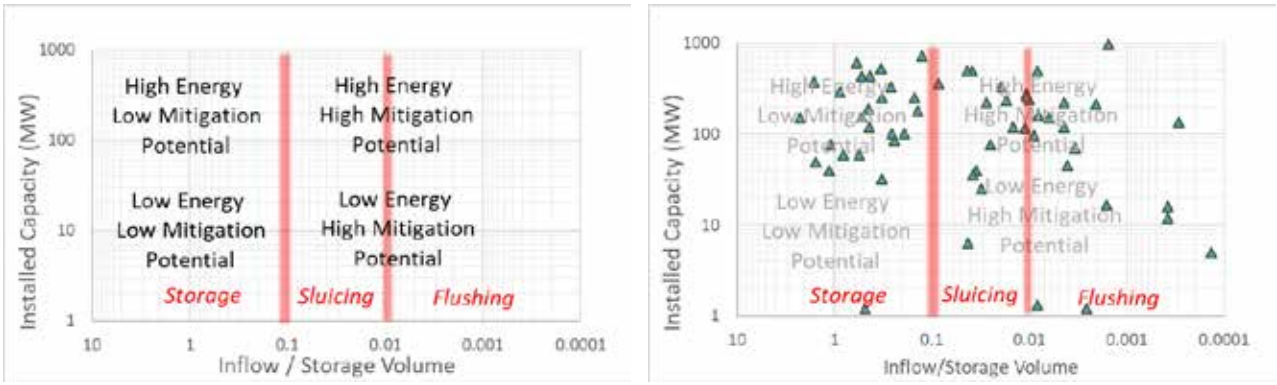


Figure 6.22. *(top) Comparison of installed capacity with inflow to volume ratios showing potential for sediment mitigation; (bottom) same graph with HPPs from MRC Hydropower database.*

These types of assessments have been applied to the Northern Lao PDR Cascade. Figure 6.23 shows that many of the HP projects on the small tributaries in the cascade catchment have high storage volumes and are unlikely to have the potential to pass sediment. However, the projects on the Nam Ou, which is the largest tributary in the region, have low volume to inflow ratios, and might be able to be managed for sediment sluicing and flushing. The inflow to volume ratios are compared to the installed capacity of each project in the Nam Ou Cascade (Figure 6.24) and demonstrates that the two most upstream projects (Nam Ou 6 & 7) have high installed capacity, but low potential for successful sediment mitigation. However, the lower five projects (Nam Ou 1 – 5) all have potential for sediment flushing and / or mitigation, suggesting there is potential to retain a sediment pathway to the Mekong River through the lower reaches of this important tributary.

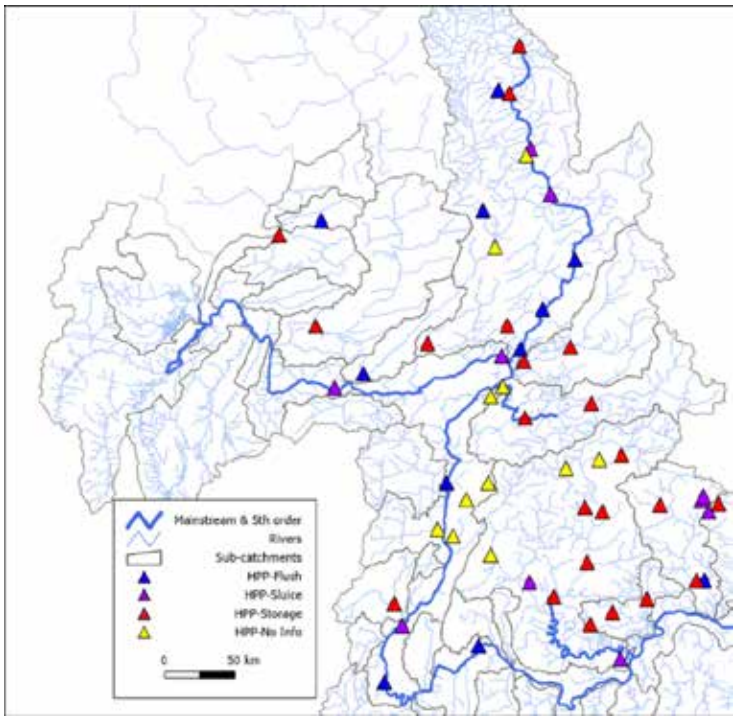


Figure 6.23. *Expanded view of Northern Lao PDR showing sediment management potential of the cascade on the Mekong and in the Nam Ou.*

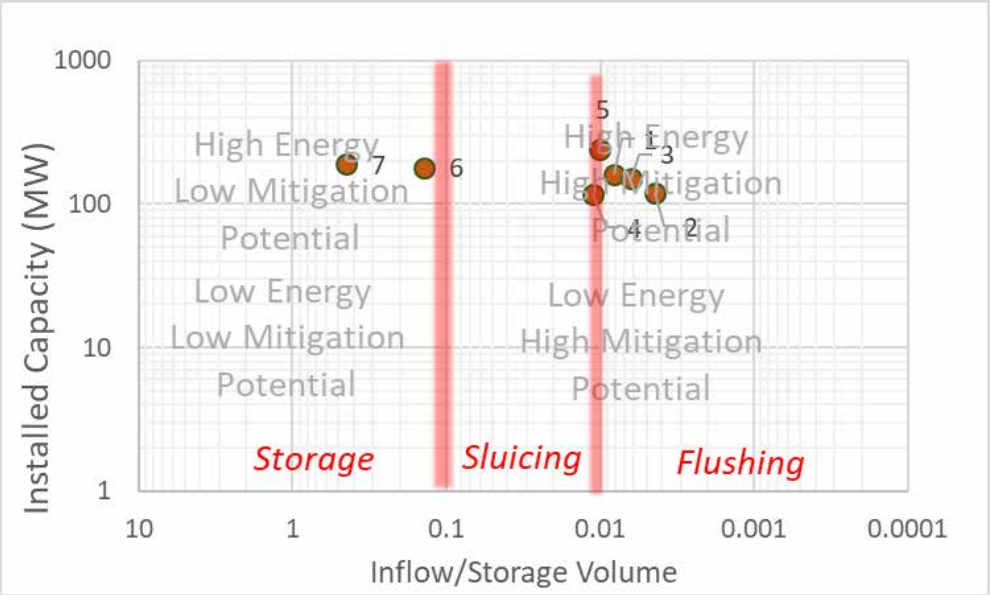


Figure 6.24. *The Nam Ou hydropower projects plotted by installed capacity and inflow to storage volume.*

Nam Ou is recognised as a major source of sediment (Lehner and Oullet-Dallaire, 2014), especially sand, and could provide episodic inputs of material to the Mekong if coordinated sediment sluicing and flushing was implemented in the system. Based on MRC sediment monitoring results the sediment inputs from Nam Ou were estimated at ~8 Million tonnes per year prior to regulation, and the Council Study results indicate approximately 6 Mt/yr of sediment being trapped in the seven projects in the cascade. Although this input is small compared to the pre-Lancang cascade sediment flux, it is significant compared to the sediment flux entering the LMB from China following establishment of the cascade, which is estimated at ~12 –15 Mt/yr. Optimising the Nam Ou cascade to pass sediment into the Mekong would increase the sediment load entering the cascade, and thus reduce the time until enough material accumulated for release.

Another advantage of managing sediment inputs from the Nam Ou is that the material is not required to pass through the full Northern Lao PDR Cascade before being transported downstream, as the material would enter downstream of the Pak Beng and Luang Prabang projects, into a short river reach that is not impounded.

Material entering in this reach of the Mekong might also reduce the erosion that is projected to affect the river reach between the Luang Prabang Dam and the upstream extent of the Xayaburi impoundment due to the reduction in sediment arriving from upstream (Figure 6.25). However, this river reach is also a high value tourism area, as it contains the Pak Ou caves, and any sediment flushing from the Nam Ou would need to take into account water level changes, downstream safety issues and aesthetics.

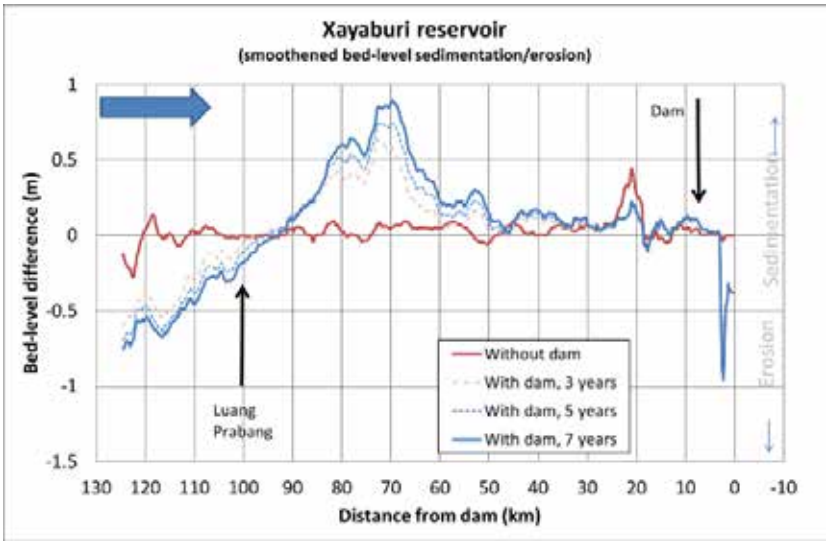


Figure 6.25. *Delft-3D modelling results of the Xayaburi impoundment. The plot shows a longitudinal view of the impoundment and indicates differences in bed level with and without the dam over a period of 7 years.*

6.1.3.3 Engineering options

Sediment management in the Mekong could be enhanced by requiring all tributary and mainstream projects to consider sediment management and passage at the project and catchment scale during the planning phase, and for sediment mitigation infrastructure to be included in all projects except those with the largest storage to inflow ratios, where sediment flushing or sluicing is unlikely to be viable..

The Case Study assumed that all projects in the Northern Lao PDR Cascade had similar infrastructure to allow sediment sluicing and sediment flushing. This may not be the case because different developers may adopt different philosophies with respect to sediment management. For example, one project may have low level gates that promote the passage of coarse material as soon as the material is deposited near the toe of the dam, where as other projects may require large accumulations of sediment to occur before the material can be flushed using higher level sluice gates.

The MRC Preliminary Design Guidance (2009) and the Mitigation Guidelines contain guiding principles and recommendations for sediment management in the Mekong. The efficacy of these guidelines could be enhanced if developers and the member countries agreed on more prescriptive 'rules' for specific projects or groups of projects, such as cascades. In the case of the Northern Laos Cascade, having similar infrastructure for sediment passage would maximise the potential for efficient sediment passage. Ideally, each project should include large, low level gates with the ability to draw down river levels to pre-existing levels, and promote the establishment of a free-flowing water column between this level and the bed of the river. These conditions create high water surface slopes leading to maximum sediment mobilisation.

6.1.3.4 Operations

Based on the Council Study results and sediment modelling associated with individual projects (e.g. Kunming Engineering, 2015), in the absence of flushing operations reservoirs are projected to require time scales of up to ~100 years for sediment accumulation in the reservoir to approach 'equilibrium' levels after which substantial volumes of deposited sediment can be discharged from the impoundments . Therefore, coordination of flushing will increase in importance over periods of decades, and the implementation of joint operations will become increasingly important to manage the discharge of higher sediment loads. In the shorter time frame of years to decades, other operational approaches could enhance sediment movement.

During the first decades of operations, frequent flushing of individual projects is an effective method for moving sediment down the axis of the reservoir, and maintaining storage volume in the upstream end of the impoundment, even if not a lot of sand and gravel is passed through the dam during each event. Frequent flushing at the most downstream projects would also assist in the maintenance of some sediment supply to the downstream river, even if the grain-sizes were limited to fine sand and silt. A benefit of maintaining low sediment volumes in the downstream impoundments is that when the upstream projects begin to pass large volumes of material, there is maximum storage volume in the lower reservoirs, and the risk of releasing very high sediment loads to the downstream environment can be reduced.

Experience and investigations in other rivers such as the Indus (Roca, 2012), have shown that frequent flushing has the benefit of reducing sedimentation in the active storage of a reservoir due to the sediment deposits assuming a lower slope following flushing, however, flushing also increases the rate of advancement of the coarse sediment deposits towards the toe of the dam where the risk of the sediment blocking or entering intakes or affecting other infrastructure is increased. However, if the dams have adequate infrastructure to pass the coarse sediment, sediment flushing could be enhanced by adopting this approach of frequent flushing.

Sediment flushing by individual projects would still require catchment communication and coordination owing to the large volumes of water that would be released. If downstream projects could draw down to minimum operating levels prior to an upstream flushing event, and then increase levels following the onset of the event, there is potential to maximise the movement of sediment downstream and provide a small amount of buffering for the large flush of water moving downstream. Additional detailed modelling runs using the actual infrastructure incorporated into each project is required to optimise the flushing regimes.

Other engineering options include sediment augmentation downstream of the final impoundment. This is likely to be a high cost option due to transport and dredging costs associated with obtaining and transporting material downstream of the final cascade. Sediment would not need to be sourced from the cascade necessarily. Given the large number of tributary projects in the Northern Laos Cascade catchment, there could be potential to dredge from projects with no sediment passing infrastructure and introduce the material downstream of the final tributary dam, where it would be transported into the mainstream, or barge it to the most downstream hydropower project. A review of gravel replenishment downstream of hydropower dams (Bunte, 2004) found that whilst ecologically successful, costs can be high on a per tonne basis owing to transportation costs. Coarse material (sands and gravels) that are most effectively trapped in impoundments but are

also the most important with respect to channel stability and habitat maintenance should be the target material in any kind of replenishment activity. This type of mitigation should be considered in the context of an integrated catchment management approach, as described in the following section.

6.1.3.5 Integrated Catchment Sediment Management

There is a large, although unquantified, volume of sediment residing within the mainstream channel of the Mekong River downstream of the Northern Laos Cascade. The Case Study has demonstrated that this sediment will be progressively eroded, resulting in an 'erosional wave' progressing downstream over time. Maximising the time required to erode the sediment in the river through catchment management is a plausible mitigation approach. A multi-pronged, catchment wide approach incorporating the following components would maintain sediment in the river channel over longer periods as compared to present activities and conditions. The MRC MCs may consider the development of a Sustainable Sand Mining Guidelines to ameliorate the hydropower impacts on a catchment level. Similar guidelines have been developed in the region (e.g. India MoEFCC, 2016).

Possible approaches include:

- Severely restrict or prohibit sand mining in the Mekong downstream of the Cascade. The removal of large volumes of sand from the mainstream by sediment mining which will not be replaced over time will increase erosion and destabilise the river channel. Severely restricting the removal of material is the most straightforward way of maintaining sand reserves in the system;
- Limit sand mining to HPP impoundments. The removal of sand from the upper reaches of HPP impoundments can provide a supply of sediment without affecting the sediment in the downstream channel over the short period (on scales of decades to centuries this will reduce sediment available for flushing to the downstream river). Removing sediment from the headwater areas can prevent the loss of storage volume and reduce the risk of upstream flooding. Extraction of this material may be more applicable to some projects, such as Pak Beng with dry season water levels are proposed to be 5 m lower as compared to the flood season. This lower water levels would allow dredgers to access sediment that was deposited during the wet season.
- Areas identified for dredging in impoundments other than the most upstream project (e.g. Pak Beng in the case study) would have to be identified carefully, as geomorphic modelling by the Case Study team has shown that erosion occurs within the headwaters of each impoundment due to the release of low-sediment water from the upstream project. Any sediment that was being deposited in a net erosional channel should be maintained to minimise impacts on bank stability. This is especially relevant for the upper reaches of Xayaburi, which extend to Luang Prabang. Increased channel depth in the vicinity of Luang Prabang could pose increased risks to the town's infrastructure.
- Identification of alternative sources of fill and building materials. Most of the sediment that is extracted from the Mekong is used to either infill floodplain or other low lying areas prior to development, or used to make concrete. Reducing the reliance on sand for these activities would reduce sand extraction and increase the volumes of materials remaining in the rivers and impoundments. The ubiquitous use of cement and concrete in construction is partially attributable to the low-cost, wide spread availability of sand in the past. A shift in construction methods could directly translate to a reduction in sand mining. Potential

areas for change include:

- Using other sources of 'clean' material for infilling floodplains, such as recycled construction materials;
- Identification of off-river suitable sand sources. The majority of floodplains in the Mekong are predominantly fine grained, and unlikely suitable for construction of filling uses. However, within the floodplain there are undoubtedly historic river channels that would contain suitable material. Detailed mapping of the floodplain environments and remote sensing techniques could be used to identify these deposits;
- Shift towards other building methods: Worldwide, alternative building materials are being developed based on recycled materials. Supporting and developing local industries that can turn a waste into a resource and reduce the dependence on river sand for construction is a win-win situation;
- Replace sand with crushed rock: Hard rock can be crushed to acceptable grain-sizes and used in place of river sands or gravels.
- Prioritising and regulating uses for river sand: Ban exportation, limit volumes that can be used as fill, and prohibit the use of sand in the construction of bank protection measures, as this creates a negative feedback.

6.1.3.6 Assessment of geomorphic and water quality impacts and potential for mitigation-Northern Lao PDR Cascade

The impacts and potential mitigation approaches for the full implementation of the full Northern Lao PDR cascade are summarised in Table 6.3. The qualitative ratings for the Potential degree of impact and Potential for substantial mitigation are in Table 6.2. Water quality risks are included although no water quality modelling was completed. In both the present Case Study and the Council Study silt and clay transport was used as a surrogate for nutrient transport.

Table 6.2. Potential impact scores and potential for mitigation scores used in the following Table 6.3.

Potential degree of impact	Potential for substantial mitigation
1 – Low: Full cascade development will not result in substantial change relative to baseline	1-There is a high potential for mitigation measures to substantially reduce impacts
2-Moderate: Full cascade development will result in substantial change relative to baseline	2-There is a moderate potential for mitigation measures to substantially reduce impacts
3- Full cascade development will result in major change relative to baseline	3-There is very low potential for mitigation measures to substantially reduce impacts

Table 6.3. Summary of potential impacts and applicable mitigation strategies associated with the implementation of the full Northern Lao PDR Cascade. Potential Severity and Potential for Mitigation scores are defined in Table 6.2.

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Severity	Applicable Mitigation Strategies	Potential for mitigation
Maintain existing river channel habitats	Bank erosion, channel incision	Lake shore and hill slope erosion related to fluctuating water levels	2	Adoption of ramp rates for lake levels, limit water level range, buttressing of lake shores;	2
		Channel scour downstream of final dam in cascade, extending to lower LMB	3	All dams have low level gates to promote sediment passage as soon as possible after commissioning;	2
				Coordinated sediment flushing involving tributaries and mainstream dams;	2
				Banning of sand and gravel mining from downstream impoundments	2
	Deep pools, rapids	Within impoundment deep pools filled in by sedimentation	3	None	3
		Deep pools in 'free flowing' reaches subject to changed flow and sediment regime	1	Maintenance of seasonality of flows to maintain 'flushing' of deep pools;	1
				Timing of sediment flushing to minimise infilling of deep pools during dry season	1

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Severity	Applicable Mitigation Strategies	Potential for mitigation
Maintain river connectivity	Sediment transfer	Trapping of medium sand and larger grain-sizes in impoundments	3	Coordinated annual sediment flushing including mainstream and tributary dams	Initial years: 3 Later years 2
		Trapping of fine sand in impoundments	2	Coordinated annual sediment sluicing and flushing including mainstream and tributary dams;	1
		Trapping of silt and clay in impoundments	1	Coordinated annual sediment sluicing including mainstream and tributary dams	1
		Maintenance of sediment pulse to coincide with flood pulse	2	Coordinated annual sediment sluicing and flushing including mainstream and tributary dams to coincide with onset of wet season	1
		High sediment concentrations and loads during sediment flushing	2	Coordinate and stagger flushing operations between mainstream (and tribs) to avoid multiple simultaneous 'flushes'	1
				Release 'clear' water from high level outlets and power station during flushing events & coordinate with natural high inflows	1
				Flush on an annual basis to minimise 'build up'	1

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Severity	Applicable Mitigation Strategies	Potential for mitigation
Maintain water quality	Water Quality	Increased temperatures (risk increases in each successive impoundment)	1-2	Include low level intakes into dam design to draw deeper water;	1
				Release water from bottom outlet of final cascade if dry season water temp impact aquatic ecosystem;	1
		Increased risk of algal bloom	3	Catchment management to reduce nutrient runoff to impoundments;	2
				Limit aquaculture development and site in area with good flushing dynamics	2
		Nutrient transport (Silt & clay used as surrogate)	1-2	Coordinated annual sediment sluicing including mainstream and tributary dams	1

6.1.4 Fisheries and Aquatic Ecology

Some alternative engineering design and operation options were already discussed in previous chapters (e.g. 6.2.1). Expected implications for fisheries and aquatic ecology are discussed in the following subchapters.

6.1.4.1 Engineering and operation options

Hydromorphological optimisations (in general)

Many Mekong fishes are substrate spawners and rely on a natural substrate composition for successful reproduction. Sedimentation processes in impoundments and the related erosional wave downstream will cause a long-term alteration of habitats (incl. floodplains) and consequently a reduction of fish diversity, abundance and biomass. Therefore, mitigation measures aiming for a more natural hydromorphology (e.g. sediment transport) can therefore also be considered as beneficial for aquatic organisms, despite the fact that they might be related to short-term stress and habitat destruction (e.g. during flushing).

Smaller reservoirs

Reservoirs cause multiple impacts linked to the size of the dam and local characteristics. In general, the larger the dam the more impacts on the ecosystem can be expected. Consequently, smaller dams and especially smaller reservoirs with potentially improved flow conditions can be considered as advantageous. Furthermore, dams not only cause local changes of habitat characteristics such as reduced flow velocity and fine sediment deposition, but can have impacts on a much larger scale, e.g. multiple habitat fragmentation and downstream sediment lack. The detailed Mitigation Guideline modelling results for the upper cascade showed that passive downstream drift of larval fish is only supported for four months during the wet season. During the remaining year, flow velocities drop below 0.2 m/s in reservoirs impeding drift and thereby reducing reproductive success and productivity. Consequently, reducing the size of the impoundment and keeping the river closer to its natural state could highly improve the situation, not only with regard to drifting larvae but also concerning habitat and water quality (e.g. by reducing sedimentation processes). This is especially true, when smaller reservoirs are connected to undammed river sections providing spawning and nursery areas for fish.

However, it has to be kept in mind that smaller reservoirs would go hand in hand with an increased number of reservoirs/barriers when aiming for a comparable high energy production. Consequently, overall connectivity has to be taken into account since a larger number of barriers is also associated with a reduced overall connectivity. The cumulative effect of multiple barriers might be rather high as each dam decreases the number of fish successfully passing the cascade. Therefore, it has to be ensured that the negative impacts caused by increasing the number of barriers does not outweight the benefits of smaller reservoirs.

Low head turbines and fish adapted spillways

In upstream direction, barriers prevent them from migrating further upstream and maybe also from reproducing successfully. However, in downstream direction, the possibility to pass the turbines or spillways can be fatal for many fish (depending on their size and the rake clearance).

Low head turbines or “fish-friendly” turbines were already discussed in other chapters. We already highlighted, that “fish-friendly” turbines might not exist but that some turbines are at least less harmful for fish compared to others. Fish kills related to downstream migration should be considered as a very severe impact as a high proportion of the population can be affected. In this context, not only direct contact with the turbine but also pressure differences represent a major problem. The injuries are related to the dam and turbine characteristics (e.g. pressure conditions), the migratory corridor of the fish (e.g. bottom- or surface-oriented), the type of swim bladder (e.g. connected or disconnected from gut, one- or two-chambered) and development stage for larvae (i.e. whether they have already filled their swim bladder or not). Therefore, any turbine adaptation, which reduces the risk of fish injuries or kills, is beneficial from an ecological point of view. However, mitigation potential for high head dams is limited due to the physical constrains of the construction (e.g. the higher the dam the higher the pressure). In this context, also fish-friendly spillways are of relevance and adaptation to make their passage less harmful for fish are beneficial from an ecological point of view.

Halls & Kshatriya (2009) showed in their study that large species might become extinct anyway if they are not efficiently redirected from the turbines even under consideration of high upstream passage efficiencies. Consequently, the option of temporary shutdown (see below) should be taken into account during important migration seasons.

Temporary shutdown and low level gates

Our analysis of Scenario 1.4 (i.e. temporal shutdown) showed that the spillway geometry at Xayaburi leads to flow velocities which are too high to support upstream migration and might be even harmful for downstream migrating fish. Consequently, this option should already be considered in the planning process and the spillway should be designed in a way which allows the river to return to its natural condition and ensures safe passage in both directions. Low level gates providing the ability to return the river to free-flowing condition are also beneficial for sediment transport and consequently habitat conditions (see also chapter 6.2.3).

For a cascade of several consecutive dams, a management plan aiming for optimum passage efficiency (i.e. with regard to the main migration timing and duration) would be required for both up- and downstream migrations.

6.1.4.2 Siting – identifying and maintaining important migration routes

As already discussed in the guidelines and chapter 6.2.3, the siting of hydropower projects is critical in determining the long-term impacts of hydropower projects. With regard to site selection, not only energy-economic and hydromorphological parameters are of concern, but also maintenance and connectivity to important habitats has to be considered. In any case, this mitigation option has to consider the catchment scale (or at least including a river section with several tributaries) and has to take place prior to the actual planning phase of a dam.

To make use of this mitigation option, detailed knowledge on migratory species and their behaviour, migration distances, spawning season and spawning areas is required. Consequently, one of the main tasks would be to collect additional data on the above stated parameters.

In general, the LMB can be sub-divided into three large migration systems (see also Mitigation Knowledge Base; Baran, 2006, Poulsen, et al. 2002). The upper system extends approximately until Vientiane, the middle system is located between Vientiane and the Khone Falls, and the lower system extends from the Khone falls downstream including the Tonle Sap and the Delta. Although this section will focus on tributary dams, a large-scale assessment of connectivity cannot take place without considering mainstream dams. Consequently, the tributaries are discussed with regard to their relative importance along the Mekong, but also in relation to planned mainstream dams (upper and lower cascade). A more detailed assessment of the lower cascade will follow in chapter 6.4.

With many of the dams still in a planning phase, there is still room for optimisation with regard to overall connectivity in the LMB, especially with regard to the migration corridor of white fish species. The following graph shows three different development stages (i.e. 2007, 2020 and 2040) with or without mainstream dams and assuming different passability rates for mainstream dams. It can be shown that the inclusion of tributary dams already had a great impact on the DCI_{migr} (see

chapter 3.6), with a significant reduction after the inclusion of Xayaburi and Don Sahong and another decrease due to the implementation of the full cascade (i.e. 11 dams).

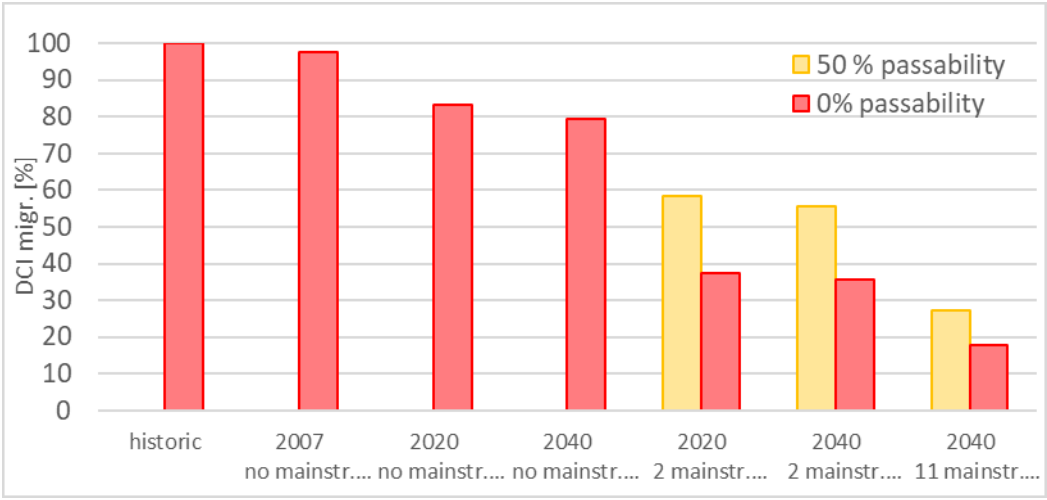


Figure 6.26. *Consecutive loss of connectivity with hydropower development expressed as Dendritic Connectivity Index for migratory species (DCI_{migr}, see chapter 3.6) (passability rates of 0 and 50% apply only for mainstream dams, tributary dams are included with 0% passability due to lack of fish passes in most cases; inclusion/exclusion of tributary dams in accordance to the 2007/2020/2040 Council Study scenarios; scenarios with two mainstream dams include Xayaburi and Don Sahong).*

With the Upper Lao Cascade being located in the upper migration system of the LMB, the Mekong mainstream represents the major migration route. Some selected tributaries are known to be relevant for migratory species such as the Nam Ou and Nam Soung. However, these tributaries are already fragmented to some degree (or will be in future) which is why they are only accessible for the first few kilometres. While tributaries might play a limited role compared to the Mekong mainstream in the upper migration system, they might become more important once the Mekong is impounded.

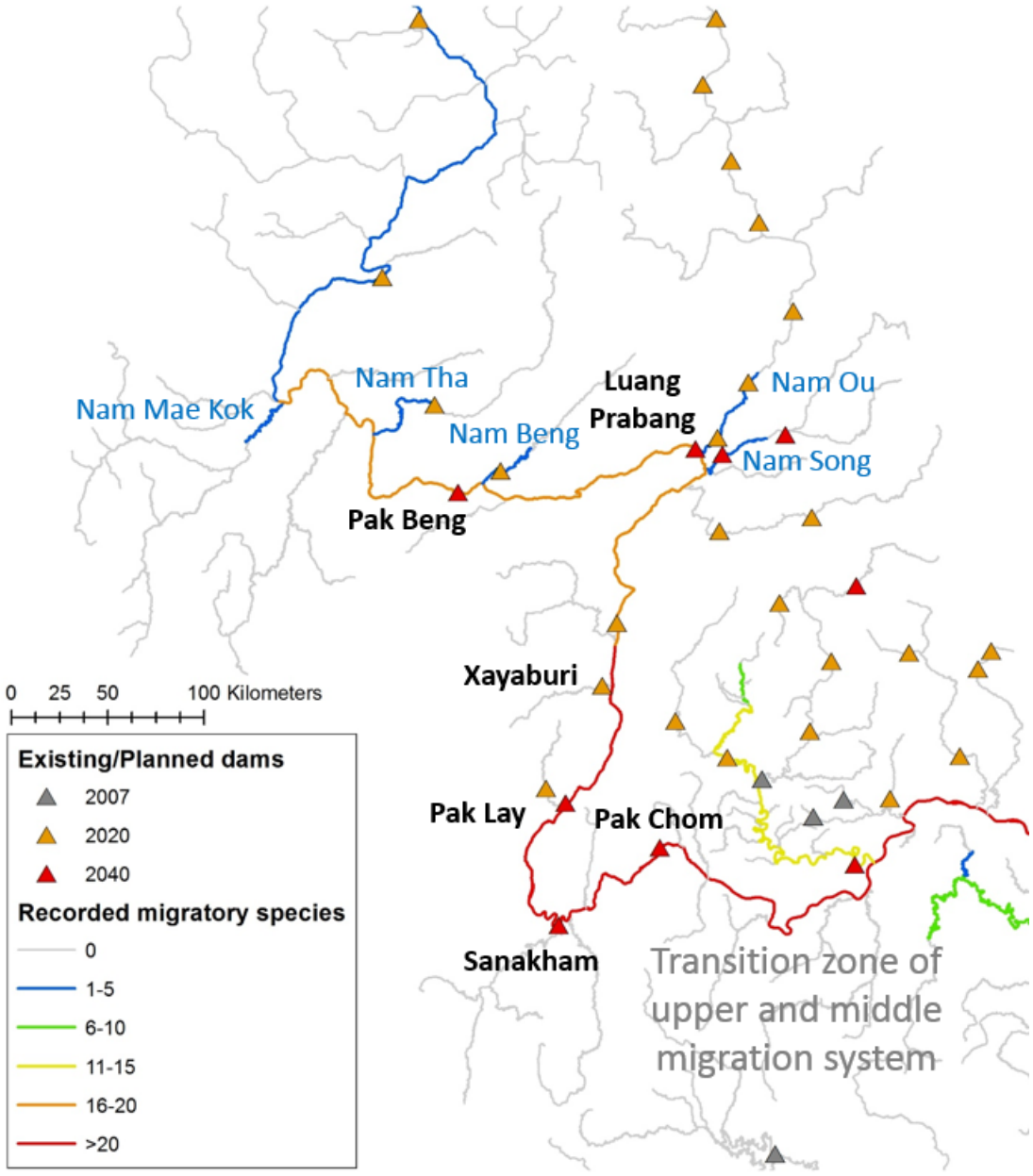


Figure 6.27. *Upper migration system with recorded migratory species and existing/planned dams (GIS data source: MRC; Migratory species occurrence on the basis of Mekong Fish Database (Grill et al. 2014 based on Visser et al. 2003).*

Further downstream, tributaries become more important which also becomes visible in the number of migratory species caught in tributaries (based on the Mekong fish database). Downstream of Vientiane, the Nam Ngum represents an important tributary within the middle migration system. However, also this migration path is at stake of being blocked by a dam in the near future. Also, the Songkhram river seems to be of high importance to migratory species. It is joined by several tributaries from the north and south and builds an extensive lowland floodplain system close to the confluence with the Mekong. Furthermore, it is still unexploited and currently includes no planned future dams.

Before reaching the location of the Ban Kum dam, four more tributaries (i.e. Nam Hin Boun, Se Bang Fai, Se Bang Hieng and Se Bang Noum) with documented catches of migratory species enter the Mekong. In general, the section between Pak Chom and Ban Kum is a rather long stretch without any planned mainstream dams. It is located between the upper and lower cascade whereby the impacts of the upper cascade (e.g. the erosional wave) might take decades (or even longer) to become visible in this area. Furthermore, the impoundment of Ban Kum would not extend too far upstream, which leaves this rather unimpacted section and its tributaries (especially those which are still passable) as an important refuge area for some species with potential positive effects extending to the upper and lower cascade.

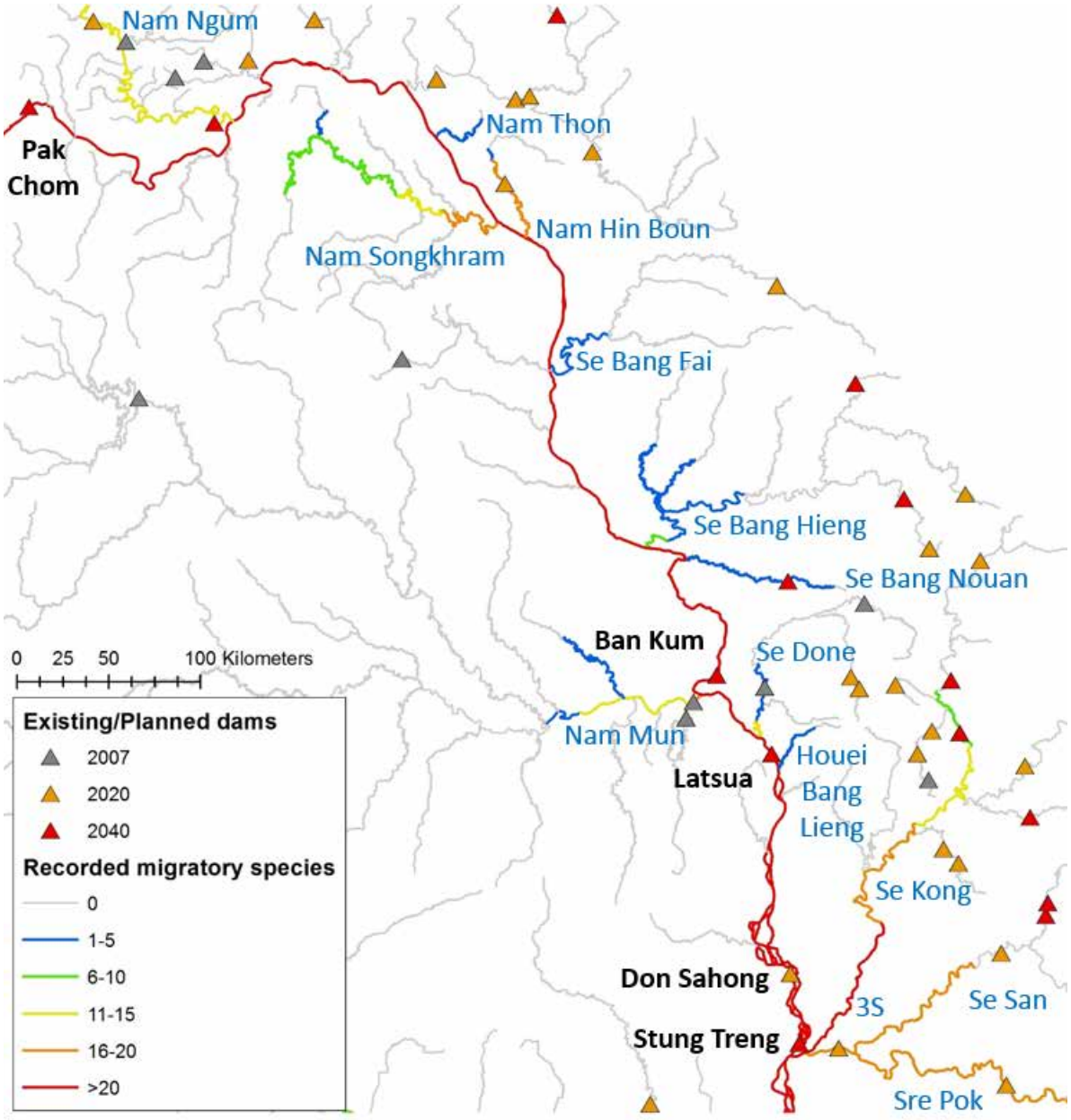


Figure 6.28. *Middle migration system with recorded migratory species and existing/planned dams (GIS data source: MRC; Migratory species occurrence on the basis of Mekong Fish Database (Grill et al. 2014 based on Visser et al. 2003).*

The section between the planned Ban Kum dam and Latsua dam is rather short, but includes two tributaries. The Nam Mun is already blocked since 1994. Although the Pak Mun Dam is equipped with a fish pass, it was proven to be not functional and therefore fish could no longer enter the tributary. After year of conflict, the gates were opened during the time of reversed flow from the Mekong to test potential benefit for fisheries. Jutagate et al. (2007) showed that at least some species (e.g. H. waandersii, which spawns during the rainy season, both up- and downstream of the Pak Mun dam) benefit from this management option. The second tributary in this section is the Se Done where the first barrier is located 40 km upstream of the confluence with the Mekong.

The section downstream of Latsua has only some small tributaries, however the Mekong itself starts branching. The Don Sahong Dam is located in the transition zone between the middle and lower migratory system of the LMB. Especially the section between Pakse and Kratie is known to contain a large number of deep pools which play an important role as dry season refuge, spawning areas or permanent habitats (Poulsen et al. 2002b; Baird 2006).

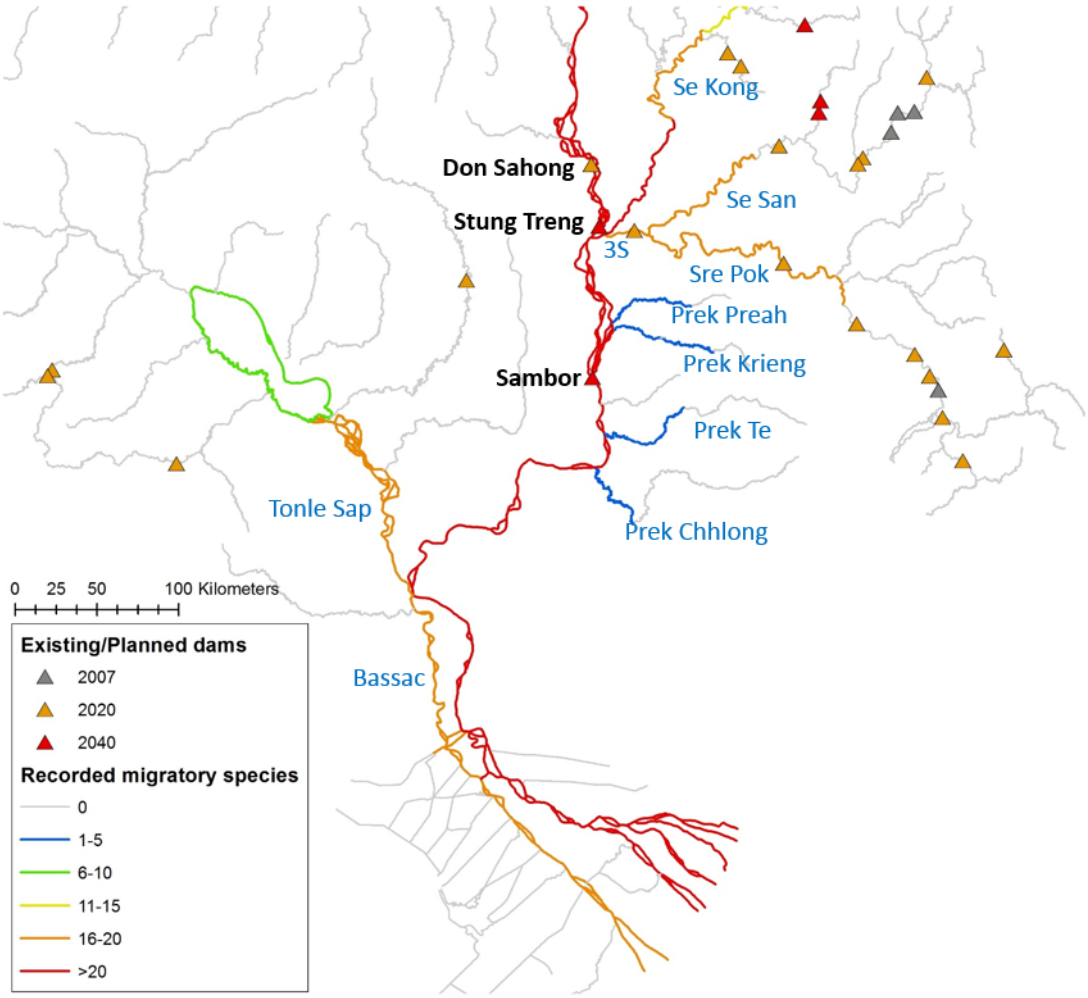


Figure 6.29. *Lower migration system with recorded migratory species and existing/planned dams (GIS data source: MRC; Migratory species occurrence on the basis of Mekong Fish Database (Grill et al. 2014 based on Visser et al. 2003).*

Between Don Sahong and Stung Treng (~40 km), no notable tributaries enter the Mekong. Further downstream, the 3S system, which plays an important role for many species and is also believed to represent a migration system on its own, joins the Mekong. However, also the 3S system contains

a large number of existing and planned dams. The Lower Sesan 2 dam which is currently under construction will be the most downstream project and disconnect most of the rivers Sesan and Sre Pok.

The 3S system is known to represent an important habitat for many species, also for fish migrating from far downstream sections (e.g. Tonle Sap and the Delta). The Sambor dam, which is planned to be the most downstream dam, will block the accessibility of the 3S system, which can have severe impacts on the whole area. Downstream of Sambor, two more tributaries enter the Mekong before it is joined by the Tonle Sap – one of the most important tributaries of the LMB. The confluence with the Tonle Sap Lake marks the starting point of the Mekong Delta with the Bassac River reaching the South China Sea as one of many branches of the Mekong.

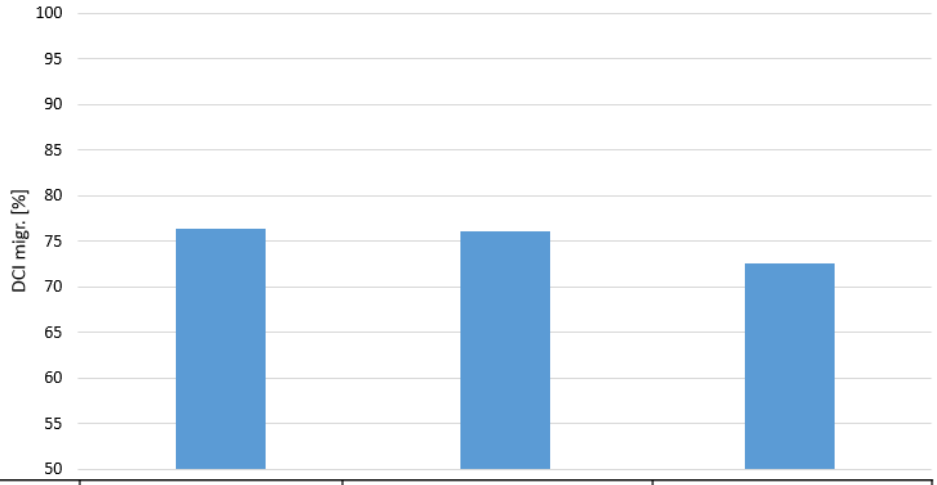
The impact of the individual dams on connectivity relies to a high degree on the implementation and functionality of mitigation measures such as fish passes. With best practice examples still missing for large tropical rivers as the Mekong, the restoration of connectivity to pre-dam conditions is highly questionable. Furthermore, sound fish pass solutions also need to ensure safe downstream passage – both for juvenile and adult age classes. Until these problems are solved, it is recommended to focus on the realisation of dams located upstream of already existing barriers.

With the Mekong being fragmented by several dams and the related habitat alterations (e.g. impoundments, sedimentation), the tributaries will become even more important refuge areas where successful reproduction can still positively influence the Mekong mainstream. However, with many of the tributaries impacted on their own, the areas providing feeding and spawning grounds become sparse and hardly accessible. Therefore, understanding the importance of the respective tributaries for certain species should be one main goal for implementing targeted management actions.

Development options for tributary dams

Assuming that the Lao upper cascade is completed (i.e. six mainstream dams) but with the tributary dams still in the development stage of 2020 (i.e. 86 tributary dams instead of 105), an optimisation of a few percent could be achieved by equipping the remaining tributary dams also with fish passes (assuming a passage efficiency of 90%).

Since most of the tributary dams planned after 2020 are located somewhere in the headwaters (and therefore outside of the main migration route of migratory species) the DCI_{migr} does not react that strong to the inclusion of fish pass options (see Figure 6.16). The majority of tributary dams were planned to be realized between 2007 and 2020. But not all dams planned for this period were already implemented. Consequently, the overall connectivity could be maintained at a higher level by the construction of fish passes or the waiver of dams that are still in a planning phase and located in highly sensitive locations.



2020 tributary dams (86 dams)	0%	0%	0%
6 mainstream dams	90%	90%	90%
2020-2040 tributary dams (+19 dams)	-	90%	0%

Figure 6.30. *Comparison of different development options for the tributary dam (Table provides assumed passability rates for mainstream and tributary dams).*

Some dams are planned in key locations, i.e. close to the Mekong mainstream and within the migration corridor or migratory species. Although the construction of a fish pass could bring some improvement (provided that they are functional), large-scale habitat alterations and disconnection of downstream migrations will still exert high pressure on aquatic organisms, and realisation of such projects should be put into question. One example is the Lower Nam Ngoum dam, which would disconnect a rather long section of the Nam Ngum, one of the most important tributaries in the transition zone between upper and middle migration system which could even become more important once the upper Lao cascade is in place.

Another example is the Lower Sesan 2 Dam which is already under construction. The dam has a height of 45m, will block parts of the Sesan and Srepok Rivers and create a reservoir of 335km² (Gätke et al. 2013). The construction of this dam will put high pressure on aquatic organisms and especially migratory species. Even though a fish pass is currently under construction (see Figure 6.31), design criteria required for assessing its suitability are currently not publicly available. However, several studies have shown that the mitigation of continuity interruption might not be very effective for this respective case (e.g. Cooper et al. 2015, Gätke et al. 2013). Especially the restoration of downstream migration is a challenge, since the impoundment will most likely block the passive drift of eggs and larvae and the dam might cause high losses of adult individuals which pass the turbines or spillways. This could cause a catastrophic decline in migratory species in the 3S system with impacts possibly also extending towards the lower migration system. According to Ziv et al. (2012) the dam will reduce the basin-wide fish biomass by more than 9%. Even with the implementation of mitigation measures, dams in such sensitive locations will bring negative effects which will not only be visible locally but at a larger scale.

Figure 6.31. *Picture of the fish pass at the Lower Sesan 2 dam. (http://www.rfa.org/english/multimedia/lowerSesanII-slideshow-07142017160537.html)*

The inclusion of fish passes should also be considered for existing dams in key locations (i.e. close to the confluence with the Mekong). A more detailed assessment could show, for which tributary dams the implementation of fish passes is ecologically important and technically possible. However, retroactive inclusion of a fish pass is often more complex and the result not always satisfactory.

Besides longitudinal connectivity, also lateral connectivity towards the floodplains plays a major role, especially for species relying on these habitats for certain periods of their life cycle (e.g. for feeding, spawning or rearing). For a more detailed assessment, data on lateral barriers would be required.

6.1.5 Impacts on Power Production and Revenue

In the alternative layouts (se Chapter 6.2 for details), the two dams downstream of Xayaburi have been split into four half-head schemes. The suggested locations of the dams are shown in the map overleaf. The Paklay and Sanakham dam locations has been kept, and two more locations has been added, displayed as “Dam 1” and “Dam 3”. Key data for the dams is presented in Table 6.4.

Figure 6.32. *Locations of alternative dams.*

Table 6.4. Key data for the smaller dams.

	Dam 1	Dam 2 (Paklay)	Dam 3	Dam 4 (Sanakham)
HRWL	240 masl	230 masl	220 masl	210 masl
Flood surcharge	+2 m	+2 m	+2 m	+2 m
Average TWL	233 masl	222 masl	211 masl	205 masl
Design flow	5140 m³/s	5140 m³/s	5140 m³/s	5140 m³/s
Fish flow	40 m³/s	40 m³/s	40 m³/s	40 m³/s

The operation of the dams have been studied in MIKE11. The dams are operated as run-of-river hydropower plants. It is assumed that the turbines can run as long as the difference between the head water level and tail water level is more than 3 meters. If the elevation difference is less than 3 meters, the power plant stops generating power. This is the case when the tail water levels get too high during the highest flows in the wet season. For Dam 4 this happens about 7% of the time and for Dam 1 about 3% of the time. Dam 2 and 3 does not have problems with high tailwaters.

To minimize the stops in generation due to too little head, we allow the head water level to rise with up to 2 meters during floods. This means that the gates are only opened when the reservoir water level reaches more than 2 meters above the highest regulated waterlevel. When the reservoir water level is between HRWL and HRWL+2m, there is spill over the gate crests. The relationship between reservoir water level and flow for Dam 3 is shown below.

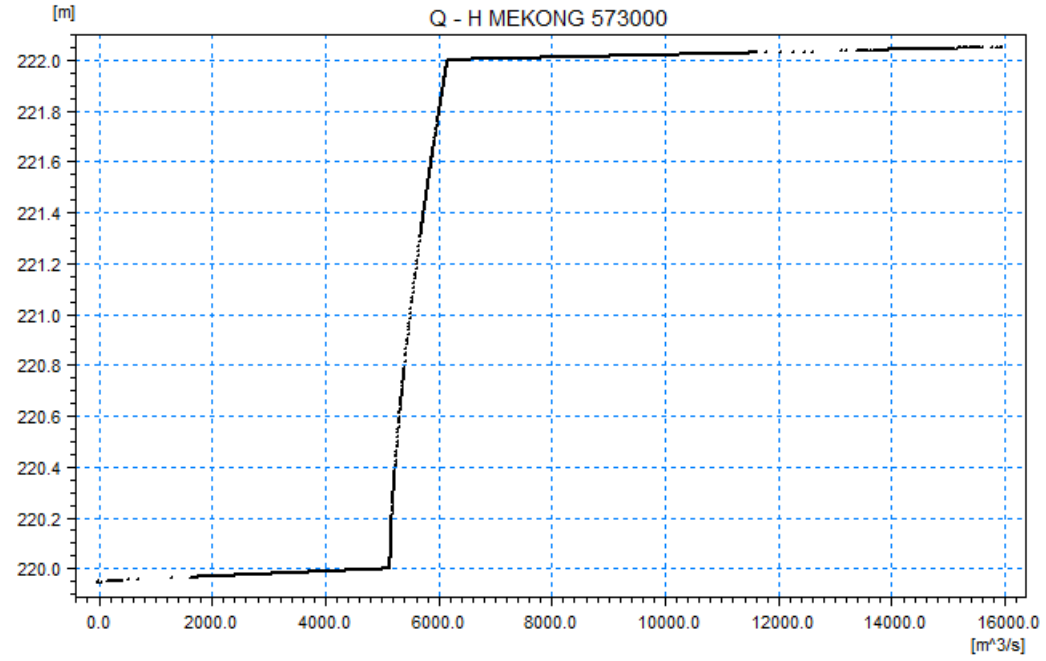


Figure 6.33. *Relationship between water level and flow at dam 3.*

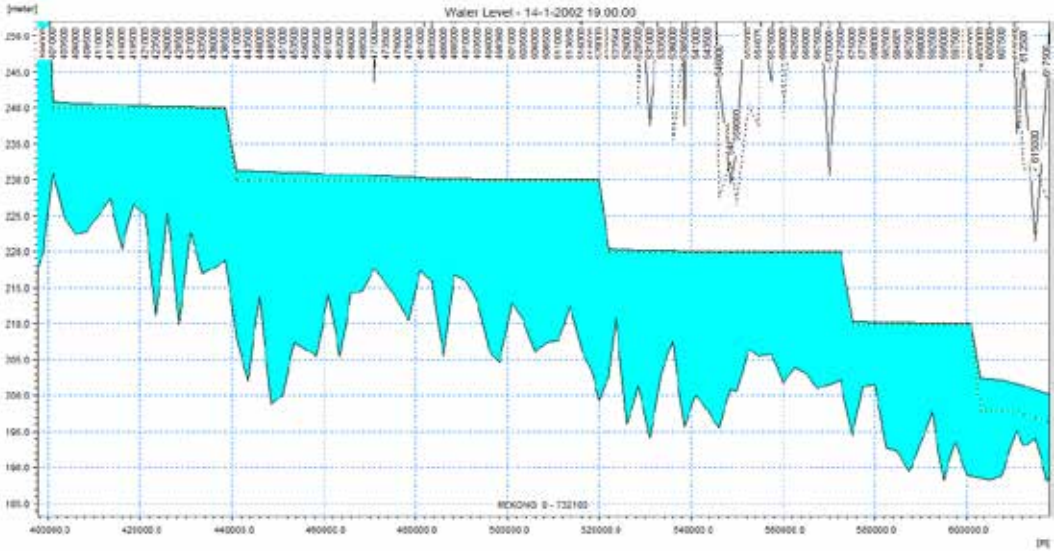


Figure 6.34. *Water levels during the dry season.*

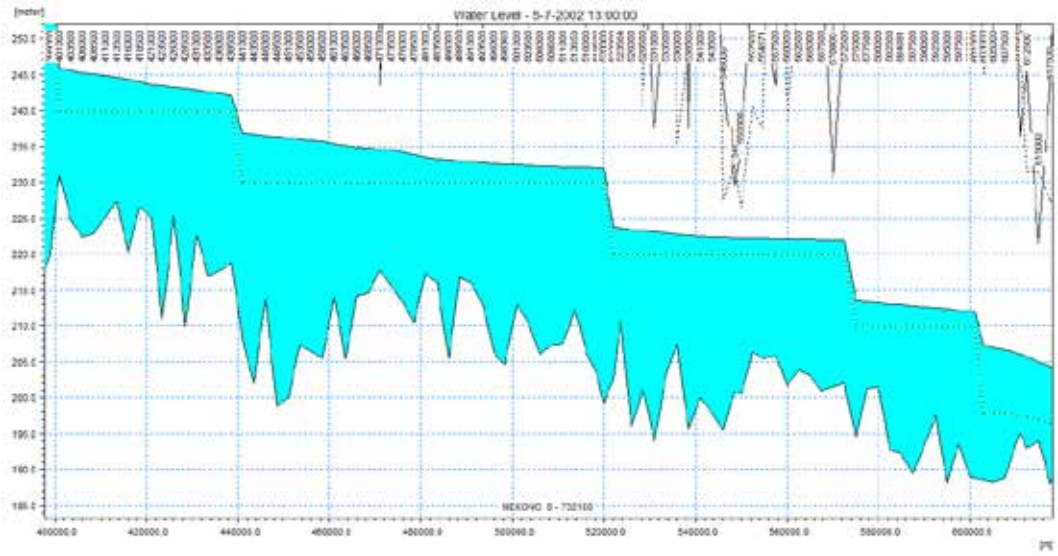


Figure 6.35. *Water levels during the wet season.*

Shut-down for fish migration

We have ass4essed a potential stop down of the generation and opening of the gates for about 3 months each year in order to enable fish migration. The economic implication of this depends on the timing of the shut-down. It is indicated that the most important period for downstream migration is the end of the wet season, but there is not yet enough information to determine the best months for shut-down. The economic implication of the shut-down will depend on which months that are chosen, as the generation varies from month to month. Average generation per month for the four half-head schemes are shown in the figure below.

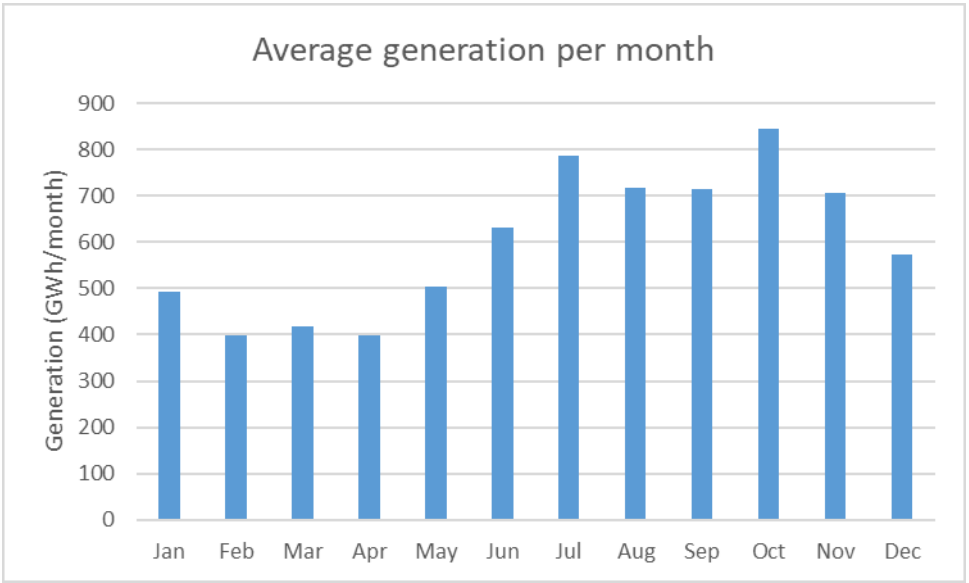


Figure 6.36. *Average generation for the four half-head schemes per month*

In Figures 6.37-39, the generation of the four dams and the flow in the river is plotted for three different options for the 3-month shut-down.

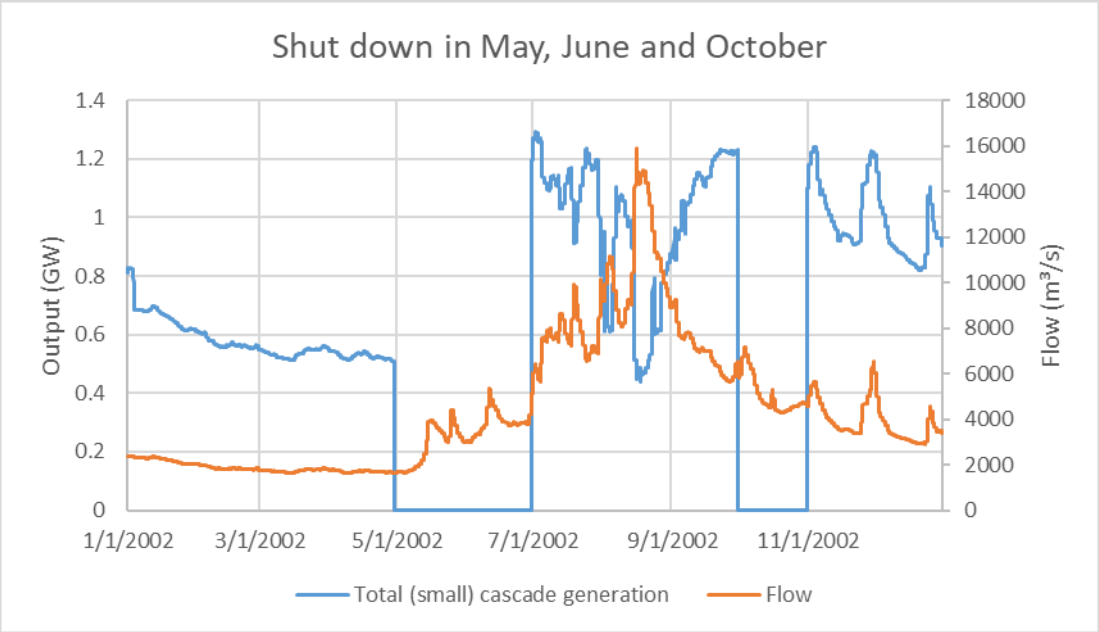


Figure 6.37. *Total output (GW) for the four small dams with shut down in May, June and October*

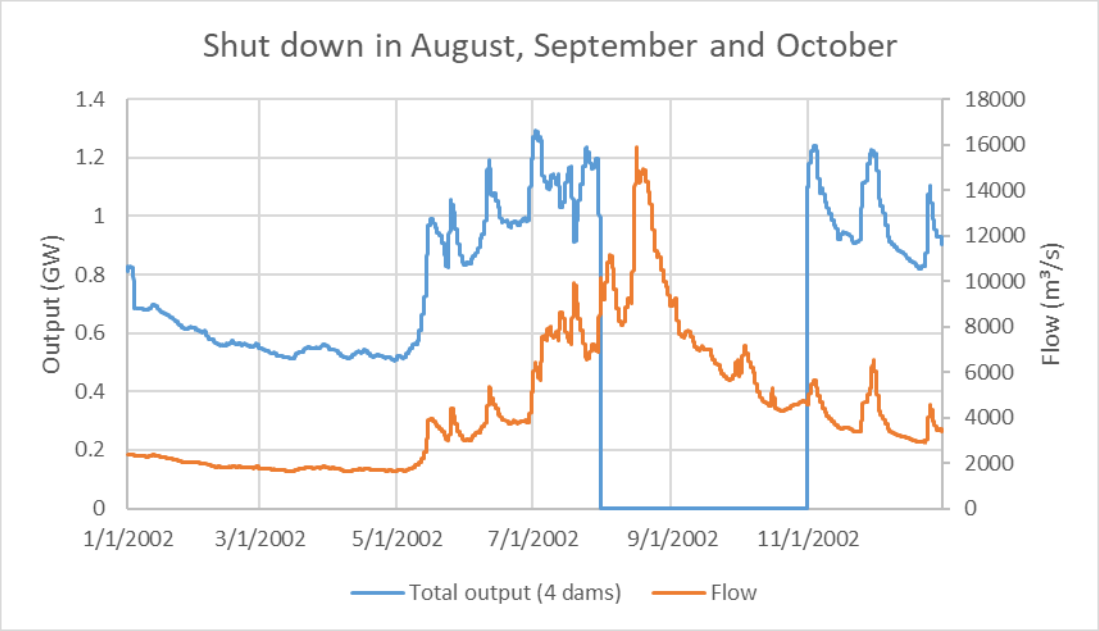


Figure 6.38. *Total output (GW) for the four smaller dams with shut down in August, September and October*

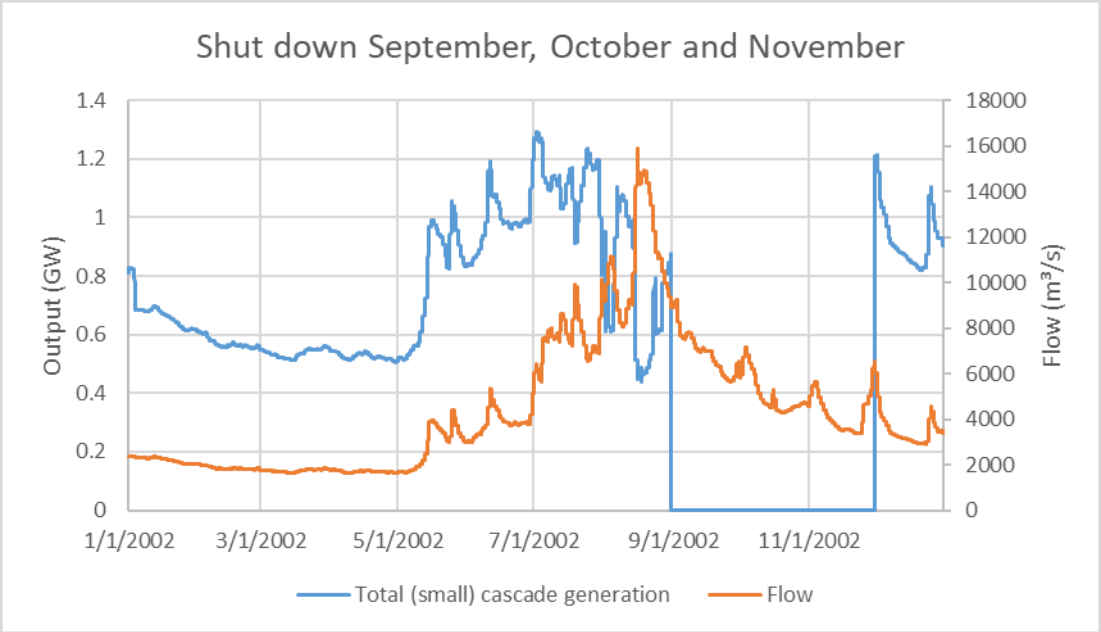


Figure 6.39. *Total output (GW) for the four smaller dams with shut down in September, October and November*

Power generation

Power generation without the shut-down have been calculated to ca. 7200 GWh/year, which is about 11% lower than the generation of Pak Lay and Sanakham in alternative 1.1.B. The shut-down for fish migration leads to another 24-27% loss of energy, depending on which months that are chosen for shut-down.

Table 6.5. Power generation for the shut-down alternatives.

	Generation 4 small dams	% lost compared to 1.1.C	% lost due to shutdown
No shutdown	7183	11%	0%
Shutdown may, jun, oct	5219	35%	24%
Shutdown aug-oct	5025	38%	27%
Shutdown sep-nov	5040	37%	27%

Impact on Xayaburi

Dam 1 is placed closer to Xayaburi than Pak Lay in the original cascade. This means that the backwater effect (rise in tailwater level) because Dam 1 is less than of Pak Lay, and the tailwater level of Xayaburi is decreased at small and medium flows. At large flows however, the tail water level at Xayaburi is increased because of the flood surcharge of 2 meters at dam 1. The results from the modelling shows that the generation of Xayaburi will slightly increase during the dry season and slightly decrease during the wet season, but that the total generation of Xayaburi will not change.

6.2 Partial Cascade Development

6.2.1 Engineering Design and Operation

Option 2 of the Case Study considers a three-project cascade comprising Pak Beng, Luang Prabang and Xayaburi. The intention is to assess the environmental benefits or leaving the reach downstream of Xayaburi undeveloped.

This option does not require any revised design requirements for the three remaining projects except that the Xayaburi tail water level will no longer be impacted by the construction of the Pak Lay project.

6.2.2 Hydrology and Flows

The three-project cascade, comprising Pak Beng, Luang Prabang and Xayaburi, has the intention to create environmental benefits by leaving the reach downstream of Xayaburi undeveloped. The mitigation of hydrological risks that have been previously indicated for the dams in the full cascade (mostly hydropeaking) can be used similarly for the smaller cascade. However, the remaining water-level fluctuations at Sanakham and Vientiane will now be lower, as the last dam is much further upstream. The long waves created by hydropeaking will be damped much stronger before arriving at Vientiane.

The hydrological impacts from (alternative) sediment-sluicing operations only have relevance when the reservoir operation is lowered rapidly at the start of the operation, and when filling is starting at the end of the operation. These operations will have downstream impacts, requiring regulation of ramping rates as shown before.

6.2.3 Sediments and Geomorphology

Restricting the Northern Laos Cascade to three projects (Pak Beng, Luang Prabang and Xayaburi) would have a net benefit with respect to sediment transport as it would reduce the total quantity of sediment trapped in the impoundments and increase the potential for sediment transmission to the downstream river.

Sediment trapping in the lower cascade (Paklay, Sanakham and Pak Chom) is estimated at up to 6.7 Mt/yr in the Council Study (MRC, 2017). The benefits of not developing additional hydropower projects downstream of Xayaburi include:

- The sediment that is not trapped or flushed from Xayaburi would be transported downstream to the lower LMB;
- The increase in sediment discharge would decrease the rate of the ‘erosional wave’ progressing downstream of the final dam in the cascade;
- The sediment remaining in the Mekong River channel downstream of Xayaburi and upstream of the final dam site (Pak Chom) would serve as an additional sediment reservoir and buffer the impacts from the cascade being experienced downstream;
- Any discharge of sediment from Nam Ou would need to be managed and discharged through only one impoundment prior to release to the downstream river;
- During sediment flushing at Xayaburi water levels could be drawn down below the minimum operating level of Pak Lay.

The elimination of the two or three downstream projects in the cascade would reduce the complexity of sediment flushing through the cascade over the long-term, as there would be fewer reservoirs through which the sediment and large volumes of water associated with flushing would need to be transmitted and discharged, but would otherwise not affect the operations of the upstream stations.

The first years of operations at Xayabouri will provide an opportunity to observe and monitor this 'Partial Cascade' option.

A comparison of impacts associated with the development of the full Northern Lao PDR Cascade and the development of the partial cascade is provided in Table 6.6.

Table 6.6. Comparison of impacts associated with full-cascade and partial cascade development. The potential for mitigating impacts is the same as presented in Table 6.3 (section 6.1.3.6) for the full cascade.

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Impact under Partial Cascade Development
Maintain existing river channel habitats	Bank erosion, channel incision	Lake shore and hill slope erosion related to fluctuating water levels	Same impacts occurring in each impoundment, but fewer impoundments equates to fewer km of hillslopes affected
		Channel scour downstream of final dam in cascade, extending to lower LMB	More sediment available in mainstream Mekong below final dam (Xayaburi) and Vientiane, so more time until erosional wave progresses to Vientiane
			More potential for flushing sediment from Nam Ou or upper Mekong due to fewer impoundments trapping sediments
	Deep pools, rapids	Within impoundment deep pools filled in by sedimentation	Fewer deep pools affected by sedimentation
		Deep pools in 'free flowing' reaches subject to changed flow and sediment regime	Maintenance of seasonality of flows to maintain 'flushing' of deep pools
			Pools downstream upstream and downstream of cascade maintained by seasonal flows

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Impact under Partial Cascade Development
Maintain river connectivity	Sediment transfer	Trapping of medium sand and larger grain-sizes in impoundments	Similar level of trapping in each impoundment, but fewer impoundments so more sediment from downstream tributaries is transported to lower Mekong. Sediment flushing could be more efficient as level in Xayaburi could be drawn down lower
		Trapping of fine sand in impoundments	Similar level of trapping in each impoundment, but fewer impoundments so more sediment from downstream tributaries is transported to lower Mekong. Sediment flushing only needs to move sand through 3 impoundments rather than 5 or 6
		Trapping of silt and clay in impoundments	Similar level of trapping in each impoundment but fewer impoundments.
		Maintenance of sediment pulse to coincide with flood pulse	More sediment entering Mekong downstream of Xayaburi so sediment pulse is larger
		High sediment concentrations and loads during sediment flushing	Fewer impoundments to flush so reduced quantities of sediment requiring flushing
			Easier to coordinate flushing of 3 impoundments as compared to 5 or 6
Maintain water quality	Water Quality	Increased temperatures (risk increases in each successive impoundment)	Reduced cumulative residence time as compared to full cascade, so less warming
		Increased risk of algal bloom	Risk is limited to 3 impoundments only

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Impact under Partial Cascade Development
		Nutrient transport (Silt & clay used as surrogate)	Reduced sediment trapping as compared to full cascade so reduced nutrient trapping

6.2.4 Fisheries and Aquatic Ecology

The partial development of the Northern Laos Cascade brings some benefits related to habitat quality and connectivity. Limiting the upper cascade to three dams would cause the following improvements:

- The impounded length would change from 391 km to 253 km and therefore cause a reduction by ~1/3 (i.e. 35 %). This would of course also reduce negative impacts related to impoundments as e.g. habitat alteration due to sedimentation (see also chapter 6.3.3), loss of free flowing river sections, deposition of drifting eggs/larvae and water quality changes.
- In case of peaking operations, it is assumed that the negative effects (e.g. stranding of larvae and juvenile fish) would also be reduced (i.e. would not extend so far downstream) compared to the development of all five dams.
- With regard to connectivity, having Xayaburi as the lower limit of the cascade instead of Sanakham would allow upstream migrating fish to travel 200 km further before encountering the first dam. As the whole upper cascade is located in the Upper LMB migration system, tributaries (which are limited in number and length between Xayaburi and Sanakham) are assumed to play only a minor role for migratory species compared to the Mekong mainstream. Therefore, a gain of 200 km can be considered as a clear benefit, especially for species having their spawning grounds in the upper migration system. Nevertheless, it remains still questionable if a partial development of the upper cascade can still ensure successful reproduction.
- As already discussed in chapter 5.5.2, the cumulative passage efficiency in up- and downstream direction depends highly on the number of barriers and their passage efficiency. Although the absolute improvement may not be very high (e.g. 14 % improvement for upstream migration), there is an improvement by factor 4 in upstream direction (i.e. 4 times higher, assuming a passage efficiency of 50 %) and by factor 11 for downstream migration (assuming a mortality of 70 %) compared to a cascade of five dams.

Table 6.7. Improvement of up- and downstream cumulative connectivity within the cascade (see also chapter 5.5.2.1).

	Upstream migration		Downstream migration	
	Passage efficiency		Passage efficiency	
Per dam	90 %	50 %	98 %	30 %
for 5 dams	59 %	3 %	90 %	0.24 %
for 3 dams	73 %	13 %	94 %	2.7 %
Improvement	14 %	10 %	4 %	2.46 %
Factor (i.e. 3 dams : 5 dams)	1.2	4.3	1.04	11.25

- With regard to catchment connectivity, we again calculated the DCI_{migr} (Dendritic Connectivity Index for migratory species, see also chapter 5.2.1). To make the influence of the mainstream dams visible, we also included the historic situation and the 2040 scenario which includes all planned tributary dams but no mainstream dams. Especially for migratory species the drop from 79 to 66 % connectivity after including the first three mainstream dams is clearly visible. Including also the two lower dams (Pak Lay & Sanakham) causes an additional loss of 5 % (from a CDImigr of 66% to 61%).
- With regard to the unweighted DCI (DCIlength) it can clearly be seen that the fragmentation of the tributaries causes a dramatic loss of connectivity. Therefore, the difference between the partial and full cascade developments is less visible here.

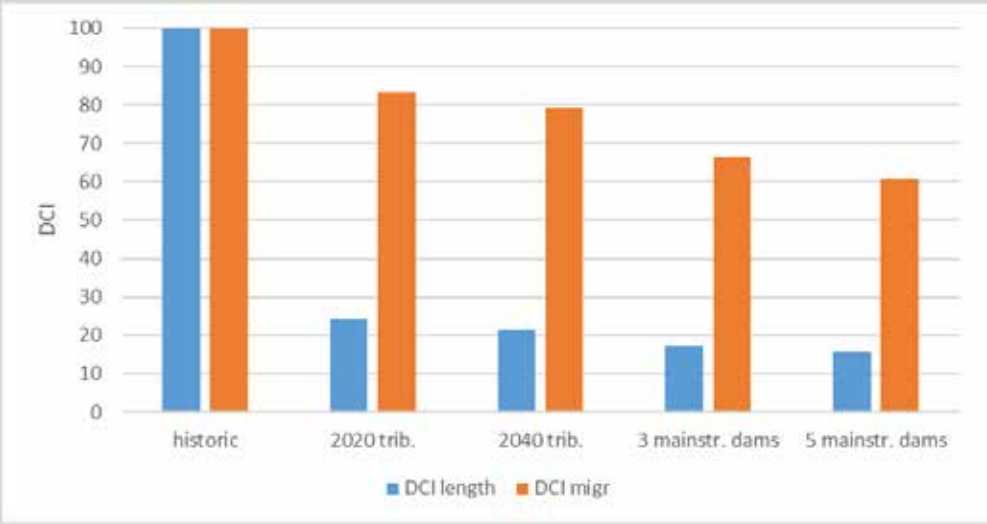


Figure 6.40. *Comparison of DCIs for partial development (i.e. 3 mainstream dams) compared to 5 dams. DCI length uses the unweighted river length while DCI migr weights the river length by the number of migratory species occurring in a section. Considered passability was set to 0% to highlight max. increase in connectivity.*

- While the Figure above bases on the assumption that the dams allow no passage (i.e. 0% passability) the benefit of partial development is greater for low passage efficiencies compared to higher rates. For 95 % passability, partial development leads only to an improvement of 1.5 % while connectivity increases by ~6% for passage efficiencies of 50% and 0%.

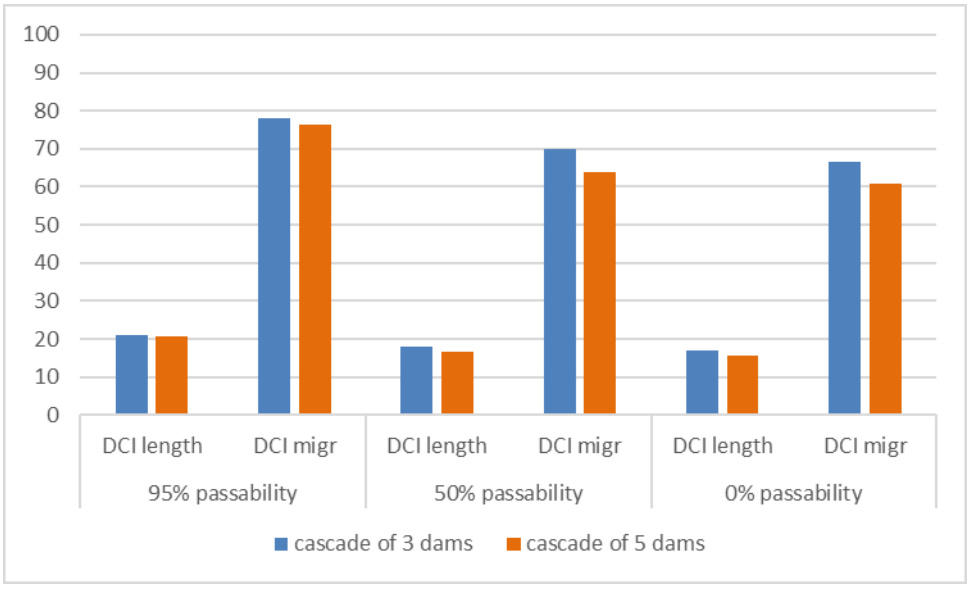


Figure 6.41. *Comparison of DCIs for partial and full development of the upper cascade assuming different passability rates.*

In any case, the first dam in the cascade (i.e. Xayaburi) should guide the way for designing any additional dams. Since the weakest link in a chain determines its strength, new mainstream dams should incorporate at least those mitigation measures considered for Xayaburi. Nevertheless, lessons learned from Xayaburi should be incorporated in future designs. Once the dam is in operation, it should be used to gather additional data on fish migration (including larval drift, turbine passage) and the efficiency of mitigation measures. Based on these findings, it will be easier to quantify the related impacts and the efficiency of the included mitigation measures. These data are not only relevant for adaptive management (i.e. for Xayaburi) but also for consideration on partial developments or the improvement of mitigation measures.

6.2.5 Impacts on Power Production and Revenue

If the two downstream dams are not built, Xayaburi HPP will have a slightly larger head, and thus a slightly higher power generation. The removal of the two dams will however reduce the total annual generation with about 8000 GWh.

6.3 Downstream Dams

6.3.1 Engineering Design and Operation

The design principles investigated in the Case Study are equally applicable to dams further downstream. In addition to the flushing and sluicing strategy tested in Option 1.2 sediment transport can also be achieved using a bypass approach. Bypass tunnels are suited to mountainous regions with steep river slopes and small reservoirs and are therefore unlikely to be suitable for the Lower Mekong. Bypass channels may be better suited to conditions on the Mekong, particularly where natural distributaries occur.

At Don Sahong, a 260 MW hydropower project is currently under construction on the Hou Sahong Channel at Kone Falls near the Cambodian border. The arrangement is shown in Figure 6.42.

Figure 6.42. *Don Sahong Hydrpower Project (AECOM – Sept 2011).*

The Don Sahong project leaves most of the river channels at Kone Falls in their natural condition so that ecological processes such as fish migration can continue with modification.

An alternative approach is being studied for the Sambor Hydropower Project in Cambodia. At this location a 2,600 MW facility was planned that would span the entire river and create a reservoir with a storage of 4.3 x 109 m3. An alternative project is now under consideration with a reduced installed capacity of 1,703 MW that would only occupy the right river channel. The left river channel will then be available to function as a bypass channel for sediment and fish migration. A further opportunity exists to sub divide the lower reservoir into two smaller reservoirs commanding the same head by constructing a second dam at the narrow section of the reservoir adjacent to the island.

6.3.2 Hydrology and Flows

All main-stream dams proposed in the downstream 'cascade' are operated as run-of-the-river schemes. That means they are lacking sufficient active storage to influence the seasonal or large-scale flow patterns, similar to the upstream (Northern) cascade. Some minor impacts can be associated to emptying and filling from dead-water level to normal operation level and vice versa for sediment flushing or other operations (see also at the end of this sub-section).

The main hydrological risk related to the downstream dams is related to the sub-daily hydropeaking. The peaking will cause rapid changes in the reservoirs and downstream reaches. The calculated water-level fluctuations that can occur daily are given below.

	Ban Kum	Latsua	Stung Treng	Sambor
Location / max. level difference	Ban kun dam DS / 4.8 m	Latsue ds / 2.9 m	Stung Trng ds / 2.5 m	Sambor ds / 4.2 m
Location / max level difference	Mouth Mun River / 4.0 m	40 km ds Latsua / 1.2 m	17 km ds Stung Treng / 2.4 m	100 km ds Sambor / 0.9 m
Location / max level differenc	Pakse / 2.8 m	87 km ds Latsua / 0.9 m	35 km ds Stung Treng / 2.3 m	Phnom Penh / 0.2 m

The table shows that maximum water-level fluctuations directly below the dams can vary between 2 to 5 m per day. This situation will occur roughly at discharges of 4000 to 5000 m3/s. The daily fluctuations are visualized in the figure below. The figure shows how the amplitude decreases downstream as simulated with a 1D unsteady flow simulation. It also shows how water levels rise and fall gradually after the switch of peak and off-peak discharge, with maximum or minimum at the end of each cycle. For this dam, the switch occurs before the real maximum or minimum of water-level has been reached at the dam site. This simulation compares well to the 1D hydraulic module of the DSF, although this result has been calculated with simplified cross-sections.

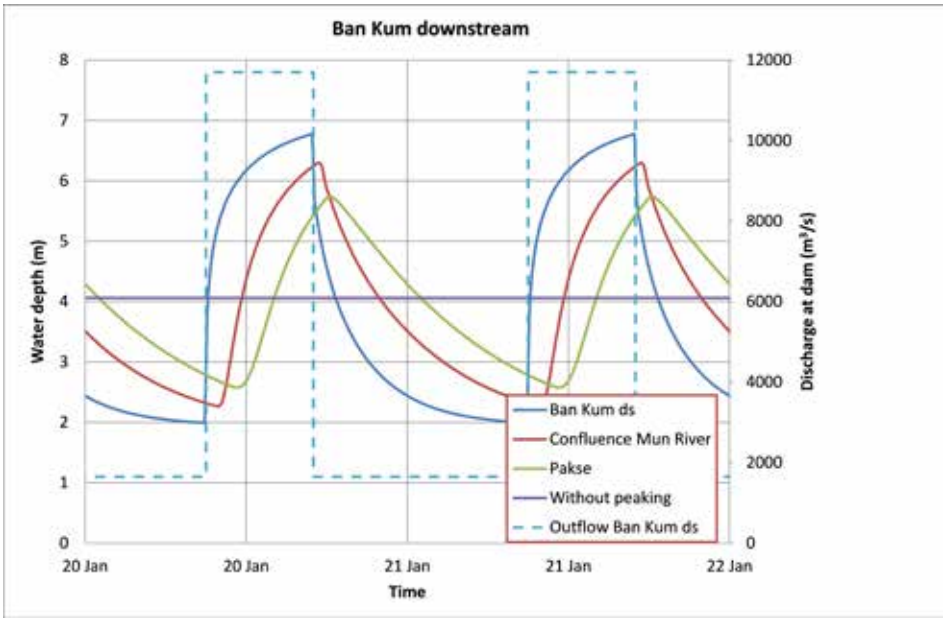


Figure 6.43. *Water-depth fluctuations approximated for maximum hydropeaking fluctuations downstream of Ban Kum dam*

The table below presents the maximum rate of fluctuation in meters per hour, associated with the maximum water-level fluctuations shown above. In most cases, these values exceed the recommended 0.1 m/hr or 0.05 m/hr that are necessary for minimizing environmental risk. Near the dam sites, the rates can range from 11 m/hr (Ban Kun) to roughly 1 m/hr (fall and rise of water levels due to peaking only).

	Ban Kum	Latsua	Stung Treng	Sambor
Location ; max. level rise ; max level fall	Ban kun dam DS ; 11 m/hr ; -8 m/hr	Latsue ds ; 1.0 m/hr ; -0.7 m/hr	Stung Trng ds ; 1.0 m/hr ; -1.0 m/hr	Sambor ds ; 1.5 m/hr ; -1.0 m/hr
Location ; max. level rise ; max level fall	Mouth Mun River ; 1.4 m/hr ; -1.2 m/hr	40 km ds Latsua ; 0.2 m/hr ; -0.1 m/hr	17 km ds Stung Treng ; 0.8 m/hr ; -0.4 m/hr	100 km ds Sambor ; 0.2 m/hr ; -0.1 m/hr
Location ; max. level rise ; max level fall	Pakse ; 0.7 m/hr ; -0.2 m/hr	87 km ds Latsua ; 0.2 m/hr ; -0.1 m/hr	35 km ds Stung Treng ; 0.7 m/hr ; -0.3 m/hr	Phnom Penh ; 0.03 m/hr ; -0.02 m/hr

The rates in the tables above were obtained without ramping: the change from off-peak to peak flows is practically instantaneous. It was found that by ramping the discharges over several hours

between peak and off-peak levels, it is not possible to eliminate these high fluctuations. For example, ramping the discharge over 2 hours causes the water-level fluctuation at 'Ban Kum dam ds' to go down from 4.8 m to 4.7 m, but with a ramping rate decrease from maximum 11 m/hr to 1.7 m/hr. The physical changes are presented in the figure below for the simulation with and without ramping. Note that ramping will lead to a reduction in power production.

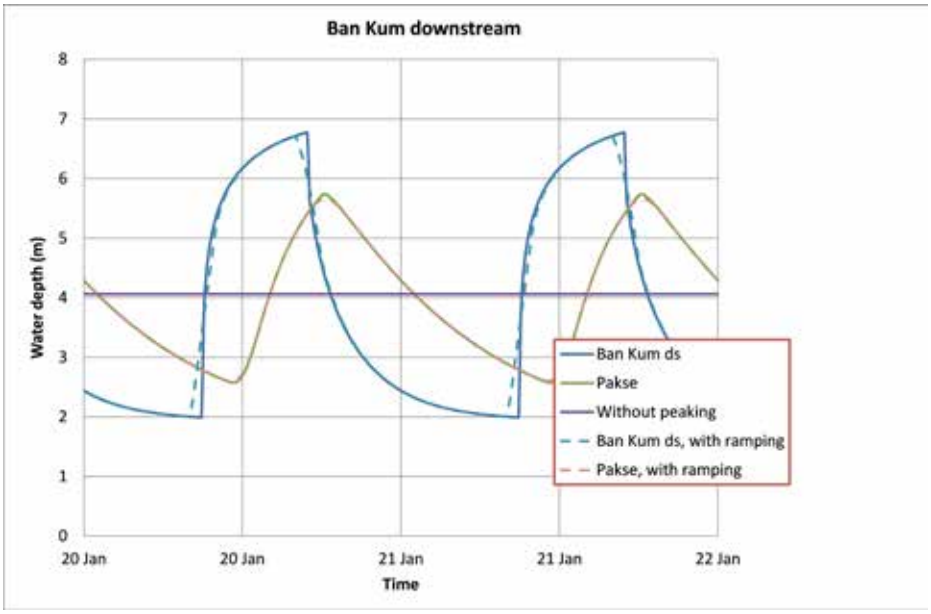


Figure 6.44. *Calculated water-level fluctuations downstream of Ban Kum, with and without using a ramping rate.*

The hydrological risks related to these larger fluctuations in water-level are substantial. Mitigation of these effects is mostly done by fully eliminating the peaking procedures. If hydropeaking is still considered, it is useful to allow the fluctuations only in the impounded sections of the cascade, while operating the lower dam as a regulator to dampen the fluctuations from the upper reservoirs and prevent large fluctuations in the downstream (not impounded) river reach.

From the (simplified) calculations it can be observed that in the lower cascade the reservoirs of each dam will affect the tailwater of the upstream dam for a large range of discharges. The backwater of Latsua dam will reach the Mun River mouth, although this has already been reduced significantly by moving the dam location downstream of Pakse. The remaining backwater effect still requires careful analysis. In analogy with Pak Beng dam, to prevent backwater problems during low-flow periods, and flooding during high flow, it may be necessary to lower the operation level during certain periods of the year.

The simulations for hydropower sub-scenarios in the Council Study do not reveal the impacts on flows from the sediment mitigation options. The draw-down of water levels at the start of the flushing and/or sluicing operations will cause a temporary increase of discharge downstream. Subsequently, the filling of the reservoir at the end of the operation, will lead to a reduction of discharge downstream. As shown in the Northern Cascade modelling results, these fluctuations remain acceptable as long as the environmental ramping restrictions are obeyed. A further quantification on basis of Council Study model output is not possible.

6.3.3 Sediments and Geomorphology

The LMB downstream of the Northern Laos Cascade can be roughly divided into the following regions with respect to hydropower development and mitigation: the Lao PDR tributaries entering between the final project in the Northern Laos Cascade and the confluence with the 3S river system, the transboundary 3S River system and the mainstream LMB including the Tonle Sap and delta. Each of these is discussed in the following sections.

6.3.3.1 Lao PDR Tributaries downstream of the Northern Laos Cascade

The Mekong River downstream of Vientiane changes hydrologically from one in which flow is dominated in both the wet and dry seasons by the inflow from China, to one where the left bank tributaries originating in Lao PDR contribute an increasingly important proportion of the total flow (MRC, 2005). The same is true with respect to sediment, with the reach between Vientiane / Nong Khai and Pakse recording large increases in sediment fluxes based on the MRC monitoring results.

The Council Study results estimate 28 Mt / yr of sediment is trapped in the Lao PDR tributary projects, with about 7 Mt / yr trapped in projects located within the Northern Laos Cascade catchment. The remaining ~20 Mt is derived from the 'left bank' tributaries, and the head water projects in the Se Kong River, with the left bank tributaries providing the largest proportion.

An enlargement of this region is shown in Figure 6.45 with the symbols providing a high level indication of whether sediment flushing or sluicing might be applicable to the projects based on the reservoir storage and inflow rates contained in the MRC hydropower database. The volumes of the impoundments relative to the inflows are typically large, suggesting that sediment management based on flushing or sluicing would have limited success. As previously stated, the inflow and volume values have been derived from the MRC database and projects may not reflect the most recent version of the project.

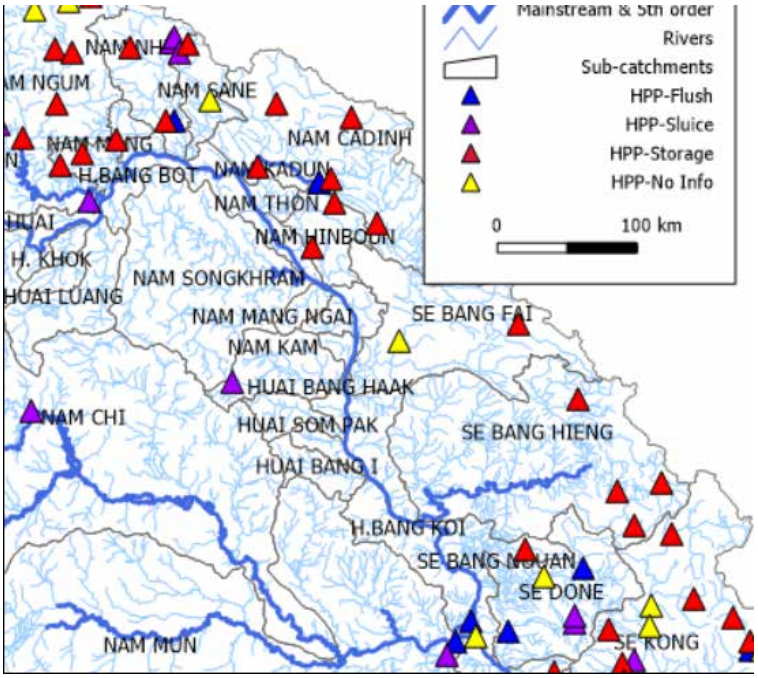


Figure 6.45. *The Lao PDR tributaries entering the Mekong downstream of the Northern Laos Cascade.*

Many of the tributary dams in this region of the Mekong have yet to be constructed, and thus an opportunity still exists to implement sediment management planning at the regional level. If planning approaches are implemented, it would be reasonable to divide this large region into smaller sub-regions, such as indicated in Figure 6.46 with the aim of maintaining some level of sediment contribution on a seasonal basis from each region.

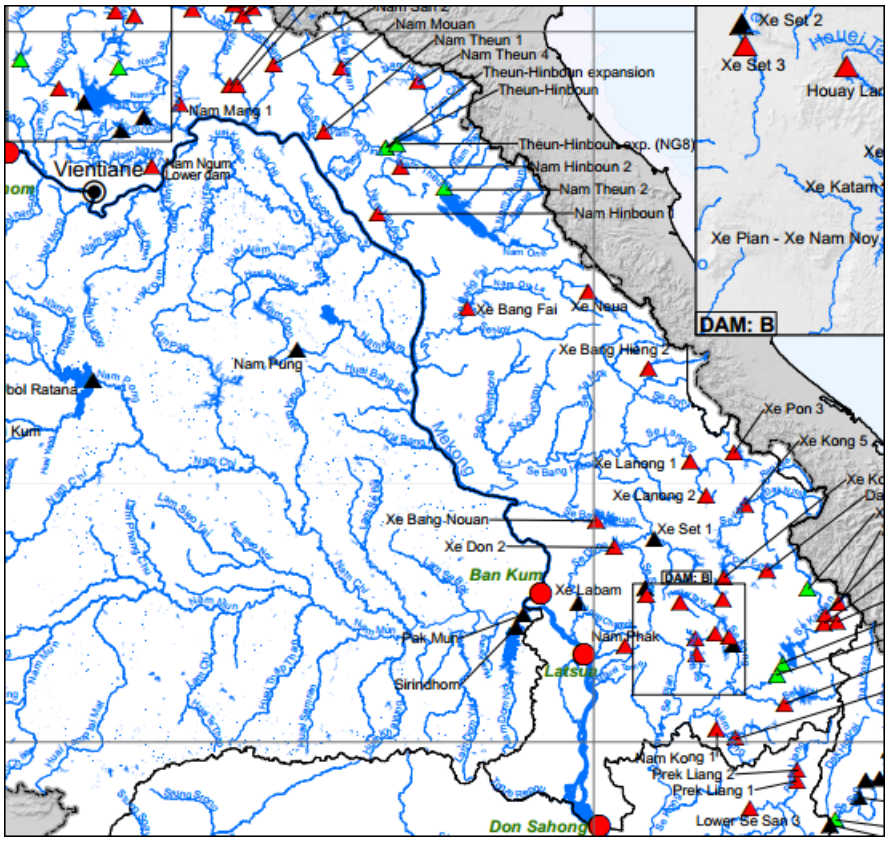


Figure 6.46. *Middle LMB showing 'left bank' Lao PDR tributaries. Boxes denote areas that could be considered as sub-regions for identifying sediment pathways. Red triangles denote projects still in planning based on the BDP 2011, green triangles are 'under construction' and black triangles indicate 'operating' power stations.*

Potential mitigation approaches include within each sub-region include:

- Identify significant sediment pathways on a sub-regional level and omit projects that would block these pathways. An example of this would be to omit the project on the Xe Bang Hieng River which is projected to have a high rate of sediment trapping (> 3 Mt of sediment per year), but a low installed generating capacity (16 MW). Omission of this project would retain a long reach of uninterrupted river extending from the headwaters of the catchment to the Mekong mainstream;
- Identify significant sediment pathways at a sub-regional level and alter the siting and design of projects to minimise the catchment areas captured upstream, minimise the size of reservoirs, minimise dam heights and include infrastructure to enable sediment passage through the system. Information about sediment inputs from individual tributaries and sub-catchments is required for implementation of this approach;
- Identify rivers with significant sediment input and do not develop additional dams downstream of existing dams to allow the maximum discharge of sediment from the

lower catchments. Similar to the previous option, information about sediment input from individual tributaries is required to implement this approach;

- If the previous two options are not possible, focus hydropower development upstream of existing dam sites as much as possible on a regional basis to maximise sediment input from the remnants of the tributaries that remain unregulated;
- Implement sand mining management at a sub-catchment and regional scale to maintain sand in the mainstream of the Mekong and tributaries as described in Section 6.2.3.5 under 'Catchment Management'. This approach has the potential to buffer the impacts of sediment starvation on the tributaries and mainstream over the short term

6.3.3.2 The 3S River Catchment

The 3S River is a transboundary catchment that contains operational and under construction hydropower schemes, predominantly located in the headwaters of the catchment (Figure 6.47). In the Se Kong sub-catchment, the headwater projects are either likely to be unsuitable for sediment flushing or sluicing (Figure 6.47, left) or there is insufficient information to evaluate the projects. In the Se San and Sre Pok catchments, headwater storages have high storage to inflow rations, but the reservoir attributes of projects in the middle reaches of the rivers show potential for sediment management (blue and purple symbols). However, these large sub-catchments lie upstream of the Lower Se San 2 and any sediment mitigation measures would need to include a mechanism to pass sediment through this lower impoundment to deliver sediment to the mainstream Mekong.

It is recognised that construction of the Lower Se San 2 is in progress, but previous work has investigated mitigation options at the Lower Se San 2 project and this work is summarised below as examples of how future projects might be modified to enhance sediment passage even though it is recognised the adaptations are unlikely to be implemented at the Lower Se San project.

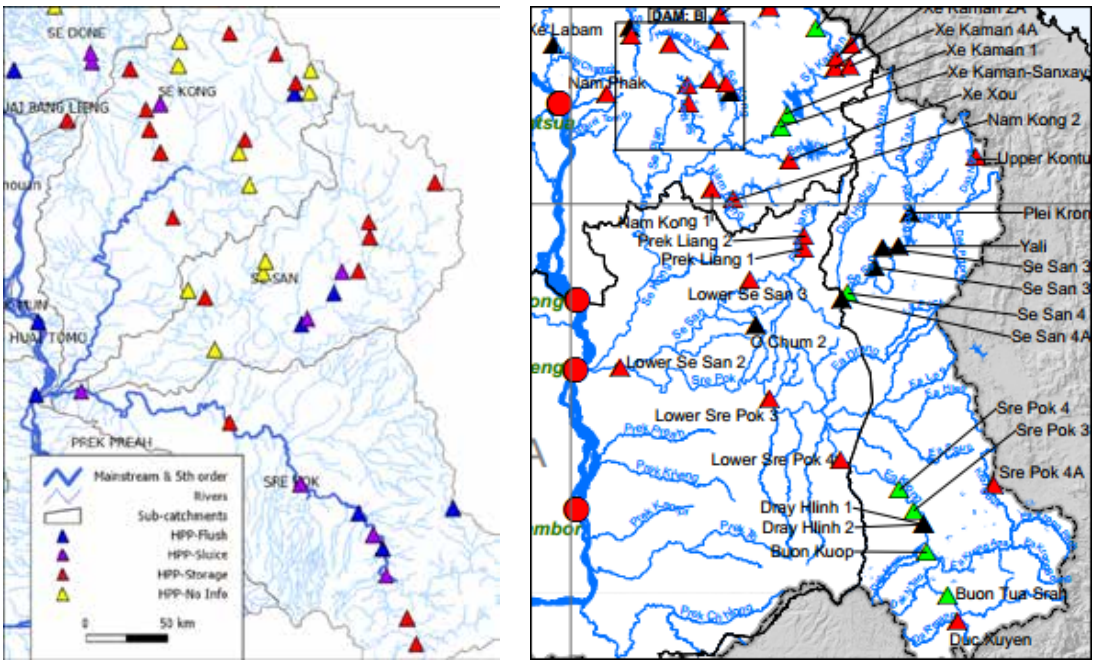


Figure 6.47. *(left) Extract from Figure 6.21 showing potential for sediment sluicing or sediment flushing, and (right) status of hydropower projects in the same region based on the BDP2011. Note the Lower Se San 2 project is under construction.*

Wild and Loucks (2015) surveyed sediment mitigation approaches for the Lower Se San 2, and noted that Annandale (2012a) identified full-draw down sediment flushing as a possible mitigation option. However the morphology of the Lower Se San 2 impoundment as planned is considered by Wild and Loucks (2015) to be too long and too wide for effective sediment management, and an alternative layout (Figure 6.48) was identified by the authors that consists of two smaller impoundments. The smaller impoundments would increase the potential for sediment passage whilst reducing the downstream impacts associated with full drawdown flushing of the degree associated with the original proposal. A net deficient in total energy generation between the 'new' and original project could be filled by the addition of two hydropower projects higher in the catchment (Se San US1 and Se San US 2 in Figure 6.49). This approach would improve sediment passage through the Lower Se San 2 area, although sediment trapping in the other projects would also have to be considered and managed.

Figure 6.48. *(top) View upstream from Se San 2 dam and (bottom) lateral view showing long dam length. These characteristics limit the ability to flush or sluice sediments. Source: http://www.rfa.org/english/multimedia/lowerSesanII-slideshow-07142017160537.html.*

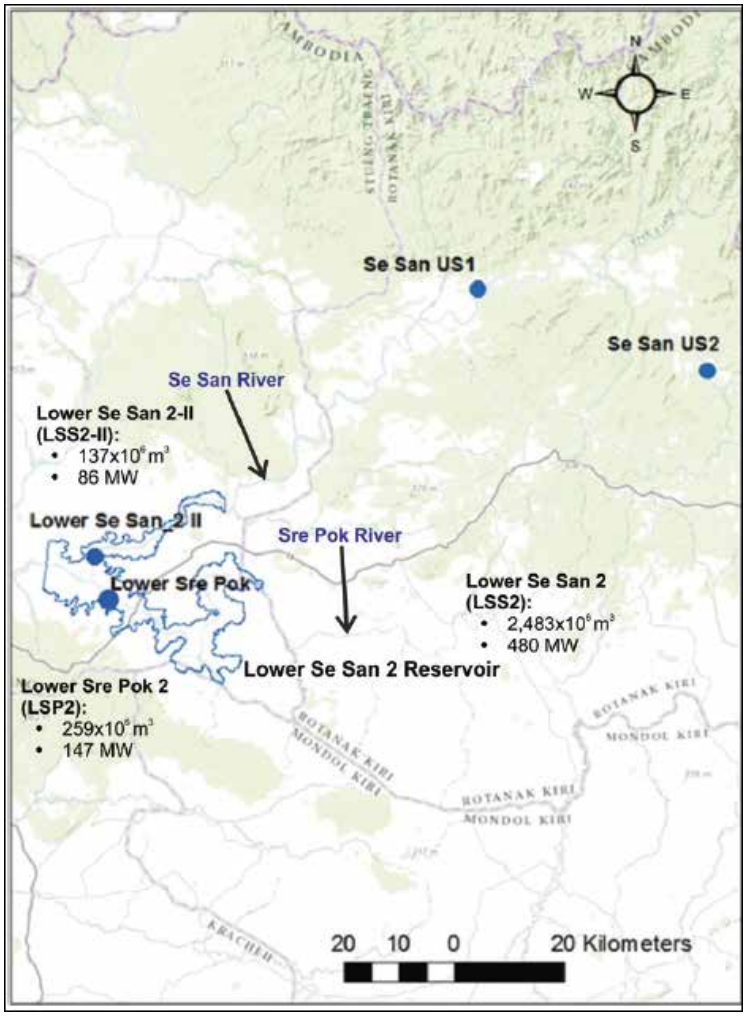


Figure 6.49. *Alternative layout for hydropower development on the Lower Se San River as proposed by Wild and Loucks (2015). Blue dots indicate the revised location of dam sites.*

Similarly, a high-level planning approach has been retroactively applied to the 3 S system by Schmitt, et al., (2017) based on optimisation of dam sediment trapping and hydropower generation. The results of the modelled planning approach are shown in Figure 6.50 and show two development pathways with the energy production capacity and sediment trapping capacity associated with each. The 'actual' development pathway (squares) shows that about 1.5Gwh/yr of energy was developed prior to the implementation of Se San 2 with a net sediment trapping rate of 55%. The 'optimised' pathway had the potential to deliver a similar energy production capacity with a sediment capture rate of only 15%. The optimised pathway has the potential to deliver 75% of the energy production capacity for a similar sediment reduction as the pre-Lower Se San 2 trapping rate of 55%. The implementation of the Lower Se San 2 project greatly increases sediment trapping along the 'actual' pathway without increasing energy production at a comparable level. Note, that these types of planning models are useful tools, but their reliability is dependent on the quality of sediment transport information used to establish the model. The lack of reliable information about sediment transport in the 3S as a basin as a whole and in each of the sub-catchments needs to be recognised when applying and interpreting this type of tool.

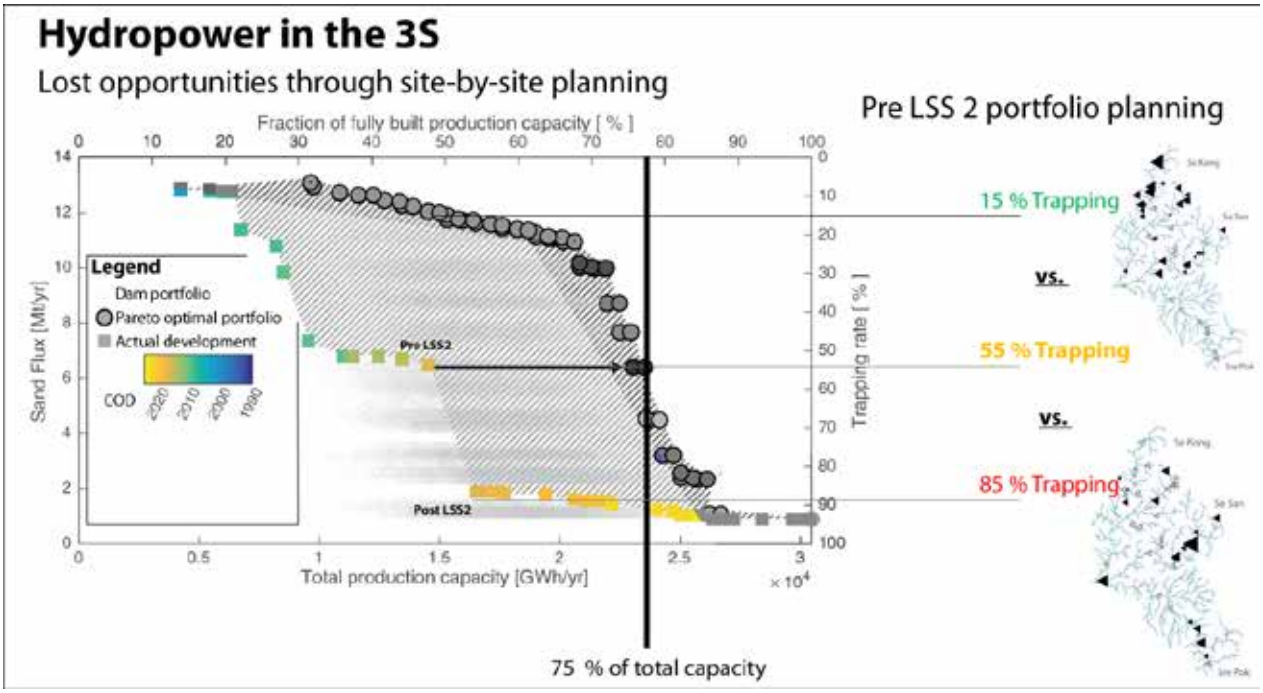


Figure 6.50. *Comparison of potential hydropower generation in the 3S as compared to sediment trapping if planning implemented at a catchment rather than project scale (Schmitt et al., 2017).*

6.3.3.3 The Lower Mainstream Dams

The five lower Mekong mainstream dams include Ban Kuom, Latsua and Don Sahong in Southern Laos and Stung Treng and Sambor in Cambodia. Figure 6.51 shows the locations of the sites and indicates the potential for sediment sluicing or sediment flushing, similar to the previously presented maps. However, sediment management on the lower mainstem Mekong presents additional challenges due to the large volumes of water required to be released for sediment flushing and the high population densities living at low elevations downstream. The morphology of Sambor, with a proposed 15 km dam length and very broad reservoir would also limit the effectiveness of these sediment management approaches, even if the inflow to storage ratio is theoretically conducive to sediment sluicing.

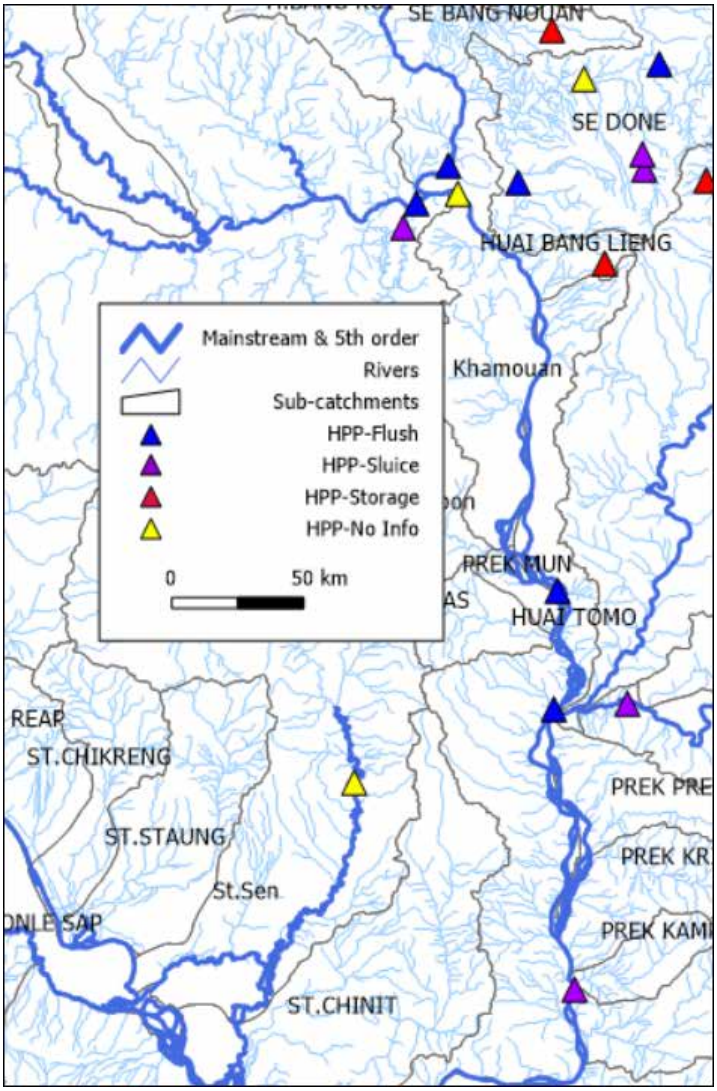


Figure 6.51. *Lower Mekong mainstream showing approximate dam locations and potential for sediment sluicing or flushing. DSH= Don Sa Hong (LA), BKM = Ban Koum, LTD = Lat Sua, ST = Stung Treng, SMB = Sambor*

In the Council Study full development scenario (MRC, 2017), the lower mainstream dams will cumulatively capture about 24 Mt/yr of sediment, with Ban Koum and Sambor projected to be the largest sediment sinks (Figure 6.52). The trapping at Ban Kuon is partially attributable to the project being the first project in the lower section of the river. The large sediment volume trapped in Sambor is attributable to the dam trapping silt and finer material as well as sand and bedload gravel. Based on the findings of the Council Study the amount of sediment transported through the final dam at Sambor is equivalent to 3% of the 2007 'baseline' sediment load. This large sediment reduction also reflects the reduced sediment load arriving at the mainstream Mekong due to sediment trapping in tributary dams.

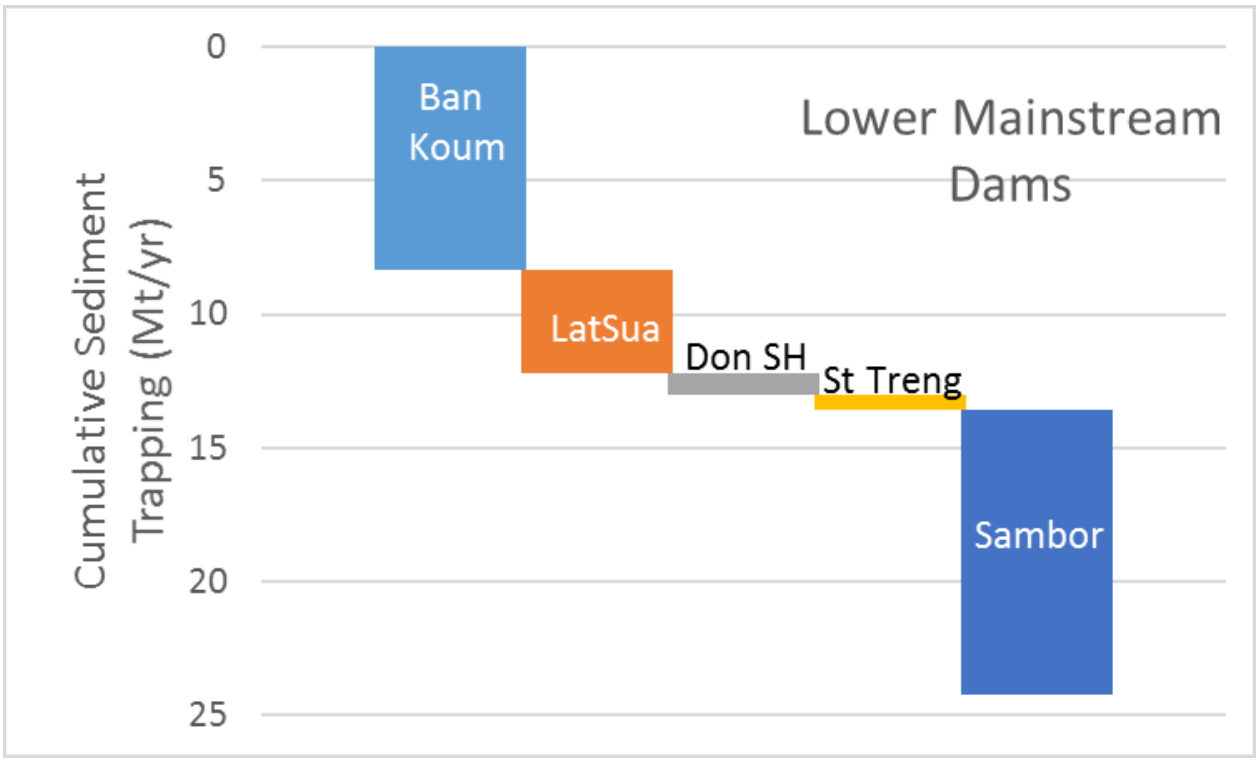


Figure 6.52. *Cumulative sediment trapping in the lower mainstream dams based on the Council Study results.*

The Council Study results are in agreement with the DHI / Govt of Vietnam (2015) Study on the Impacts of Mainstream Hydropower on the Mekong River (Delta Study) that found that whilst all mainstream dams captured sand and coarser sediments, Sambor had a high potential to trap silt as well as sand (Figure 6.53), with silt inputs of 40 Mt / yr being reduced to about 12 Mt/ yr in the outflow (different development scenario as compared to the Council Study). Silt and clay tend to contain the highest proportion of nutrients in sediment loads due to the high surface area to volume ratio of the size fractions. A reduction in nutrient transport in the lower Mekong will have implications for the ecology of the lower river system, including the Tonle Sap and delta.

The near total trapping of sand in the mainstream and tributary impoundments predicted by the Council Study modelling results will have grave implications for the mainstream Mekong downstream of Sambor. This area of the river is alluvial and will respond to changes in sediment loads through changes in channel depth and width. The 'quality' of the floodplain with respect to nutrient content will also be reduced due to the reduction in sedimentation.

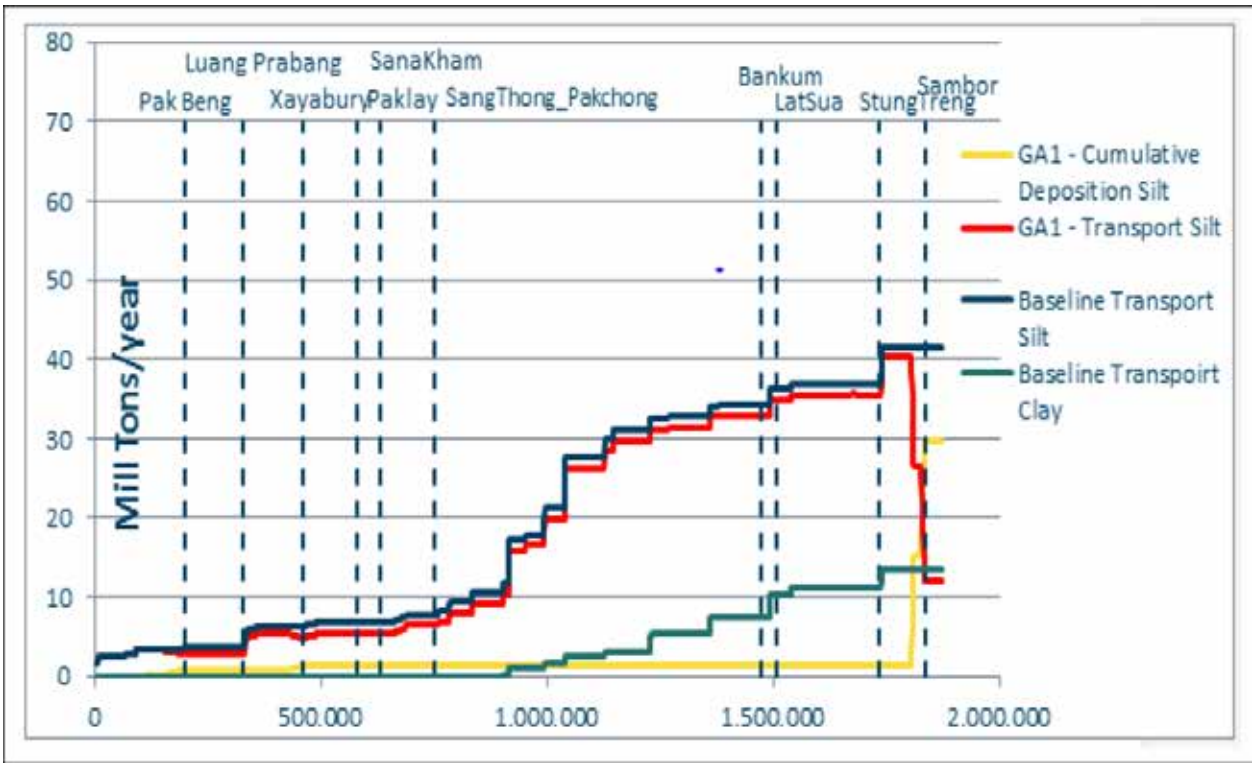


Figure 6.53. *Results from the DHI/Govt of Vietnam (2015) Mekong 'Delta' study showing the high silt trapping rate in Sambor.*

6.3.3.4 Council Study hydropower mitigation modelling scenario

The Council Study hydropower 'mitigation' sub-scenario included sediment flushing at all of the dams (as previously discussed) except Sambor, where a smaller version of the project was included based on the work of Wild and Loucks (2015). The alternative layout is based on a partial blocking of the mainstream, with a 'natural' sediment and fish bypass channel maintained (Figure 6.54). This mitigation approach provided the largest increase in sediment delivery downstream of any dam site relative to the unmitigated scenario, with sediment delivery to the delta increased from 5 Mt/yr to 19 Mt/yr (MRC, 2017). A similar increase in nutrient transport also resulted from the modified design (Because nutrients tend to be associated with the finer-grained sediments, maintaining the transport of silt and clay through Sambor is of great importance to the lower floodplain and delta. The 15 Mt/yr increase in sediment load is relatively small compared to pre-development loads (~160 Mt/yr),

Although not quantified in the model, this approach would provide additional benefits as the sediment transport would reflect the 'natural' seasonality of the river as much as possible recognising the impacts from the upstream hydropower projects.

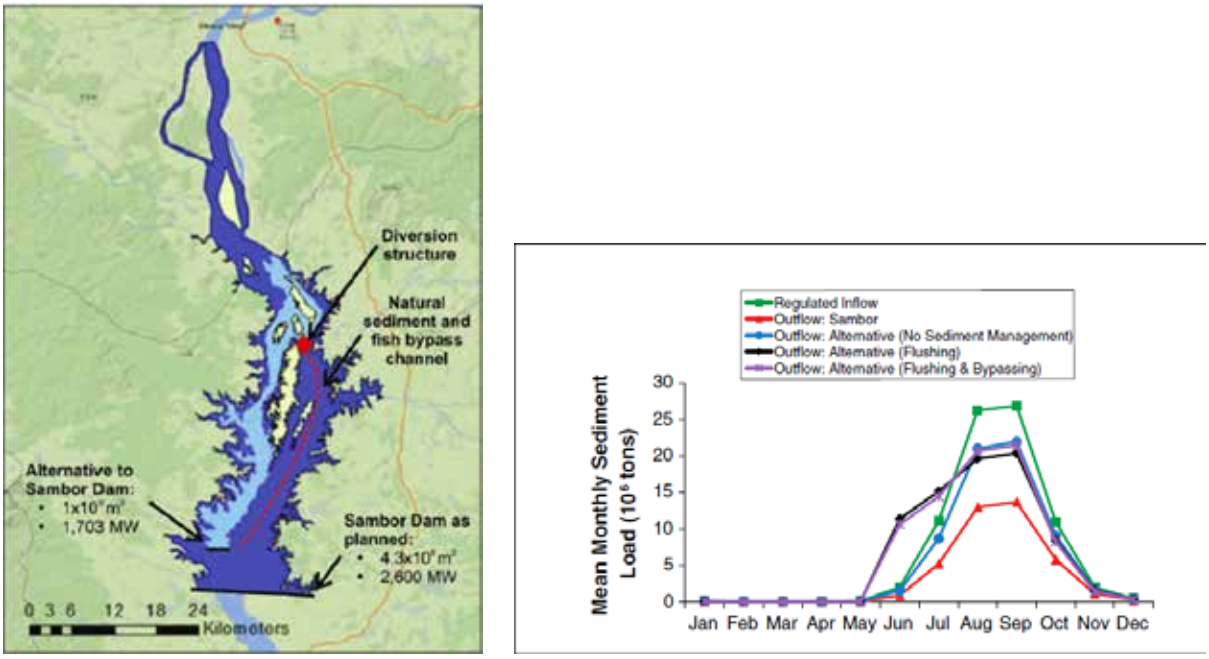


Figure 6.54. *Alternative layout option for Sambor that maintains a large 'naturally' flowing channel to provide sediment bypass (Wild and Loucks, 2015).*

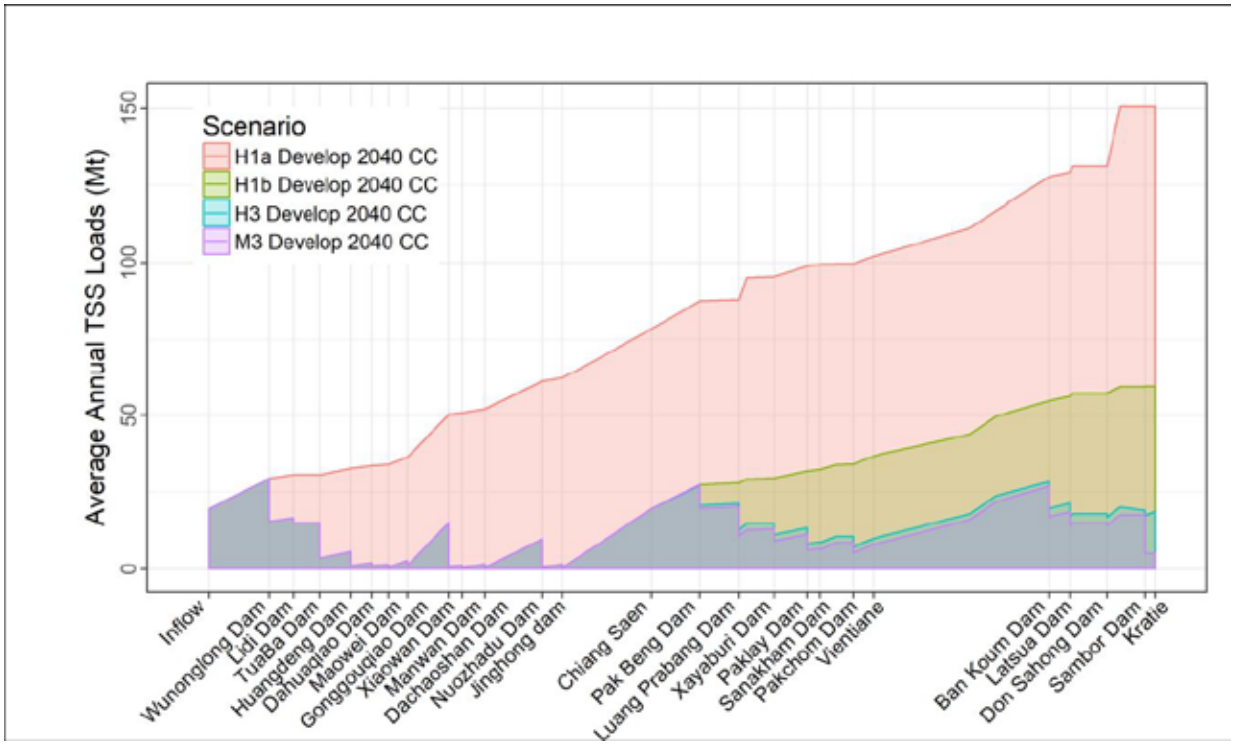


Figure 6.55. *Sediment results from the Council Study hydropower sub-scenario runs. M3 is the 2040 development scenario without mitigation and H3 is the same scenario with mitigation. H1a is a baseline (no post 2007 dams), and H1b is development without mainstream dams.*

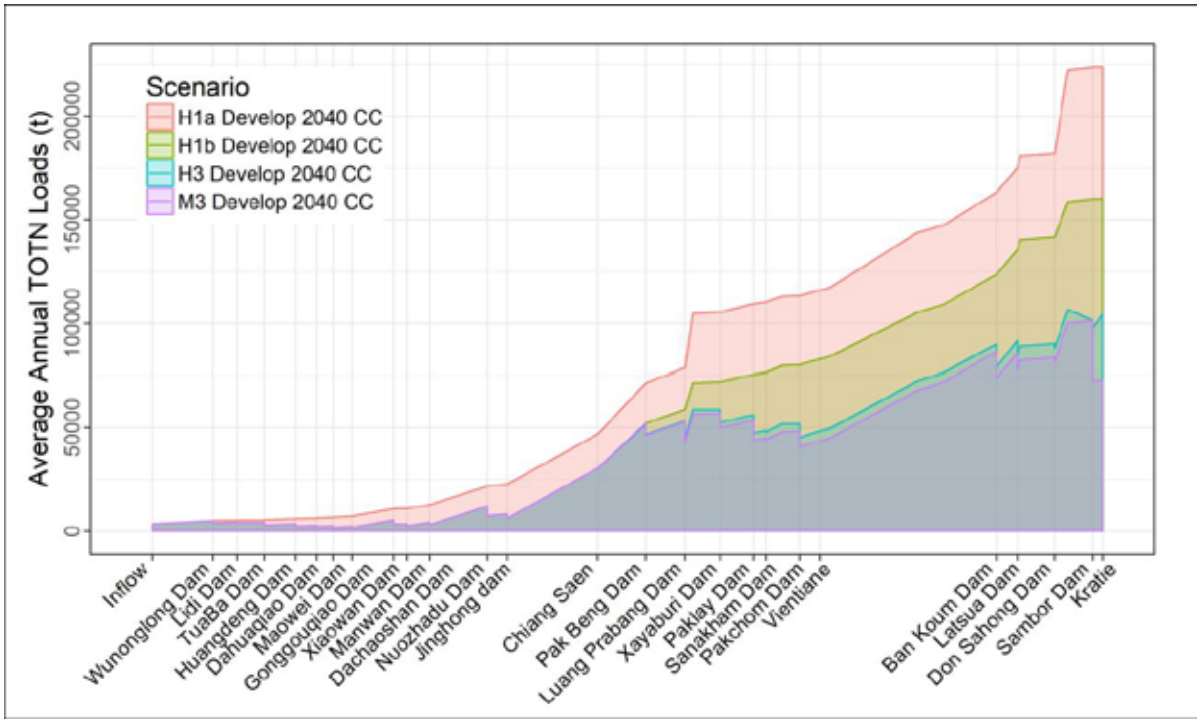


Figure 6.56*. Total Nitrogen results from Source model showing increase in nutrient release from Sambor with modified project design. Scenarios as described in previous figure.*

Mitigation approaches that might be applicable to the downstream mainstream dams include:

- Do not develop any mainstream dams downstream of the Northern Laos Cascade to maximise the transport of sediment and nutrients through the system with the aim of maximising the connectivity between the river basin and the delta and Tonle Sap systems. The sediment load from the tributaries will be greatly reduced due to trapping in the tributaries, so maximising transport of any sediment input in the mainstem is a sound mitigation approach;
- Only develop the projects that have the highest chance of implementing successful sediment management through flushing and sluicing on a routine basis. This would limit development to the smallest volume impoundments such as Lat Sua and Stung Treng;
- Develop all projects except Sambor which would reduce sediment trapping in the lower Mekong by almost 50%;
- Implement an alternative layout for Sambor with or without any of the other mitigation approaches. An alternative layout has been described in previous sections of this report and in Wild and Loucks (2015). This layout is projected to decrease sediment trapping by greater than 50% relative to the original design (Figure 6.54, right);
- Implement engineering works to stabilise the alluvial channel. River sand should not be used as fill for this purpose.
- Implement a comprehensive sand mining management strategy that minimises the removal of sand from the main channel of the Mekong, Bassac, Tonle Sap and distributaries of the delta to retain channel stability for as long as possible. This option is complimentary to all other mitigation strategies.

Table 6.8. Summary of potential impacts and potential for mitigation for tributary dams and mainstream dams located downstream of the Northern Lao Cascade.

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Severity	Applicable Mitigation Strategies	Potential for mitigation
Maintain existing river channel habitats	Bank erosion, channel incision	Lake shore and hill slope erosion related to fluctuating water levels	3	Reduce number of impoundments	2
				Restrict lake level fluctuating range and implement restrictions on ramping rates	3
		Channel scour downstream of dam in tributaries and mainstream Mekong	3	All dams (including tributary) have low level gates to promote sediment passage as soon as possible after commissioning	2
				Coordinated sediment flushing involving tributaries and mainstream dams	2
				Banning of sand and gravel mining from downstream of impoundments	2
				Optimise number and siting of projects to maintain sediment pathways	2
	Deep pools, rapids	Within impoundment deep pools filled in by sedimentation	3	None	3
		Deep pools in 'free flowing' reaches subject to changed flow and sediment regime	1	Maintenance of seasonality of flows to maintain 'flushing' of deep pools	1
				Timing of sediment flushing to minimise infilling of deep pools during dry season	1

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Severity	Applicable Mitigation Strategies	Potential for mitigation
Maintain river connectivity	Sediment transfer	Trapping of medium sand and larger grain-sizes in impoundments	3	Reduce number of dams and re-site projects to maintain sediment pathways	1
				Coordinated annual sediment flushing including mainstream and tributary dams	2
				Reduce size of impoundments and optimise morphology for sediment bypass or flushing	2
		Trapping of fine sand in impoundments	2	Reduce number of dams and re-site projects to maintain sediment pathways	1
				Coordinated annual sediment sluicing and flushing including mainstream and tributary dams	Initial years: 3 Later years: 2
		Trapping of silt and clay in impoundments	1	Maintenance of sediment pathways and annual sediment sluicing	1
		Maintenance of sediment pulse to coincide with flood pulse	2	Maintenance of sediment pathways and coordinate sluicing and flushing to coincide with onset of wet season	1
		High sediment concentrations and loads during sediment flushing	2	Coordinate and stagger flushing operations tributary dams to avoid multiple simultaneous ‘flushes’	1
				Release ‘clear’ water from high level outlets and power station during flushing events & coordinate with natural high inflows	1
				Flush on an annual basis to minimise sediment ‘build up’	1

6.3.4 Water Quality

The development of hydropower on the lower Mekong River mainstream and in the tributaries will alter the physical attributes of the system in ways that will directly and in directly affect water quality. Potential water quality changes associated with the physical changes include:

- Sediment trapping in reservoirs will translate into a reduction in the concentration of suspended sediment in the river and impoundments and lead to an increase in water clarity. This impact will be most pronounced during the dry season when unregulated inflows of sediment are reduced, and the residence time in dams is greatest owing to low inflows. Figure 6.57 summarises results from the Case Study showing a large increase in the proportion of days when sediment concentrations will decrease below 50 mg/L. In the lower Mekong mainstream, the sediment load discharged from Sambor is projected to be ~4.5 Mt/yr, transported in a total water discharge of 432,500 Mm3. On average, this would produce a discharge with ~1 mg/L suspended sediment. Large increases in water clarity can promote algal growth, and increase water temperatures deeper in the water column as compared to more turbid conditions;

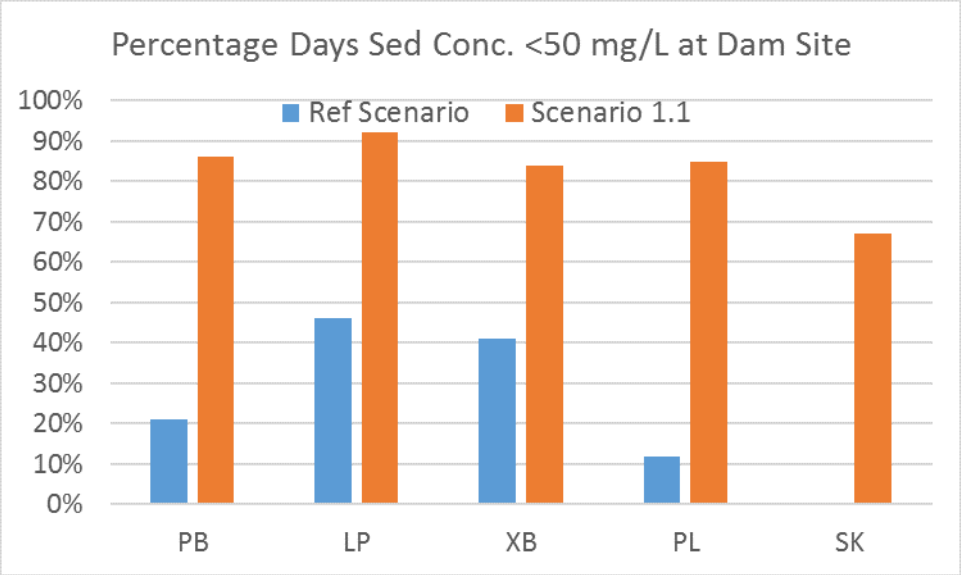


Figure 6.57. *Results from the Case Study showing the percentage of days during the dry season with sediment concentrations are predicted to be below 50 mg/L.*

- Water velocities will decrease in the backwater reaches of hydropower developments. This reduction in velocity is responsible for the decrease in sediment transport, but can also directly contribute to water quality changes as slowly moving surface waters may support increased algal growth, especially if water temperatures and water clarity increase. These conditions can also promote thermal stratification and the development of an anoxic layer in the base of the impoundment;
- The developments of impoundments will increase the residence time of water in the basin, and increase the surface area of water exposed to warming. Collectively these changes will promote an increase in water temperature. The increase in active volumes of hydropower impoundments is shown in Figure 6.58 for the Council Study development scenarios. The actual increase in volume is much greater, because the 'inactive' volume needs to be considered when determining residence time in reservoirs that are not thermally stratified (e.g., the entire reservoir volume is replenished rather than just

the active volume). Increased water temperatures will be most pronounced during the dry season when retention times are greatest, and light penetration is increased due to low sediment concentrations. The storage of water in successive impoundments will compound this impact;

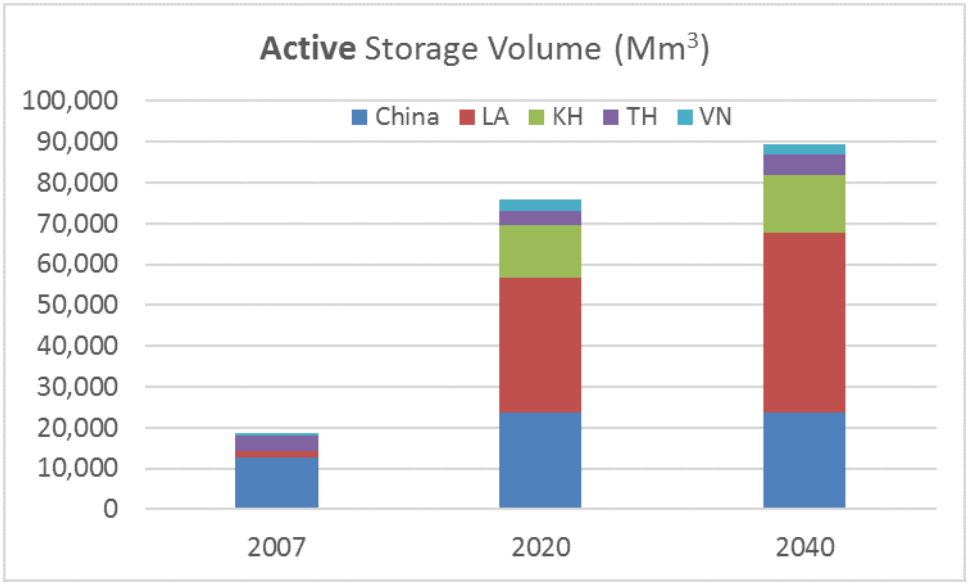


Figure 6.58. *Increase in active storage in the LMB associated with each of the development scenarios in the Council Study. Data from MRC (2017).*

- The large storage dams on the tributaries may release water that is low in dissolved oxygen if the lake stratifies and the water intake is located below the depth of the thermocline. This risk is greatest during the first years of operations when inundated vegetation is decomposing and consuming available oxygen in the water column;
- Large quantities of nutrients will be trapped in the reservoirs associated with sediment trapping. The Council Study modelling work adopted a partitioning ratio of 33% dissolved nitrogen and phosphorus with 66% associated with particulates. The large reduction in nutrients discharged from the dams is predicted to have an impact on downstream ecosystems. The nutrients retained within the impoundments can also affect water quality and may promote high levels of algal growth as nutrients are released from sediments into clear, warm, slow moving water. Additional nutrients will be added to the reservoirs through the decomposition of inundated organic material;
- Tributary dams that are operated in a hydropeaking mode may cause fluctuating water temperatures in the downstream rivers. Water stored in a reservoir is typically either warmer than (surface waters) or cooler than (bottom waters) water in an unregulated tributary in the same area. When the power station is discharging, the water is likely to contribute the majority of flow in the lower river, and alter water temperatures relative to 'ambient' conditions. During periods of power station shutdown, unregulated inflows will control water temperature in the river. These fluctuations can occur over periods of hours, depending on the hydropower production schedule.

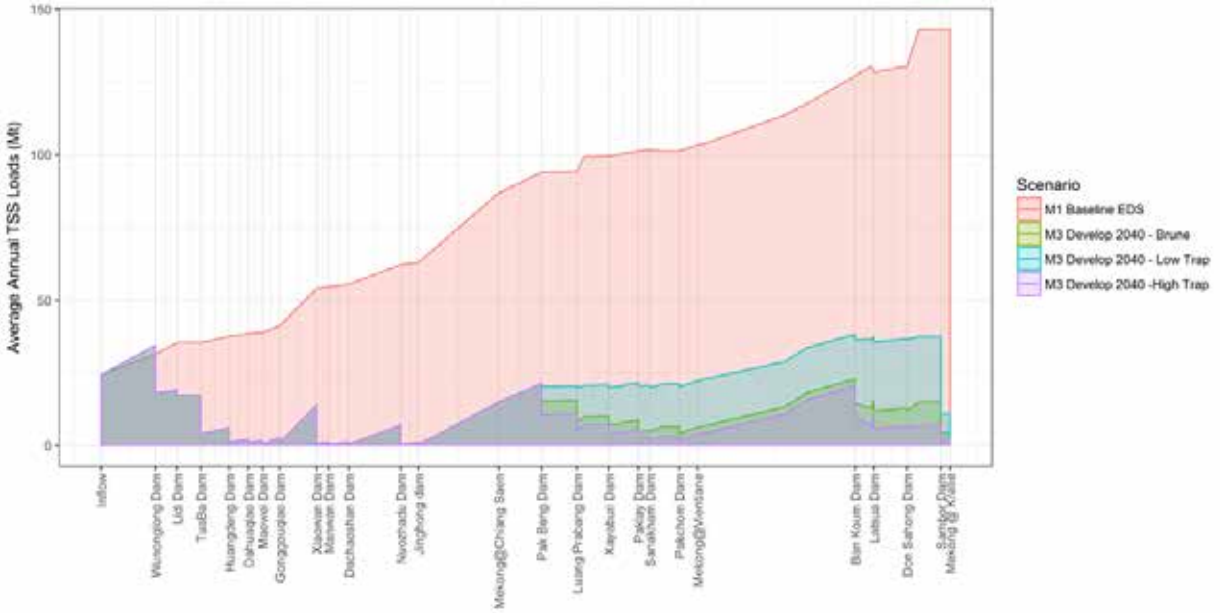


Figure 6.59. *Modelled nutrient transport in the mainstem Mekong based on eSource modelling of the Council Study development scenarios. Data from MRC (2017).*

Potential mitigation measures for water quality changes include the following:

- Designing new/planned reservoirs to have low volume, high exchange rates that minimise water quality changes whilst water is in storage;
- Siting hydropower projects upstream of large tributaries such that a substantial inflow of well oxygenated water with seasonally appropriate temperatures will be maintained downstream of the damsite;
- The inclusion of infrastructure that allows the intake and / or release of water from multiple levels in reservoirs. This is especially important in some of the large volume tributary dams where thermal stratification is likely to occur. The release of low oxygen water can be mitigated through the release of high oxygen water at the same time. This can be accomplished either through a variable level intake to the turbines, or high-level gates that can be operated independently;
- The inclusion of infrastructure within the power house that increases the oxygenation of water as it passes through the turbines (e.g. air injection);
- The inclusion of re-oxygenation weirs or other infrastructure to increase the oxygen content of water after release from the impoundment;
- Catchment management approaches that minimise the additional discharge of nutrients into hydropower impoundments. The development of hydropower frequently accompanies an increase in agriculture due to the improved availability of water. Minimising nutrient rich runoff into hydropower reservoirs is an important and viable mitigation measure, but requires a catchment wide adoption of sustainable agricultural practices. Maintaining buffer zones around reservoirs can also have positive benefits;

Table 6.9. Summary of potential water quality risks and mitigation strategies. Only temperature and nutrients included in the assessment as no water quality monitoring was completed.

Desired generic outcomes	Indicators	Impact description under 2040 Scenario	Severity	Applicable Mitigation Strategies	Potential for mitigation
Maintain water quality	Water Quality	Increased temperatures (risk increases as water stored in multiple impoundments)	1-2	Include low level intakes into dam design to draw deeper cooler water	1
				Release water from bottom outlet of dam if dry season water temp impacting aquatic ecosystem	1
		Increased risk of algal bloom	3	Catchment management to reduce nutrient runoff to impoundments	2
				Limit aquacugrain-size lture development and site in area with good flushing dynamics	2
		Nutrient transport (Silt & clay used as surrogate)	1-2	Coordinated annual sediment sluicing including mainstream and tributary dams	1

6.3.5 Fisheries and Aquatic Ecology

The lower cascade includes the dams Ban Koum, Latsua, Don Sahong, Stung Treng and Sambor. Besides the Don Sahong dam which is currently under construction, all other dams are still in the planning stage. Currently, detailed information is only available for the Don Sahong and the Sambor dam, which will be discussed in more detail in the following section.

6.3.5.1 Don Sahong Dam

The Don Sahong is the middle dam and currently the only existing dam (although still under construction) of the lower cascade. It is located at a unique location within the LMB which marks the transition of the middle and lower migration system. At the Khone Falls in southern Laos and near the border to Cambodia the Mekong divides into 17 side channels with countless cascades and water falls which partly act as natural obstruction. Nevertheless, some of the channels facilitate the passage of species migrating to their spawning, nursing and feeding areas– at least during certain times of the year. According to Baran et al. (2005), the Hou Sahong channel is the only channel providing a year-round migration route for migrating fish.

In general, locating a dam in one of many parallel channels might cause less environmental impacts, provided that fish migration is still supported by other channels. However, in the case of Don Sahong the dam is located in the Hou Sahong channel which many scientist claim to be the most important pathway for migratory fish in this section (Cowx et al. 2014). Although modification in secondary channels (Hou Sadam and Hou Xang Pheuak) were performed to compensate for the lost migration routes through the Hou Sahong, the two side arms are rather different compared to Hou Sahong. While Xang Pheuak divides into several channels, Hou Sadam is rather narrow and carries considerably less flow.

Long-lived fish species might be highly adapted to using Hou Sahong for upstream and downstream migration (homing behaviour), especially since other migration routes in this area (e.g. Khone Falls) could cause injuries and mortality. Since those species are often know the use the same migration paths in their lifetime it might be hard for them to adapt to alternative routes (Cowx et al. 2014).

Furthermore, since the Hou Sahong will receive even more flow compared to natural conditions (see figure below), this could attract additional fish which might follow the main discharge towards the dam and potentially pass the turbines. The location and discharge of the Don Sahong dam could increase the proportion of downstream drifting larvae in this channel which are then passed through the turbines with potential devastating effects for the entire population.

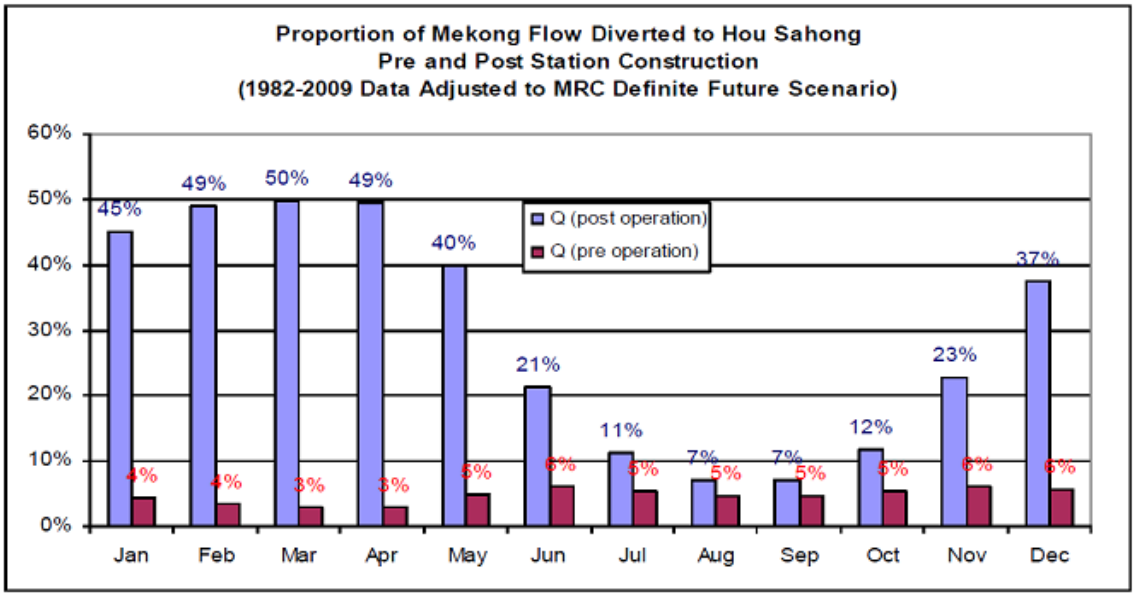


Figure 6.60. *Proportion of Mekong flow diverted to Hou Sahong pre- and post-construction of Don Sahong (Cowx et al. 2014).*

In the planning phase, several options existed for the exploitation of hydropower in this unique river section. One of these options, the Thako project that was planned for Khone Phapheng, would have produced a comparable energy output but without creating a barrier or impoundment. Nevertheless, it was not given serious consideration and was discarded based on the assumption to have negative impacts on tourism. However, Cowx et al. (2014) argue that the evaluation did not consider the biological value of maintaining Hou Sahong for fish migration when comparing Thako with the Don Sahong option. From an ecological point of view, Thako would have clearly been the better option.

Nevertheless, some mitigation measures were considered, as e.g. morphological improvements in other channels, which (if proven to be functional and sufficient) will clearly bring benefits for migratory species. Nevertheless, Cowx et al. (2014) recommend additional mitigation measures to improve up- and downstream passability:

Upstream

- detailed hydraulic assessment (depth, velocity) of suitable migration corridors and further adaptations in side channels to make up for Hou Sahong as a migration corridor
- Increased discharge in side channels (especially during the dry season)
- Ensured attraction towards Hou Xang Pheuak

Downstream

- Inclusion of a diversion screen with a suitable clear distance to prevent immigration of adult species
- Flow modifications (e.g. inclusion of a baffle) to avoid passive drift of eggs and larvae

Since the Don Sahong dam is already under construction, the monitoring of impacts on aquatic organisms are very important and in line with the current mitigation plan which aims for adaptive management of connectivity issues. However, once the negative impacts of the Don Sahong dam become visible, subsequent adaptations (e.g. in Hou Sadam and Hou Xan Pheuak) might be too late for some species.

6.3.5.2 Sambor Dam

The Sambor dam is currently the lowermost dam of the planned cascade of eleven mainstream dams. Besides its high impact on sediment transport (see Chapter 6.4.4), it would also significantly impact the local connectivity and especially the accessibility of the 3S system for upstream migrating fish.

Currently, two options are discussed for this dam, whereby the second option can already be considered as an adaptation aiming for mitigating negative impacts. In the first option, the dam would span over the entire Mekong mainstream (18 km in length). With a height of 54 m its impoundment would almost reach Stung Treng (~80 km in length). As fish pass solutions for large tropical rivers as the Mekong are not yet state of the art, solutions for such wide and high dams are most likely ineffective and could cause a total blockage of fish migration in upstream direction. Issues with regard to downstream migration (i.e. losses related to turbine/ spillway passage or reduced flow velocity in the impoundment) were already discussed in previous chapters, but would of course also apply for the Sambor dam.

In comparison, the second option would cover only one of the Mekong channels, leaving an alternative route for sediment and fish. The related dam would only cover a width of 2.9 km. Furthermore, with a height of 20 m the related impoundment would only affect 35 km of river length. Due to the location of the second option (i.e. not where the Mekong divides into several branches but further upstream; see right side of Figure 6.61), the second option would also require the inclusion of a fish pass. A high proportion of upstream migrating fish will most likely follow the

mainstream towards Sambor (i.e. main current) and will then search for a possibility to migrate upstream where the dam blocks their migration. It is very unlikely that upstream migrating fish migrate return to the junction several kilometres downstream to find the passable side channels. This problem could also be solved by locating the dam a little further downstream (i.e. at the Mekong diversion). Furthermore, it is very likely that the second option of Sambor would require two dams – one for diverting the flow towards the main channel and the hydropower dam itself. Depending on the characteristics and location of the upstream dam, an additional fish pass might be required at this location. With regard to downstream migration, the smaller option shows clear advantages. However, guiding systems would be required to guide adult individuals towards the passable channel. Solutions for diverting downstream drifting larvae are not yet state of the art, but the characteristics of the diversion could be designed in a way to favour the save passage of eggs and larvae towards the free-flowing section. Of course, the efficiency of this option depends to a large degree of the conditions in the side-channel. Detailed habitat modelling would be required to define flow rules which ensure not only the passability of the channel but also its suitability as an alternative habitat for species which cannot thrive in impounded sections.

Comparing the two Sambor options, there is a clear preference for the smaller alternative – not only with regard to connectivity, but also with regard to hydromorphological alterations (i.e. sedimentation and nutrient delivery). Nevertheless, under consideration of the sensitive location of the dam (i.e. within the migration path of the 3S system, Tonle Sap and the Delta), not building this lowermost dam would clearly be the best option from an ecological point of view.

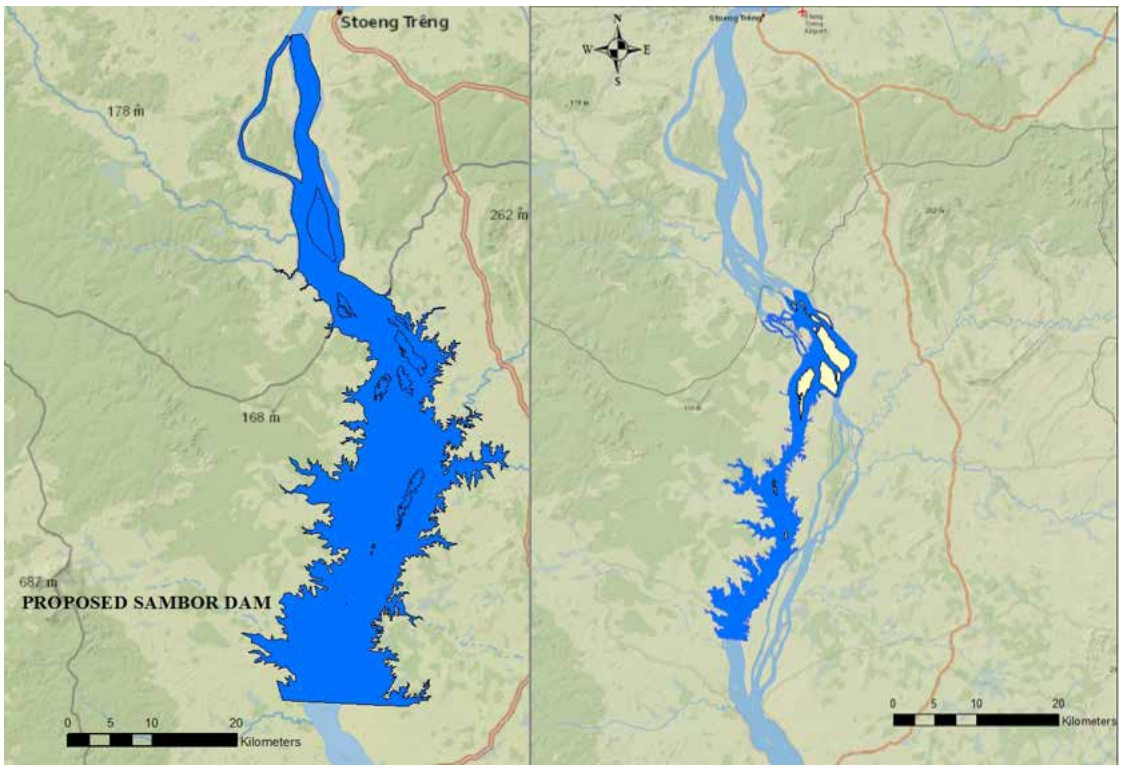


***Figure 6.61**. Two options for Sambor dam (left: original project; right: smaller project aiming for mitigation; Annandale 2014).*

6.3.5.3 Impacts on the overall connectivity

As in previous chapters, we will assess the impact on the overall connectivity for migratory species (DCI_{migr}) in the Mekong catchment, if the lower cascade (or parts of it) were to be implemented. The impacts on overall connectivity depend to a high degree on the functionality and efficiency of connectivity mitigation measures. The graph below shows the consecutive decline of the DCI_{migr} after inclusion of individual dams or partial cascades with passability rates between 0% and 90%. If mitigation measures are considered (as it is the case for Xayaburi and Don Sahong) and if adaptive management takes place, passability rates of 50% and more could be achieved. Nevertheless, the DCI_{migr} reacts with a clear decline to each additional dam.

If the considered fish pass solutions would be proven to have lower efficiencies (i.e. <50%) or if no mitigation measures were to be considered (0% passability) the loss in connectivity would be devastating. Either way, the graph highlights that the inclusion of downstream dams (i.e. Don Sahong or the whole downstream cascade) has a clear negative impact on the connectivity of LMB migration routes. The greatest decline (after inclusion of the Don Sahong Dam) is related to the completion of the lower cascade which is mostly related the Sambor dam potentially blocking the accessibility of the 3S system for upstream migrating fish.

However, if only nine dams of the cascade would be built (excl. Stung Treng and Sambor; i.e. second scenario from the right in the graph below) the implementation of functional fish pass solutions in the 3S system would increase the DCI_{migr} by several percent (results not included in the graph).

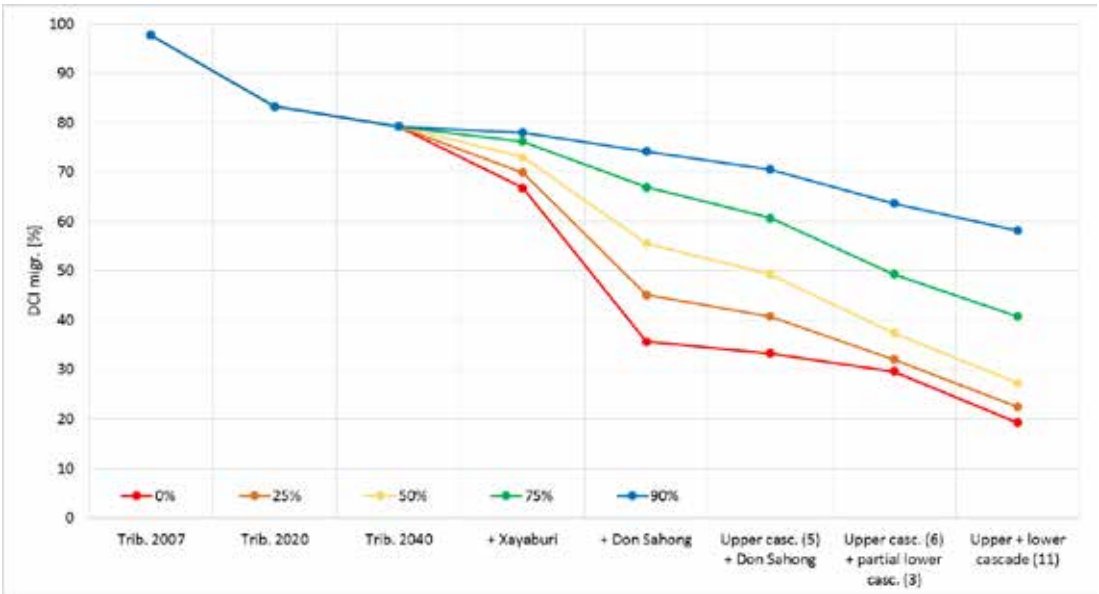


Figure 6.62. *Development of the DCI_{migr} for successive Mainstream development and different mainstream passability rates (i.e. 0 – 90%).*

Finally, we would like to show a comparison of the upper and the full cascade with regard to the DCI_{migr} under consideration of different passability rates. While the Upper cascade will reduce the connectivity for migratory species by up to 20% (i.e. from ~80 to ~60%), the inclusion of the whole cascade can cause an additional loss of up to 40% (with a DCI_{migr} of 20%).

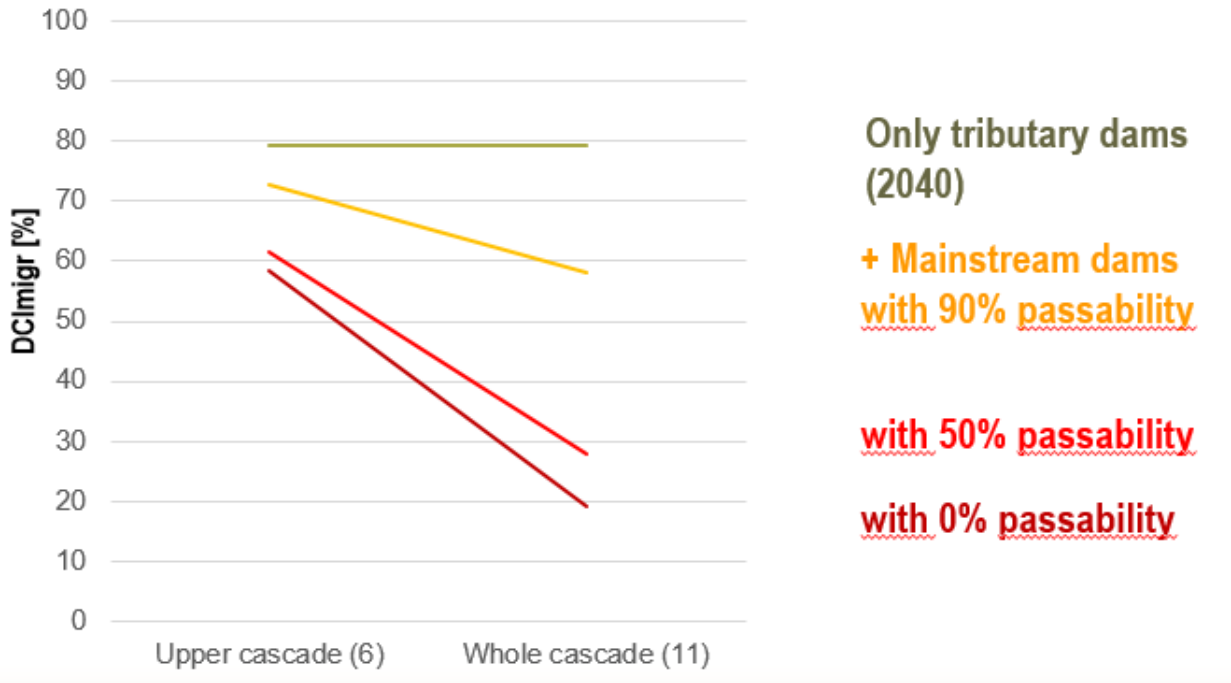


Figure 6.63. *Comparison of the DCI_{migr} for the upstream and whole cascade for different passability rates (i.e. 0 – 90%)*

In the end, the resulting connectivity depends to a high degree on the functionality of the fish pass. Consequently, the results are subjected to great uncertainty (see range of possible outcomes related to different passability rates in Figure 6.62 and 6.63). Furthermore, it has to be mentioned, that the DCI only considers the passability of the dam itself and neglects connectivity losses related to the impoundment itself or mortalities caused by turbine/spillway passage. Fish passes usually only bridge the dam itself, but are not able to mitigate the reduced downstream drift of eggs and larvae, not to mention the associated large-scale habitat alterations. Downstream migration facilities are not yet state of the art – especially not for large tropical rivers – and their efficiency yet has to be tested. Since the DCI represent an abiotic measurement of basin-connectivity, it is not able to reflect the real impact or efficiency of mitigation measures for aquatic organisms. Even if fish passes are built in a way which allows the passage of most fish, this does not necessarily mean that upstream migrating fish can still find suitable spawning and rearing grounds in the highly impacted sections upstream. Consequently, fish pass functionality should not be equated with conservation of populations, which depends on many factors.

6.3.5.4 River channel habitats

Impacts on river channel habitats would be mostly comparable to impacts discussed for the upper cascade. The dams would be operated as cascade of run-of-river schemes and impacts on seasonal or large-scale flow patterns are unlikely. Short-term (i.e. sub-daily) flow fluctuations are possible but would cause significant water-level fluctuations with safeguard issues downstream and might therefore be limited to impounded sections with the most downstream dam acting as a re-regulation weir.

Impacts caused by changing the river from a free-flowing system towards an impoundment were already discussed in previous sections. The related habitat alterations (e.g. sedimentation of fine particles, increase in depth and water quality, alteration of flow conditions) will cause a drastic reduction of species adapted to natural, free-flowing river conditions. Although no detailed assessments were performed with regard to flow conditions in the impoundments, it is likely that the passive drift of eggs and larvae will be inhibited at least during certain periods of the year (e.g. dry season), as it was shown for the upper cascade.

The following graph shows the location of deep pools and rapids in relation to the main impact sections (i.e. upper and lower cascade). It highlights, that the two cascades put a large number of deep-pool habitats, as well as species relying on those habitats, at risk. Likewise, the lower cascade will impound several rapids which play an important role in the life cycle of many species (e.g. with regard to feeding and/or spawning).

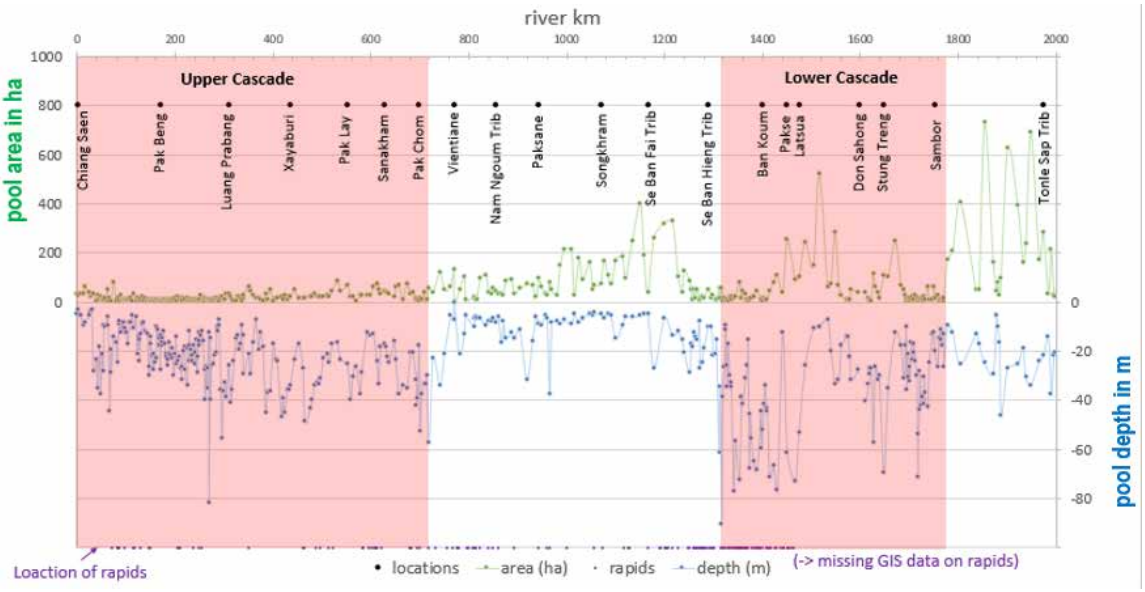


Figure 6.64. *Location, depth and area of deep pools and location of rapids along the Mekong mainstream (red: upper and lower cascade; (note: the line between the pools does not reflect the riverbed elevation but is there to support the readability of the figure).*

The largest impacts on sediment transport are expected from Ban Koum (uppermost dam in the lower cascade) and Sambor, which would potentially also trap silt and finer sand (see chapter 6.4.3). Consequently, the sections downstream will suffer from significant morphological alterations (caused by the sediment starvation), which will also effect adjacent floodplains.

Sediment flushing at the upper dams and the implementation of the smaller version of the Sambor dam would bring great benefits for downstream habitats, floodplains and the delta and could at least mitigate some impacts caused by the LMB-cascade itself. However, as discussed in chapter 6.4.3, impacts caused by Chinese and tributary dams are already very severe and the effect of mitigating impacts related to the lower cascade is relatively small if compared to pre-development loads. The greatest effect could be achieved by reducing and re-siting planned dams, not only in the mainstream, but also in tributaries.

6.3.6 Impacts on Power Production and Revenue

For the dams Pak Chom, Ban Koum, Latsua and Stung Treng, it is expected that the mitigation measures will be similar to the upstream cascade, and that the impact of the mitigation measures on generation and revenue also will be similar. Fish passages and sediment flushing as for the upstream cascade gives a loss of about 5%.

The Don Sahong is planned only on one branch of the river, exploiting only a small part of the total water flow, and no additional mitigation measures are suggested.

For the Sambor project, an alternative design with a lower head and a bypass river branch is suggested. The impact on revenue will depend on how much flow that goes through the bypass. If 1/3 of the river flow is allocated to the bypass, then the generation for the alternative dam will be about 45% less than that of the original dam. The construction costs will however also be less, as the alternative dam is much smaller than the original design.

6.4 Tonle Sap and Delta

6.4.1 Engineering Design and Operation

The Case Study has shown that the mainstream cascade has very little effect at Tonle Sap and the Delta. However, major storage dams on the tributaries do have an important impact because they are trapping sediment and removing seasonal variation in downstream discharge. Loss of seasonal discharge variation has the potential to reduce or remove the Tonle Sap reversal flow that is very important for fish productivity.

Revised operation of major tributary projects could be used to restore seasonal variation in mainstream discharge, especially in the Northern Nam system of tributaries as well as the downstream 3S system. As an example, the reservoir at the Nam Ngiep 1 project provides 7,010 mcm of storage and was originally constructed to provide seasonal regulation and uniform energy output throughout the year. Storage projects at Nam Ngum 2 and 5 have subsequently been constructed and a further project at Nam Ngum 3 is currently under construction. As a consequence, it is no longer necessary for the seasonal storage at Nam Ngum 1 to be fully used. Indeed, it is more energy efficient to keep the reservoir level higher to increase the average generating head. The original and modified operating rule curves are shown in Figure 6.65. With higher reservoir levels, the frequency of spilling is increased (grey trajectories in Figure 6.65) and seasonal flood flows are released into the Mekong.

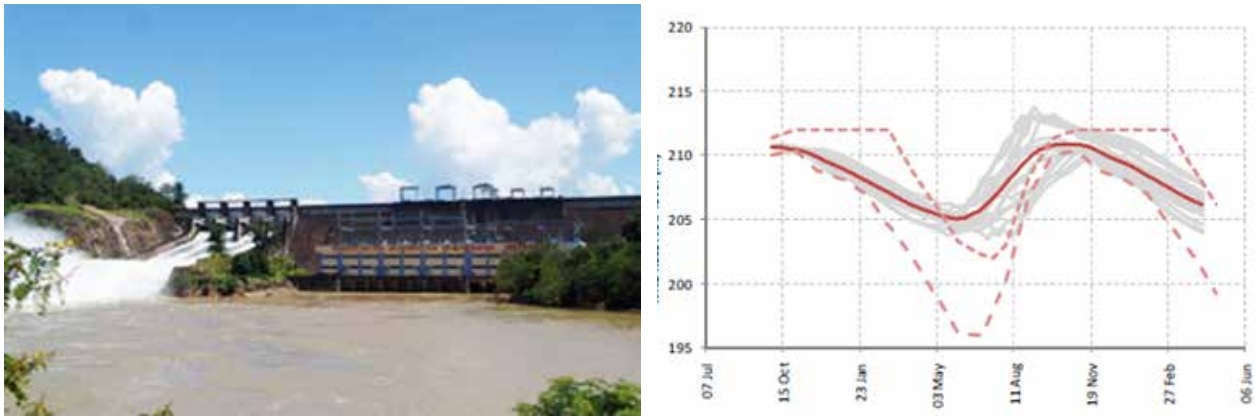


Figure 6.65. *Nam Ngum 1 Hydroelectric Project.*

Nam Theun 2 is another major tributary storage project capable of delivering a near constant output throughout the year. In fact uniform annual energy production is not interesting to the power off taker (EGAT). The average monthly release into the Downstream Channel from the Nam Theun 2 project is shown in Figure 6.66. It will be noted that the release is not uniform throughout the year and tends to follow a wet season and dry season pattern. This is because EGAT tend to under dispatch in December and January in order to conserve energy for the period March to October when energy consumption in Thailand is highest. If this pattern were developed further, a natural seasonal downstream release could be re-created. For the Tonle Sap and Delta systems especially this mode of operation and flow release in the 3S system will have the potential of being beneficial.

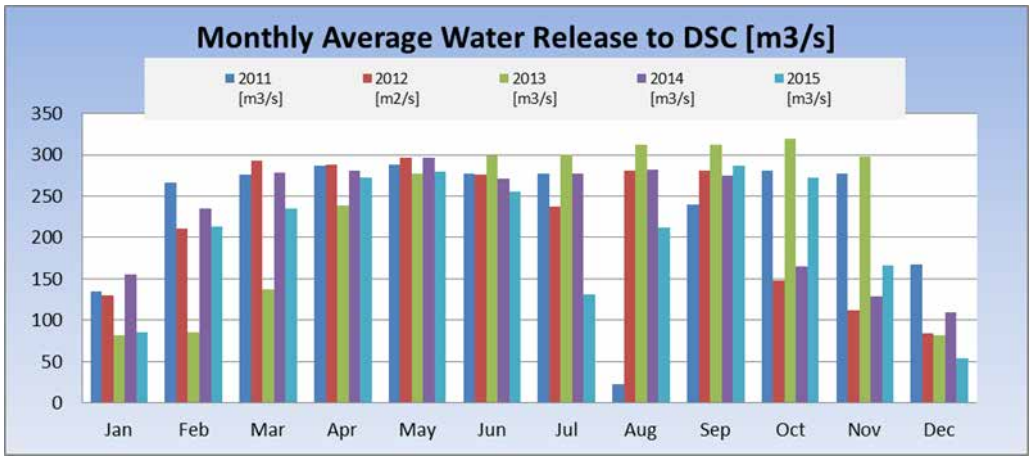


Figure 6.66. *Nam Theun 2 Downstream Releases.*

6.4.2 Hydrology and Flows – Tonle Sap and Delta

The seasonal river delta, including the Tonle-Sap lake and the inundating flood plains, is affected by hydropower impacts. Although the Case Study focuses mainly on the impacts and mitigation of the main-stream dams, it is relevant to consider the entire 'picture' when the Mekong delta is considered. The assessment in the Case Study addressed both seasonal changes and sub-daily variations. The assessments show that:

- The sub-daily flow variations generated by operations at Sambor dam will damp out along the reach between Kratie and Phnom Penh.

- No seasonal impacts are expected from the main-stream dams in Lao and Cambodia, as they are operated as run-of-the-river stations with hardly any active storage. However, the impacts of the overall hydropower development (including the tributary and Chinese dams), have found to have noticeable impacts on seasonal flow behaviour in the delta.

6.4.2.1 Seasonal flow impacts in the Delta

Several studies, including the Delta Study and BDP studies, calculated that the high-flows (particularly on the start of the wet season) will decrease, low flows will increase, and onset of wet season will start later. Figure 6.67 presents the water-level hydrograph. This hydrograph is obtained by averaging discharges for each calendar day over the considered 24-year period, using the model results from the Council Study sub-scenarios. The situation represents the effect of the 2040 dam development in tributaries and Chinese dams, as simulated by the DSF modelling tools. It clearly visualises the above mentioned seasonal effects. Adding to these impacts, are also the expected climate change (also included in the 2040 result in this figure) and sea-level rise, Sea-level rise will affect a large part of the Mekong delta in Vietnam, as this is a relatively flat area where backwater and tides can protrude far inland.

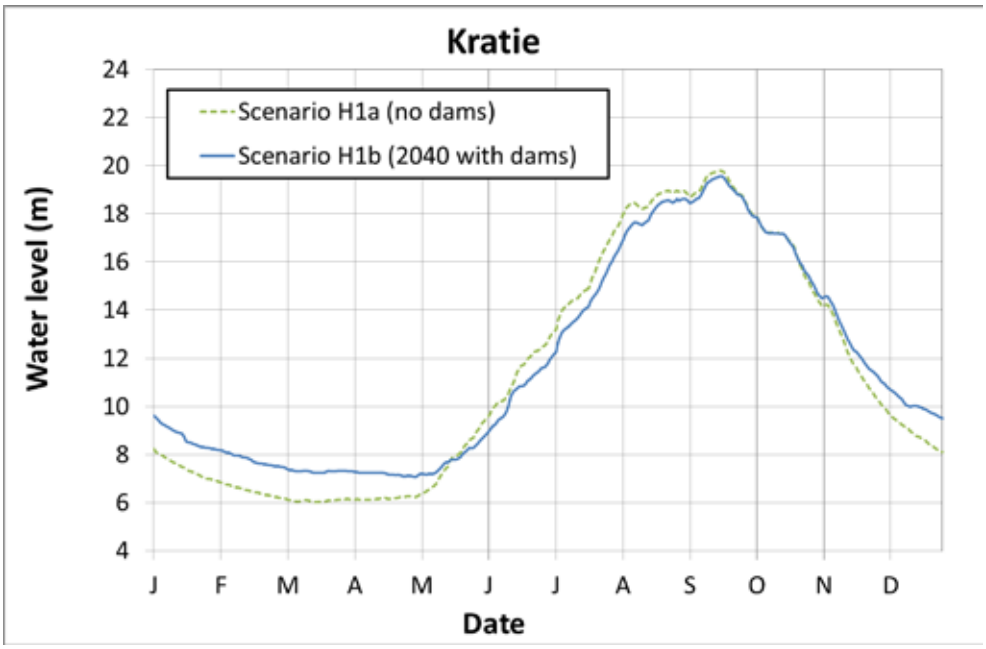


Figure 6.67. *Calculated water levels at Kratie, daily averaged over 24 years, for sub scenarios H1a and H1b from the Council Study (2040 situation with and without Chinese and tributary dams).*

The flow indicators for seasonal flow impacts and risks in Table 3.6 (section 3.3.1.1), are quantified based on five-day average flows. The output of model results of the Council Study simulations are used to quantify the indicators on the stations indicated in the following map (Figure 6.68). Note that the following stations are considered relevant: Pakse; Kratie (just downstream of Sambor dam); Kompong Cham (halfway between Kratie and Phnom Penh); Phnom Penh (Port); Prek Kdam (in Tonle Sap River); Neak Luong (in Mekong branch, halfway between Phnom Penh and Tan Chau); Tan Chau (station directly downstream of Vietnamese border).

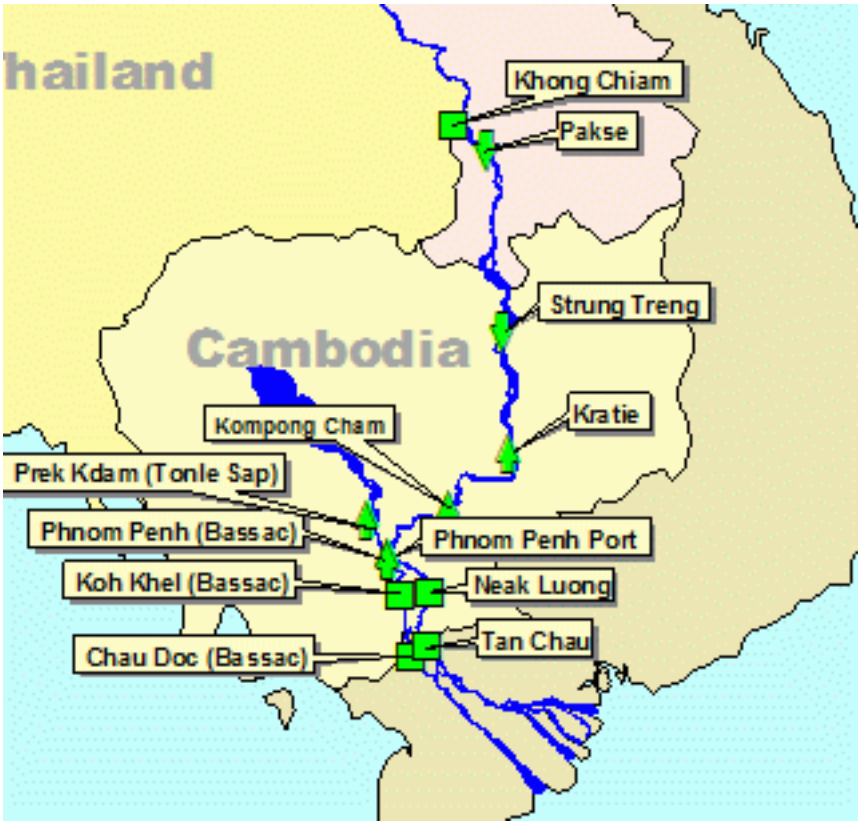


Figure 6.68. *Map showing the relevant hydrometric stations for which the hydropower impacts are evaluated.*

The DSF-simulations were executed for a period of 24 years, representing the discharge series of 1985 to 2008, but with correction for climate change, and with and without dam development for the year 2040. The daily output of these model runs, for each of the relevant stations in the Mekong and Tonle Sap, were processed to obtain the relevant 5-days indicator values as function of time. Also considered are the model results of the Delft3D-FM model which was introduced in section 4.

Figure 6.69 and 6.70 show the relative change in maximum discharge and minimum average discharge for all the considered years, and for the relevant stations. These are the results for the Council Study sub-scenario H1a (no dam development, 2040 conditions with climate change) and sub-scenario H1b (ide, with Chinese and tributary dams, but without all LMB mainstream dams). The figures confirm the decrease of (5-day average) maximum discharge and increase of the minimum discharge along the entire reach.

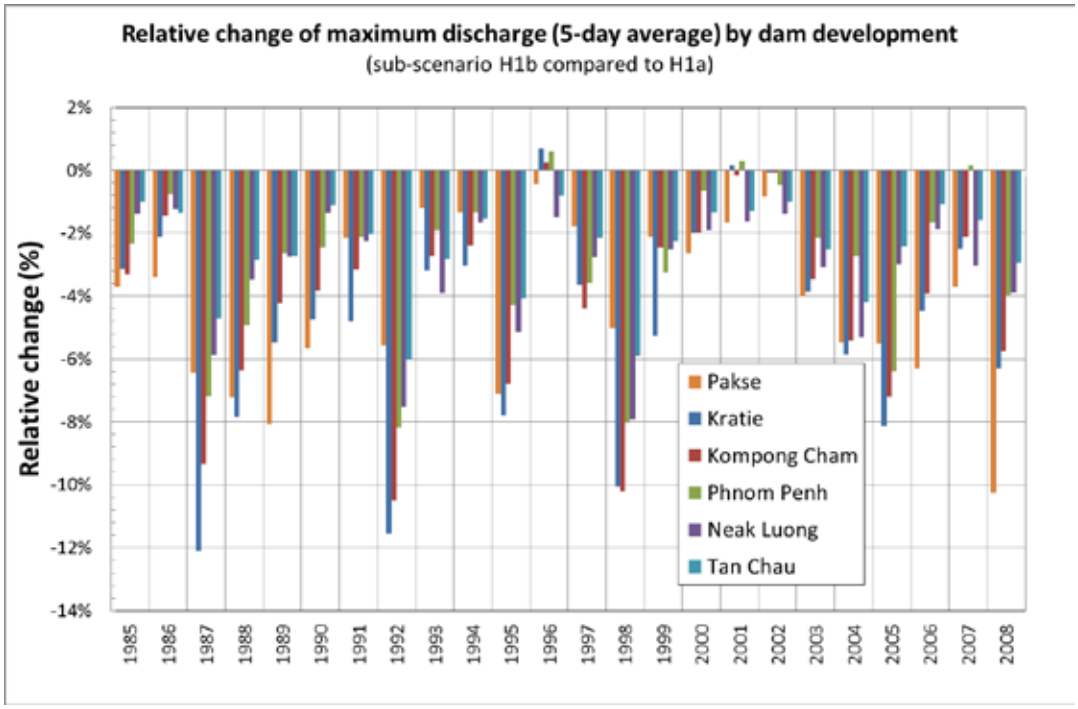


Figure 6.69. *Calculated relative change in maximum discharge for sub-scenarios H1a and H1b from the Council Study simulations (2040 situation with and without Chinese and tributary dams).*

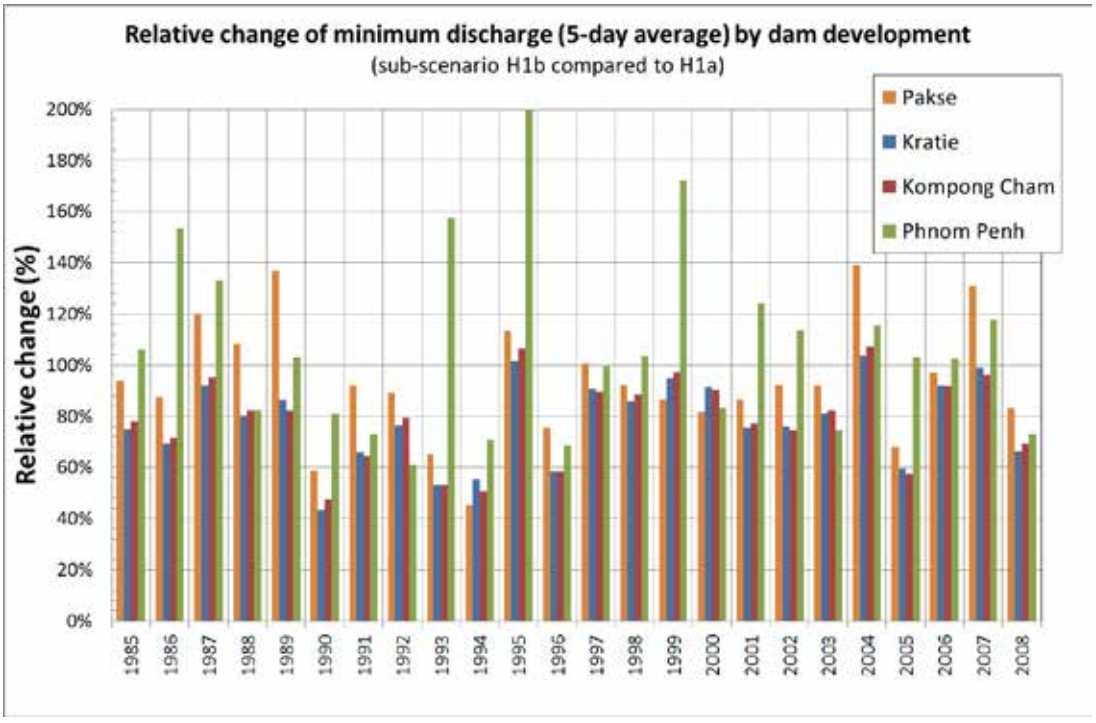


Figure 6.70. *Calculated relative change in minimum discharge for sub-scenarios H1a and H1b from the Council Study simulations (2040 situation with and without Chinese and tributary dams).*

In section 5.2.2.1 the compliance with PMFM flow procedures is used to test the effectivity of mitigation measures. In general the PMFM flow procedures (Procedures for the Maintenance of

Flows on the Mainstream) provide upper threshold to the maximum discharge for each month in the flood season (i.e. using acceptable flows framework for planning purposes). The following table shows the thresholds for the relevant stations in the delta. A similar table can be drawn for the dry-season planning thresholds, although these are formulated more in terms of a range with a lower bound, see table 6.11 for this lower bound.

Table 6.10. Thresholds for flood-season planning according to PMFM, daily discharges.

Station	July	August	September	October
Pakse	24,334	30,720	31,087	20,618
Kratie	32,607	41,627	42,936	31,081
Tan Chau	16,386	19,723	21,154	20,837

Table 6.11. Thresholds for dry-season planning according to PMFM, daily discharges (90%FDC).

Station	December	January	February	March	April	May
Pakse	2,888	2,148	1,502	1,224	1,272	1,654
Kratie	4,605	3,019	2,036	1,679	1,615	1,950
Tan Chau	8,175	5,154	3,277	2,130	1,713	2,014

In general, it can be found that with the reduction of maximum discharges and increase of low discharges, the future conditions with full dam development improve the compliance to the PMFM criteria compared to the pre-dam situation. Therefore, further testing of the results on the thresholds has not been carried out further in this Case Study.

6.4.2.2 Tonle Sap

The relevant hydropower impacts for Tonle Sap are triggered by the seasonal changes in hydrograph of the Mekong River at the mouth of the Tonle Sap River at Phnom Penh. The following text box explains the behaviour of the Tonle Sap, and its influence on the rest of the Delta. To judge the impacts of the hydrology, it is important to understand the nature of these components.

The role of Tonle Sap in the seasonal flows in the Mekong delta:

- During the low-flow season the Tonle-Sap lake is outflowing towards the Mekong
- At the start of the wet season in the upper part of the LMB, the rise of the Mekong levels causes the Tonle Sap River to reverse its flow, and start filling the lake. The rise of flood waters in the lower reaches remains limited, as part of the high flow is now going towards Tonle Sap.
- The later start of the rains in the Tonle Sap basin, cause a delayed start of inflow from tributaries in that basin, which adds to the filling of the lake. Filling continues until levels in the Mekong River start to fall, and the Tonle Sap river reverses again.
- During the fall of the Mekong River levels, the extra outflow from Tonle Sap lake causes the flows downstream of Phnom Penh to remain high for some period.
- The flow reversal at beginning of wet season occurs with a much lower Mekong discharge compared to the falling stage flow reversal, indicating that the water level difference initiates the flow reversal.

It was found that the flow impacts on Tonle Sap from the mainstream dams in Lao and Cambodia are negligible. However, the impacts of Chinese dams and tributary dams on the flow hydrograph are significant. Summarizing, hydropower development has the following impacts to the system, when considering the Tonle Sap Lake:

1. The later start of the high flows in the Mekong causes a later reversal of the flow towards the lake. In this case the water level fluctuation remains the same, but in- and outflowing volume through the Tonle Sap river decreases.
2. Because the water level difference between lake and Mekong is the most important parameter for the discharge through the Tonle Sap river, the in- and outflow of the lake will also reduce
3. In the dry season, the lake will empty less compared to the base line scenario, leaving a larger area permanently inundated. During the wet season less water flows into the lake, causing a decrease in maximum water level and a smaller inundated area.
4. It was found that the lake will store less water with hydropower development compared to the case without the hydropower development. This is because the reservoirs of the dams take over the storage process from the lake Tonle Sap.

The details of the calculations behind these observations are presented in Pronker (2017). They are in line with the previous studies. In Figure 6.71 the calculated discharge in the Tonle Sap River (Council study sub scenarios) is shown for the scenarios without dam development and with dam development. A close look to this figure reveals the observations as mentioned previously; reversal starts later, and maximum discharges is reduced, both for the inflow and the outflow. In Figure 6.72, the calculated water levels for the sub scenarios H1a and H1b are shown for a specific year to illustrate in more detail the differences in water level in the lake. The water levels are in the order of 0.4 m lower during the wet period and in the order of 0.2 m higher during the dry period.

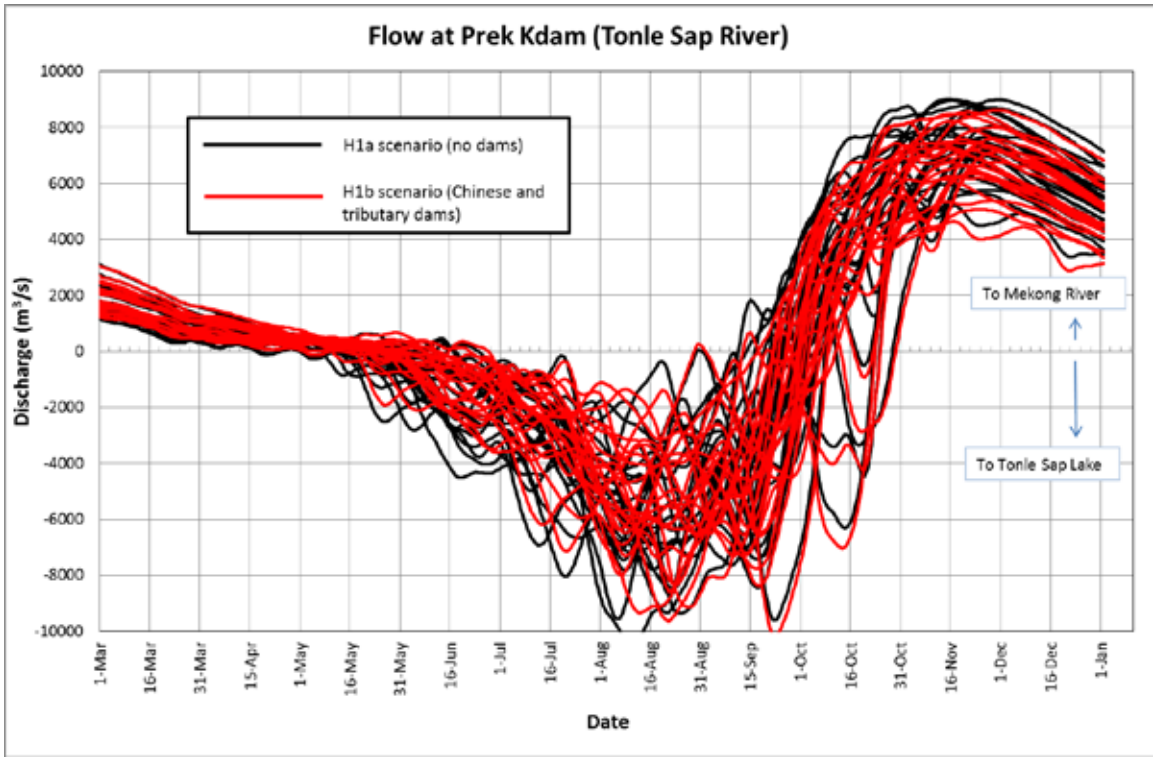


Figure 6.71. *Calculated discharge at Prek Kdam for every year (24-year period) for sub scenarios H1a (black lines) and H1b (red lines) from the Council Study (2040 situation with and without Chinese and tributary dams).*

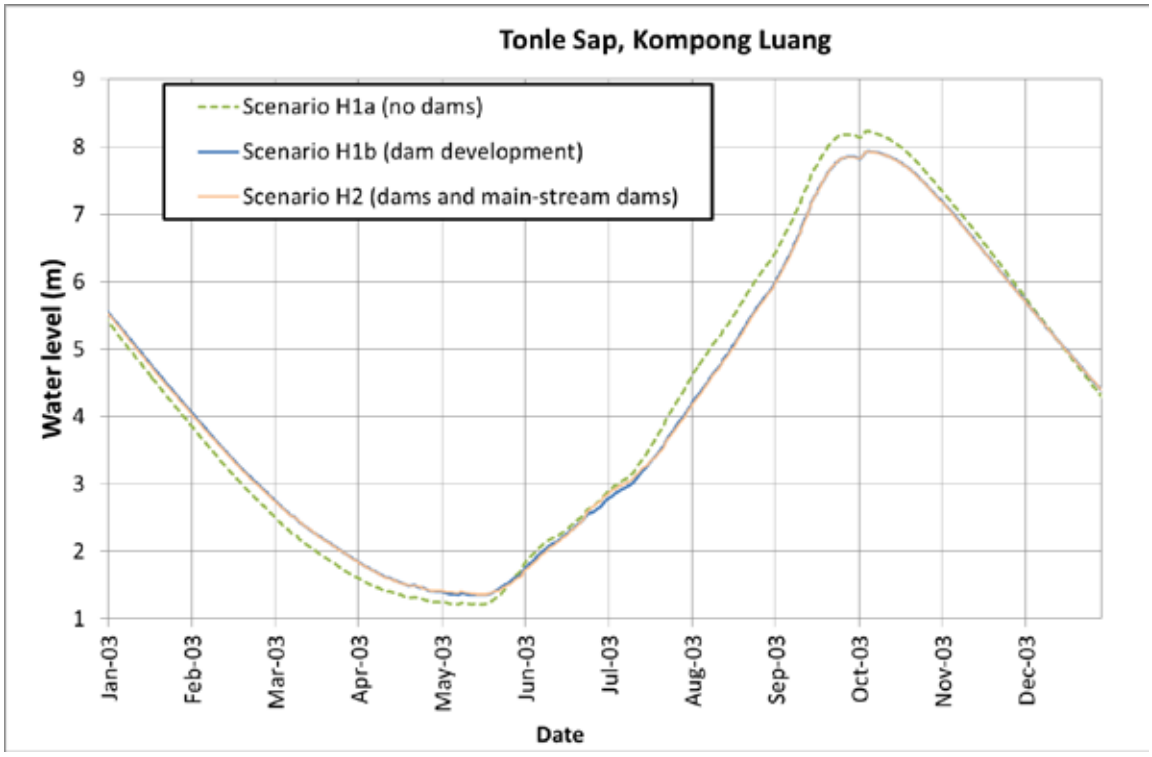


Figure 6.72. *Calculated water level at Kompong Luang in Tonle Sap for the different hydropower sub scenarios in the Council Study (equivalent hydrograph of the year 2003, adapted for 2040 conditions)*

The seasonal changes in the Mekong River that give rise to these changes in Tonle Sap are difficult to mitigate. Mitigation approaches that can be considered are:

1. The release of a high flow from upstream reservoirs to allow the flow reversal to return to its earlier start. This does not only involve free passage of the first floods, but also additional releases from the reservoirs. Calculations presented in Pronker (2017) shows that a flood volume of order of 640 million m3 has to be released to correct the timing of flow reversal. Figure 6.73 shows how such a release will look like. Note that this figure shows that around June 2nd there is a short period where flow starts to flow again, which is caused by tidal influences (neap tide) and the following increased discharge in the downstream branches.
2. Increase the channel dimension of Tonle Sap River. Although this contributes to increased filling of the lake, it also causes the lake to drain faster in the dry season (less water in dry season). In turn this also decreases the absorption of hydropower impacts by the lake, and hence it allows these impacts to have a larger influence in the downstream reaches. Pronker (2017) presents calculations for a deepening of 2 m, or widening of 150 m of the entire Tonle Sap River.
3. Creation of a bypass channel or short-cut channel, allowing additional inflow from a more upstream location of the Mekong at high-flow conditions. This channel can be considered as an increase of the overland-flow that is already present in this area during floods, and has an approximate length of 80 km, 100 m wide. It is recommended to construct a regulation structure in the channel to control the flows.
4. Controlling the tributary inflows to the Tonle Sap, by storing water during the start of the wet season, and release it at the end of the rising stage of the lake to be able to increase lake levels a bit further.

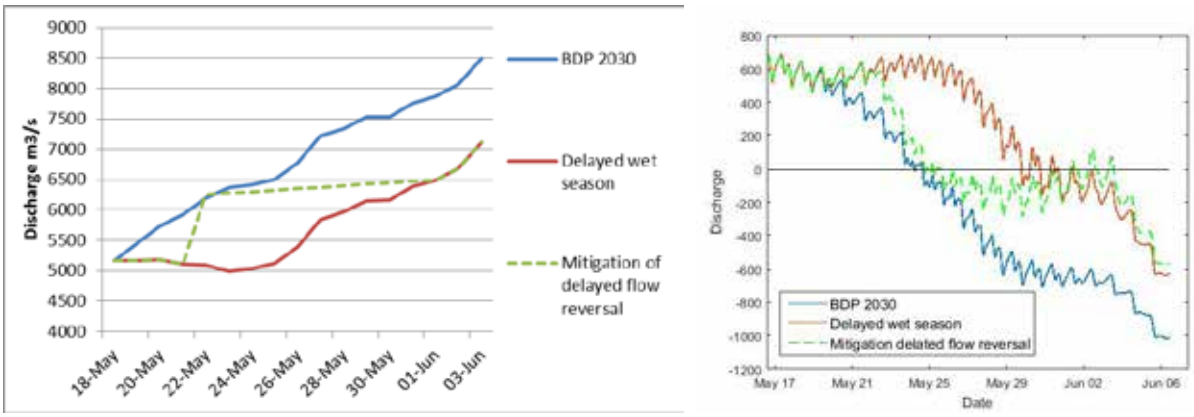


Figure 6.73. *BDP scenario with additional releases from upstream reservoirs to mitigate the delay of the wet season (calculations using the Delft3D-FM simulations).*

It should be noted that any mitigation measures for Tonle Sap flow impacts, as presented in this sub-section, do also modify the flows towards the delta. Therefore, any mitigation in this region should be considered system-wide.

6.4.2.3 Delta and flood plains

As shown in the previous subsection, the interaction between Tonle Sap and the Mekong flows are relevant for the downstream river. After Phnom Penh the Mekong splits into the Bassac and the

Mekong River. Figure 6.74 below shows the contribution of Tonle Sap to the downstream delta. During filling of the lake the discharge to the delta is 'reduced', while during the draining of the lake the discharges are increased.

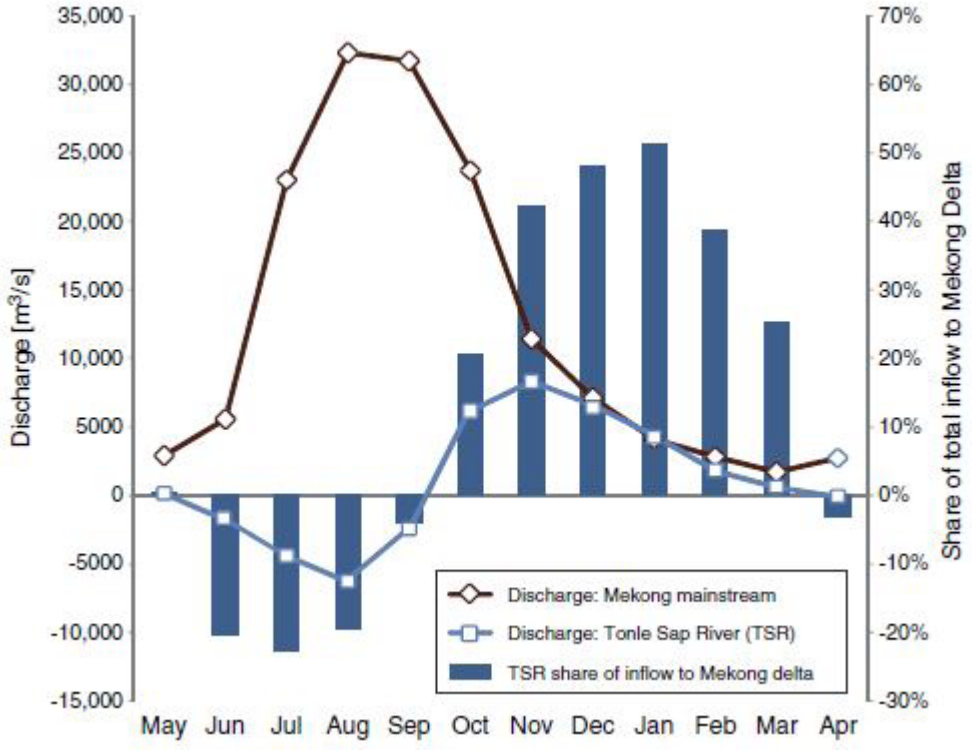


Figure 6.74. *Interaction between Mekong flows and Tonle Sap lake (Kummu et al., 2014)*

Also, the impacts of hydropower development are reduced by the storage effect of Tonle Sap. It has been concluded that only the large seasonal impacts of the full hydropower development including the Chinese dams has an impact to these flows. **There is no noticeable influence from mainstream hydropower dams on the flows in the lower parts of the delta.**

To judge the impacts of the hydrology, it is important to understand the nature of these components.

Flows in the delta and flood plain (Plain of Reeds):

- The Mekong flow distributes over the Bassac and Mekong branches, first at Phnom Penh, and then further downstream through canals connecting these two branches.
- The tidal influence of the East Sea (South Chinese Sea) is of a mixed diurnal and semi-diurnal character (with spring-neap tidal cycle). Diurnal fluctuations are in the order of 2.2-3.2 m at the mouth. During low river discharge, the tides influence water levels up to the Cambodia border.
- The river surface expands significantly during the flood season. The flood plains can be divided into Cambodian and Vietnamese floodplains. Area inundated yearly in Cambodia is about 11,000 km2 (Manh et al., 2014), starting downstream of Phnom Penh. The two main inundated areas in the Vietnamese part of the delta are Luong Xuyen Quadrangle (LXQ) and the Plain of Reeds (PoR). The latter are compartmented by dike rings of different heights to increase agricultural production. They start to fill later in the flood season at the highest peaks, after the first harvest of rice in July. Overland flow in Cambodia contributes to a second flood peak in the delta because of its slow travel time.
- Salt intrusion from the sea is important for the water quality in the estuaries. The process and extent of the salt intrusion varies over the year. During the wet season the river discharge is dominant over tidal mixing, and a salt wedge is present. At high discharges the fresh water pushes the salt wedge back, and salt intrusion remains limited to a few kilometres land inward. During the dry season the tide mixes fresh and saline water, and the estuaries become well mixed. The salt water is able to penetrate at least 40 km into the estuary.
- The increase of cross-section area in the estuary due to erosion is relevant for salt intrusion. The main cause of erosion is sand mining, because impacts of dams are expected only at much larger time scales. The increase of cross-section causes an increase of salt intrusion. Explanations and calculations are presented in Pronker (2017).

The assessments show that the overall dam development causes the following impacts on the delta:

1. The high flows are reduced, but less significant than at Kratie and Phnom Penh: Council Study simulations show that the reduction at Kratie can be in the order of 10%, while at those conditions the reduction at Tan Chau is in the order of 5%.
2. There is an increase of low flow discharge towards the delta branches. This would decrease the risk of salt intrusion in the dry season. However, this is partially compensated by the sea-level rise which causes salt intrusion to increase (change in tidal mixing, and increased chance of stratification).
3. The main flood plains in Vietnam will inundate less far due to the decreased floods, and the modified timing of floods. The flooding of these areas are not only delayed with one week, but inundation depths are decreased with 10 to 20 cm.

Mitigation of these flow impacts cannot be found in modifications of hydropower operation, as the pulses and releases are absorbed partially by Tonle Sap. The upstream measures should therefore

be unrealistically large, and destructive for the upstream reaches. For the floodplains and the delta it is therefore more appropriate to find solutions in the area itself, which can at least mitigate part of the negative impacts on inundation and salt intrusion. Mitigation measures that could be considered are:

- Prevent the reduction of inundation area in the flood plains by preventing further raising of the dikes, or even reduce the dike elevations. Also, an improvement of overland flow over the Cambodian flood plains (by additional channels) can contribute to restoring the extent of inundation area. The table below show the calculated effect of these measures. Details are presented in Pronker (2017).

Scenario	Inundated area PoR [km^2]	Inundated area LXQ [km^2]	maximum water level in PoR [m]	Inudation period above dikerings [days]
Base	310	190	3.42	89
BDP 2030	200	160	3.22	73
Lower Dikerings	380	210	3.01	69
Extra canals to FP	220	160	3.22	74

- For salt intrusion local approaches, such as staircase bottom profiles; (movable) sills; increased roughness, can be considered. The effectivity of such measures in the Mekong estuaries requires more study and preferable 3D modelling approaches.

It should be noted that any mitigation measures for Tonle Sap flow impacts, as presented in the previous sub-section, do also modify the flows towards the delta. Therefore, any mitigation in this region should be considered system-wide.

6.4.3 Sediments and Geomorphology - Tonle Sap and Delta

6.4.3.1 Tonle Sap

The Tonle Sap system will be affected by the cumulative reduction in sediment associated with the development of the tributary and mainstream dams in the LMB, and by any changes to the sediment input from local tributaries discharging directly to the lake. Planned hydropower development in the Tonle Sap catchment (Figure 6.75) includes four tributary dams, one developed in the large Stung Sen catchment that enters near the mouth of the lake, and three on tributaries flowing northward into the central or northern lake basins. No information about the characteristics of the dams is contained in the MRC hydropower database, so it is not possible to provide a high-level evaluation of whether sediment flushing or sluicing may be applicable to the projects.

The present sediment load entering and exiting the lake through the Tonle Sap River is comprised of predominantly silts (~60%) and fine-sands (~20%). These size fractions will have a high rate of trapping in Sambor, and following development of Sambor, the sediment load available for transport into the Tonle Sap from the Mekong will be limited to clay and material able to be eroded from the mainstem of the Mekong River. The presence of medium sand in the channel of the Mekong in the vicinity of Chaktumak but the lack of this size fraction in the suspended load of the Tonle Sap River suggests that the energy of the Tonle Sap River is insufficient to carry medium sand in suspension, and there is likely to be a large decrease in the amount of sediment entering the Tonle Sap Lake following implementation of the full development scenario.

Changes to the sediment balance in the Chaktomuk may also lead to changes in the flow dynamics between the Mekong River and the lake. Sediment starvation is likely to promote erosion of the alluvial river channels, including channel deepening. The flow balance between the Mekong and the Tonle Sap is driven by the water level differences between the two water bodies. As channels deepen, this relationship will change, and a new flow balance may evolve that requires higher flows in the Mekong to promote a reversal. These types of feedbacks could also occur at the entrance to the lake, where a delta exists. As sediment is reduced, channels will straighten and deepen and will alter the flow dynamics into and out of the lake.

Maintaining the flow reversal in the Tonle Sap is an identified goal in the PMFM, and maintenance of the sediment dynamics of the system should also be considered a high priority, if the present system is to retain its functioning.

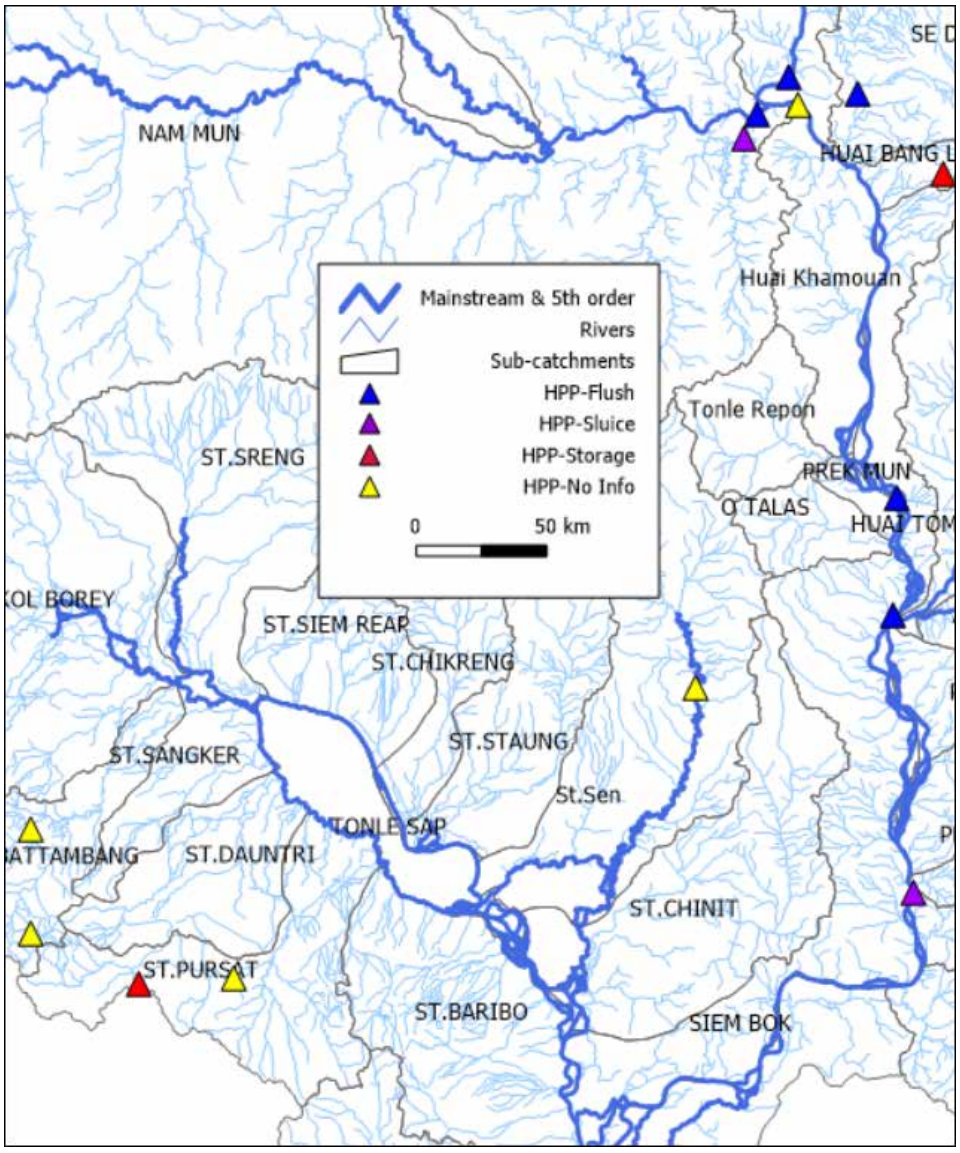


Figure 6.75. *Map of the Tonle Sap system showing the location of dams and potential for implementing sediment flushing or sluicing based on storage volume to inflow ratios.*

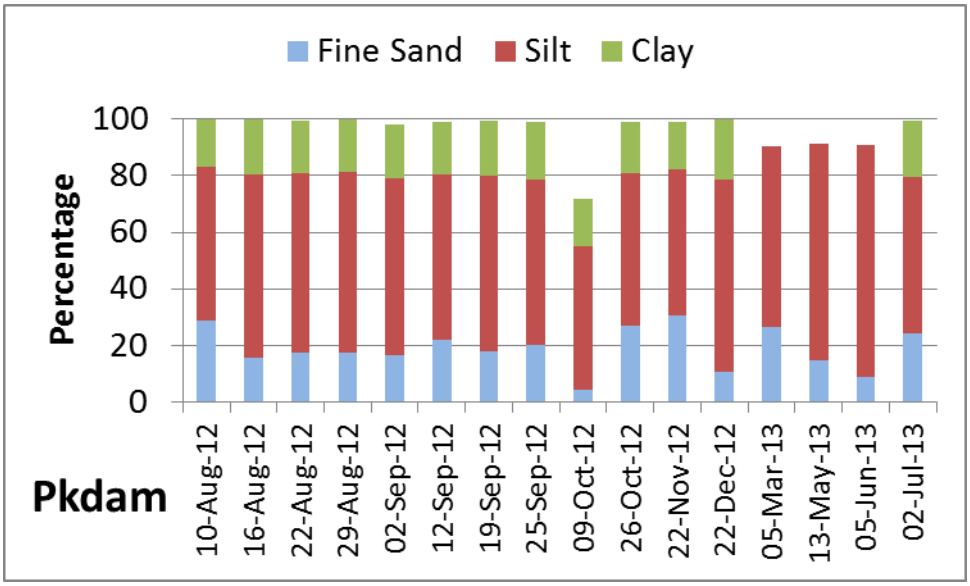


Figure 6.76. *Grain-size distribution of sediment transported in the Tonle Sap River. Data from MRC monitoring.*

Potential mitigation measures to address the changes associated with the 2040 development scenario are limited, but through a catchment approach some continuity of sediment supply to the Tonle Sap Lake may be able to be maintained.

No sediment budget is available for the lake, but local rivers account for approximately 50% of the water inflow to the Tonle Sap, so it is likely that a considerable percentage of sediment is also locally derived. Prior to implementation of any hydropower projects within the Tonle Sap catchment, the sediment load associated with each target river, and any other large rivers that have not been identified for development should be measured, and major sediment pathways should be identified for sand and silt. An optimisation process that seeks to maximise energy generation and minimise sediment trapping should be completed.

To be successful, this approach requires monitoring of sediment fluxes under a range of flow rates, and an understanding of where sediment is generated in the catch and how it might change into the future. For example, sediment inputs from a low-lying floodplain can be very high due to land disturbance or agricultural practices, but may decline over time if agricultural methods that reduce soil erosion are adopted, or reforestation reduces erosion on hill slopes.

Sediment production 'potential' based on watershed characteristics, slope and rainfall is shown in the top map in Figure 6.77, with dark red areas indicating high sediment production. The map on the right shows the locations of proposed power developments in the Tonle Sap catchment. Not surprisingly, each of the hydropower developments is associated with an area of potentially high sediment input and rainfall. Categorising these rivers and optimising hydropower development to maximise energy and minimise sediment trapping is the most cost -effective sediment mitigation measure available.

Potential sediment mitigation measures for the catchments targeted for development include sediment bypass channels, developing small volume impoundments that could be effectively flushed on an annual basis, and / or sluicing sediments through the impoundment during periods of high sediment input.

Other mitigation measures include a regional wide sand mining / management strategy that reduces the removal of sand from the river channels to promote stability.

Figure 6.77. *Comparison of potential sediment production (based on watershed and runoff characteristics) with the location of the proposed dams.*

6.4.3.2 Delta

The geomorphology of the Mekong delta will respond to the cumulative changes in sediment delivery from the upstream catchment, alterations to the riverine flow regime (including channelization and regulation for irrigation), and changes in coastal currents and waves. There is evidence that the pattern of deposition near the mouths of the delta distributaries has altered between 2003 and 2012 (Figure 6.78), with the changes attributable to a range of activities including reduction in sediment delivery due to damming, sand mining, and subsidence related to groundwater extractions (Anthony et al., 2015). This highlights the need to consider how the reduction in sediment delivery will interact with other land use pressures in the lower catchment.

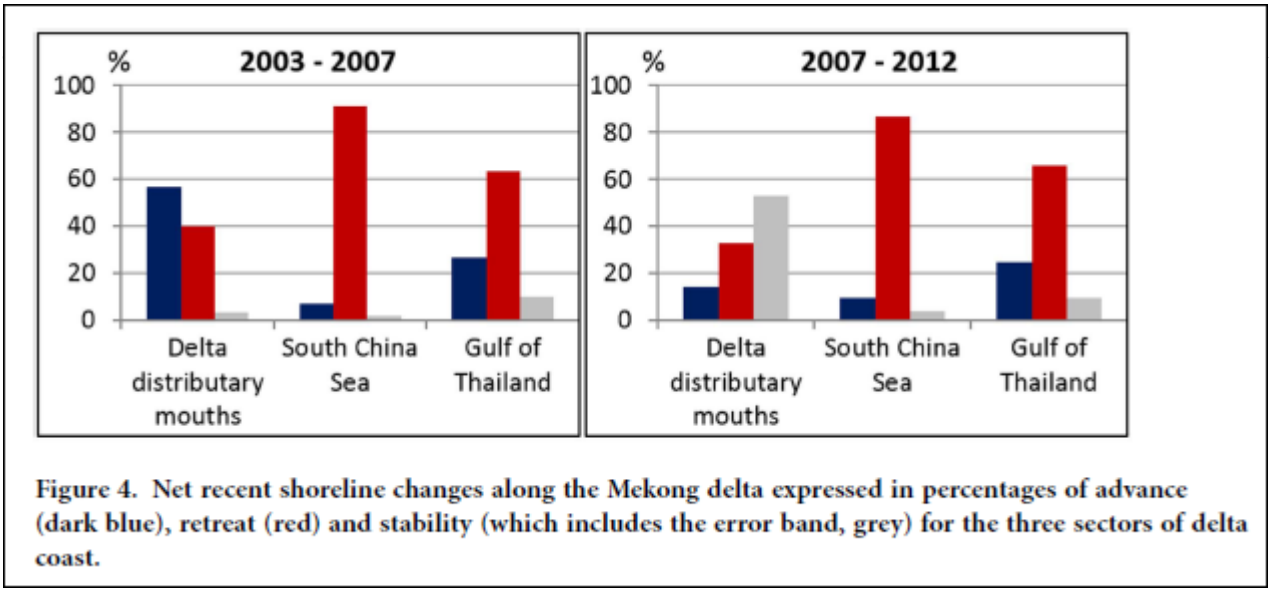


Figure 4. Net recent shoreline changes along the Mekong delta expressed in percentages of advance (dark blue), retreat (red) and stability (which includes the error band, grey) for the three sectors of delta coast.

Figure 6.78. *Net shoreline changes along the Mekong delta expressed in percentages of advance (blue), retreat (red) and stability (which includes the error band, grey) for the three sectors of delta coast (Anthony et al., 2015).*

6.4.3.3 Summary of Sediment Trapping and Geomorphic Implications for the LMB

The cumulative projected sediment capture in the mainstream and tributary dams in the LMB under the Council Study 2040 development scenario is summarised in Figure 6.79 and 80. The cumulative energy production of the full development scenario for the mainstream dams as a function of sediment trapping is shown in Figure 6.81.

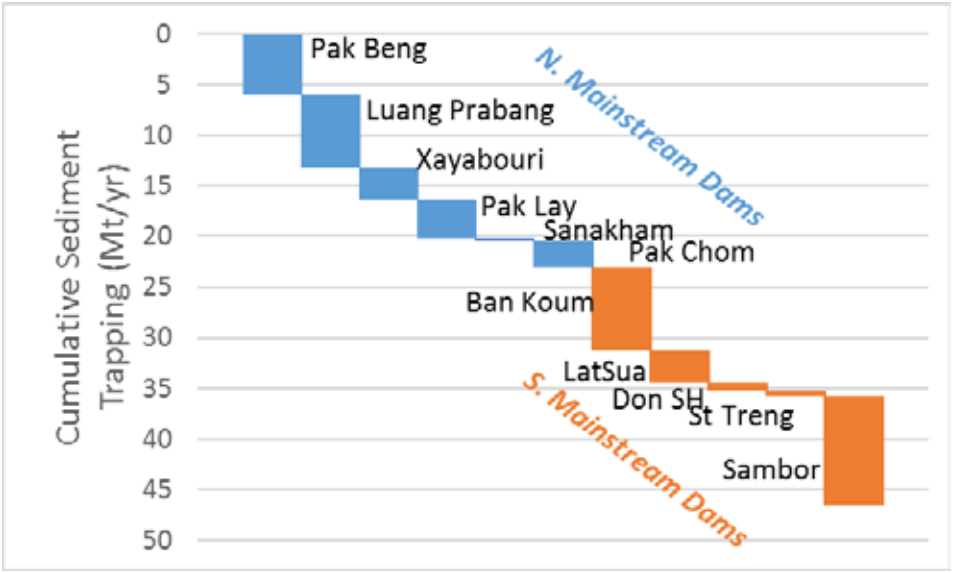


Figure 6.79. *Cumulative projected sediment capture in the mainstream dams in the LMB based on the Council Study 2040 modelling scenario.*

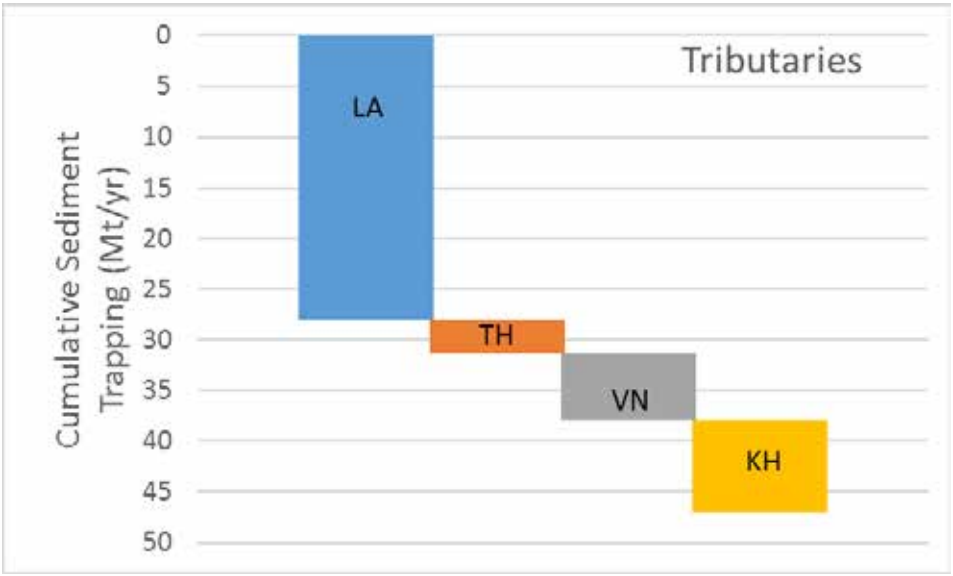


Figure 6.80. *Cumulative projected sediment capture in the tributary dams in the LMB based on the Council Study 2040 modelling scenario.*

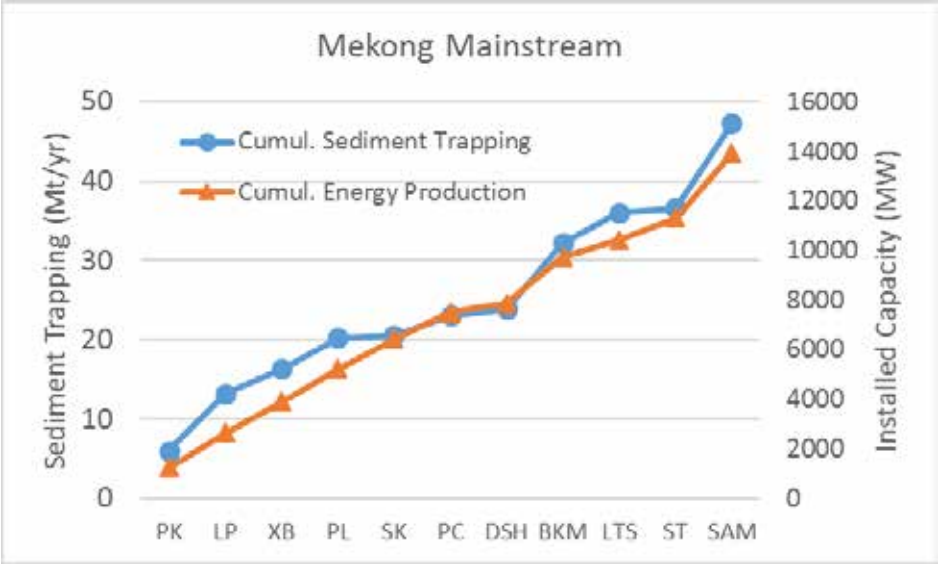


Figure 6.81. *Cumulative sediment trapping compared to cumulative energy production in the LMB mainstream hydropower projects based on the Council Study 2040 development scenario.*

The comparisons show that a similar quantity of sediment, between 45 – 50 Mt/yr, is trapped in the tributaries and the mainstream impoundments, indicating a total sediment loss of almost 100 Mt / yr, distributed over the basin. Within the tributaries, the sediment capture in Lao PDR accounts for over half of the total loss attributable to tributaries.

Geomorphologically, this continual reduction in sediments down the length of the system will induce a large increase in erosion, as any material that is eroded from the channel is unlikely to be replaced. Sand and gravel will be the most affected, as silt is projected to be transported through many of the impoundments, although not the lower large Sambor.

The bed material characteristics of the Mekong River are shown in Figure 6.82 and 83 and demonstrate that the channel is dominated by medium and fine sands, with silt becoming increasingly important in the delta. The capture of these grain-sizes in the mainstream and tributary dams will increase the erosion of the materials and lead to wide spread channel changes. Impacts will be most acute in the solely alluvial reach downstream of Sambor, where the extent of river channel changes is potentially very high due to the lack of structural controls (e.g. bedrock).

The mitigation approaches that could address these potentially extreme impacts include the implementation of a catchment wide, coordinated effort to maximise the passage of fine and medium sand through the river, combined with local controls on sand extraction. Maximising sand throughput in the system will require a catchment wide re-think of the planned hydropower projects to identify and maintain important sediment pathways, combined with appropriate infrastructure at hydropower projects to maximise sediment passage through impoundments. Local controls on sediment extraction need to reflect and recognise the true value of maintaining sand in the system, as compared to its present ‘worth’ as an inexpensive land reclamation and construction material.

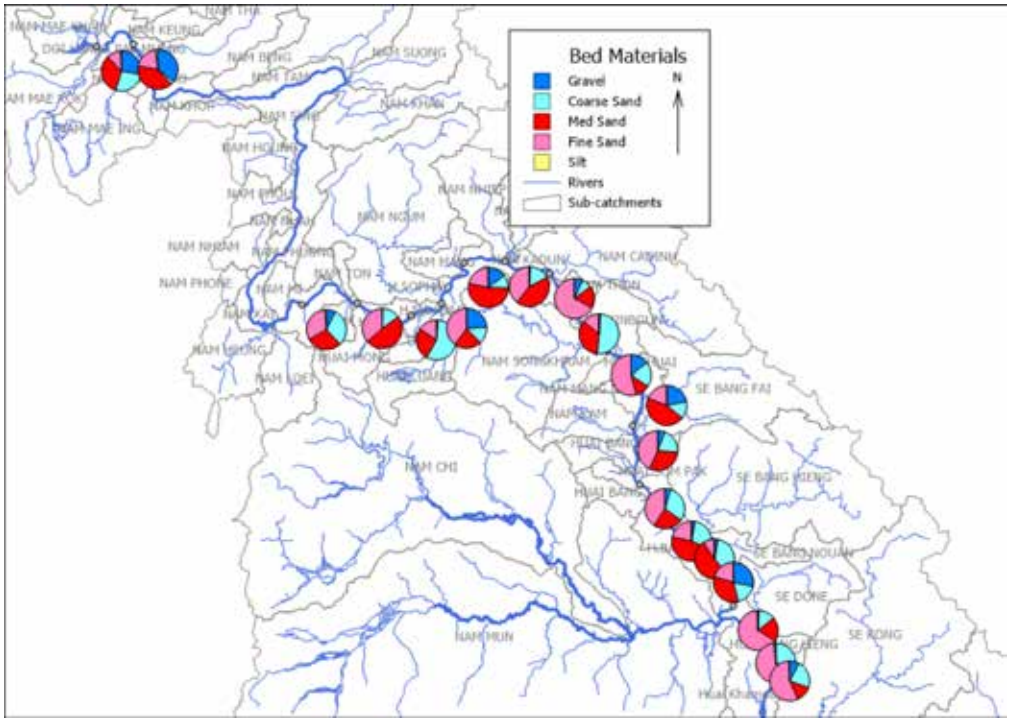


Figure 6.82. *Bed materials in the Mekong River channel in 2011. Data from MRC Discharge Sediment Monitoring Program.*

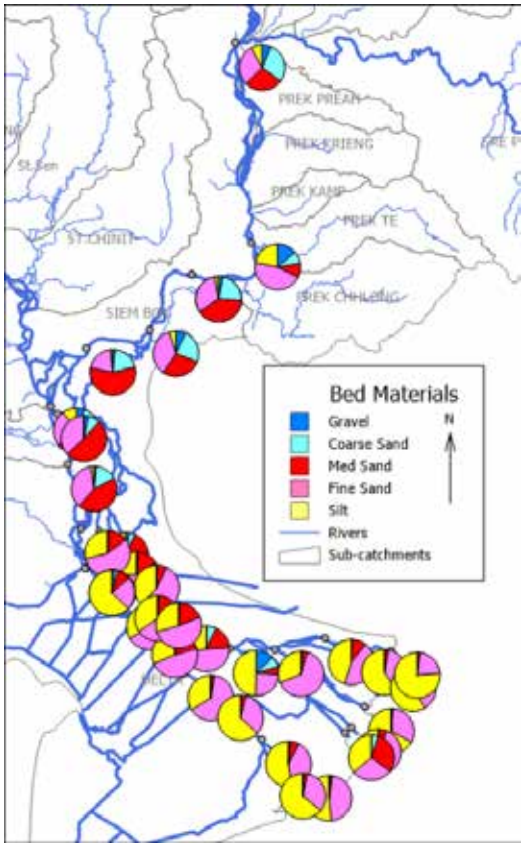


Figure 6.83. *Bed materials in the Mekong River delta in 2011. Data from MRC Discharge Sediment Monitoring Program.*

6.4.4 Water Quality – Tonle Sap and Delta

The cumulative impact of hydropower development in the UMB and LMB will have the following potential water quality impacts in the Tonle Sap and delta systems:

- An increase in water temperature during the dry season due to the increased retention time of water in impoundments;
- A decrease in nutrients due to trapping of sediments and associated nutrients in reservoirs;
- A change in the proportion of dissolved to particulate nutrients being transported in the river due to a large reduction in particulate nutrients;
- An increase in water clarity resulting in increased light penetration that could increase water temperatures and promote algal growth in the Mekong River;
- An increase in water clarity in the Tonle Sap Lake due to a reduction in sediment transport in the Mekong mainstream. If large quantities of sediment continue to enter the lake from local tributaries and turbidity remains high, there may be little change to light penetration in the lake even if sediment concentrations decrease. However, if the reduction in sediments is sufficient to increase light penetration, then algal growth in the lake waters may increase;
- Changes to the intrusion of salt water into the delta due to increased dry season flows, and a delay in the onset of flood flows;

Mitigation approaches for these impacts depend on catchment scale planning and management. The trapping of fine-silt in the large Sambor project is a major contributor to the potential changes in water clarity and nutrient transport in the lower river system. Omitting this project, or modifying it such that fine-sediments can be transported around the project infrastructure would provide some mitigation for the identified downstream impacts. If there was the potential to pass sediment through or around Sambor, then managing sediment flushing in upstream impoundments to provide seasonally appropriate sediment pulses would mitigate against some of the changes in nutrient concentrations and turbidity levels in the lower river and Tonle Sap system.

Managing flows at a catchment scale such that seasonal appropriate flow enters the downstream Mekong River and delta is another mitigation approach that is appropriate for the management of water quality issues such as salt intrusion.

6.4.5 Fisheries and Aquatic Ecology - Tonle Sap, Delta and Overall Basin

6.4.5.1 Tonle Sap and Delta

As shown by detailed assessments , the northern Lao cascade would not have a great impact on the Tonle Sap and Delta. Since the cascade only includes run-of-river schemes, the seasonal flow distribution does not change and will therefore not impact the flow reversal of the Tonle Sap. The previously discussed erosional wave stemming from sedimentation in the upper cascade will migrate downstream very slowly. However, once it reaches the lower part of the LMB, it could of course also impact the Tonle Sap and the Delta region. Despite the negligible impact of the Upper Lao cascade, we must not forget that alterations of the distinct flow regime (wet and dry season with flow reversal) already occurred with regard to storage projects in China and the LMB tributaries. A detailed assessment of those impacts is, however, not part of this study.

The study also showed that hydropeaking in the upper cascade (in the case of ramping operation) does not extend very far downstream and would also not impact the lower part of the LMB. Hydropeaking in the lower cascade would cause significant water level fluctuations, which would also cause safeguard issues. Consequently, the lowermost dam would have to act as a re-regulation weir, which would also avoid impacts on the Tonle Sap and the Delta. For long distant migratory species which utilize the whole LMB (i.e. from the Delta- and Tonle Sap region far upstream into the upper migration system), population declines can be expected, especially if important spawning grounds are located in the area of the Upper Lao cascade. However, with other developments going on in the catchment, the real source of impact might be hard to identify. As already discussed in chapter 6.5.3, the Upper Lao cascade does not effectively trap silt and clay, which means that nutrient supply into the Tonle Sap and the Delta is still supported. This could, however, change with the implementation of the lower cascade, and especially if the large version of Sambor is realized.

In comparison to the upper cascade, the downstream cascade would have a more direct and visible impact on the Tonle Sap and the Delta region. Apart from hydromorphological alterations, (see chapter 6.5.2 and 6.5.3) a clear impact from blocking the upstream migration route towards the 3S system and over the Khone falls can be expected. Furthermore, the large number of impoundments in the Lower cascade will reduce the abundance and biomass of juvenile fish drifting downstream and reaching the Tonle Sap and Delta region.

According to the Council study, the increase in dry season flows will cause a decrease in average salinity. This may cause a reduction of habitats for estuarine species with preferences for brackish water. However, these changes are mostly related to storage hydropower plants in China and LMB tributaries. On the long run, riverbed incision and erosion in addition to a sea level could probably increase salt-water intrusion.

According to the Delta study, the realisation of the whole mainstream cascade (i.e. 11 dams) could reduce fishery yields by 50% in Vietnam and Cambodia. A high impact would be expected for white fish species (i.e. long distance migratory species) which make up ¾ of the top 10 commercial species (HDR & DHI 2015).

At this point, a detailed assessment of potential impacts or the effectiveness of mitigation measures is not possible for the lower cascade since there are still too many unknown factors (e.g. characteristics of the dams, complex interaction between impacts, e.g. hydrology, morphology, connectivity, nutrient supply, habitat- and migration requirements of all species).

A significant reduction of negative impacts can actually only be achieved by avoiding the completion of the whole cascade. With the impacts of Don Sahong and Xayaburi still unknown and the efficiency of implemented mitigation measures not yet analysed, it would be best to monitor these locations for at least 5-10 years to learn more about their effects and to be able to assess to which degree sustainable hydropower development is possible in the LMB.. Furthermore, the construction of the Sambor dam will have devastating impacts on the lower LMB. Without Sambor, the impact of Don Sahong and the upstream cascade could still be mitigated to some degree and is potentially buffered by the remaining connectivity to the 3S system. Also, the smaller version of Sambor requires in-depth assessment and planning and should only be realised if successful migration can be assured for all species.

6.4.5.2 Overall Basin Scale

According to the Council study, the additional construction of nine mainstream dams will result in an irreversible, negative impact on the LMB ecosystem with the greatest impact stemming from the most downstream dams (i.e. Stung Treng and Sambor). This is not surprising considering the increasing cumulative effect of mainstream dams and the fact, that downstream dams have a greatest impact on migratory species compared to headwater dams.

Impoundments represent a highly altered environment. Depending on their location in the LMB (i.e. upper Mekong mainstream, lower Mekong mainstream, tributary) and storage capabilities (i.e. reservoir vs. impoundment) they will show different characteristics. Overall, the mainstream dams would transform 920 km of the Mekong to impoundments (384km and 468km for the upper and lower cascade respectively), which represents 37% of its entire Mekong in the LMB. This will cause a loss of typical riverine habitats both in aquatic and riparian zones.

The low flow velocities will cause a sedimentation of substrate and the river bed will be covered by a fine silt layer. While some aquatic organisms (such as snails, bivalves, shrimps and crabs) may become more abundant in reservoirs, other organisms, such as benthic invertebrates with preferences for stony or sandy habitats, will no longer find suitable conditions. Although benthic invertebrate biomass is generally assumed to increase, there will be a significant shift in the species composition. Since many fish species have also distinct food preferences (e.g. for insects on stones and sand, mayflies or snails), they may not be able to switch to food sources which may increase in abundance (e.g. bivalves, shrimps, crabs and zooplankton). Consequently, fish species specialized on free flowing conditions will decline. Changes in sediment concentration will increase water clarity along the Mekong, which could increase algal growth (if not offset by reduced nutrient input) and cause an increase of fish species feeding on algae. Water quality changes (e.g. temperature, oxygen saturation) could cause additional impacts for the aquatic fauna.

BioRa zones		1		2		3	4		5		6	7	8
Impact zones		Upper cascade				Middle reach	Lower cascade				Tonle Sap		Delta
R = river; I = impounded		R	I	R	I	R	R	I	R	I	R	R	R
Percentage of I/R per zone		59	41	12	88	100	68	32	50	50	100	100	100
Main channel resident	Migratory	-100	-100	-100	-100	-100	-100	-100	-100	-100	-85	-70	-80
Main channel spawner		-100	-100	-100	-100	-80	-100	-100	-90	-100	-55	-60	-80
Floodplain spawner	Floodplain		-80		-80	-20	-20	-80	-40	-80	-45	-65	-65
Floodplain resident						-15	-30	-30	-65	-65	-55	-50	-55
Eurytopic	Generalist	10	80	40	80	55	35	80	-5	100	5	-5	15
Rhithron resident	Others	0	-100	0	-100	10	-5	-100	-30	-100			
Estuarine resident								20		-50	-55	-50	-50
Anadromous						-100	-100		-55		-35	-20	-35
Catadromous			-100		-100		-95	-100	-25	-100	-25	-20	-30
Marine visitor								-50		-80			-10
Non-native	Non-native	115	50	110	50	85	75	100	80	100	55	55	80
Biomass		-55		-75		-65	-40		5		-30	-35	-25

Colours indicate the degree of changes. Bold&black numbers highlight guilds with >10% contribution to the catch in the respective BioRA zone (based on BioRA Technical Report Vol 1, Appendix G).

The **Upper cascade** is dominated by migratory and rhithron resident fish species. These white fish species will not be able to thrive in impoundments and will be replaced to some degree by generalist and non-native species. Nevertheless, biomass is expected to decrease in the upper cascade (-55 to -75%).

The **Middle reach** will mostly be impacts by reduced sediment transport caused by the upper cascade. Erosion will highly alter the sediment composition towards larger fractions and exposed rocky habitats, while sandy habitats will decrease. Aquatic organisms (especially benthic invertebrates and fish) will react to these habitat alterations, whereby species relying on sandy habitats will decrease in abundance.

In the **Lower cascade**, floodplain spawners (grey) and residents (black) are also expected to decrease together with main channel spawners (white). Floodplain spawners will mostly react to induced changes related to hydrology and sediment transport. While run-of-river impoundments are usually not favourable to fish production, the impoundment created by the Sambor dam would be much shallower and larger compared to the rest of the cascade and could cause a slight increase of the overall biomass in this area (mostly caused by the increase of generalist species). Likewise, OAAs could also favour from impounded areas and show a slight increase.

The **Tonle Sap** system may be able to buffer some of the impacts by its direct tributaries. The flow reversal is expected to be preserved, even if slightly changed. However, the lake will be affected by the reduction in sediments supplied by the Mekong River and the fragmentation of migration routes for white fish.

In the **Delta**, a reduction in estuarine/ brackish habitats, caused by hydromorphological changes and a reduction of salt-water intrusion in the dry season will have a clear effect on estuarine species. Also here, all guilds (except for erytopic and non-native species) are expected to decline and will cause a biomass loss of 25%.

Overall, **fish biomass** is assumed to decrease significantly. All fish guilds are expected to decline, except for erytopic (generalist) and non-native species. The largest decrease is expected for migratory species (i.e. – 85 to -100%) throughout the LMB after the construction of all mainstream dams and interruption of important migration routes. Although the increase in non-native and eurytopic species will be substantial (i.e. between 55 and 115%), it is very unlikely that this can offset the biomass loss of indigenous and more valuable fish. Consequently, fish biomass is expected to decrease. Cage culture and culture-based fisheries are highly unlikely to be able to compensate the loss of natural biomass production. With the loss of specialized species, **biodiversity** will significantly decrease throughout the LMB. The Council Study further concludes, that the **ecosystem integrity** will be reduced to predominantly “largely modified”, and maybe even drop to “critically modified” in the Delta.

Unfortunately, even under consideration of mitigation measures (see scenario H3_HPP in Figure CS), there will be no significant improvement related to the induced changes to fish biomass and composition.

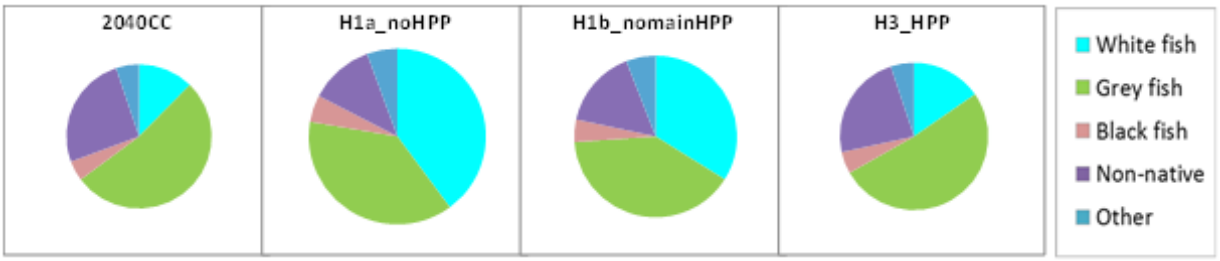


Figure 6.84. *Predicted change in fish biomass and composition for the Mekong mainstream in the LMB (source: Council Study BioRA Technical Report Vol. 4; Fish biomass for H1a_noHPP approximates that of 2007 baseline).*

7. Findings and Conclusions from 2nd Interim and Final Phase Case Study Activities

7. Findings and Conclusions from 2nd Interim and Final Phase Case Study Activities

7.1 Basin Scale Assessment of the Results

A very comprehensive analysis using the latest and best available data has been implemented. It builds on data and analyses undertaken in other recent major studies in the Basin (e.g. Basin Development Scenario Assessment (MRC, 2011), Mekong Delta Study (DHI, KDR, 2015) as well as the 1st Interim Mitigation Guidelines and Manual (MRC, 2015) by also linking the Case Study to Basin Scale implications).

The information used in the analysis includes the most recently updated MRC fish and sediment monitoring data (for fish; consumption-based yield data and AMCF sampling data as well as related studies as e.g. Halls, 2010; Halls & Kshatriya, 2009; Hortle & Bamrungrach, 2015 and; for sediments Koehnken, 2015).

The selected analyses, models, data and related input parameters have been, and are continuing to be discussed with Member Countries as part of this project.

The impacts and related mitigation approaches for the hydropower cascade must be seen in a basin wide context. The upstream Lancang dams and the tributary dams have substantial impact on the hydrological, biological and sediment inputs to the cascade, as previously discussed. These cannot be mitigated by implementing measures in the cascade alone, but must be dealt with either at the Lancang and tributary dams themselves OR through use of basin scale offset and management approaches.

Hence, integrated hydropower planning at the system scale (basin, catchment) should be the New Frontier for the LMB countries (see also Oppermann et al. (2013 and 2017) for discussion on the benefits of system scale hydropower planning). Loucks (2003) also neatly links this to maximization of benefits by stating – “the interdependence of system components and decisions strongly argues for managing them in an integrated holistic and sustainable manner if maximum benefits are to be obtained from them”. For this to be realised the Member Countries will need even more integration than at present within the cooperation continuum and move from cooperation towards even more joint action as portrayed to the right in Figure 7.1.

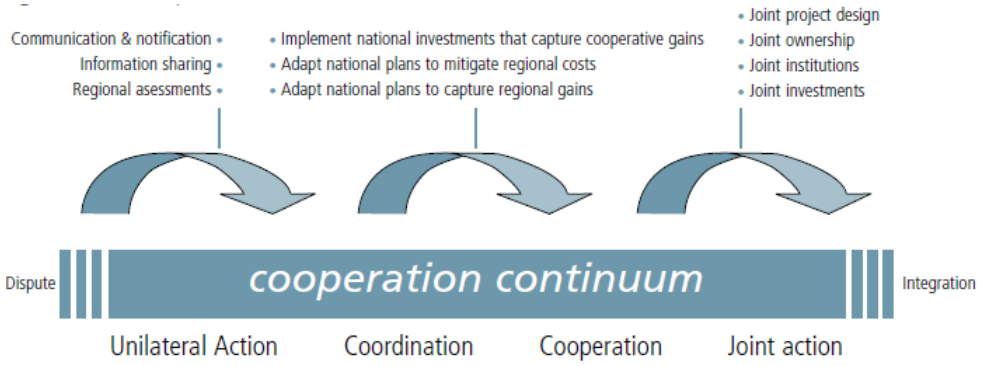


Figure 7.1. *A cooperation continuum for transboundary management of water resources as portrayed by Sadoff et al. (2008).*

Considerations for Joint Action are already vested in the Mekong Agreement (MRC, 1995) and its associated initiatives like the Basin Development Plan (MRC, 2011) and the Preliminary Design Guidance (MRC, 2009). These serve as a good starting point for further Joint Action.

Joint Action also may include opportunities for joint development and Benefit Sharing as considered by recent MRC initiatives (MRC, 2014 and 2015). The MRC's comprehensive review of good industry practice was undertaken with the MRC Member Countries and provides a supporting framework to guide possible Joint Action. Joint Action represents the greatest level of coordination and cooperation at a Basin Scale and is normally formalized in treaties and strong institutions, where benefit sharing arrangements such as joint ownership and management of assets can form the basis (Sadoff et al., 2008 and Lillehammer et al., 2011). The Lesotho Highlands Water Project (LHWP) with its Treaty (LHWC, 1986) is an example of Joint Transboundary Action (Lesotho and South Africa). The LHWP Treaty explicitly states how benefits from cooperative development will be shared (royalties from water, electricity from HPP, other ancillary benefits etc.). Benefit Sharing can be defined as follows (Lillehammer et al., 2011) – "A framework for governments and project proponents to maximize benefits across stakeholders, through relevant spatial and temporal scales by use of various mechanisms, and consistent with the principles of sustainability".

Integrated hydropower planning at system/basin scale is envisaged in the MRC's Strategic Plan 2016-2020 (MRC 2016) as part of the overall Integrated Water Resources Management approach. Such an approach, at basin level, will cater for the incorporation of sustainable planning within a spatial and temporal context allowing for the application of the full mitigation hierarchy, from avoidance through minimization, mitigation and compensation/offsets. This approach is particularly relevant where biodiversity offsets are planned. Cumulative impacts from upstream, tributary and instream hydropower projects which alter seasonal and diurnal flow and sediment patterns, will affect defined critical biodiversity hotspots habitats. Integrated system planning may reduce these cumulative impacts at a basin scale (Nature Conservancy/IDB, 2013) making this approach highly relevant for the future hydropower planning of Mekong mainstream and its tributaries.

When mitigating within the spatial context at basin scale, and in line with the mitigation hierarchy, the status of the LMB ecosystems will benefit from early avoidance mitigation approaches. Examples might include maintenance of intact river routes and alternative dam designs. The latter has actually been studied for Sambor, and is amongst others reported in Wild and Loucks (2015). An illustration of the original proposed Sambor Dam and the smaller alternative is shown in Figure 7.2. The latter includes a natural sediment and fish bypass channel.

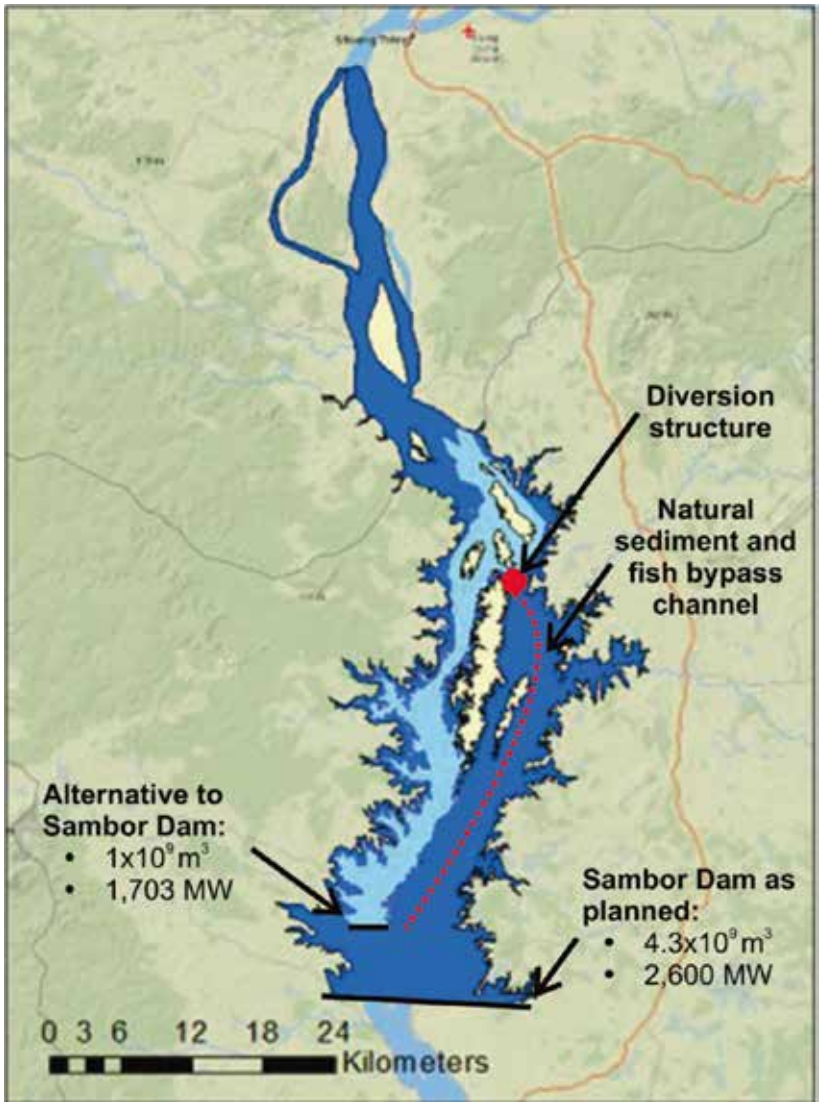


Figure 7.2. *Map of the original proposed Sambor Dam and the smaller alternative (Source: Wild and Loucks, 2015)*

7.2 Mitigation at Lao Cascade and Downstream Dams

The cascade studied in Northern Lao PDR includes major dams and, without mitigation, these will pose significant additional environmental impacts on the basin. However, the mitigation methods documented in the Guidelines (MRC, 2015) have been applied to seek to mitigate the impacts and risks imposed by the Lao mainstream cascade. These applications generally enhance and "operationalise" the approach taken at the Xayaburi project which are based on recommendations in the PDG (MRC, 2009).

The extensive and detailed assessment carried out in this study concludes that:

- The mitigation options tested reduce the downstream impacts compared to "no mitigation" scenario to varying degrees;
- The investment in the cost of construction and operation of the mitigation solutions is well justified by the reduced loss in economic value and benefits from reduced environmental

impacts in the cascade reach and further downstream;

- There remains a number of basin scale impacts from the Lao mainstream cascade that cannot be fully mitigated (for example transport of coarser sediments).

These same conclusion will also be the same with regard to the downstream dams and tributary systems assessed during Phase 4.

In addition, as can be expected, with these large-scale and pioneering application of mitigation approaches, there are a number of uncertainties with regard to the effectiveness of some mitigation measures (specifically the upstream and downstream fish passage).

The application of these mitigation approaches needs to be intensively and jointly monitored by MRC member countries at Xayaburi (currently under construction) to assess the effectiveness of mitigation and to build important knowledge that may be applied in the design and operation of potential future dams in the mainstream and tributaries of the Mekong.

In addition, residual impacts and risks arising from this cascade of dams need to be considered at a basin scale (see above section on basin scale findings and recommendations) to understand potential transboundary management and cooperation options to overcome these impacts (including those of benefit sharing discussed in Chapter 7.1.1).

7.3 Thematic Findings and Recommendations

7.3.1 Hydrology and Flows

For the larger time step, annually and inter-annually, the hydrological changes depend heavily on the active storage volume of the reservoirs. At present, the flow regime is strongly influenced by the Chinese dams that have over-year storage, which is already traceable in the change of the timing and magnitude of the dry- and wet-season flows. ***As the dams in the Lao cascade are all run-of-the-river (small storage), they will have negligible influence on the overall annual flow regime, particularly if compared to the effects of the Chinese dams and tributary dams.***

The short-term (sub-daily) variations in discharge and water levels due to operations of the cascade, such as peaking, can be mitigated by imposing maximum ramping rates and minimum environmental flow criteria. These are defined by constraints from the other fields, such as (fish) environment, water quality and sediment transport. ***The impact of the Lao cascade on the flow regime further downstream, towards Pakse, on the Tonle Sap system, and further downstream to the Mekong Delta, will be hardly noticeable, as long as these cascades are operated as run-of-the-river reservoirs.***

From the Council Study hydropower sub-scenarios can be concluded that the main impacts to the delta are the seasonal changes which are primarily caused by the tributary reservoirs and Chinese reservoirs (UMB), and not by the LMB mainstream dams. The presence of such a large storage volume in the basin creates opportunities to release flow pulses to restore time-dependent features, such as the timing of flow reversal in the Tonle Sap. Nevertheless, both the impacts of dam development, as well as pulses released from these dams, only have relatively small influence on the flows in the estuarine parts of the delta (and the salt intrusion). This is

caused by partial absorption of the flow-pulses and impacts from dams, by the large storage of the Tonle Sap and the inundated floodplains (Plain of Reeds). For the most downstream parts of the delta therefore solutions for mitigation of flow impacts have to be found locally (e.g., lowering dike levels in flood plains, and prevention of sand mining).

7.3.2 Sediments and Geomorphology

The sediment and geomorphology modelling investigations indicate that sediment loads entering the cascade will be considerably lower than historic values due to the trapping of sediment in the Lancang Cascade and in the tributary dams included in the BDP 2030 baseline scenario. Of the sediment that does enter the cascade, all of the gravel, coarse sand and medium sand will be trapped, as will most (but not all) of the fine sand. Silt and clay will be transported through the impoundments, although seasonal accumulation of fines during the dry season followed by re-mobilisation is expected. The modelling results suggest that ~6 Mt/yr of sediment will be discharged from the downstream dam, and the grain-size distribution will be limited to silt and clay. Deposition of the inflowing sediment will be greatest in the Pak Beng reservoir, due to it being the most upstream impoundment. Due to the low level of sediment input, long time periods, in the order of decades, are likely to be required before sediment deposition extends down the long impoundments and reaches the dam wall.

Geomorphic changes associated with the operation of the cascade include:

- Channel incision at the upstream ends of all impoundments, except Pak Beng due to erosion associated with the inflow of low sediment water at relatively high velocities from the upstream reservoir;
- Channel infilling (deposition) of sediment where water velocities decrease, with virtually all gravel, coarse and medium sand captured, and most fine sand captured;
- The progression of an erosion-wave downstream of the final dam site (Sanakham). The erosion of sediment from the channel is projected to increase sediment concentrations at Paksane to near BDP 2030 levels for a number of years.

Mitigation measures investigated in Scenarios 1.1A&B, associated with providing a minimum flow, fish passage, or flood and water level control, are not considered to alter sediment trapping in the cascade compared to the no mitigation scenario (1.1.0). Similarly, the hydropeaking regimes with mitigation investigated in Scenario 1.3 are not considered to alter sediment trapping or geomorphic changes relative to the non-hydropeaking flow regime.

Sediment flushing after 7-years was found to be viable and increased sediment discharged from the impoundments from <5% to 35% compared to the annual sediment discharge. The efficiency of sediment flushing depends on the volume of sediment available for transport, the draw down rate, and the duration over which the river was maintained at minimum level. Fine sand was consistently mobilised by flushing, with medium sand mobilised when draw down was very rapid. ***The volume of sediment mobilised provides a positive benefit in the river reach downstream of the final dam, and the benefit could be maximised by managing the timing of flushing events to coincide with periods when there is a greater likelihood that sediment will deposit in the channel.***

Maximum suspended sediment concentrations in the discharge during flushing were found to occur for short periods of time and be within the natural range of the LMB. If greater sediment loads were available for mobilisation, these concentrations would be likely to increase and future investigation and optimisation are required.

Longer model runs of 16-years demonstrated the progression of sediment deposition along the reservoir, and suggest that flushing has the potential to mobilise larger sediment loads in the future. Although flushing may not be 'required' or highly efficient until one or more decades after project implementation, the inclusion of appropriate infra structure to allow flushing to be completed is considered critical for the long-term operation of the cascade. ***Adaptive management should be introduced with respect to flushing, and the downstream ecosystem condition and the maintenance of a fine-sand supply to the downstream river should get high priority.***

The Council Study modelling demonstrates that the implementation of the tributary and mainstream dams associated with the 2040 Full Development Scenario will reduce sediment transport by 97% in the river. Changes of this magnitude will fundamentally alter the geomorphology of the river system, and widespread channel erosion, channel incision and bank erosion can be expected. The geomorphic changes will translate into widescale alterations to the distribution and characteristics of aquatic and riparian habitats.

Management of the mainstream dam sites alone cannot mitigation the potential impacts associated with the 2040 scenario. Tributary projects need to be managed to maximise the passage of sediment, and operations need to be coordinated to maximise mitigation success and minimise impacts on power production. Identifying important sediment pathways and either maintaining as free-flowing, or focussing mitigation efforts in these areas provides the best mitigation approach for the LMB.

7.3.3 Water Quality

No specific water quality mitigation measures were modelled in the Case Study. ***A risk analysis of the modelled scenarios found that there is an increased risk of algal blooms in the cascade under all of the scenarios*** due to the following factors:

- There is a low risk of wide spread thermal stratification of the reservoirs, but there is a risk of localised stratification near the dam walls, or potentially near tributary confluences;
- There is a high likelihood that water temperatures will increase during storage during the dry summer months due to an increase in the residence time of water in the cascade reach;
- There is a high risk that water clarity will increase due to sediment deposition;
- There is a risk that nutrient inputs to the reservoirs will increase over time associated with an increase and intensification of agriculture in the region.

Downstream water quality is likely to be affected by warming within reservoirs, and the discharge of potentially high levels of algae. There is also a risk of water containing low concentrations of dissolved oxygen being discharged during the first few years of operation associated with the degradation of organic matter following inundations.

Nutrient levels in the discharge water are likely to decrease in response to sediment trapping, but because most nutrients are associated with very fine sediment, which will not be trapped in the impoundments, the reduction in nutrients is likely to be relatively less than the reduction in sediments. There is also the potential for nutrient levels to increase, either temporarily or permanently, through the initial degradation of organic matter in the impoundment area, and/or the intensification of agriculture or other activities in the catchment that contribute nutrients to the waterway.

The Council Study results highlight that nutrient transport will be affected by sediment trapping in impoundments. The best approach for maintaining nutrient transport is to maintain sediment transport on an annual basis through the system.

The most appropriate mitigation approach for water quality is adaptive management and catchment management, as the water quality risks are derived from catchment activities and inputs as well as the development of the cascade. Long-term adaptive management will benefit from the inclusion of infrastructure at the design stage of hydropower projects that facilitates the release of water from multiple levels within the impoundment, and from long-term monitoring to understand the seasonal and longer term evolution of the impoundment.

7.3.4 Fisheries and Aquatic Ecology

The modelling results indicate, that the mitigation of habitat fragmentation (i.e. the construction of fish pass facilities) has a clear positive effect within the cascade and downstream. Assuming that the fish pass is functional for most species and age classes (which can only be shown by long-term monitoring) ***most species and life stages will benefit.*** Nevertheless, migratory species might still drastically decline or become extinct in the long run due to high losses caused by turbine mortalities and interrupted larval drift in the reservoirs. Turbine mortality could be reduced by the implementation of finer rakes, which would be beneficial for larger/long-lived species. The ***interruption of larval drift cannot be mitigated with the present hydropower design.*** The implementation of the whole cascade (11 dams), it is assumed that migratory species will drastically decline. Some small populations might be able to sustain in the middle-reach (i.e. between the upper and lower cascade) if they still find suitable conditions to complete their life-cycle. Likewise, species limited to the lower migration system which still find suitable habitats for spawning, rearing and feeding might persist. Overall, the diversity and biomass of migratory species will significantly decrease, not only as a result of fragmentation but also due to large-scale habitat alterations (e.g. creation of impoundments).

The results demonstrate that ***flushing can be carried out in a way that fish are not significantly affected in the downstream zones*** (2 & 3), however, ***flushing always is associated with drastic impacts on the fish community within the reservoirs.*** In spite of the positive effects of flushing in terms of sediment transport, the downstream river sections will still suffer from a lack of sediment, which, of course, can be attributed to the existing Chinese dams but is also intensified by the Lao cascade. The hydromorphological consequences of sediment deficit will result in loss of sand bars and other habitat features leading to reduced fish biomasses on the long term. Another consequence is the likely ***riverbed incision, which will result in a decoupling of the adjacent floodplain habitats*** and reduced floodplain fish productivity. One solution, practiced in large European rives (Rhein, Danube), would be to dredge coarse sediments in the upper most reservoir and ship the sediments downstream the cascade. However, the results of this study highlight that management of the mainstream dams alone cannot be considered as sufficient.

Finally, ***the peaking restrictions show significant improvements compared to peaking-scenarios without restrictions.*** Having un-ramped hydropeaking at the four upper dams and using the lowermost dam as a ***re-regulation reservoir is beneficial for the downstream impact zones but still causes significant degradation within the cascade*** and therefore this is not recommended.

According to the Council Study and the Mitigation Guideline project, the greatest impacts on fish are related to;

- fragmentation of up- and downstream migration routes,
- sedimentation in impoundments and related morphological alterations downstream,
- change of flow characteristics to hybrid water bodies in impoundments.
- Even though the tested mitigation measures can bring some local improvements, they might not be able to sufficiently improve the conditions for the aquatic ecosystem:
- With regard to fragmentation, there are currently no state-of-the-art mitigation measures for large tropical rivers as the Mekong. The monitoring at Xayaburi will show whether and to which degree the applied fish pass design is functional, if the downstream migration facility able safely bypass downstream migrating adults and to which degree the turbines can be considered as “fish-friendly”. Likewise, the monitoring ad Don Sahong will show if fish are able to adapt to the new conditions, if they find alternative migration routes and if they are able to overcome the barrier in both directions. There are still high insecurities in the assessment of mitigation efficiency. However, studies around the world showed that the restoration of connectivity in tropical systems is rather challenging, especially under consideration of related large-scale habitat alterations.
- Sedimentation in impoundments and reservoirs, not only in the Mekong mainstream but also in the tributaries, has a great impact on the eco-morphology of the river and consequently on habitats for aquatic organisms. Assessments within this study highlighted that significant improvements can only be achieved if mitigation measures are implemented at the basin scale (i.e. under consideration of all existing and planned dams). Nevertheless, the application of mitigation measures is limited in some cases (as e.g. the large Sambor dam). In such cases, avoidance has to be applied instead, e.g. by reducing the size of the dam/impoundment or by waiver of the entire dam.
- In addition, impoundments also induce the loss of free flowing river sections. The resulting hybrid waterbodies represent neither a river nor a lake and provides only habitats for generalist species with limited habitat preferences. Again, the mitigation of this impact is usually not possible without changing the overall scheme of the hydropower plant (e.g. smaller reservoirs) or its operation (e.g. by opening of the gates for several months per year).

This, once more, highlights the importance of avoidance as one important part of the mitigation hierarchy. Despite the fact that many tributary dams were already developed or are currently under construction, additional impacts for migratory species should by avoided by considering the following recommendations:

- Identification of important un-fragmented migration routes within the LMB.
- Critical review of planned hydropower plants within this range (ideally also under consideration of other aspects, as e.g. key habitats, sediment pathways, hydrology etc.).
- Assessment of expected impacts and their mitigation potential.

- Waiver of hydropower plants in sensitive locations (i.e. downstream of existing dams and within important migration routes), with high expected impacts and low mitigation potential.
- Investigation of impacts caused by existing tributary dams; prioritisation based on their relative impact (e.g. with regard to fragmentation) and the possibility to implement mitigation measures subsequently (e.g. implementation of fish passes). This is also recommended for irrigation dams.

Even though mitigation measures are important for reducing the negative impacts of hydropower development, is has to be acknowledged that mitigations are not capable of compensating the whole range of ecological impacts associated with hydropower development and that the construction of new dams will inevitably put additional pressure on the aquatic ecosystem. In this context, it has to be recognized that it may not be possible to achieve both, a high level of exploitation (as currently envisaged by hydropower development plans) and the preservation of aquatic ecosystems and all related ecosystem services.

7.3.5 Hydropower Operations and Economics

7.3.5.1 Feasibility and Operational Viability of the Mitigation Options

When assessing the feasibility and operational viability of the proposed mitigation options for the cascade, these are in general considered to be relevant for future and planned hydropower schemes. Many of these are already included in the Xayaburi scheme (flood protection, fish passages, minimum flow etc.). A challenge with respect to both management and financial viability is the scenario group 1.2 with flushing and sluicing. This was discussed also in chapter 3.1.3 proposing also a central authority dispatching optimal cascade performance and according to which the developers are paid for available capacity and not energy for. Peaking without any restrictions, e.g. scenario 1.3.0 is not environmentally acceptable.

7.3.5.2 Economics of the Mitigation Options

Hydropower modelling demonstrated that the mitigating measures that cause the largest losses of power generation and revenue are the measures involving reservoir drawdown. In scenarios involving drawdown both for flood protection and for sediment management as well, the loss may amount to as much as 6% of the revenue. This is substantial and would require some compensation mechanism for the operators, for example a tariff adjustment.

Peaking operation with various mitigation measures, but with ramping restrictions only at Sanakham, leads to a revenue increase in the order of magnitude of one percent (with the exact figure depending on the RoR scenario it is compared to), as shown in section 5.2. One may argue that the peaking regime that has been investigated is gentle in the sense that it operates for around 8 hours, respective 16 hours without abrupt changes to the flow. It is also worth noting that the water level amplitude is well below one meter most of the time. Still the peaking regime gives an abrupt flow change twice during every 24 hours, except for in the flood season, so there is a certain environmental stress involved.

Peaking could be justified, especially under commercial considerations, by the possibility of delivering energy at the time of the day when it is needed, as opposed to the Run-of-the-River

regime, in which an equal amount of energy is produced when the need is less, during night hours. ***Environmental considerations will however need an applicable and firm ramping rate for the hydropeaking to be considered.*** This has been thoroughly discussed in chapter 5.6. From a developer point of view, the peaking regime is of course attractive due to the increased revenue. It is a notable finding of the study that the revenue increase due to peaking, turned out to be less than expected (i.e., in the order of 1 pct).

7.3.5.3 Alternative Schemes Layouts

The comparison between a typical full height mainstream project and the equivalent two half height schemes indicates that the combined construction cost of the two half height schemes will be approximately 15% greater. Conversely, the project finance cost for the two half height schemes is lower because energy and revenue is available approximately four years earlier. The overall implication is that the cost of energy from the half height schemes is approximately the same, and possibly lower, than the single full height scheme. This conclusion is based on river discharges, foundation conditions and cross sections being typical of the Low Cascade reach of the Mekong.

The impact on energy output has been examined in Section 6.2.5 of this report by considering sub division of the Pak Lay and Samakham projects. The average energy of the sub-divided projects is approximately 7% lower than the full height alternative. The reduction is mostly attributable to the increased impact of raised tailwater levels.

A three month wet season shut down results in an energy reduction of approximately 30%. This energy reduction is not a product of sub diving the projects, it is a result of shut down. This loss would need to be assessed against the advantage of mainstream hydropower development on the Mekong that has the potential to preserve the ecology of one of the world's most important rivers.

8. Research questions and concept notes

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8.1 Geomorphology, Sediments and Water Quality

8.1.1 Sediments and geomorphology-information gaps

A central objective of the Case Study has been to identify sediment mitigation measures applicable to the LMB. The successful identification of appropriate mitigation approaches depends on a site-specific understanding of hydropower project and the characteristics of the river at a range of spatial and temporal scales. This approach is necessary because hydropower operations affect rivers locally, through the blocking of sediment transport, creation of impoundments and regulation of flow, and over great distances through changes in the magnitude, duration, frequency, rates of change and seasonality of flow and sediment regimes.

Project activities have included the identification of geomorphic and sediment transport 'risks' in the LMB including an in-depth Case Study based on modelling the Northern Lao PDR Cascade. These investigations have drawn upon the MRC flow and sediment monitoring results and available catchment information, and have provided insights into the potential impacts and appropriate mitigation measures in the LMB, but have also highlighted information and data gaps. Many of the identified gaps are consistent with the information needs and gaps identified by the MRC Initiative for Sustainable Hydropower Project 11, Improved Environmental and Socio-Economic Baseline Information for Hydropower Planning" (MRC, 2014), and this report should be consulted for additional detailed information regarding monitoring, including recommendations for additional monitoring locations. The relationship between monitoring, hydropower information needs and basin indicators was summarised by ISH11 as shown in Table 8.1.

The recommendations provided here also reflect information needs identified during the collaborative work with the Council Study modelling team.

Table 8.1. Information needs for hydropower planning and management (Source: MRC, 2014).

MRC-Centralized Parameter Groups	Hydropower Relevance	Example Basin-Scale Indicators
Sediment characteristics: suspended and bedload concentrations and fluxes, seasonality, grain-size distribution, organic content, mineralogy, lithology	▸ Influx of sediments to impoundments is critical for siting and design of hydro schemes; understanding sources and sinks and how these might change into the future helps plan for future trends ▸ Need to understand sediment and geomorphic processes to design and implement effective mitigation measures ▸ Changes to sediment fluxes downstream of power stations can affect geomorphological and ecological processes and have social impacts ▸ Separating changes due to hydropower from the effects of other basin developments/actions at transboundary locations.	✔ Changes in sediment budget and sediment characteristics (grain size distribution) at locations over time ✔ Changes in river morphology, habitat ✔ Coastal erosion rates
Geomorphic characteristics and habitat quantity & quality: channel cross-sections, channel characteristics (depth, roughness, hydraulic radius, etc.) longitudinal channel profiles, planform features (e.g., width, number of channels, sinuosity, braiding), composition of channel (bedrock controlled, alluvial, combination, presence of woody debris)		
Geomorphic rates: rate of channel migration, rates of channel infilling or incision, bank stability		
Land-use characteristics & linkages to sediment availability: land cover, vegetation cover, vegetation types, catchment elevation and slopes, landforms, susceptibility to erosion		
River dynamics: flow regime, coefficient in variability of depth, heterogeneity of current velocities floodplain connectivity, Tonle Sap reversal		
Tidal sediment dynamics: rates of change and locations for transport, deposition, erosion		

Sediment monitoring and transport in the LMB. Accurate sediment monitoring results are required to predict the quality and quantity of sediment affected by HP impoundments, to model potential mitigation strategies, and to quantify changes in the river system. Recent MRC coordinated monitoring by the Member Countries (Discharge Sediment Monitoring Program, DSMP) has provided suspended sediment results and sediment characteristics for main stream sites in the LMB for the period 2011 - 2013, but since that time monitoring has been sporadic, and results have not been collated, undergone a QA/QC process or been interpreted. The following actions are recommended:

- **Maintain monitoring on a continuous basis and analyse results.** The LMB is undergoing rapid change, and having a continuous monitoring record is important for tracking these

changes and understanding how the relationship between flow and sediment transport is altering over time. Gaps exist in the monitoring due to administrative and funding issues, and boat, motor and equipment failures. To address this, monitoring agreements and funding should be based on multi-year periods and new agreements should be finalised well before the previous cycle ends. Contingency arrangements for having back up equipment should failure occur should be included in the monitoring planning process.

- **Harmonise and upgrade instrumentation.** A range of monitoring methodologies are used in the DSMP. An inventory of the equipment being used should be completed, and an evaluation of the state of the existing equipment should be completed. A goal of the DSMP should be to implement the same methodology at each location such that the results are compatible. Discharge monitoring should be based on using ADCP, which can also be used to measure bedload transport (see next recommendation).
- Suspended sediment monitoring should be completed using a uniform methodology at each site, based on either the depth integrating D96 with an appropriate power source, or a point-integrating sampler that is not dependent on the rate of deployment.
- **Include bedload monitoring using ADCP technology.** The grain-sizes most impacted by hydropower development are sand and larger sized material. Sand is transported in suspension at high flows, and as bedload during high to moderate. Gravel sized material is transported as bedload during high flow. Under the DSMP bedload is determined at a limited number of sites in the LMB using a physical sampler (BL-52). Sampling with this equipment is difficult in small rivers, and almost impossible under the high flow conditions present in the LMB when most sediment transport occurs. There is a reliable and easily executed method to measure bedload movement using ADCP based on a 'loop-test', which quantifies the rate of bed movement relative to a fixed position. This methodology has been successfully implemented at Nong Khai in the LMB and it is strongly recommended that it be adopted at all sites where ADCP is available.
- **Include major tributaries in monitoring regime.** The Mitigation Guideline Case Study and the Council Study results have highlighted the importance of hydropower developments in tributaries on sediment transport in the LMB. It is recommended that major tributaries be included in the sediment and flow monitoring regime to quantify changes to sediment inputs related to tributary regulation. Monitoring should include sediment grain-size as well as sediment quantities.
- **Invest in in situ grain-size analyser.** Hydropower impoundments preferentially capture sand and larger sized sediment. Sediment grain-size distribution is determined at a limited number of locations in the DSMP using material filtered from large volume samples. The grain-size analyses are time-consuming, and are prone to error due to the grain-size transformations that can occur during filtration and resuspension of the material. Technology exists that can measure grain-size in situ and provide a profile of grain-size distribution over the water column. It is recommended that adoption of this technology be investigated.
- **Management and integration of sediment and flow data.** Sediment monitoring results are only useful if they have undergone a quality control process and can be easily accessed and integrated with flow data. At present the results are not stored in a central data base, and there is no easy way of accessing the sediment and flow measurements. The Aquarius software package was purchased several years ago by the MRC, but its use has been limited. It is recommended that this package be adopted for managing the flow data and for storing the sediment results. Ideally water quality results should also be accessible via Aquarius.

Large scale geomorphic investigations and monitoring in the LMB

The LMB mainstream has a wide range of geomorphic characteristics over its ~2,400 km length between the Chinese border and the South Sea. Identification and characterisation of different river zones has been completed, but little work has been done to quantify the present (or past) rates of fluvial geomorphic change in the river. Estimations of bank erosion or accretion rates or a quantitative understanding of the distribution of erosion / deposition patterns are lacking, and are critical to predicting how quickly changes are likely to occur in response to changes associated with hydropower developments.

Understanding how the river is presently adjusting to the reduction in sediment loads, and having suitable information to predict how the river may change in the future would assist in the evaluation and management of hydropower projects in the LMB. The following activities would fill identified gaps in the geomorphic understanding of the Mekong.

- **Develop a sand budget for the LMB.** Hydropower projects preferentially trap sand and coarser material in impoundments. This promotes increased erosion of sand from the main channel downstream of power station discharge points. Developing a sand budget that quantifies how much sand is being trapped, available for transport in different river reaches (including tributaries), and being transported. This information will provide an indication of how quickly 'erosional waves' are likely to progress downstream of dams and hence the time-scale associated with downstream impacts from hydropower developments. The information is useful for catchment management, and will assist with the calibration of sediment models. Volumes of material extracted by sand and gravel mining need to be included in the budget.
- **Repeat river surveying.** River channels change in response to changes in sediment availability. Repeat surveying of river cross-sections and long-sections can be used to identify and quantify channel changes, and assist with quantifying sand removal from the channel (related to previous recommendation). Hydrographic monitoring sections are surveyed on an annual or twice annual basis, and can be used to identify some changes, however hydrographic stations are typically sited in stable river reaches, often with strong bedrock control. Alluvial river reaches that are more susceptible to change should be identified and surveyed on a regular basis. Alternatively, remote sensing techniques such as Lider could be used over sections of the river at repeat intervals to provide a detailed indication of river bank changes, but this approach would be limited to exposed banks, and wouldn't capture in channel changes.
- **Analysis of historic aerial photos.** There is a large catalogue of historic aerial photos which is held by the MRC which could be used to examine changes to fluvial geomorphology over the past ~50+ years. Specific reaches were sediment extraction has occurred for prolonged periods should be included in the analysis to discern whether these reaches are under going higher rates of change. Where possible, additional investigations documenting deposition on flood plains or within the Tonle Sap system should be conducted.

Coordination and communication of sediment management in the Mekong

Hydropower projects in the UMB and LMB will periodically flush or sluice sediments as mitigation measures. Potential impacts associated with these activities include a decrease in water level in the impoundment, and an increase in water level, flow and sediment load downstream of the dam. These changes have the potential to impact the ecosystem and communities near the river, and could be substantial if multiple projects flushed sediments simultaneously. It is recommended that protocols be developed for hydropower operators related to the notification and coordination of flushing or sluicing events.

Updating and maintenance of the MRC Hydropower database. Sediment transport and associated geomorphic impacts associated with hydropower development are frequently related to the physical attributes of the hydropower project (dam height, location on river, upstream catchment area, volume, depth and surface area of impoundment etc.) and the operating pattern (daily, weekly, and seasonal fluctuations in discharge). Having an accurate database of hydropower attributes would be a useful tool for catchment planning and development of mitigation strategies. Hydropower projects change and evolve, so the database needs to have a high level of maintenance to ensure the most up to date information is consistently available.

8.1.2 Water quality information gaps and research needs

Water quality information relevant to hydropower development and management include parameters that have a direct effect on hydropower infrastructure or efficiency (e.g. suspended solids, nutrient concentrations linked to noxious algal growth in reservoirs, metals, acidity), and those that have the potential to be altered in the river system due to the implementation and operation of hydropower developments (e.g. suspended solids, temperature, dissolved oxygen, bacterial levels, nutrients, oils, chemicals). Water quality changes can also have flow on effects for the ecology in a reservoir, or in the downstream environment. For these reasons, it is important that influent water quality to a reservoir, potential water quality changes during storage, and the water quality of power station releases to the downstream environment all be considered and monitored during the planning, implementation and management of hydropower projects. The water quality information needs identified by the ISH 11 Project for water quality are summarised in Table 8.2.

Table 8.2. Information needs for hydropower planning and management (Source: MRC, 2014).

MRC-Centralized Parameter Groups	Hydropower Relevance	Example Basin-Scale Indicators
Suspended sediment characteristics: size and composition of material	▸ Water quality can affect hydropower infrastructure ▸ Need to understand influent water quality to predict and manage potential changes during storage, and to assess whether inflowing water is changing over time ▸ Need to understand changes to water quality during storage so can differentiate between hydropower development impacts and other impacts (such as aquaculture or land run-off) ▸ Need to understand any downstream impact on water quality due to hydropower operations, and to distinguish between hydropower impacts and other land use impacts	✔ Water quality standards for human health, drinking water, water for aquatic ecosystems, water for domestic uses, water for agricultural and industrial uses ✔ Aquatic biota indicators linked to EHM and Aquatic Biological Indicators (e.g. impact of oxygen or nutrient changes)
Physico-chemical water quality characteristics: temperature, pH, electrical conductivity, acidity, clarity, alkalinity, dissolved oxygen in surface and sub-surface water		
Metals: total and dissolved iron, manganese, zinc, mercury, arsenic		
Nutrients & carbon: concentration, speciation, seasonal variability, changes during storage		

The project identified water quality risks relevant to hydropower operations, and evaluated these risks for the Northern Lao PDR and lower Mekong Rivers. Water quality issues alter over the life-cycle of a hydropower project and an adaptive management approach based on monitoring is the best mitigation approach in the LMB. The following actions are recommended to address the water quality information gaps identified during the project.

- **Nutrient content of sediments.** Nutrients have a high affinity for sediments, with nutrient transport generally correlating with sediment surface area. Nutrients will be trapped within reservoirs along with sediments, but understanding the distribution of nutrients by grain-size is required for accurate prediction and management of hydropower impacts. The lack of understanding between nutrient transport and grain-size is highlighted by the Council Study where fixed ratios of Nitrogen and Phosphorus were assumed to trapped with sediments due to a lack of LMB specific information. This assumption becomes less applicable as the grain-size of sediment being transported is reduced due to the trapping of sands and gravels.
- The MRC Water Quality Monitoring Network (WQMN) includes the measurement of total phosphorus and nitrogen species on samples collected from the surface of the river, but these samples do not accurately reflect the distribution of sediments, and hence nutrients, over the entire water column or across the river cross section. The collection of additional depth integrated water samples by the DSMP for nutrient analysis by grain-size class is recommended to address this information gap.
- **Determination of additional water quality parameters.** The WQMN includes the following nutrient parameters: total nitrogen, nitrate, nitrate ammonia and total phosphorus, nitrate. Expanding the parameter set to include dissolved reactive phosphorus and organic carbon is recommended to enhance the usefulness of the monitoring result. Dissolved phosphorus is the phosphorus species that is biologically available and is frequently the limiting factor for algal and other plant growth in freshwater systems. The availability of dissolved phosphorus is an important determinant for algal growth in impoundments, and understanding the concentration and trends of this parameter in the LMB is necessary for hydropower and overall catchment management.
- The inclusion of particulate organic carbon (e.g. fine or coarse particulate organic carbon, FPOM, CPOM) would provide a better understanding of the link between sediment movement and ecological processes. At present, there is a poor understanding of how organic carbon is moving through the Mekong, and how hydropower developments may alter these processes.
- The periodic inclusion of metals, pesticides, total petroleum hydrocarbons (TPH) and other industrially or agriculturally derived toxicants is recommended for evaluating potential water quality risks associated with these toxicants. These types of parameters are periodically determined by the WQMN (e.g. Water Quality Diagnostic Survey 2007 and 2011 or assessment of Water Quality in the LMB 2008), and aligning these investigations with sediment, hydrologic and ecological monitoring would provide an integrated data set useful hydropower developments and for the tracking of long-term basin wide trends.
- **Measurement of water clarity.** The project has identified an increased occurrence of algal blooms as a high risk associated with the implementation of the Northern Lao Cascade and the large impoundments in the tributaries and on the mainstream. The WQMN includes Total Suspended Solids, but does not directly measure water clarity, which is directly related to light penetration and algal growth. Because water clarity varies with the grain-size as well as the concentration of suspended matter in the water column, TSS does not provide sufficient information to track water clarity. The measurement of water clarity in situ is a rapid and simple exercise and it is recommended that it be included in the WQMN physical-chemical parameter list.

- The WQMN results are stored in a spreadsheet and distributed after undergoing a QA/QC process at the MRC. The usefulness of these results would increase if they were integrated with flow and sediment monitoring results. Ideally one database should be developed and maintained that contains water quality, sediment and flow information, such that relationships between water quality and flow rates or sediment concentrations could be quickly established, and water quality loads could be easily calculated. These recommendations are consistent with the findings of the ISH 11 Project.

8.1.3 Review of monitoring locations

Although not an information 'gap' the proposed distribution of hydropower developments on the Mekong mainstream and in the tributaries raises concerns about the locations of monitoring sites into the future. Some existing river monitoring locations will become impounded, and other sites may provide limited information due to hydropower developments both upstream and downstream of the site. A review of existing flow, sediment and water quality monitoring sites is warranted and relocating or establishing new sites should be considered in locations that would provide relevant and ongoing information about the status and trends in the river under future development scenarios. Establishing new sites prior to abandoning older sites is recommended so there is a period when information from both locations is collected, providing an opportunity to link old and new monitoring results.

8.2 Fisheries and Aquatic Ecology

This chapter aims at documenting the current knowledge as well as research needs on environmental baseline data, impact assessments and mitigation measures in the LMB. Thereby, the discussed topics focus on aspects which were discussed within the project and this case study.

8.2.1 Baseline – Biological background data

The Mekong represents a regional hotspot for biodiversity (Termvidchakorn & Hortle, 2013) supporting a rich flora (e.g. non-cultivated submerged or floating water plants, phytoplankton) and fauna (e.g. invertebrates, fish, amphibians, reptiles, birds, mammals). The number of species is continuously increasing as taxonomists reclassify existing species and identify new ones (NCCV, 2013).

The Mekong Fish Database (MFD; Visser et al. 2003) already provides data on >500 fish species, which can be complemented by information from fishbase (fishbase.org) and selected literature. However, these studies also raise open questions with regard to still unknown life cycle patterns (e.g. population structure, critical habitats). Due to the large number of species and lack of ecological studies, many species are hardly explored. It is therefore recommended to improve the status on biological background data throughout the Mekong basin.

The assignment of fish species to certain guilds is especially relevant for the assessment of impacts and related mitigation measures. The most detailed classification currently available is provided by MRC (2009), which divides species into ten guilds, based on rough life cycle patterns (i.e. migratory behaviour, spatial distribution in the catchment). While this existing classification scheme is of high value for the overall assessment of risks and impacts, a more detailed classification could further improve the assessment of individual impact types and locations. Ecological guilds are used to

express species' preferences and dependencies and therefore allow to draw conclusions on their sensibility. Guilds can be built with regard to several habitat parameters and resource uses such as

- Flow conditions (flowing, stagnant)
- Instream structures (woody debris etc.)
- Choreotopes (substrate composition)
- Temperature
- Oxygen
- Spawning habitats (e.g. stones, plants, sand, mussels etc.)
- Feeding preferences (e.g. Valbo-Jorgensen et al., 2009)
- Migratory behaviour (triggers, distance, etc.)
- Lifespan (short, long)

While some of these parameters are already known for selected species, this assessment should be extended to cover the most important species and also other aquatic organisms. With this in mind, biological monitoring related to the ongoing hydropower developments can provide important insights on species' preferences and guild classifications.

Although the current species distribution can roughly be estimated (e.g. on the basis of the Mekong fish database and other studies), there are still open questions with regard to

- **Population structures:** Usually species covering a greater area in the LMB whereby the interaction (e.g. genetic exchange) or isolation of individual populations is not well documented. Additional studies (e.g. including genetic analyses) could provide additional insights, which are also relevant to assess the anthropogenic induced isolation of sub-populations.
- **Critical habitats:** Some critical habitats are already known and discussed in the reports (e.g. deep pools, rapids, Ramsar sites etc.). However, in each species' life cycle there may be certain habitats which play a significant role for the completion of their life cycle (e.g. unfragmented access to spawning and feeding grounds). The knowledge of species-specific habitat requirements should therefore be further extended.
- **Fisheries yield:** The fisheries yield can be estimated directly (yield per area) or indirectly (consumption and market sales). As market data are not widely available, approaches on the basis of yield per unit area or household consumption are often used to estimate the system's yield (Campbell, 2009). Several studies estimated the total consumption of fish and other aquatic organisms in the LMB (e.g. Hortle, 2007). Hortle & Bamrungrach (2015) estimated the fisheries yield-per-unit area for different zones (major floodzone, rainfed zone and permanent waterbodies). The results were extended by Halls (2010), who refined details on the biomass per country and fish guild. However, with regard to impact assessment related to individual developments, more knowledge on the distribution of fish biomass is required, e.g. at different section of the Mekong mainstream and within tributaries. Therefore, it is recommended to perform quantitative fish samplings at selected points throughout the LMB (both at the Mekong mainstream and tributaries) to learn more about the distribution of fisheries biomass.

The refinement of biological background data is not only important from a mere scientific point of view, but also it improve the quality of impact assessments throughout the basin and the development of suitable mitigation measures with regard to hydropower-related impacts.

8.2.2 Impact assessment and mitigation

With regard to the ongoing hydropower development and other impacts on the catchment and local scale, it is important to assess species' sensibility to distinct habitat alterations.

8.2.2.1 Seasonal flow alterations

The ecological integrity of a river depends to a high degree on an intact hydrological cycle. The magnitude, duration, frequency, timing and rate of change of the flow are responsible for type-specific sediment compositions (e.g. prevention of clogging), water quality conditions (e.g. temperature, oxygen), availability of energy sources (e.g. nutrients), biotic interactions (e.g. spawning), and finally species diversity and abundance.

More detailed studies are required to improve the knowledge on impacts related to changes of the hydrologic cycle. In this context, the knowledge with regard to migration triggers is still incomplete, but it is assumed that for the majority of species it is associated with changes in river flow (NCCV, 2013). The most important triggers under discussion in tropical freshwater fish are water level, current, discharge, precipitation, lunar cycle, water colour, turbidity and the apparition of insects (Baran, 2006).

Beside this, the seasonal flow plays an important role in providing seasonal habitats. Especially in the Mekong, the inundation of floodplains and wetlands and the related provision of nutrients is essential for the productivity of the system as a whole. Natural variations (wet and dry years) and their impact on the productivity of the system were already analysed in previous studies. However, against the background of already induced hydrologic alterations, the investigation of environmental flow rules including requirements of adjacent floodplains is highly recommended. Blake et al. (s.a.) took an effort in discussing environmental flow in the Songkhram basin (which includes a functional floodplain system) under consideration of cross-sectoral and interdisciplinary linkages within the Mekong region. The application of such an environmental flow at a regional scale and under consideration of floodplains and the Tonle Sap system, would also require assessments on how to implement such environmental flow rules. This might require the development of detailed action plans which orchestrate the joint operation of multiple, cross-border dams.

8.2.2.2 Sub-daily flow alterations

The impact pathways are highly complex but the interaction of the season, frequency, magnitude, duration, photophase (day/night) are most likely to determine the effects on specific species and age classes (Young et al., 2011). There are still substantial knowledge gaps with regard to (1) pulse type and life stage, (2) water quality and fish behaviour (e.g. influence of oxygen and temperature on migration), (3) habitat complexity, (4) habitat changes (e.g. changed morphology caused by hydro peaking), (5) long term, cumulative effects and (6) mitigation (Young et al., 2011). Especially for the development of suitable mitigation measures, knowledge and clear understanding of mechanisms and relationships causing the impacts are necessary.

Schmutz et al. (2014) used an extensive field dataset to analyse the impact of different types of hydrological and morphological indicators in combination with fish community data. Their results demonstrated that fish react to a combination of peak frequency, ramping rate and habitat

conditions, with an equal importance of habitat and flow criteria. Consequently, effective mitigation measures should consider the complexity of hydromorphological processes determining the functional (hydraulic) habitat conditions (Schmutz et al., 2014).

In particular, the effects of stranding (also with regard to other pulsed flow effects) are well documented (e.g. Bauersfeld, 1978; Hamilton & Buell, 1976; Olson & Metzgar, 1987) and depend on the local morphology, substrate type, down-ramping rate, critical flow (i.e. minimum operating discharge), frequency of fluctuations, prior flow conditions, duration of stranding and timing of pulse, fish size and fish species (e.g. Young et al., 2011; Bauersfeld, 1978; Hunter, 1992, Parasiewicz et al., 1998; Schmutz et al., 2014; Olson, 1990; Hoffarth, 2004). Also the ramping range (amplitude, magnitude) is an important indicator which is relevant for downstream displacement, reduced spawning or altered migration (Young et al., 2011).

It is assumed that an adaptation of the operation mode (ramping rates) of the hydropower plant, especially the deceleration of downramping after a peak period, can bring great ecological benefits. Furthermore, the reduction of the peaking amplitude (e.g. by increase of the base flow and/or decrease of the hydropower capacity) should be considered. Within this study, these issues could only be tackled marginally. However, this knowledge is critical for managers to predict and mitigate possible negative effects.

With regard to the Mekong, there are currently no in-depth analysis related to hydropeaking impacts (including stress, catastrophic drift and stranding) and it is therefore recommended to perform assessments at regional storage hydropower plants with the focus on:

- stranding of fish along the changing channel margins;
- downstream displacement and drift;
- red dewatering/ spawning interference;
- untimely or obstructed migration;
- indirect impacts by e.g. loss of food, high turbidity, stress and increased predation as well as increased bank erosion.

8.2.2.3 Water abstraction

Due to run-of-river scheme, water abstractions and diversions were not assessed in detail within this case study. This issue was somehow tackled while discussing the Don Sahong and Sambor dams (small version), which do not cover the whole mainstream but only one channel. Due to the lack of detailed habitat modelling within the side channels, absolute minimum flow values (Q95%) were assumed within this study for the mere purpose of calculating energy revenues. However, it was stated in several chapters that those values should be considered as absolute minimum flow and that the release of higher flows is highly recommended. When the Don Sahong starts its operation, the Hou Sahong will receive a higher flow proportion – especially during the dry season. It has to be assessed, whether the flow in the alternative channels (e.g. Hou Xang Pheuak) is sufficient to sustain fish migrations.

Detailed studies would be required to define suitable environmental flow rules for unexploited side arms – especially if they should also serve as a natural bypass for fish migration and sediment

transport. Besides the definition of a minimum flow thresholds a dynamic component, reflecting the natural hydrology of the river, has to be incorporated. The selected flow should be sufficient for;

- Fish passability (minimum depth and minimum flow velocity)
- Triggering and supporting spawning migrations (including migration peaks)
- Seasonality and natural reallocation of sediment (mobilization of fine sediments to prevent soil clogging)
- Preservation of seasonality and diversity of type-specific habitats (e.g. floodplain habitats)
- Suitable increase- and downramping velocities (for hydropeaking)
- Suitable conditions of oxygen and temperature

In any case, the defined environmental flow has to be evaluated with regard to its biological relevance and effectiveness for the specific river and its organisms. Therefore, the selected EF has to be monitored and, if necessary, adapted accordingly.

8.2.2.4 Continuity interruption

The ecosystem productivity of large tropical river-floodplain systems like the Mekong is highly dependent on the undisturbed connectivity between river and floodplain habitats (Bayley, 1995). Many species rely on distinct habitats to fulfil their life cycles (e.g. spawning and nursery habitats) (King et al., 2009; Louca et al., 2009; Tonkin et al., 2008) and perform migrations between them. Consequently, the disruption of river continuity is considered the main cause of impact to aquatic organisms, especially migratory fish. However, there are still many open questions with regard to continuity restoration. Besides the collection on additional data with regard to fish migrations (baseline data), detailed impact assessments have to investigate the actual impact of dams (e.g. turbine mortality, fish pass functionality, passive drift etc.) to be able to design or adapt mitigation measures.

Fish passage

While standards for fish pass design are already available for temperate rivers (e.g. USA, Europe), examples of functional fish passes in tropical rivers are sparse which makes it even more important to investigate the following points and to adapt existing guidelines accordingly:

- Detailed understanding of the hydro-morphological and hydraulic conditions at the site
- Basic knowledge on migratory species (baseline data)
- Assessment of suitability of different fish pass types or other additional solutions (e.g. adapted operation mode)
- Design of an adaptive approach including monitoring (i.e. planning of an adjustable fish pass which allows the consideration of monitoring results during construction and operation)

Fishtek Consulting (2015a,b) assessed the hourly fish biomass passage rate at Xayaburi over an entire year. Peak migration (i.e. with 1,200 kg/hr) occurred with the onset of the wet season (May). The highest observed value in this month was 5,000 kg/hr. In addition, the swimming capabilities of the local fish fauna were assessed and incorporated in the design of the fish pass. With Xayaburi

starting its operation in 2019, it will be important to test the functionality of the fish pass and to assess potential bottlenecks. Equally, monitoring has to take place at the Don Sahong dam and its surrounding channels. This knowledge is essential for the future design of fish passes in the region.

Although there are definitions in place (e.g. PDG), fish pass functionality can be interpreted in different ways and can differ greatly with regard to season (flow conditions), species of concern, size or age-class of fish and fish biomass. In the end, the relevant question is, however, whether a fish pass can provide safe passage in sufficient numbers to sustain healthy populations. To answer this question, long-term monitoring and is required.

Turbine/spillway passage

We already highlighted, that “fish-friendly” turbines might not exist but that some turbines are at least less harmful for fish compared to others. Fish kills related to downstream migration should be considered as a very severe impact as a high proportion of the population can be affected.

The injuries are related to the dam and turbine characteristics (e.g. pressure conditions), the migratory corridor of the fish (e.g. bottom- or surface-oriented), the type of swim bladder (e.g. connected or disconnected from gut, one- or two-chambered) and development stage for larvae (i.e. whether they have already filled their swim bladder or not). In this context, also spillways passages can be harmful for fish.

Halls & Kshatriya (2009) identified 58 highly migratory species threatened by Mekong mainstream dams which contribute 38.5 % to the total weight of all recorded species in the catch surveys. On the basis of passage success and mortality rates of 10 selected species, they modelled the cumulative barrier and passage effect for migratory species at the LMB with a detailed projection matrix. While small species (up to 40 cm in length) were assumed to show a mortality of 2-15 %, larger species might be confronted with mortalities of up to 80 % per dam Spillway mortality varies from 0.2 - 99% depending on the height and design of the spillways. Injuries and mortality are caused by abrasion against the surface, sudden pressure changes, rapid current changes (shearing effects) or supersaturation (Backman et al., 2002).

Despite the fact that mainstream dams may be equipped with “fish-friendly turbines” (as e.g. stated for Xayaburi), it is important to monitor the injuries and mortalities related to passage of such turbines. Considering the cumulative effect of several dams, especially large species will suffer from this pressure, which is why facilities preventing fish from harmful passage routes and introducing them to a safe bypass system are required. Testing should focus on those size classes which can pass the rakes and can therefore not be prevented from entering the turbines. Such analyses could be performed at Xayaburi. Tagging and monitoring of adult species could show whether and to which degree the provided fish pass is capable of re-directing fish from the turbines towards the alternative migration corridor and which mortalities occur with regard to turbine or spillway passage.

Passive drift in Impoundments

While adults migrate actively up- and downstream, ichthyoplankton develops while drifting passively downstream (Termvidchakorn & Hortle, 2013; Poulsen & Valbo- Jørgensen, 2000; Halls et al.,

2013; Agostinho & Gomes, 1997, Nakatani et al., 1997, Agostinho et al., 2000). Since reproduction often coincides with floods, the rising flows carry the eggs and larvae to downstream river sections and/ or lateral floodplains which are important nursery habitats. The possibility to return to or repopulate downstream reaches is important for long-term reproduction success (Poulsen et al., 2004; Agostinho et al., 2000).

The loss of free flowing river sections can also go hand-in hand with the loss if passive drift. The assessments of the upper Lao cascade showed that passive drift might only be supported for a few months during the wet season. Cowx et al. (2015) and Hortle et al. (2012) investigated the drift of larval and juvenile fish along the LMB. These studies also highlight the disruption of downstream dispersal of ichthyoplankton and juvenile life stages is widely unexplored. Assessments should not only investigate the seasonal and species-specific loss due to impoundments, but also injuries related to turbine and spillway passage. This is a major issue, since there are currently not suitable mitigation measures which could be applied to divert a sufficient proportion of these life stages into a bypass.

Preservation of downstream migrations (for all life stages) could by achieved by a shut-down mode of operation. Thereby, the spillway gates will be opened and the river will return to its natural condition, at least during certain (ecologically important) periods over the year. This strategy restores the connectivity of the river and has the additional benefit of reducing the risk of flooding upstream. The shut down mode of operation was already adopted for some projects in the region (e.g. Pak Mun dam, Xe Bang Fai 1 Hydroelectric Project). However, this option is easier to apply in tributaries, which are influenced by the hydrology of the Mekong (e.g. flow reversal) and might not be able to continue their production during the wet season. These schemes might therefore not be comparable to mainstream dams, where a shut-down for several months would be related to high production losses.

Considering a shut-down procedure from a mere ecological point of view could of course bring great benefits. In upstream direction, it could support the passage of the high biomass peak of migrating fish. If the fish pass is functional and can handle the biomass, an opening might not be required. In downstream direction, the opening could support both, drifting eggs/larvae and adults species. Although the existing literature provides the approximate month for upstream migration peaks, downstream migrations might occur less uniformly and spread over several weeks or months. Furthermore, not all species migrate at the same time, and the opening of gates during a certain period would only support some species but not all. Therefore, timing is essential and more detailed analysis on the most suitable operation-mode (duration, timing, key species) are required.

Loss/disconnection of floodplains

The ecosystem productivity of large tropical rivers like the Mekong also depends to a high degree on undisturbed connectivity between river and floodplain habitats. Besides floodplain degradations related to changes of the hydrologic cycles (seasonal flow alterations), the remaining floodplains may be disconnected from the Mekong mainstream and tributaries due to flood control and irrigation facilities. It is important to map those structures on a basin scale and to assess potential mitigation measures (e.g. inclusion of fish passage systems).

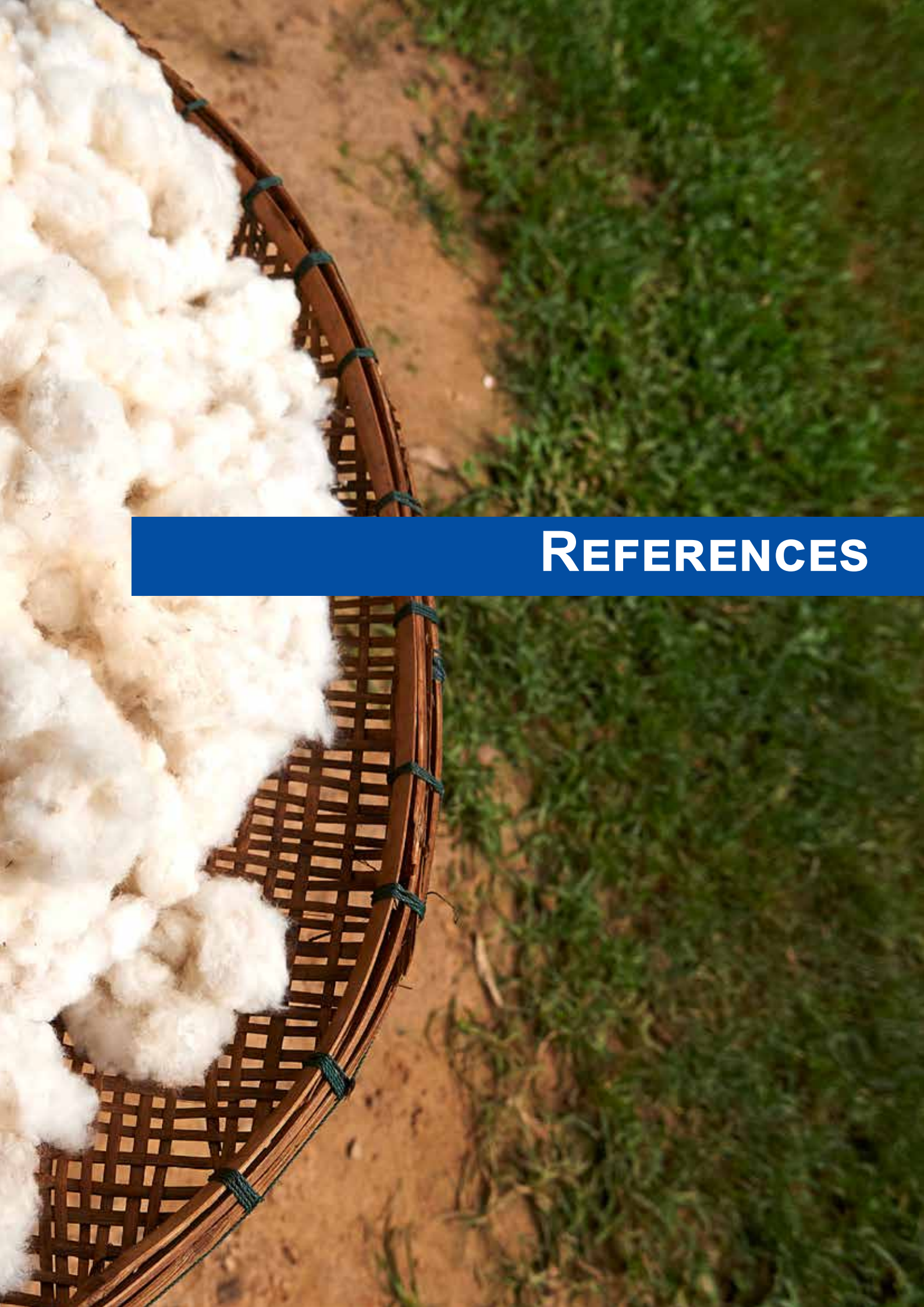
8.2.2.5 Flushing of impoundments

Sedimentation in impoundments and reservoirs can cause large-scale morphological alterations downstream. Mitigation measures aiming for a more natural hydromorphology (e.g. sediment transport) can also be considered as beneficial for aquatic organisms. Many Mekong fishes are substrate spawners and rely on a natural substrate composition for successful reproduction. Apart from that, sedimentation processes in impoundments and the related erosional wave downstream can cause a long-term alteration of habitats (incl. floodplains) and might be related to a reduction of fish diversity, abundance and biomass. Consequently, reservoir flushing is an important mitigation measure for sediment re-mobilisation and, thus, the restoration of natural sediment dynamics including the formation of type-specific habitats. Nevertheless, it is also associated with negative effects on physical-chemical conditions (e.g. turbidity, oxygen deficiency, hydropeaking) impacting fish directly (e.g. increased drift, gill and skin injuries, stress, fish kills) and indirectly (e.g. reduced food supply caused by increased drift and loss of benthic invertebrates, reduced growth, lost habitats due to sedimentation) (Kemp et al. 2011; Jones et al. 2012; Crosa et al. 2009; Henley et al. 2000).

To mitigate those negative effects, the definition of certain turbidity thresholds and their compliance during flushing is of high importance. The intensity of impacts depends mainly on the concentration and duration of exposure (see Figure 2.12), but also the size and texture of particles, water temperature, chemical and physical conditions (Stone & Droppo, 1994). In addition, other flushing-related water quality changes, as e.g. the release of organic matter and the consecutive oxygen depletion may lead to suffocation of fish and benthic invertebrates (Waters, 1995; Garric et al., 1990).

Flushing has to be carried out in a way that fish are not significantly affected in the long run in the downstream river sections. Suspended concentrations during flushing may increase significantly (depending on the rate of accumulation of sediments and the frequency of flushing) and may therefore cause additional stress for aquatic organisms. In general, the definition of certain turbidity thresholds is relevant to mitigate negative impacts. Such thresholds exists for temperate rivers (e.g. EIFAC, 1965), but are not applicable to the Mekong. TSS concentrations always have to be assessed with regard to natural conditions including seasonal variations. For the Mekong, high turbidity thresholds occur naturally (i.e. 1,400 mg/l at Chiang Saen in June) which is why Mekong-specific thresholds have to be established (ideally by the incorporation of species- and age-specific reactions to different turbidity levels). However, detailed monitoring of suspended concentrations and the related negative effects on fish and other aquatic organisms is recommended. The following open questions have to be answered to better understand and manage the effects of flushing operations:

- Identification of species or age classes sensitive to increased turbidity.
- Identification of migration triggers connected to turbidity.
- Definition of turbidity thresholds on the basis of natural events (flood season).
- Modelling and assessment of different reservoir-flushing operation rules with regard to their induced conditions (e.g. flow velocity, turbidity).
- Measurements of turbidity during flushing operations and investigations on the actual effect on the local fish fauna.
- Development of guidelines to reduce possible impacts.



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Annexes

Annex A – Hydraulic and Morphological Modelling Results and Description of Model

Annex B – Hydropower modelling results

Annex C – Description of the Hydropower Model

Annex D – Hydrology and Flow results

Annex D1 - Seasonal flow distribution

Annex D2 – Sub-daily flow distribution

Annex E – Fish biomass

Annex F – Detailed Indicator Scoring Matrixes

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