Annex 3:

Sediment Expert Group Report

Review of Sediment Transport, Morphology, and Nutrient Balance

Review of Sediment Transport, Morphology, and Nutrient Balance

Report to:

Mekong River Commission Secretariat

by:

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Sediment Expert Group

Review of Sediment Transport, Morphology, and Nutrient Balance

1.0 INTRODUCTION AND SCOPE

The context for this review is provided by two relevant documents. The first is "*Preliminary Design Guidance for Proposed Mainstream Dams in the Lower Mekong Basin"* (MRC-PDG) published by the Mekong River Commission (MRC) in 2009. The second is "*Optimization Study of Mekong Mainstream Hydropower*" published in 2009 by the Lao Department of Electricity. This MRC-PDG document highlights that impacts and risks associated with mainstream dams are particularly relevant with respect to:

- Effects on sediment and river morphology, with associated risks to the economic life of the mainstream impoundment of water and safe operation; and effects on long-term river bed stability, river bank erosion, and channel changes in the downstream reaches.
- Potential water-quality changes, especially with regard to water pollution and effects on aquatic ecosystem functions and services, as well as wetland systems, both in the mainstream channel above the dams and localized effects downstream.
- Potential for longer-term sediment and nutrient flow changes in the downstream Mekong system (including the Tonle Sap and the Mekong Delta) in relation to the cumulative effects of dams in a cascade.

The potential impacts of mainstream hydropower dams on sediment transport and morphology were also recognized by the Lao Department of Electricity. In their report, they point out that in reservoirs:

- Sedimentation of coarse sediments at the mouth of the reservoir can worsen local inundations and disturb navigation.
- Sedimentation in the reservoir in front of the sediment sluices can prevent correct functioning of gates.
- Sedimentation in the whole reservoir decreases its dead capacity and reduces its time life, affecting long-term hydropower profitability.
- Sedimentation can lead to high dredging maintenance costs.

Their report goes on to note that downstream of the dam, excessive trapping of sediment in the reservoir leads to disequilibrium between the water and sediment discharges (this is often termed the 'hungry water' phenomenon) and bed incision in alluvial reaches, with the following consequences:

- Decrease in mainstream and tributary water levels.
- Decrease of lateral water table levels, with possible consequences on agriculture and domestic water uses.
- Bank erosion due to shortage of coarse materials.
- New reef appearance and draught shortage for navigation.
- Increase of the velocity in the downstream part of tributaries creating bed erosion due to lower Mekong river level.

Given the potentially detrimental impacts of hydropower dams on sediment and morphology, it is encouraging that the Developer recognizes that there are issues concerning sediment, morphology, and nutrients with respect to the proposed Xayaburi Dam. As early as page 1-4 in the Executive Summary of the Feasibility Report (2010), the Developer notes the need for:

> *“….protecting the turbines, avoiding deposits upstream of the barrage, as well as not reducing sediment inflow downstream, which may cause subsequent bank erosions and less protein for fish consumption and less nutrient in water for agriculture.”*

and on page 1-6 the Developer states explicitly that in producing the preliminary design:

> *“MRC preliminary design guidance was adopted”*

It is clear from this brief review that the MRC, the Lao Department of Electricity, and the Developer all concur regarding the need to fully account for sediments, morphology, and the nutrient balance in the design and operation of the proposed Xayaburi Dam, and that the Developer agrees that, in this context, the MRC-PDG presents acceptable design guidance.

Having established that consensus exists on these fundamental points, the objectives of this review are to:

- consider potential impacts identified by the Developer and the measures proposed to avoid, manage, and mitigate those impacts;
- identify gaps and uncertainties; and
- make recommendations with respect to:
  - closing significant gaps,
  - making modifications to the design and operation of the dam to avoid or mitigate sediment, morphology, and nutrient impacts, and
  - implement long-term monitoring and adaptive sediment management so that hydropower can be generated sustainably and, ideally, in perpetuity.

The scope of this review is prescribed by the requirement for the MRC Prior Consultation Review to consider the potential for transboundary impacts and long-term, cumulative effects associated with construction and operation of Xayaburi Dam as one of a cascade of hydropower dams on the Mekong mainstream and its tributaries.

Transboundary impacts stem from integration of the local and reach-scale effects through time and space and centre on the physical, environmental, and agricultural consequences of reducing the supply of sediment and sediment-associated nutrients to:

- the river downstream,
- its floodplains,
- linked, seasonally flooded lakes and wetlands (especially the Tonle Sap),
- the delta, and
- the coastal zone (including the offshore sediment plume).

Prediction of possible long-term, cumulative effects associated with Xayaburi in the context of other existing and planned dams, some of which are not yet even at preliminary design stage, is approached through scenario analysis. The six scenarios considered are:

1. Scenario 1: Baseline – 2000: Three existing Chinese mainstream dams (Manwan, Dachaoshan, and Jinghong), plus fifteen Tributary Dams.
2. Scenario 2: Definite Future – 2015: Eight[1] existing and planned mainstream Chinese dams, plus twenty-six Tributary Dams.

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[1] It is recognized that Mengsong Dam has been indefinitely postponed, but it is nevertheless included in this analysis for completeness.

3. Scenario 4: Definite Future – 2015: Eight existing and planned mainstream Chinese dams, plus twenty-six Tributary Dams, plus six mainstream dams in Lao PDR.
4. Scenario 3: Foreseeable Future Scenario (i): Eight existing and planned mainstream Chinese dams, plus seventy-one Tributary Dams.
5. Scenario 4: Foreseeable Future Scenario (ii): Eight existing and planned mainstream Chinese dams, six mainstream dams in Lao PDR, plus seventy-one Tributary Dams.
6. Scenario 5: Foreseeable Future Scenario (iii): Eight existing and planned mainstream Chinese dams, six mainstream dams in Lao PDR, five Cambodia dams, plus seventy-one Tributary Dams.

2.0 SUMMARY OF IMPACTS CONSIDERED AND MEASURES PROPOSED BY THE DEVELOPER

2.1 Impacts and Measures

In the Feasibility Report, the Developer makes multiple references to sediment impacts and measures included in the preliminary design to manage or mitigate them. Annex A presents tabulated Impacts and Measures considered by the Developer, together with a response (agree/disagree) and comments by the Sediment Expert Group (SEG). Table A.1 provides the basis for the remainder of this section, which deals, in turn, with impacts and measures relating to Sediments, Morphology, and Nutrients.

2.2 Sediment Impacts and Measures

In the Executive Summary of the Feasibility Report, the Developer clearly recognizes that it is necessary to take special measures to pass sediment downstream. On page 1-4 it is stated that, in designing the dam, the Developer will,

> *"Maintain sediment passage by installing sluices for sediment flushing, protecting the turbines, avoiding deposits upstream of the barrage, as well as not reducing sediment inflow downstream, which may cause subsequent bank erosions and less protein for fish consumption and less nutrient in water for agriculture."*

In Section 1.6 of the Executive Summary, the Developer introduces the MRC-PDG document by reference to five aspects of the river, including Sediment Transport and River Morphology. Specifically, on page 1-8 it is noted that,

> *"preliminary design in the feasibility study is designed to maintain sediment passage by installing sluices for sediment flushing, avoiding deposits upstream of the barrage, as well as not reducing sediment inflow downstream."*

However, it is noted that further investigations will be required before the design will conform to the MRC-PDG. Specifically, the next paragraph on page 1-8 states that,

> *"For the next study, Outline design, the hydraulic lab will be carried out and the result from the model will be used to design a sand flushing in conformity with the MRC's Design Guidance."*

Given these statements of intent in the Executive Summary, there are rather few further statements concerning sediment (including gravel, sand, silt, and clay) in the body of the Feasibility Study. All relevant statements are listed, responded to, and commented on in Table A.1 in Annex A. There are also very few references to sediment in the Environmental Impact Assessment (EIA), although on page 5.3, the Developer indicates that sediment trapping will be avoided as,

> *"Sediment sluice gates will be constructed for sediment drainage."*

The Developer expects these gates can be operated so that no sediment entering the reservoir from upstream will be trapped in the backwater reach upstream of the reservoir, the reservoir itself or close to the dam. With regard to local sources of sediment, the Developer notes on page 5-9 of the EIA that soil erosion during construction could be as high as 380.7 tonnes/hectare/year (t/ha/yr), with an average rate of 196.3 t/ha/yr. A rate of 15 t/ha/yr is considered 'severe' according to the Table on page 5-8 of the EIA. Once construction is complete, the Developer predicts on page 5-9 of the EIA that,

> *"During the operation period, the impact on erosion can be defined as no impact."*

In summary, in terms of sediment impacts, the Developer believes that (i) there will be no sediment trapping in the reservoir because Xayaburi will be designed and operated as a 'run-of-river' hydropower dam, (ii) sediment deposited close to the dam will be sluiced, and (iii) increased erosion will cease once construction is complete. In managing and mitigating the temporary increase in sediment input to the Mekong River due to local erosion during construction, the Developer suggests relying on the very high dilution factor due to the great size of the river together, with adoption of international Best Practice erosion control practices as necessary to control erosion.

Since no sedimentation is expected within or upstream of the reservoir during the operating period, sediment management measures suggested by the Developer are limited to sand flushing conduits designed to re-suspend sand deposited immediately upstream of the power house and no measurements of suspended sediment loads are included in the proposed long-term monitoring programme.

2.3 Morphological Impacts and Measures

As the Developer only expects elevated sediment production during construction, and given that it is concluded that the reservoir will not trap sediment during its operating period, the Developer only expects limited sediment-related, morphological impacts upstream or downstream of the dam. Further, on page 11-12 of the Feasibility Report, because the proposed design is for a run-of-river dam, the Developer concludes that downstream fluctuations in stage will be avoided – so that downstream bank erosion will not be generated through stage fluctuations resulting from hydropower operations. Notwithstanding this, it is stated on page 6-7 of the EIA that morphological impacts will be mitigated by plans to,

> *"construct the river bank protection downstream from the barrage"*

This suggests that downstream morphological impacts on the Mekong River sufficient to necessitate mitigation are actually expected by the Developer.

2.4 Nutrient Balance Impacts and Measures

On page 5-12 of the EIA, the Developer foresees that impacts on water quality will be inevitable, noting that,

> *"During construction period water quality in the river will have affected by the turbidity and siltation from earth work in the project area. High turbidity loaded in downstream of Mekong River is expected."*

In the EIA, the Developer notes that, with respect to the nutrient balance, impacts will relate to:

- Sediments released during construction (Mitigation: establish sediment traps and utilise the high degree of dilution in the river).
- Increase in pH due to concrete construction (No mitigation – rely on dilution effect).

- Increase in pollution with biological oxygen demand and nutrients and solid waste from staff (Mitigation: install septic system and sewage treatment as well as solid waste disposal).
- Increased oil contamination (Mitigation: construct oil/grease trap for waste water from all construction activities).

In summary, a range of Best Practice measures to manage and mitigate impacts on nutrients during construction are proposed. During the operation period, the Developer states in the EIA that no significant impacts on water quality (including nutrients) are expected because the dam is run-of-river and inflow equals outflow on a daily basis. Consequently, no measures to avoid or mitigate nutrient impacts are proposed by the Developer.

3.0 MRC-SEG TECHNICAL REVIEW

3.1 Sediment

3.1.1 Documents Consulted

In addition to the Feasibility Study and EIA, other relevant documents provided by the Developer that were reviewed include:

- Xayaburi Hydroelectric Power Project, EPC Contract Document, Exhibit II: Scope of Work and Particular Requirements, Appendix 1, Design Report, September 2010. (Referred to as the “Design Report.”)
- Xayaburi Hydroelectric Power Project, Lao PDR, Physical Hydraulic Model Studies, Interim Report on River Diversion (Stages 1 and 2), December 3, 2009.

In addition, the SEG consulted academic papers on sediment, morphology, and hydropower in general, as well as reports and publications relevant to sediment dynamics and morphology in the Mekong River, specifically.

3.1.2 Sediment Impacts and Measures Described in the MRC-PDG

Sediment impact and management provisions in the design documents were evaluated with respect to the MRC-PDG. Provisions regarding sediment and its management are outlined in Section 4 of the MRC-PDG, which provides background on strategies for sustaining reservoir capacity, mitigating downstream sediment starvation, and managing sediment in cascades of dams. The principal concerns are dealt with in paragraphs 90 and 91 of the MRC-PDG. As they relate to potential local and transboundary impacts of Xayaburi Dam, these include:

- Sediment deposition in backwater reach upstream of the reservoir, which could result in:
    - morphological changes including shoal formation and bed aggradation, leading to increased flood probability at Luang Prabang. The assessment of potential flooding effects presented in Section B.3 of the Design Report does not account for this possibility.
- In-reservoir sedimentation, which could lead to:
    - reduced depths and water quality in deep pools,
    - reduced reservoir volume, leading to decreased storage capacity,
    - possible increase in the probability of landslides, and
    - dam overtopping during extreme flood conditions (if the capacity of the reservoir to attenuate flood waves was to be compromised).

- Localized sedimentation close to the dam, which could:
    - adversely affect the power house intakes and operation of the low-level sluices, and
    - accelerate turbine abrasion damage, particularly if the quartz content of the sediment is high.
- Reduction in sediment discharged downstream, which (as described in paragraphs 95 to 97 of the MRC-PDG) could:
    - adversely affect the fluvial geomorphology of the river due to "sediment hungry" water released downstream of the dam,
    - trigger adverse morphological responses including: loss of existing sediment features in non-alluvial reaches; channel instability (bed degradation, bank retreat, and planform changes) in alluvial reaches; reduced sediment supply to floodplains and wetlands including the Tonle Sap; and land loss in the Mekong Delta and along the adjacent coastline, and
    - reduce the extent and sediment concentration of the plume offshore of the Delta.

Pages 18 to 21 of the MRC-PDG describe sediment management measures that may be employed to avoid or mitigate these potential impacts. These include:

Upstream of the reservoir:

- *Sediment traps* (paragraph 110) – structures constructed in the river upstream of the reservoir to capture part of the sediment load.

In-reservoir:

- *Sediment routing* (paragraphs 99 through 101) – operating the dam to transport as much of the sediment load as possible through the reservoir for discharge downstream by maintaining high sediment transport capacity during the period of the year when the sediment concentration and discharge are highest. This means avoiding trapping sediment by releasing sediment-laden water and impounding sediment free water.
- *Sediment bypass channel* (paragraph 102) – used to convey sediment around the reservoir and discharge it downstream.
- *Sediment flushing* (paragraphs 103 through 108) – re-suspending previously deposited sediment in the reservoir and discharging it downstream of the dam. This is only feasible if river-like flow conditions can be re-created in the reservoir by drawing down the water surface elevation using low-level outlets that have the ability to pass free surface flows at very low elevations at the dam.

Localized sediment deposition:

- *Pressure flushing* – flushing deposited sediment through low-level conduits to keep intake structures clear and minimise the amount of sediment that passes through the turbines. This technique is usually implemented by maintaining a high water surface elevation at the dam (i.e., no need for reservoir draw down), while concurrently opening the low-level outlets.

Downstream of the dam:

- *Sediment augmentation* (paragraphs 112 through 115) – introducing sediment into the river downstream of the dam to replace the sediment trapped in the upstream reservoir and by so doing reduce the extent and intensity of adverse impacts caused by 'sediment hungry' water.

3.1.3 Evaluation of Candidate Sediment Management Measures

The SEG reviewed the candidate sediment management techniques proposed in the MRC-PDG and concluded that the only techniques feasible for implementation at Xayaburi Dam are sediment routing, sediment flushing, and pressure flushing. Sediment routing and flushing could be used in tandem to reduce local and transboundary effects. Pressure flushing is only able to reduce the local effects of sediment accumulation immediately in front of the power house intakes. The basis for these statements is explained in the following sub-sections.

Localized Deposition:

The Developer expects that sediment will accumulate in front of the power intakes and suggests using low-level conduits to sluice sediment through the dam. The SEG agrees that this should be possible through pressure flushing, which is performed by maintaining a high water surface elevation, while releasing water through the low-level outlets (Figure 3.1). However, the SEG point out that experience from many other dams demonstrates that pressure flushing will only remove localized sediment deposits immediately upstream of the power house.

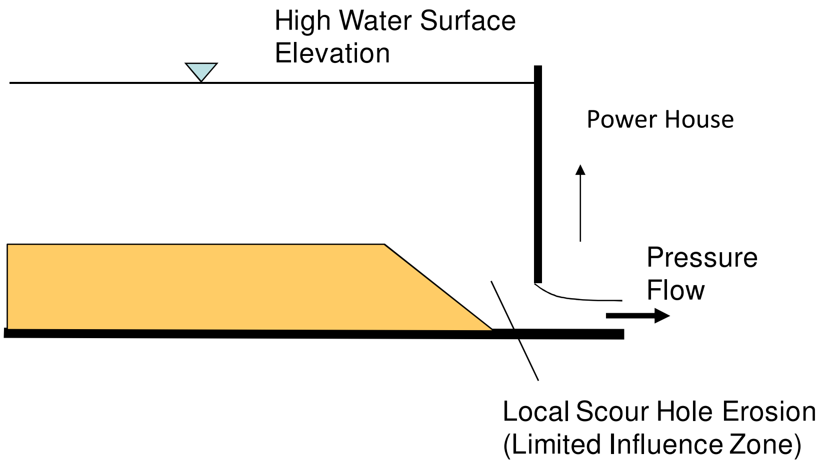

Figure 3.1. Pressure flushing to remove localized sediment deposits.

In-reservoir Sedimentation:

The SEG conclude that ***Sediment Routing*** is feasible at Xayaburi and that, if the spillway gates as currently designed were opened completely during high-flow events with high sediment concentrations, it might be possible to generate sufficient transport capacity throughout the reservoir to pass a substantial proportion of the incoming sediment (especially the finer fraction) without its ever settling in the reservoir (Figure 3.2).

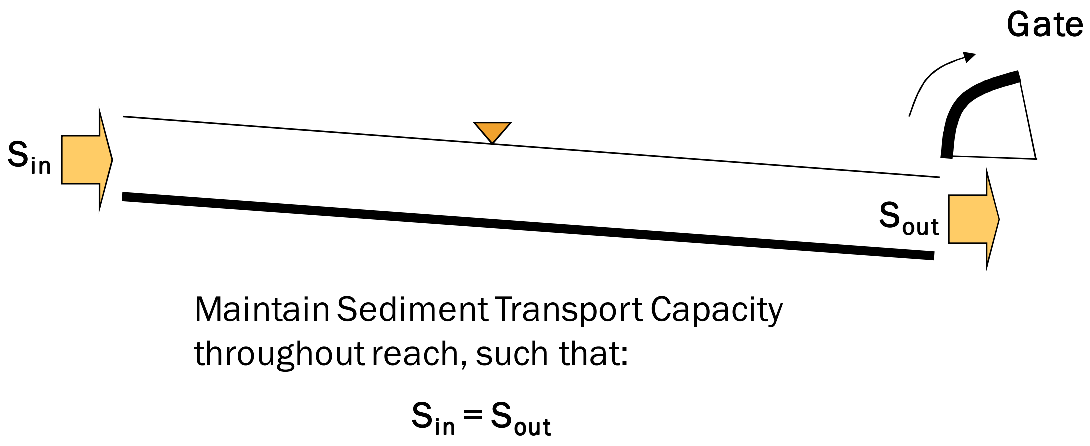

Figure 3.2. Schematic illustrating the concept of routing.

If no attempt is made to manage sedimentation in the reservoir, it is likely to eventually fill with sediment. The time taken for this to occur is impossible to predict as it depends on future sediment inputs to the reservoir that will be affected by multiple influences including trapping in reservoirs upstream, climate change, land-use change. However, consideration of the results of preliminary calculations and 1-dimensional (1-D) modelling by the SEG suggests that, in the long term, optimum sediment routing could generate a new equilibrium condition in the reservoir, limiting sedimentation to about 60% of the original volume.

If the timing of annual sediment routing operations could be matched to key periods for fish migration, the required design modifications could possibly help minimise the impacts of the dam on fish as well as sediments. Also, if this measure were implemented during a period of high discharge, it might be possible to continue hydropower generation during sediment routing operations, provided the sediment concentration of the flowing water is not too high and sufficient discharge were available for concurrently passing water through the turbines.

Sediment flushing requires operators to draw the water level at the dam down and increase the water surface slope through the reservoir, creating river-like flow conditions that re-suspend previously deposited sediment from the bed and banks and carry it downstream of the dam through the low-level outlets (Figure 3.3). The SEG conclude that flushing of sediment from the reservoir would not be feasible at Xayaburi with the current dam design because the sluices planned for the power house are too small and the spillway is too high to accomplish draw down flushing. This conclusion is based on expert evaluation of the current design coupled with the results of model simulations (as reported in Annex C). Hence, building a dam with the capability to implementation of flushing operations would require design modifications. Specifically, it would be necessary to install large, low-level outlets capable of conveying flushing flows through the dam without impediment, so recreating flow conditions in the reservoir that mimic natural, pre-dam conditions.

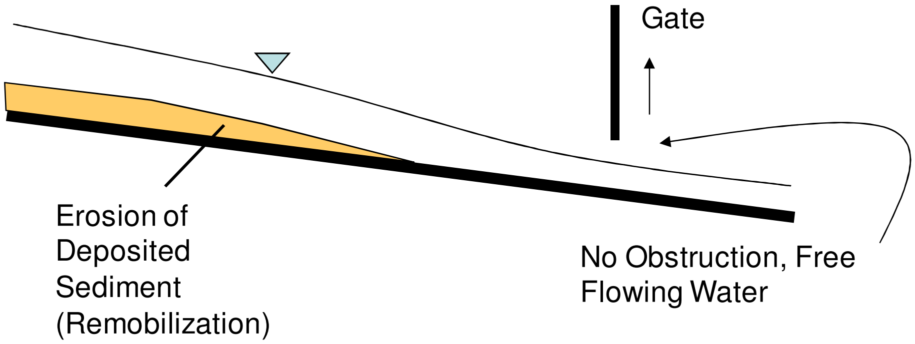

Figure 3.3. Reservoir flushing operations require the presence of large capacity low-level outlets that can draw the river down to create free-flowing conditions at the dam. This flow condtion re-supends sediment deposited during hydropower operation and discharges it downstream through the dam.

Preliminary estimates made by the SEG suggest that modifiying the design of the dam and successfully implementing flushing could limit long-term sedimentation in the reservoir to about 30% of the original reservoir volume. Implementing flushing and routing operations could increase the time to equilibrium from hundreds to thousands of years, depending on how future sediment inputs respond to trapping in upstream reservoirs, climate, and land-use changes.

Sediment concentrations would be unnaturally high during flushing and so it would be essential to comply with the advice provided by fisheries and environmental experts to avoid adverse impacts on fish and wildlife. It would not be possible to generate hydropower during flushing operations.

In summary, if sediment inputs to the reservoir remain at historical levels and no attempt is made to manage reservoir sedimentation at Xayaburi, the reservoir may completely fill with sediment within decades. Conversely, sediment trapping upstream and implementation of sediment management through flushing and routing could lead in the long term to the reservoir reaching an equilibrium state that conserves as much as 70% of its original volume.

The time scale for filling to occur will be lengthened by sediment trapping in existing and planned reservoirs upstream (especially in China). Uncertainties regarding the trap efficiencies of upstream dams, as well as the unpredictable nature of morphological responses to reductions in sediment load and the unknownable impacts of future climate and land-use changes on future incoming sediment loads, preclude accurate prediction of the useful life of the reservoir with the current dam design.

Based on its review of the impacts considered and measures proposed by the Developer, the SEG conclude that the Developer does not believe that sediment will be trapped in the reservoir except immediately upstream of the power house and that locally accelerated erosion will cease once construction is complete. Hence, long-term management proposed by the Developer focuses entirely on removing sediment in front of the power house intakes. However, references to the need for bank protection indicate that the Developer is concerned about possible morphological and environmental impacts in the river downstream of the dam. As the project will be a run-of-river scheme, the Developer believes that there will be no significant impact on water quality.

Conversely, the outcomes of the SEG Technical Review indicate that, if the dam design were modified to optimise routing and flushing operations, and these were conducted on a reugular basis, its trap efficiency could be significantly reduced. This means not only that all the sediment impacts alluded to earlier would be minimised, but also that the capability of the dam to generate hydropower in a sustainable manner could be maintained, ideally, in perpetuity.

These conclusions are supported by experience with dams on other large rivers. For example, Samanxia Dam on the Yellow River, China suffered severe reservoir sedimentation soon after construction, losing a significant proportion of its storage within a few years of closure (Morris and Fan 1997). The initial layout of the dam and the length of its reservoir were similar to Xayaburi. Installation and operation of additional sediment management features (including a significant number of low-level gates in the dam), together with a policy of 'releasing the dirty water and retaining the clean water' by opening diversion tunnels and low-level gates during selected periods every year have allowed operators to regain significant amounts of reservoir volume and maintain storage capacity since the 1970s.

It follows from this review of possible sediment management measures that the current design does not comply with the MRC-PDG or international Best Practice in relation to reservoir sediment management. This because, although the dam has the capability to pressure flush sediment from close to the power house, it does not have the optimum capability for reducing sediment trapping in the reservoir through sediment routing and flushing.

3.2 Morphology

3.2.1 Sediment and Morphological evolution

Rivers convey sediment as well as water but, while the water passes quickly to the sea, sediment may stay in the catchment for periods ranging from a few months to thousands of years. This is the case because sediment may be stored for long periods between transport events. Most sediment is derived in the Headwaters and Upper Course of the river where weathering breaks down exposed rock and landslides and steep tributaries deliver the rock fragments to the main stream (Schumm, 1977). For example, most of the sediment carried by the Mekong River is believed to be derived from the Upper Mekong Basin and the Vietnamese Uplands.

Sediment is next transferred through the Middle Course, with easily transported, fine sediment moving relatively quickly in suspension (suspended load) while less mobile, coarse sediment travels more slowly along or near the bed (bedload). As a result, bed sediment size tends to decrease with distance from the sediment source zone. Although the Middle Course is primarily a sediment transfer zone, moving sediment is exchanged with that stored in floodplain deposits, especially during floods.

The Lower Course is naturally dominated by sediment storage in channel bars, floodplains, wetlands, seasonally flooded lakes and, particularly, the river delta. Eventually, sediment derived from the basin is supplied to the coastal zone, where forms a sediment plume and interacts with marine processes to form features such as marshes, beaches and splits.

The dimensions, cross-sectional shape, slope and planform pattern of the river (together described as its morphology) adjust gradually through time to the flow of water and the supply, transport, exchange and storage of sediment. Over long periods of time, river morphology evolves naturally towards what is termed a *graded condition* of dynamic equilibrium in which the capacity of the river to transport bed material load (that is, sediment of a size similar to that making up the channel bed) is matched to the supply of such sediment from the channel and basin upstream (Knighton, 1998).

3.2.2 Morphological response to changes in coarse and fine sediment supply

Hydropower dams trap a percentage of the sediment in transit between its source and natural storage zone. This disturbs the balance between sediment supply and transport capacity, promoting sediment deposition upstream of the dam and sediment scour downstream. However, reservoirs are more effective in trapping coarse sediment (moving as bedload) than they are in trapping fine sediment (suspended load). The spatial distributions of morphological responses to trapping of coarse and fine sediment also differ markedly. Specifically, channel changes caused by imbalance in the coarse load occur locally, while the impacts of a significant reduction in fine load are felt much farther downstream and over a far wider area, including not just the channel but also floodplains, wetlands, seasonal lakes, the delta and the coastal zone. Response times also differ. Local morphological responses to trapping of coarse sediment begin almost immediately, but it may be decades before the extent of morphological changes caused by the trapping of fines becomes apparent.

Once triggered, imbalances in the dynamics of coarse and fine sediments drive a complex series of morphological adjustments to river and coastal landscapes. These adjustments continue until, eventually, a new balance between sediment supply and transport capacity is achieved. This process is complex, difficult to predict and may take decades, centuries or even millennia to complete.

3.2.3 Importance of morphology to water quality and ecosystem health

Experience from rivers worldwide demonstrates that the types of complex morphological adjustment triggered by the trapping of significant quantities of coarse and fine sediment upstream of hydropower and storage dams have adverse physical and environmental impacts that may be irreversible.

For example, in bedrock controlled reaches, sediment bar and bed features are lost, leading to changes in roughness, fluvial hydraulics and downstream flood risk. In alluvial reaches, the channel may be destabilised by bed and bank erosion leading to sequences of degradation, aggradation, bank erosion and planform metamorphosis that put people’s lives at risk, destroy floodplains property and infrastructure, degrade wetlands and disrupt interconnections with groundwater and seasonal lakes. In the delta, the balance between river and coastal processes may be disturbed, leading to serious erosion of valuable agricultural land and habitats, while at the coast reduction in the supply of river sediment leads to loss of coastal land, marshes, beaches and spits. In all cases, there are likely to be consequential impacts on local and national economies through loss of sediment resources, agricultural productivity as well as reductions in ecosystem services and biodiversity. Fortunately, experience also shows that such impacts may not be inevitable; they can to some extent be avoided or mitigated, provided the design and operation of the dam has the capability to pass and flush, rather than trap, sediment.

3.3 Nutrient Balance and Consequential Environmental Impacts

3.3.1 Overview

The effects of a hydropower dam and reservoir on the nutrient balance in the river system can have significant environmental impacts, depending on the design and operation of the dam.

Within the reservoir, impacts are primarily related to:

- trapping of nutrients attached to sediments,
- reduced turbidity (increased light penetration in the water column) due to sediment settling out of suspension,
- increased algae growth due to accumulation of nutrients, reduced turbidity, and increased water retention time, and
- changes in fluvial conditions and sediment features in the reservoir.

Thermal stratification of the water in a reservoir can amplify all of these impacts.

Downstream of the dam, nutrient-related environmental impacts result mainly from:

- release of nutrient-deficient water due to sediment trapping during normal operations,
- changes to the nutrient balance (e.g., reduced nutrient input to downstream ecosystem), and

- release of water with unnaturally high concentrations of sediment and associated nutrients during flushing operations.

3.3.2 Nutrients

A significant proportion of the nutrients phosphorus (P) and nitrogen (N) in a river are associated with the sediments. Consequently, when sediment is trapped in a reservoir, nutrients are also retained and this leads to nutrients accumulating in the reservoir through time.

In general, nutrients are primarily associated with the finer sediment particles (e.g., clay, silt, and fine sand). Clay particles are particularly important as they are good adsorption media for phosphorus, but the more organically rich silt can also contain significant amounts of phosphorus. Nitrogen compounds are also more commonly associated with organically-rich silt.

Transport, trapping, and biological availability of P and N attached to sediments depends on how the nutrients are bound to the sediment particles and the size of the sediment particles to which the nutrients are attached. Unfortunately, no detailed data on nutrient binding and the size of particles involved are currently available for the Mekong River System.

While detailed data are unavailable, the MRC Water Quality Report (2008) mentions that, on average, a third of the total phosphorus (total P) in the Lower Mekong Basin is found as soluble orthophosphate (PO4-P). This suggests that about two thirds of the P is associated with sediments.

Data from the MRC database show that, at Luang Prabang in 2004-2005, soluble phosphate on average made up 70% of total P, suggesting that only 30% was associated with sediments. However, the proportion of soluble phosphate found in samples varied between 50 and 90%. In data collected further downstream in the Mekong River at Prek Kdam (between Phnom Penh and the confluence with the Tonle Sap River), bio-available P bound to sediment constituted 30 to 40% of total P. Similarly, the soluble proportion at the hydrometric stations upstream and downstream of Xayaburi (Chaing Sean and Vientiane) made up, on average, only 30% of total P in 2004-2005. This finding corresponds closely to the general level reported for the Lower Mekong Basin as a whole.

It is apparent that the proportion of total P associated with the sediment is highly variable, but generally constitutes one to two thirds of the total. Consequently, a significant proportion of the phosphorus load carried by the river could potentially be retained in the reservoir at Xayaburi.

Data for nitrogen are only available for the hydrometric station at Chiang Sean – more than 200 km upstream of Luang Prabang. Records for this station indicate that between 10 and 80% of the total nitrogen (total N) occurs as particulate N, with an average of approximately 50%. Hence, a significant proportion of the nitrogen load could also accumulate in the reservoir.

Assuming that about two thirds of the phosphorus and half of the nitrogen carried by the river is associated with the fine sediment, the SEG estimate that, for the current design and proposed operating regime, nearly half of the incoming total P and a third of the total N are at risk of being retained in the reservoir. However, design modifications to the dam and its operation to optimise sediment routing and flushing have the potential to reduce these upper-bound estimates to as little as 5%.

It is likely that fine sediment will accumulate in the deep pools if the dam is built and operated as proposed, especially during the dry season. SEG interpretation of inferred conditions and the results of more detailed modelling suggest that flushing would be of limited effectiveness in re-suspending fine material that has settled in deep pools. This could adversely impact the nutrient balance and habitat quality in these parts of the reservoir and it emphasises the desirability of sediment routing.

While local nutrient impacts might be marked, according to an MRC Water Quality Assessment made in November 2008, the annual total P transport at Luang Prabang constitutes only approximately one third of the transport at the hydrometric stations further downstream (Nakhon Phanom, Kong Chiam, and Pakse). Consequently, the impacts of Xayaburi on nutrient loads and balances in the river would decrease with distance downstream.

Based on the SEG estimate of sediment trapping behind Xayaburi Dam with the proposed design and operating regime, the dam would be likely to result in a reduction of up to about 15% in total P in the lower reaches of the Mekong, which would still be likely to lead to consequential environmental impacts that are both measurable and significant to habitats and ecosystems. However, such impacts are avoidable. Implementing the design and operation modifications recommended in the review, to optimise sediment management, could reduce the impact on P to the point that it would not be detectable. The data necessary to support an equivalent assessment for total N are currently unavailable.

In summary, interpretation of preliminary calculations and analysis of modelling results performed by the SEG, coupled with experience gained through the operation of other dams worldwide, suggest that it should be possible to maintain the nutrient balance in the river after construction of the Xayaburi Dam by routing and flushing most of the sediment-associated nutrients downstream, provided that recommended modifications are made to the design and operation of the dam to optimise the its capability for adaptive sediment management.

However, the SEG's interpretation of potential nutrient loads and balances is based on preliminary calculations and modelling and it is recommended that additional surveys, monitoring, and analyses are performed to determine the size of sediment (clay, silt, or fine sand) to which nutrients are primarily attached and reduce uncertainty concerning the quantities of nutrients that could be routed or flushed downstream under different design and operational scenarios.

In fact, this information is necessary in order for the proposed design to fulfill the requirements of the MRC-PDG. Specifically, paragraph 120 in the MRC-PDG requires that mainstream dams pass fine suspended sediment, and therefore sediment-associated nutrients, in a way that most closely mimics the natural timing of sediment transport dynamics in the river (i.e. routing is preferred to flushing). Paragraph 142 further notes that healthy river ecosystems support the livelihoods of many people living along the banks of the Mekong River (e.g. nutrition and income). Indeed, the supply of nutrients is in several reports recognised as important to ecological services in the entire Lower Mekong Basin, including the Delta, the Tonle Sap and other floodplain wetlands, as well as the river itself. It is for these reasons that mainstream dams must avoid significantly inhibiting downstream transport of nutrients. Finally, paragraph 161 of the MRC-PDG requires that operation of the dam should aim to maintain sufficiently high levels of dissolved oxygen (DO) and sufficiently low levels of phosphorus, nitrogen, and biological oxygen demand (BOD) as discussed in the next sub-section.

3.3.3 Water Quality

Deposition of suspended sediment and organic material (both fine and coarse) reduces turbidity and thereby allows more light penetration. This may result in enhanced growth of algae and aquatic plants. Provided that nutrient levels are not limiting, aquatic weeds may proliferate, especially in calm areas, and planktonic algal blooms may occur. Data from the MRC database indicate that the nutrient levels in the river are sufficient to support such accelerated growth. Excessive growth of algae and weed can adversely impact water quality through, for example, oxygen depletion.

Based on available data, the SEG estimates that due to reduced flow velocities compared to open river conditions, it will usually take water between 1.5 and 15 days to pass through the reservoir, but that this could increase to a maximum of 25 days during periods of very low discharge. These preliminary estimates concur with the view expressed in paragraph 144 of the MRC-PDG that relatively short retention times limit algal growth and water-quality problems in run-of-river reservoirs. However, if retention times approached the maximum possible value during the dry season there would be a risk of undesirable algal blooms that would require management through adaptive adjustments to the operating regime. The capability to deal with any algal blooms adaptively would depend on implementation of a monitoring programme to support adaptive management of water-quality issues in the reservoir to avoid undesirable environmental impacts, especially during the dry season. Monitoring would, in any case, be necessary to fulfill the relevant criteria set out in the MRC-PDG.

The SEG also agree with the statement in paragraphs 144 and 149 of the MRC-PDG, that the probability that water might become thermally stratified in long, narrow reservoirs like that planned for Xayaburi is relatively low. This conclusion is based on estimated retention times and modelled velocities. However, the risk of adverse impacts on water quality due to siltation, algal blooms, weed growth, and the accumulation of other organic debris in deep pools in the reservoir should be established through monitoring and additional assessments. Risk assessment must explicitly account for effects of water exchange/stratification and the oxygen balance in deep parts of the reservoir.

3.3.4 Habitats

Sedimentation will change the fluvial environment and thereby the type of bed sediment unless sediment routing or flushing are performed to carry incoming sediment and organic debris downstream through the dam. In the upper part of the reservoir and the backwater reach, sedimentation may result in bed aggradation and the formation of bars and shoals. Such changes will alter habitat conditions available for aquatic life at these locations. Changes within the reservoir may include accumulation of fines and organic sediments, especially in the deep pools.

It is true that the existing functioning of the river as a river ecosystem will be converted into that of a reservoir even if no additional sediment accumulates in the reservoir. In general, changes will favour a biotic system dominated by species that prefer lower velocities and calmer conditions. Nevertheless, if heavy, siltation may still negatively impact the emerging ecosystem, resulting in less than optimal biodiversity.

In this context, it is likely that sediment routing and flushing would be beneficial to physical habitats and the reservoir ecosystem, as these operations temporarily recreate river-like conditions that would reduce the tendency for silt and organic debris to accumulate, especially in the deeper parts.

3.3.5 Local Nutrient Inputs

Raised water surface elevations, together with current and wave action may lead to bank erosion along the margins of the reservoir. Where retreating banks undercut steep hill slopes, this could induce landslides in any marginally stable slopes. From a sediment-associated nutrient perspective, this could contribute additional sediment and organic, nutrient-rich material to the reservoir that could accumulate there, especially at the margins and in the deep pools. If excessive, local inputs from bank erosion and landslides could have significant, negative impacts on in-reservoir habitats. To gauge whether problems are likely to require mitigation, a risk assessment for significant bank erosion and landslide activity, together with an impact assessment for the impacts on habitats within the reservoir is required.

3.3.6 Consequential Environmental Impacts Related to Downstream Morphological Changes

Increased erosion downstream of dams on alluvial rivers has been observed following implementation of many hydropower projects worldwide. This may involve bed and/or bank erosion. The EIA carried out for Xayaburi Dam recognised this problem and the Developer outlined mitigation measures intended to reduce such erosion.

In non-alluvial reaches, “sediment hungry” water is unable to erode the channel boundaries, but it may still erode pre-existing sediment features within the channel and river corridor. With the current design, this is likely in the non-alluvial, bed rock controlled reaches of the Mekong between the dam site and Vientiane. The outcome would be to reduce the extent and diversity of sediment-related habitats, as well as reducing the availability of sediment-associated nutrients.

If, as suggested by the Developer, hard bank protection were installed to prevent erosion in the alluvial sub-reaches, this would further inhibit natural flora and fauna. The outcome could be a dramatic change in the river ecosystem, leading to a reduction in biodiversity.

The risk of adverse environmental impacts occurring downstream of run-of-river hydropower dams is real. For example, damming of the River Danube in Austria resulted in a significant lowering of the channel bed downstream in Slovakia (Refsgaard *et al*. 1998). Environmental consequences extended to floodplain forests and wetlands due to the effect of channel incision in lowering of the groundwater table and reducing water and nutrient availability (Teodoru *et al*. 2005, 2006). Given the economic, social and environmental importance of the river and its floodplains, detailed assessment of the potential for such impacts downstream of Xayaburi Dam should be performed.

Avoiding sediment trapping and ensuring practically unchanged nutrient transport to downstream river reaches, wetlands, and lakes is likely to require periodic flushing of accumulated sediments as well as sediment passing by routing operations. Indeed, the MRC-PDG recommends flushing at least every 2 to 5 years. However, if a significant amount of sediment is allowed to accumulate before flushing, this could result in unnaturally high concentrations of sediment and associated nutrients during the flushing event that might be harmful to downstream ecosystems and, especially, fish. To avoid this, it may be necessary to flush more frequently than would be necessary solely to avoid sediment and morphological impacts.

Sediment routing is preferred to flushing environmentally, as it more closely follows the natural sediment discharge pattern, which is described as desirable in the MRC-PDG document. In practice, it will be necessary to adapt routing and flushing operations to optimise the environmental as well as the sediment performance of the dam and so it is recommended that the dam design be modified to increase its capacity for sediment management that is both adaptive and environmentally-aligned.

4.0 GAPS AND UNCERTAINTIES

4.1.1 Gaps and Uncertainties Concerning Sediment and Morphology

In the course of undertaking this review, the SEG has encountered multiple unknowns and large uncertainties concerning current parameters and future conditions in the LMB. Uncertainties are particularly large with respect to sediment yields, sediment properties, and the extent, sequence and timing of potential geomorphic responses to altered sediment loads.

Although the best available information has been used to estimate future sediment loads that are likely to be input to the Xayaburi Reservoir, such estimates are clouded by uncertainty concerning past, present and future sediment loads in the Mekong Basin. This situation may seem surprising given that the Mekong is a major transboundary river that has been extensively monitored and modeled. It therefore requires substantiation.

With respect to sediment inputs to the LMB, several studies have attempted to detect reduced sediment loads in the Mekong as a consequence of closure of mainstream dams in China, including

Manwan Dam, in 1993. Lu and Siew (2005), Kummu and Varis (2006) and Fu and He (2007) all concluded that loads have decreased, though they differ with regard to the magnitude of the reduction. Conversely, Walling (2005 and 2008) contends that the mainstream dams have had little impact.

Analysis of annual sample distributions of SSC and TSS in the Mekong mainstream at Chiang Saen, Luang Prabang and Nong Khai by Adamson (2009) indicate a reduction in sediment load post 1993, though not all of the differences in mean concentrations are statistically significant. Linking these reductions to sediment trapping upstream is, however, complicated by the fact that the sampling regime used from the mid-1990s onwards differs to that used in the 1960s and 1970s. On the other hand, reservoir inspections demonstrate that Manwan *does* trap substantial quantities of sediment, so downstream impacts should be expected simply based on considerations of sediment continuity.

On balance, it is reasonable to conclude that closure of Manwan Dam in 1993 has resulted in decreased sediment concentrations in the LMR. But it is not possible to be precise concerning the order of the impacts, which varies between 25% and 65%, depending upon which sites and data sets are considered.

The difficulty of predicting future sediment loads is increased by uncertainties concerning not only the impacts of existing and planned dams but also the effects of global warming and land-use changes associated with development of the Mekong Basin for agriculture and primary industries, and how these might influence basin sediment yields.

The SEG was unable to obtain reliable information regarding the properties of sediment present in the Mekong River. Gaps exist concerning sediment size distributions (e.g. how much of the load is clay, silt, fine sand, etc.), the relative proportions of fine (suspended) versus coarse (bedload) sediment transport, and the sources of different types of sediments.

Lack of information also limits the type of geomorphic assessment that can be performed. Based on the data currently available, it is not possible to be precise about how the river morphology would respond to changes in sediment loads triggered by construction and operation of the dam. What is clear from previous experience at other dams and rivers with run-of-river hydropower dams is that morphological responses are likely, will most probably include bed degradation and bank retreat in alluvial reaches, and could extend over wide areas, with the potential for consequential impacts of in-stream and riparian environments, habitats and ecosystems.

Assessment of potential flooding effects in Section B.3 of the Developer's Design Report does not consider the possibility that morphological responses in the backwater reach upstream of the reservoir (for example, shoal formation and bed aggradation), could lead to increased flood probability at Luang Prabang. The results of preliminary modelling performed by the MRC suggests that sedimentation sufficient to markedly increase flood risk is unlikely, but further investigations should be performed to explore the likelihood and potential effects of sedimentation in the backwater reach upstream of the reservoir.

In the Design Report, the Developer does not mention the need for active storage to support planned peaking power generation during the low-flow season. However, such storage is usually used in run-of-river hydroelectric stations to manage diurnal power supply needs and it seems likely that it will also be the case at Xayaburi Dam. No consideration of how sedimentation might affect the magnitude of such storage has been presented by the Developer.

The SEG, therefore, conclude that there are significant gaps in both the Xayaburi Feasibility Report and EIA concerning potential sediment and morphology impacts upstream, within, and downstream of the reservoir and measures that might be taken to avoid or mitigate any such impacts. This indicates the need for sediment monitoring and modelling during the design, construction, and operational phases of the Xayaburi project.

However, the SEG agree with and accept the view expressed by the Lao PDR Ministry of Energy that sediment models and predictions based upon them are subject to large uncertainties that are, to a degree irreducible. This is the case because uncertainty stems not only from limitations of data availability and model accuracy but also from natural variability – which is an attribute of the river that cannot be reduced. Recognising that uncertainty will never be eliminated by even the most advanced modelling, the sensible way forward is to proceed with caution, designing the dam so that it has the greatest practical capacity for adaptive sediment management, and putting uncertainty on the safe side of the sediment impact risk assessment. Later in this review, the SEG therefore recommends modifications to the proposed design that will allow for both routing and flushing operations to manage sediment adaptively.

4.1.2 Gaps and Uncertainties Concerning Nutrients

The documents supplied by the Developer do not establish the nutrient balance for the Xayaburi Reservoir. Further, significant knowledge gaps involve:

- nutrients (nitrogen and phosphorus) association with different sediment size fractions,
- nutrient binding (especially phosphorus) to incoming sediments for evaluation of nutrient mobility and bioavailability,
- potential in-reservoir accumulation of fines (clay, silt, fine sand, and organic debris) and coarse (sand and gravel) sediments in terms of both quantity and spatial distribution,
- turnover of nutrients within sediment accumulations,
- possibility for thermal stratification in the reservoir during the dry season and evaluation of impacts in the deep pools, including evaluation of the risk of oxygen depletion, and
- risk that local landslides could adversely affect nutrient loadings and water quality.

With regard to the final bullet point, the potential exists for erosion by currents and waves coupled with the effects of raised and changing water levels to trigger failure of banks and slopes that presently marginally stable. This justifies assessment of the likelihood of problems requiring mitigation to reduce consequential risks to people, property, nutrient loadings and habitats that might result from bank erosion and landslide activity along the shores of the reservoir.

There are also gaps in knowledge concerning the nature and spatial distribution of sediment features between Xayaburi and Vientiane and their vulnerability to erosion should the dam release significantly ‘sediment hungry’ water.

Furthermore, there is a need for assessment of the way that the morphological and consequential environmental risks of initiating degradation and/or bank erosion in the alluvial reaches downstream of Vientiane during construction and operation of the dam change as function of the capacity for adaptive sediment management provided by current and recommended dam designs.

5.0 TRANSBOUNDARY AND CUMULATIVE EFFECTS

5.1 Transboundary Impacts

Assessment of the Transboundary impacts of Xayaburi Dam on sediments, morphology, and nutrient balances in the Lower Mekong depends on knowledge of:

- sources and dynamics of sediments in the river system,
- binding and bioavailability of sediment-associated nutrients,

- the trap efficiency of the reservoir with respect to sediment by size fraction (i.e., how much of the incoming load is sand, silt, and clay and how much of each size of sediment is trapped in the reservoir), and
- the capability of the dam to transport sediment downstream through routing and flushing operations.

Given the significant gaps in knowledge concerning each of these issues that were identified in Section 4 of this document, it must be emphasised that assessment of the impacts of Xayaburi on sediments, morphology, nutrients, and consequential environmental impacts in a basin-wide context using existing, available information can only be indicative and is subject to high uncertainty.

Based on the preliminary assessments of the current design and planned operation of the dam (as outlined in Section 3 – MRC-SEG Technical Review), the SEG concluded that a significant percentage of the incoming sediment is likely to be trapped in the reservoir. Trapping the coarser fraction of the sediment load would generate impacts within Lao PDR, but trapping a percentage of the finer fraction at Xayaburi could generate transboundary impacts further downstream. In assessing possible transboundary impacts, it is significant that the fine fraction of the sediment load (i.e. particles with diameters less than about 63 µm) behaves very differently to the coarser sand and gravel-sized sediments, so that estimating the trap efficiency for fine sediment requires a different approach.

The sediment module in ISIS (hydrodynamic modelling software developed by Halcrow Group Limited) is able to simulate the transport of fine sediment, but applying this model requires input data on the size distribution of sediment input to the reservoir from upstream. Consequently, the gap with respect to sediment size distribution data identified in Section 4 introduces large uncertainties to ISIS modelling and limits the results to being indicative. Accepting this, the results of preliminary, 1-D modelling indicate that Xayaburi may trap on the order of two thirds of the incoming load of fine sediment following closure of the dam. Transboundary sediment impacts and morphological responses (of the types described in Sections 1 and 3) to trapping on this order would likely be apparent in the Lower Mekong River, including not only the channel but also the floodplains, wetlands and seasonal lakes, the delta, the nearby coast and the offshore sediment plume.

With the proposed design and operating regime, construction and operation of the dam would be likely to result in a reduction of up to about 15% in total P in the lower reaches of the Mekong. The equivalent figure for nitrogen cannot be estimated due to the lack of data.

It must, therefore, be concluded that, based on available evidence and on the balance of probabilities, Xayaburi Dam would likely be responsible for transboundary sediment, morphology and nutrient impacts, leading to consequential environmental impacts that are both measurable and significant to communities, economies, habitats and ecosystems in the Mekong River, as well as its floodplains, wetlands, and delta.

However, preliminary analyses performed by and on behalf of the SEG indicate that the moost serious transboundary sediment, morphology, and nutrient impacts could be avoided if appropriate modifications were made to the design and operational strategy to enhance the capability for routing and annual flushing, coupled with monitoring and adaptive sediment management to minimise fine sediment and nutrient retention within the Xayaburi reservoir.

Based on interpretation of preliminary calculations of trapping efficiency and the results of 1-D modelling, the SEG estimates that, if the recommended modifications were implemented, it would be possible to transport 70 to 90% of the fine-grained sediment and so limit the transboundary impact of Xayaburi on nutrient loads in the Lower Mekong to a reduction of less than about 2% – a decrease that would not, in practice, be detectable.

It is therefore concluded that, provided the Xayaburi Dam is redesigned and operated with the multipurpose objectives of (i) generating hydropower sustainably and, ideally, in perpetuity, (ii) avoiding adverse impacts where possible and (iii) mitigating impacts where they cannot be avoided, it is possible for the project to avoid measurable impacts on, for example, nutrient balances in downstream river, wetland, seasonal lake, deltaic, and coastal environments.

However, it must be emphasised that achieving this outcome will require adaptive adjustments of the sediment management measures to optimise their effectiveness, and adoption of a holistic view that encompasses all relevant aspects of the river system throughout the entire LMB. For example, it is vital that sediment management operations avoid significant changes to the seasonal sediment regime, as recommended in the MRC-PDG. This is necessary to ensure that floodplains, wetlands, and other seasonally flooded areas downstream receive sediments and nutrients at the appropriate times. This is of utmost importance to maintaining both agricultural productivity and ecosystem services in these important areas.

Notwithstanding these conclusions, uncertainties in an evaluation of the transboundary impacts on sediment and nutrient loads in Lower Mekong River are currently unacceptably high. Uncertainty should be reduced through monitoring the transport of fine sediments and total and inorganic fractions of nitrogen and phosphorus at multiple locations from upstream of Xayaburi Dam to the Mekong Delta. The information gained from the current monitoring programme addresses only part of this need and is not consistent with the requirement to include all size fractions and nutrients.

Enhanced monitoring would support calculation of the sediment and nutrient balances, including exchange and turnover, either through dynamic modelling or a reach-scale, mass balance approach.

5.2 Cumulative Effects

Assessment of the cumulative effects required the SEG to identify the main sources of sediment in the Mekong Basin and account for the impacts of sediment trapping in existing and proposed dams on the sediment and nutrient loads in the Lower Mekong River. The account presented in this section summarises the technical treatment in Annex B.

5.2.1 Relative Sediment Yields

There is no consensus regarding the absolute quantities of sediment transported in the Lower Mekong Basin. Not only does the annual load vary widely from year to year, but also changes in sampling procedures and changes to sediment yield from the Upper Basin due to dam construction both cloud any long-term monitoring records. While trends of change can be detected, uncertainty is high (see Adamson, 2009 for a review) and this currently precludes the possibility of constructing a quantitative sediment budget for the basin. However, it is generally accepted that the sediment yield is particularly high in three distinct regions, and the relative contributions of these regions are listed in Table 5.1 and illustrated in Figure 5.1.

Table 5.1. Estimated relative sediment contributions from the main source areas

River Reach	Geology / Region	Contribution to Total Sediment Load (%)
Upstream of China Border	Ailoa Shear Zone and Tibetan Gorges	45
China Border to Pak Chom	Wang Chao Fault Zone and rest of catchment	5

Pak Chom to Delta	Central Highlands, Khoral Plateau, and rest of catchment	50

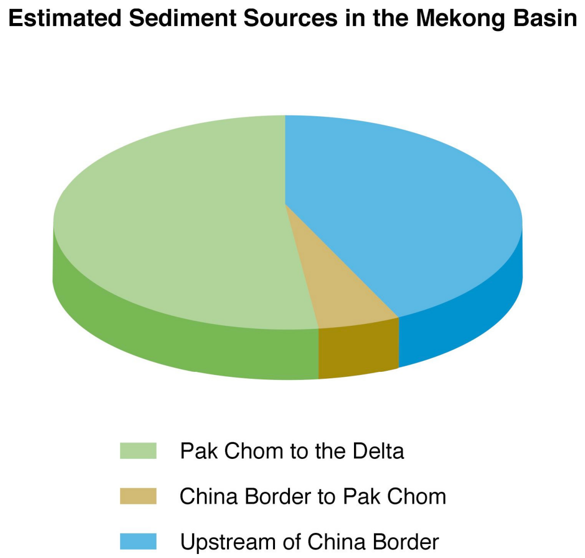

Figure 5.1. Estimated sediment source areas within the Mekong Basin (see Annex B for further explanation).

Using these estimated sediment sources, it is possible to construct a *relative* sediment budget and use this as the basis for estimating the contribution of sediment trapping behind existing and planned dams to reductions in the sediment load in the Lower Mekong River, based on the locations of the dams relative to the main sediment source areas.

In assessing long-term, cumulative impacts of sediment trapping behind existing and planned dams in the MRB, the basis used for the relative sediment budget is the river system in its pre-disturbance state: that is, prior to any reductions in sediment load due to trapping in reservoirs. Hence, in the cumulative sediment impact analysis, a sediment load of 100% corresponds to around 160 MT/y, which is believed to be the natural sediment yield of the Mekong Basin (Walling, 2005; Kummu and Varis, 2006).

5.3 Sediment and Morphology Impacts

Sediment and morphological impacts were assessed for six scenarios:

1. Scenario 1: Baseline – 2000: Three existing Chinese mainstream dams (Manwan, Dachaoshan, and Jinghong), plus fifteen Tributary Dams.
2. Scenario 2: Definite Future – 2015: Eight[2] existing and planned mainstream Chinese dams, plus twenty-six Tributary Dams.
3. Scenario 3: Definite Future – 2015: Eight existing and planned mainstream Chinese dams, twenty-six Tributary Dams, plus six mainstream dams in Lao PDR.
4. Scenario 4: Foreseeable Future Scenario (i): Eight existing and planned mainstream Chinese dams, plus seventy-one Tributary Dams.
5. Scenario 5: Foreseeable Future Scenario (ii): Eight existing and planned mainstream Chinese dams, six mainstream dams in Lao PDR, plus seventy-one Tributary Dams.

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[2] It is recognized that Mengsong Dam has been indefinitely postponed, but it is nevertheless included in this analysis for completeness.

6. Scenario 6: Foreseeable Future Scenario (iii): Eight existing and planned mainstream Chinese dams, six mainstream dams in Lao PDR, five Cambodia dams, plus seventy-one Tributary Dams.

Full descriptions of these scenarios and the basis on which their sediment trap efficiencies were estimated are provided in Annex B.

Table 5.2a lists, and Figure 5.2 illustrates, the estimated relative reductions in sediment loads in the Lower Mekong caused by trapping by reservoirs in the command areas of each of the three dominant sediment sources. These estimates are based on the assumption that no measures are taken to optimise sediment management at the dams and they are based partly on indicative calculations and partly on expert judgement. The ranges of possible reduction in sediment load listed in Table 5.2a and shown in Figure 5.2 indicate the uncertainties inherent to this type of predictive assessment.

It was pointed out in Section 3 of this document that trapping efficiencies differ for the fine and coarse components of the sediment load. As stated in Section 4 of this document, data gaps currently prohibit quantifying the relative amounts of coarse and fine sediment carried by the Mekong River. Therefore, to investigate possible impacts related specifically to the trapping of coarse or fine sediment an indicative calculation was performed on the assumption that 10% of the total sediment load consists of coarse sediment, with the rest constituting the fine sediment load. This assumption is based on expert judgment and experience from other large rivers. Based on this assumption, indicative estimates of the percentages of coarse sediment and fine sediment likely to be trapped by the reservoirs are presented in Figure 5.3. In this graph, for fine sediment, 100% corresponds to the pre-disturbance, natural yield fine sediment load (which makes up 90% of the total sediment load). For coarse sediment, 100% corresponds to the pre-disturbance, natural yield coarse sediment load (which makes up 10% of the total sediment load).

Taking into account the proportions of fine sediment likely to be trapped, Table 5.2b lists, and Figure 5.4 illustrates, estimated cumulative reductions in nutrient loads in the downstream areas of the Mekong Basin. These are discussed in Section 5.4.

Table 5.2a. Estimated long-term, cumulative reductions in sediment loads for base case and five future scenarios.

Sediment Source	Geology / Region	Contribution to Natural Sediment Load (%)	Sediment Trapped in Reservoirs											
			Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
			Baseline – 2000		Definite Future 2015		Definite Future 2015 + 6 Lao PDR Dams		Foreseeable Future (i)		Foreseeable Future (ii)		Foreseeable Future (iii)	
			Main	Tributary	Main	Tributary	Main	Tributary	Main	Tributary	Main	Tributary	Main	Tributary
Upstream of China Border	Ailoa Shear Zone and Tibetan Gorges	45%	35-40%		40-45%		40-455		40-45%		40-45%		40-45%	
From China Border to Pak Chom	Wang Chao Fault Zone and rest of catchment	5%					5%				5%		5%	
Pak Chom to Delta	Central Highlands, Khoral Plateau and rest of catchment	50%		5-10%		10-15%		10-15%		20-30%		20-30%	10-35%	20-30%
	Sub-total Trapped:		35-40%	5-10%	40-45%	10-15%	45-50%	10-15%	40-45%	20-30%	45-50%	20-30%	55-85%	20-30%
	Total Trapped:		40-50%		50-60%		55-65%		60-80%		65-85%		75-100%	
	Remaining Sediment Load:	100%	50-60%		40-50%		35-45%		20-40%		15-35%		0-25%	

Table 5.2b. Estimated long-term, cumulative reductions in nutrient loads for base case and five future scenarios.

Scenario 1	Scenario 2	Scenario 3	Scenario 4	Scenario 5	Scenario 6
Baseline – 2000	Definite Future 2015	Definite Future 2015 + 6 Lao PDR Dams	Foreseeable Future (i)	Foreseeable Future (ii)	Foreseeable Future (iii)
15-35%	20-40%	20-45%	25-50%	25-60%	30-65%

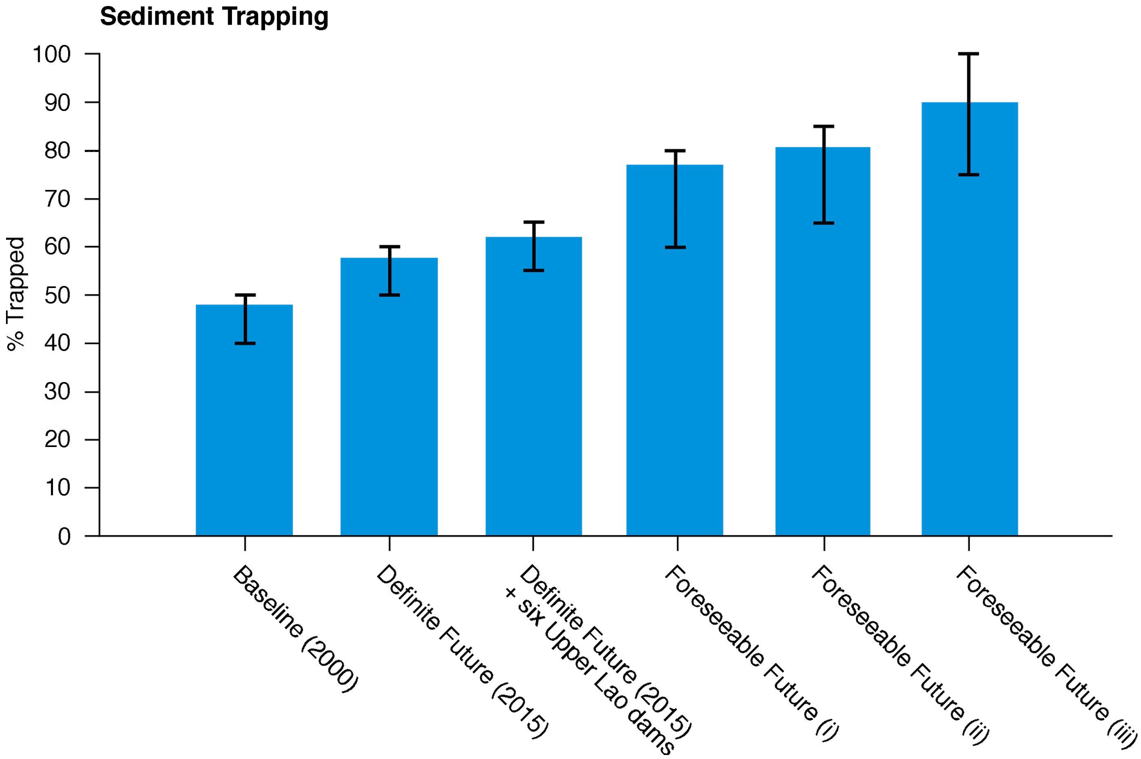

Figure 5.2. Estimated reductions in sediment loads in Lower Mekong Basin caused by trapping in reservoirs with no sediment impact mitigation measures. Note: 100% = pre-disturbance Mekong Basin sediment yield estimated to be around 160 MT/year (Walling, 2005; Kummu & Varis, 2006).

The findings listed in Table 5.2a and illustrated in Figure 5.2 suggest that, in the long-term, dams in the Upper Mekong Basin in China are likely to reduce future sediment loads supplied to the Lower Mekong River by nearly half under the Definite Future - 2015 scenario. The implication for sediment loads at Xayaburi is that sediment input will decrease progressively as the dams upstream become operational.

There is already evidence to support this prediction in that it is reasonable to conclude that sediment loads at Luang Prabang have decreased since the closure of Marwan Dam in 1993 (Adamson, 2009). It is expected that this situation will last for several hundred years once the majority of the planned Chinese dams are built. It should be noted, however, that this projection ignores the likely impacts of global warming and land-use changes on future sediment yields from the basin.

Under the definite and foreseeable future scenarios, the estimated percentage of pre-disturbance sediment reaching the delta decreases progressively as the number of dams increases until, under Scenario 6 (Foreseeable Future Scenario (iii)), 75% or more of the pre-disturbance sediment load previously supplied to the Mekong Delta is trapped upstream.

The second largest anticipated reduction in sediment loads is attributable to the seventy-one tributary dams planned in the LMB. The five future mainstream dams in Cambodia are expected to further reduce the sediment load by a proportion nearly double that attributable to the six mainstream dams planned for construction in the Lao PDR. In this context, the quantity of sediment predicted to be trapped by Xayaburi Dam (based on the design and operating regime proposed by the Developer) is relatively small. It is, however, a component of sediment reduction which, if realized, would likely generate transboundary impacts that would, in the long-term, contribute to cumulative effects.

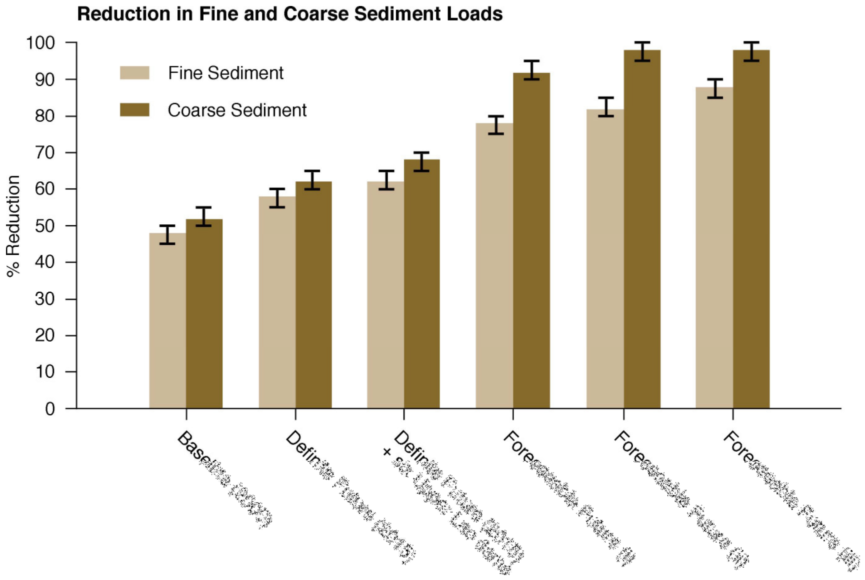

Figure 5.3 Indicative estimates of reductions in fine and coarse sediment loads in the Lower Mekong caused by trapping in reservoirs with no sediment impact mitigation measures. Note: 100% = pre-disturbance yields of fine and coarse sediment, estimated to be around 144 and 160 MT/year, respectively (Walling, 2005; Kummu & Varis, 2006).

Experience from other large rivers subject to the cumulative effects of multiple dams indicates that substantial reductions in sediment supply are likely to trigger complex morphological responses. The nature, extent, and sequence of morphological adjustments cannot, however, be predicted without detailed analysis that is currently precluded by the gaps identified in Section 4 of this document. However, given that both fine and coarse loads are likely to be reduced substantially, what can be expected is that morphological responses would be widespread and persistent, with multiple consequential damages to communities, agricultural productivity, fisheries, economies, habitats, and ecosystems, not only in the river and riparian zones but also in floodplain, delta and coastal areas.

This assessment is based on available information and previous work by respected academics and researchers. The evaluation methodologies that were used are known and accepted technology. However, due to the limited amount of information available, the results are generalized and subject to high uncertainty.

Avoiding long-term, cumulative sediment and morphological impacts will require collective action by all signatories to the 1995 Mekong Agreement to ensure that each and every dam owner and operator in the LMB to implements reservoir sedimentation management technologies to minimize trapping upstream of their dam, by passing and flushing sediment downstream. Failure to do so risks severe disruption to sediment dynamics and, hence, the morphology of the Lower Mekong River, its Delta and nearby coast. Optimising the design and operation of Xayaburi Dam with respect to sediment management is a crucial element of such collective action and (given future uncertainties) the participation of its designers and operators in avoiding and/or mitigating long-term, cumulative sediment and morphological impacts will require design modifications that allow for adaptive management however future sediment loads may change.

For Xayaburi Dam a pre-feasibility level analysis was conducted, which indicates that it should be possible to indefinitely retain about 70% of the original reservoir volume through modifying the current design to facilitate the degree of drawdown required for effective reservoir flushing. Optimal sediment management at Xayaburi Dam would not only contribute to minimizing cumulative impacts on river and delta morphology, it would also lengthen the lifespan of the hydropower dam, allowing it to generate electricity for a period far exceeding its probable design life with the current design and operating regime.

Nutrient Impacts

5.3.1 Scenario 1: Baseline – 2000

According to the results listed in Table 5.2a and illustrated in Figure 5.2, the supply of fine sediment to the Delta would be reduced by nearly half its natural, pre-disturbance value in this scenario. The associated reduction in nutrients would be expected to be somewhat smaller because nutrients associated with sediments make up only one to two thirds of total nutrient transport (Table 5.2b and Figure 5.4). In this relative analysis of nutrient impacts, 100% corresponds to the nutrient yield of the Mekong Basin I its pre-disturbance state, when the average annual sediment yield was on the order of 160 MT/y.

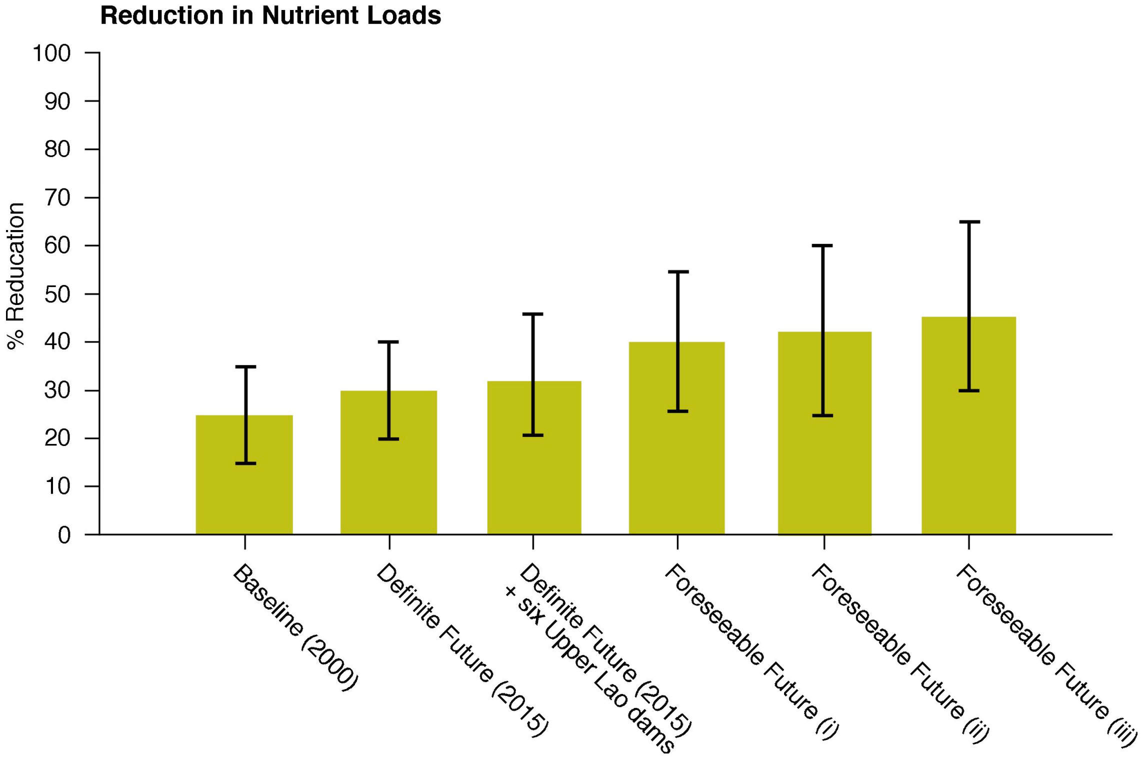

Figure 5.4 Estimated nutrient trapping in reservoirs with no sediment impact mitigation measures. Note: 100% = pre-disturbance Mekong Basin nutrient yield.

Assuming that between one and two thirds of the total phosphorus and about one half of the nitrogen are associated with sediments, and accepting a cumulative trap efficiency of 40-50%, a reduction in nutrient transport on the order of 15-35% can be expected. Retention of nutrients of this order must be regarded as significant, with the potential for measurable, consequential impacts on agricultural productivity as well as river, floodplain, wetland, lake and deltaic ecosystem services in the Lower Mekong Basin.

5.3.2 Scenario 2: Definite Future – 2015

The SEG estimates that dams in this scenario may trap approaching 55-60% of the fine sediment previously supplied to the delta. Using the assumptions applied in Scenario 1, this is predicted to result in 15-40% of the pre-disturbance nutrient load being retained in the reservoirs upstream. Significant consequential impacts would be expected on ecology, fisheries and agricultural productivity in the river, floodplains, wetlands, seasonally flooded lakes, delta and nearby coastal areas due to reductions in nutrient availability.

However, further uncertainty is introduced under this scenario in that this estimate assumes that the relation between fine sediment and nutrient transport in the tributaries is similar to that in the mainstream. Field surveys, monitoring, and more detailed studies of sediment-nutrient associations in selected tributaries are required to reduce this uncertainty.

5.3.3 Scenario 3

In this scenario, a cascade of six dams is added in the Lao PDR and the proportion of fine sediment trapped behind dams is predicted to increase from 55-60% in Scenario 2, to 60-65%. Based on the same methodology applied in the previous scenarios, this could result in a reduction of 20-45% in nutrient transport compared to the natural condition.

In the context of this scenario, the scale of the overall reduction in nutrient loads makes the contribution attributable to the cascade of dams in the Lao PDR (including Xayaburi Dam) appear relatively small. It cannot, however, be concluded from this that trapping of sediment-associated nutrients at Xayaburi becomes insignificant in this scenario. On the contrary, it becomes even more important.

This is the case, first, because fine sediment and associated nutrients are likely to be diminishing and increasingly precious resources in this scenario and, second, because the adaptive capability to manage sediment transport through the cascade of mainstream dams in Laos will depend on optimising the capacity for routing and flushing operations at each of the dams – including Xayaburi. It would be regrettable if the design of Xayaburi were to constrain the capacity to manage sediment routing and flushing operations effectively in transporting sediment through the series of dams in the cascade.

In fact, the SEG believes that the proportion of fine sediment and sediment-associated nutrients trapped behind Xayaburi Dam can be reduced to a small percentage if the recommended modifications to its design and operation are accepted by the Developer. In this case, a significant contribution to cumulative, transboundary impacts due to nutrient retention at Xayaburi can be avoided.

5.3.4 Scenario 4

In this scenario, further tributary dams are added the proportion of fine sediment trapped behind dams would increase to about 75-80%. Based on the same methodology applied in the previous scenarios, this could result in a reduction of 25-50% in nutrient transport compared to the natural condition, with a likely increase in nutrient and consequential impacts.

5.3.5 Scenario 5

Calculations for this scenario suggest that the proportion of fine sediment trapped behind dams would increase to 80-85%. Based on the same methodology applied in the previous scenarios, this could result in a reduction of 25-60% in nutrient transport compared to the natural condition and a further increase in cumulative impacts.

5.3.6 Scenario 6

The SEG predicts that in this scenario, dams may be expected to trap 85-90% of the fine sediment previously supplied to the lower reaches of the Mekong. This could lead to a reduction of 30-65% in the delivery of nutrients to lower reaches of the river system.

The increase in cumulative impacts stems not only from the fact that there are more dams in the basin but, particularly, from the fact that the additional mainstream dams are located further downstream on the Mekong and have large reservoirs and long retention times. The SEG found that it would be difficult to pass sediment through these reservoirs and that not even flushing would be effective as a sediment management measure. Consequently, the reservoirs in Cambodia and Vietnam risk retaining significant quantities of those fine sediments and associated nutrients that remain in the fluvial system.

Based on the prediction that a significant proportion of the remaining fine sediment and nutrients would be trapped in reservoirs in Cambodia and Vietnam, significant consequential impacts are expected on the ecology and productivity of the river, floodplain, wetlands, seasonally flooded lakes, delta, and near-delta coastal region. Furthermore, a significant increase in retention time in the large reservoirs in Cambodia and Vietnam, coupled with increased light penetration due to reduced sediment concentrations may generate conditions suitable for algal blooms. This could amplify the uptake of soluble nutrients in the reservoirs, further depleting nutrient transfer downstream and exacerbating cumulative environmental impacts.

For all these reasons, severe consequential impacts, including significant environmental degradation and marked reductions in productivity, can be expected along the Mekong River, in the Tonle Sap in the delta, at the coast and in the ocean sediment plume. In this context of this scenario, the relative contribution of Xayaburi, although further diminished, becomes ever more crucial to conserving the remaining supply of fine sediments and nutrients to what is likely to be a sediment- and nutrient-impoverished, river and coastal system.

Limitations of data and time availability have precluded consideration by the SEG of the potential for designing and operating the additional mainstream dams in this scenario in ways that optimise sediment management and support the attainment of multipurpose objectives for generating hydropower while protecting environmental resources and ecosystem services. There is, however, a significant risk that these large reservoirs will act as significant sediment traps – as has occurred with many other hydropower dams worldwide. Evidence to support this view comes from the Upper Mekong River, where large Chinese reservoirs (especially that of Manwan Dam) has already accumulated a considerable volume of sediment and appears to have lead to reductions in the supply of sediment and nutrients to river reaches downstream.

These findings emphasize the importance of optimising sediment management capabilities and operations at all existing and planned dams, including Xayaburi. It places a duty on the nations in the Lower Mekong Basin to construct and manage dams and reservoirs in a sustainable manner that minimises their tendency to trap and retain sediment. This can be best accomplished by designing, constructing and operating dams to generate hydropower sustainably, while managing sediments and nutrients to minimize the contribution of each dam to transboundary and cumulative effects. This will not only reduce impacts on the environment and agricultural productivity, it will also reduce potential liability for compensation payments to transboundary stakeholders.

6.0 SUMMARY, RECOMMENDATIONS, AND CONCLUSIONS

6.1 Modifications to Dam Design

Based on the findings of its technical review, the SEG recommends that the dam design proposed by the Developer be modified to enhance and optimise its capacity for sediment routing and flushing. It is beyond the remit of the SEG to attempt to specify design details, but the aim of the modifications should be to design a dam suitable for generating hydropower sustainably and, ideally and with appropriate maintenance, in perpetuity. This means that the dam must have the capability to allow future generations of dam operators to manage sediments adaptively, by making changes to the way that sediment routing and flushing operations are implemented as appropriate to future conditions and changing priorities for river and resource management in the Lower Mekong Basin.

In essence, the recommended design would involve modifications to the spillway and provision of low-level outlets with dimensions sufficient to allow operators to re-create the river-like flow conditions required to execute flushing operations.

The capability to manage sediment adaptively is essential because modeling uncertainty concerning future sediment loads and operating conditions is high. Even if model uncertainty can be reduced, it cannot be known precisely how future sediment inputs and dynamics in the river will be affected by the construction and operation of dams upstream in the Mekong drainage network and, further, how they will respond to changes in climate and land use in the basin. Future uncertainties are sufficiently large to preclude design of a dam fit only to meet sediment conditions as they are currently parameterized – they are insufficiently well known now and, in any case, the future is bound to be different.

The best way to deal with these irreducible uncertainties is to design a dam with the maximum capability for implementing sediment management measures – allowing its operators to optimize sediment management operations regardless of how the characteristics of the sediment and nutrient transport system evolve in the future and making it possible for operators to respond positively to changing priorities for the management of natural resources of the river. This is not only common sense; it also ensures that the design complies with the principles set out in the MRC-PDG for adaptive management.

The risk with designing a dam at Xayaburi that has less than the optimal capacity for sediment management is that such a decision will be deeply regretted in the future.

6.2 Modifications to Operations

It is recommended by the SEG that the Developer rethinks the proposed operating procedures with respect to optimising sediment routing and flushing, based on exploiting the enhanced sediment management capabilities provided by the recommended design modifications. The Developer should then demonstrate the effectiveness of the revised design and operating regime in:

- avoiding sedimentation to the highest degree possible and mimicking the natural time distribution of sediment transport downstream by sediment routing, and
- flushing downstream as much as possible of the sediment that is deposited in the reservoir, while selecting flushing times and durations to avoid undesirable environmental impacts associated with artificially high concentrations of sediments and nutrients.

The Developer should perform these demonstrations through mathematical modelling to:

- Determine how much sediment will accumulate in the reservoir and when an equilibrium condition will be achieved using the enhanced sediment management measures (complying with paragraph 94 of the MRC-PDG).
- Prepare sediment yield estimates to feed into computations of cumulative effects should Xayaburi be operated as one of a cascade of mainstream dams (in compliance with paragraph 98 of the MRC-PDG).
- Provide the basis for ensuring that Xayaburi Dam can achieve multipurpose objectives to generate hydropower sustainably and, ideally, in perpetuity while minimising adverse impacts on sediments, morphology and nutrients.
- Underpin the on-going assessments necessary to support adaptive adjustments of sediment management measures based on a holistic view that encompasses multiple aspects of the

entire Lower Mekong Basin. This is of utmost importance to maintaining the productivity and environmental integrity of the Basin.

The extent to which biodiversity is affected by nutrient imbalance in the reservoir will depend on the degree of siltation and accumulation of organic debris that accompanies the change from fluvial to more lake-like conditions. It is, therefore, recommended by the SEG that detailed investigations are carried out to identify whether siltation, the accumulation of organic debris, and the potential for dry season thermal stratification in deep pools are likely to require mitigation and, if so, specification of the most appropriate mitigation measures.

Retention times should usually be too short to generate problems with algal blooms. However, retention times in excess of 15 days during the dry season could allow increased algae growth and it is, therefore, recommended that additional assessments of the potential impacts on water quality in the reservoir are carried out.

It is highly recommended that an environmental flow strategy is set-up for the river downstream of the dam that takes into account the dynamics of sediment-associated nutrients and, especially, how sediment flushing operations can avoid potentially serious, adverse impacts on downstream environments and ecosystems. However, it is important to note that such a strategy could not be fixed: in fact it would need to be updated and adapted as knowledge gained from long-term monitoring accumulates, during operation of the dam.

Following the MRC-PDG carefully to allow for adaptive operation of the dam that ensures sufficient transport of sediment-attached nutrients downstream through the reservoir, while minimising damage due to nutrient spikes during flushing operations is highly recommended and could, most likely, allow operators to avoid impacting natural resources downstream of the dam. However, a more detailed assessment of this issue is needed to demonstrate this and it is recommended that the necessary investigations and simulations be performed.

6.3 Modifications to the Monitoring Programme

6.3.1 Monitoring Specified in the MRC-PDG

The MRC-PDG document (Paragraphs 122, 136, 137, 138, and 139) is very clear concerning the requirement to set-up a comprehensive sediment monitoring programme covering all relevant temporal and location issues.

The MRC-PDG document makes it clear that to comply with the requirements of the MRC-PDG, monitoring should:

- be initiated before the construction starts (to establish a baseline to be used to establish reference conditions);
- continue through construction (to allow detection and solution of any problems);
- be maintained throughout the operating period (in order to support adaptive management of sediments and nutrients);
- include monitoring stations located:
  - upstream of the dam in the reservoir and backwater reaches,
  - at the dam site itself, and
  - in the river downstream of the dam site; and
- record both the quantity and composition of sediments (grain size distribution, associated nutrients, organic constituents, and bio-indicators).

6.3.2 Monitoring Recommendations

Based on the requirements set out in the MRC-PDG, and bearing in mind the findings of the technical review reported in Section 3 of this document, the SEG recommends modifications to the monitoring programme outlined by the Developer so that the programme is fit to the purpose of supporting adaptive sediment management throughout the operating period of the dam. This will also bring the monitoring programme into compliance with the requirements set out in the MRC-PDG.

The standards and methods used should be the same or compatible with the existing sediment monitoring in the LMB and sediment monitoring should be coordinated and synchronized with monitoring programmes for Hydrology, Water Quality, Biota, and Fisheries – as recommended in the MRC-PDG. More specific recommendations stem from the points raised in the technical review.

In terms of baseline sediment studies, the SEG strongly recommends that:

- a baseline be established with respect to sediment contour levels and compositions in different parts of the planned Xayaburi Reservoir. There should be a particular emphasis on the farthest upstream reaches and the deeper parts of the river, including the deep pools; and
- a baseline survey is performed to establish the spatial distribution, extent, and composition of sediment features within the predominantly non-alluvial reach of the river between the Xayaburi Dam site and Vientiane.

With respect to nutrients, the EIA suggests that monitoring surveys be conducted biannually, with one survey during the dry season and one during the wet season. However, there is a need to supplement these surveys with additional measurements made throughout the year so that the data can be used to:

- develop a budget for all fractions of inorganic N and P as well as total N and total P; and
- describe the association (sorption and binding) of nutrients with the different size fractions of the suspended sediment load (clay, silt, and fine sand), which is fundamental to understanding how nutrient dynamics will relate to sediment trapping.

Although low chlorophyll levels are expected at the proposed dam site, it is further recommended that the baseline survey:

- include chlorophyll measurements covering the entire annual variation.

The objective is to establish a pre-dam condition against which future changes can be compared so that the risk of inducing excessive algal and weed growth during the dry season can be properly evaluated and, if necessary, managed adaptively.

In the same context:

- baseline conditions for turbidity and light penetration into the water during different seasons should be established.

Biomonitoring performed to support development of the EIA for the Xayaburi Dam has so far been carried out by collection of Ekeman sampling at the same locations used for water-quality sampling and a relative restricted number of species and organisms have been found. The SEG believes that the sampling method may be giving a biased picture of the benthic organisms living in this reach of the river. It is, therefore, recommended that semi-quantitative methods are added to the monitoring programme and that further locations are visited to broaden the range of substrates sampled beyond the restricted range that can be investigated using an Ekeman sampler.

During the construction period, monitoring of sediment and nutrient-related impacts upstream and downstream of the dam site should include: inorganic nutrients fractions as well as: total P and total N, suspended solids, organic content (COD or BOD), chlorophyll, oxygen, pH, temperature, light adsorption/penetration capacity, oil/grease components, and bacterial levels. Sampling frequency should vary between monthly and weekly, depending on the type of construction activities on-going at the time. During periods of intense construction activity, sampling frequency may need to be even higher.

It is recommended that a risk assessment be carried out with respect to the potential hazards associated with other pollutants based on information available concerning materials to be used during construction. Where harmful substances have the potential for environmental damage, these must be added to the monitoring programme for the relevant period of the construction phase.

It is recommended that sediment and nutrient monitoring continues throughout the operating period with the aim of supplying data relevant to the following issues:

- Sediment accumulation (quantity and composition) in the reservoir with an emphasis on sediment features at the upstream and lateral margins and siltation in deep locations, including the deep pools. Frequency: at least biannually, prior to and following the monsoon. This frequency may be adjusted as experience is gained on the actual rate of sedimentation.
- Sediment (quantity and composition), sediment features, and morphological changes along the river reach between the dam site and Vientiane. Emphasis to be placed on river banks and flood-level lines, mid-channel islands, and sediment deposits at tributary junctions. Frequency: at least annually, following the monsoon; later adapted as experience dictates.
- Water quality flowing into and out of the reservoir, including: all fractions and total amounts of inorganic nutrients, suspended sediment, organic content (COD or BOD), chlorophyll, main taxonomic groups of algae, oxygen, pH and temperature, and light adsorption/penetration capacity of the water. Frequency: monthly.

During sediment flushing, sampling should be carried out with a frequency that is suitable to establish the maximum sediment concentration in water being used to flush deposited sediment from the reservoir. The purpose of monitoring is to alert dam operators should flushing cause sediment concentrations to reach a level potentially harmful to fish and other aquatic fauna.

Throughout the dry season it will be necessary to monitor the vertical gradients of temperature, oxygen, and pH at the deepest locations in the reservoir in order to detect thermal stratification and unacceptable environmental deterioration. Sample frequency will depend on the occurrence of vertical gradients in the variables, but should initially occur every second week.

Finally, it is recommended that monitoring include measurement of the biomass, composition and extent of benthic flora and fauna at representative cross sections in the reservoir, and the river between the Xayaburi Dam site and Vientiane.

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ANNEXES

ANNEX A. SEDIMENT IMPACTS AND MEASURES WITH COMMENTS FROM SEDIMENT EXPERT GROUP

Table A.1. Sediment Impacts and Measures identified by the Developer, with comments from the Sediment Expert Group.

Page	Text*	Agree/ Disagree	SEC Comment(s)
1-4	*Maintain sediment passage by installing sluices for sediment flushing, protecting the turbines, avoiding deposits upstream of the barrage, as well as not reducing sediment inflow downstream, which may cause subsequent bank erosions and less protein for fish consumption and less nutrient in water for agriculture*	Disagree	While the SEG agrees with the sediment management objectives, we believe that the proposed sluices below the power house intakes cannot alone provide the capability to achieve these objectives. The outcomes of model studies executed by the Developer indicate that pressure flushing can re-suspend sediment deposited immediately in front of the intakes. However, with a ponded area extending ~100 km upstream, it will be impossible to flush deposited sediments that are located far from the structure using the proposed flushing conduits. To avoid trapping sediment in the reservoir it will be necessary to install large, low-level gates for sediment routing and reservoir flushing.
1-5	*The power house, with an installed capacity of 1,280 MW with ten Kaplan units and with a total discharge of 5,000 m^3/sec. Sediment sluices are included*	Agree	Installation of sediment sluices is a suitable measure for flushing sediment immediately in front of the power house intakes.
1-6	*Sediment Transport and River Morphology*	Agree	Indicates that the Developer recognises sediment and morphology as issues to be considered according to PDG.
1-6	*with regards to Xayaburi Hydroelectric Power Project, the MRC preliminary design guidance was adopted and the design is in conformity with the guidance*	Disagree	It is incorrect to say that the preliminary design conforms to the PDG. The reasons for disagreement are provided in the remainder of this table and expanded on in the main body of this review.
1-8	*The preliminary design in the feasibility study is designed to maintain sediment passage by installing sluices for sediment flushing, avoiding deposits upstream of the barrage, as well as not reducing sediment inflow downstream.*	Disagree	There are two methods of flushing sediment deposited upstream of a dam: pressure flushing and draw down flushing. Pressure flushing is intended to remove sediment immediately in front of intakes. Draw down flushing is used to re-entrain sediment deposited in a reservoir and discharge it downstream of the dam. Draw down flushing can reduce the rate and total amount of sediment that accumulate in the reservoir and so reduce its trap efficiency The proposed sluices beneath the power house intakes are suitable for pressure flushing but for draw down flushing. A design modification involving larger, low-level gates would be required to allow draw down flushing at Xayaburi.

Page	Text*	Agree/ Disagree	SEC Comment(s)
1-8	*For the next study, outline design, the hydraulic lab will be carried out and the result from the model will be used to design a sand flushing in conformity with the MRC's Design Guidance*	Disagree	Even at feasibility stage evidence is required that sediment can be managed sustainably not only at the dam but also throughout the reservoir.
5-1	*in some particular area underlying by clastic sediments where slope cuts in very high angle minor landslide locally found*	Agree	Recognises that landslides do occur in the area.
5-7	*River deposits: This material is composed of clay, sand and silt and gravel which found mainly along the Mekong River. It is noted that sand and gravel deposits are commonly found along the river, especially at Ban Thadua and Ban Pakh.*	Agreed	The Developer clearly recognises that sediments in the Mekong include a wide range of grain sizes, ranging from gravel to clay. Different management measures are required to manage different size fractions.
5-27	*Figure 5-11 : Location Map of Sand/Gravel Deposits and Rock Quarry*	Disagree	One of the proposed sources for sand (B Pak Houng) is the channel and terrace downstream of the dam. We believe it to be questionable whether removing sediment from the channel downstream of the dam during construction is wise, given that the sediment supply is likely to be reduced once the dam is complete, which at best will greatly lengthen the time necessary for the sediment lost to be replaced by transport from upstream. At worst, the lost sediment may not be replaced until sediment storage in the reservoir reaches equilibrium.
5-31	*Sand and gravel deposits are generally common in Mekong River where the gradient is low.*	Agree	Recognises that sand and gravel deposits are common features of the Mekong. It follows that they are important for morphology and habitat as well as being a potential natural resource. Further, the fact that the Developer recognises that sand and gravel are deposited 'where the gradient low' indicates that they must agree that a reduction in water surface gradient upstream of the dam is bound to reduce sediment transport capacity and result in the deposition of sand and gravel in the reservoir.
5-31	*Ban Pak Houng: This site is about 8 km downstream from the dam site. Mostly the sediment deposit in this area is sand and found in two different types as:* • *Sand deposits in the channel (Mekong River) as sand bar,* • *Sand deposits as terrace which is normally 0.2 to 0.5 m above the level of sand bar.*	Agree	It is correct to note that sediment provides both in-channel (sand bar) and terrace (and floodplain) features along the river.

Page	Text*	Agree/ Disagree	SEC Comment(s)
6-1	*River, such as stream flow, water level and suspended sediment load, as well as meteorological information at some selected stations have been collected for the feasibility study*	Agree	It is appropriate that sediment transport records from selected hydrometric stations have been accessed, but notable that no additional measurements of sediment load specific to the project reach are being recorded at the gauging stations related to the project. No explanation is given for this omission. The decision not to collect detailed sediment data must be considered in the context of the limited data available for suspended load concentrations and annual loads in the Mekong (see Table 6.1 of the Feasibility Report). Monitoring sediment transport prior to and during construction is required to meet PDG, as is monitoring following implementation.
7-1	*Sediment sluices were foreseen, incorporated in the power house.*	Agree	Incorporation of sluices shows that the Developer recognises that there will sediment issues at Xayaburi.
7-9	*Flow available for power generation computed deducting from the river flow the water used for navigation, fish passing and sand flushing, according to the following preliminary assumptions:* • *Water used for Fish Passing & Navigation: 20 m^3/s (constant)* • *Water used for Sand Flushing: impacts on the river flow according to the graph of Figure 7-5. More elaborate criteria for the use of water for fish passing and sand flushing purposes have been developed for the final energy production estimates, as illustrated in the following Paragraph 7.6.*	Agreed	It is agreed that flow available for power generation must be computed by deducting from the river flow water used for navigation, fish passing and sand flushing. However, in the opinion of the SEG, additional flow will need to be allocated to manage sediment by sediment routing and draw down flushing.
7-33	*It was considered that all sand flushing operations and the operation of the fish passing facilities off the flood season can be concentrated in the night time.*	Disagree	The MRC-PDG makes it clear that sediment routing is preferable to sediment flushing because it mimics the natural seasonality of sediment transport. Also, with the current design, the only sediment management that can be accomplished would be pressure flushing of deposited sediment immediately in front of the power house. Sediment management will require draw down flushing as well as pressure flushing and this cannot be accomplished overnight. It may require sediment management operations that persist for several days at a time.

Page	Text*	Agree/ Disagree	SEC Comment(s)
7-35	*The total energy production, including the excess energy, as shown in the Annex A5, is computed without taking into account the flow lost because of the assumed night operation of the fish passing facilities and of the sediment flushing outlets. Because it is not possible at the present level of the studies to provide a realistic estimate of the flow used for these purposes, total energy production figures are not shown.*	Agree	Although this statement seems inconsistent with Table 7.2, the SEG agrees that firm figures for power generation cannot be produced until the flows needed to support sediment management measures and operations have been established. Also, the SEG notes that overnight pressure flushing can only remove sediment deposited immediately in front of the power house. To be effective, sediment management will also require draw down flushing for several days at a time and this will affect power generation.
8-13	*no sediment data are presently available…….*	Agree	The SEG agree with the Developer that practically no sediment data are presently available for the proposed Xayaburi Dam site and reservoir reach. Detailed design cannot proceed without sediment data, yet no detailed sediment data collection is proposed for the next phase. Hence, we recommend that the Developer implement a sediment data collection programme.
8-13	*during the site visits carried out it was noted that the Mekong River is sand and silt laden, also in dry season.*	Disagree	We agree with the Developer that the Mekong is sand and silt laden. However, while sediment is transported year round, it is significant that concentrations and volumes of sediment transported are FAR higher during the monsoon season than they are during the dry season.
8-13	*It shall thus be expected that the sediment flushing outlets will be operating quite frequently. It is considered that the outlets shall be operated in night time, off the primary and secondary energy production hours. This would allow opening the outlets even on a daily basis if needed, without sacrificing the revenues of the project.*	Agree	Plans for frequent (nightly) operation of the flushing conduits suggest they are intended to act as pressure flushing facilities. However, pressure flushing will only be effective in removing sediments close to the power house and cannot be used to flush nor route sediment that is prone to settling out in the reservoir some kilometres upstream of the dam.
11-12	*The Project can provide the following additional benefits to the Lao PDR and the Mekong region as the whole: (i) reservoir operation for power generation does not alter the flow regime as outflow equals to inflow, therefore, avoiding of water fluctuations and consequent bank erosion;*	Agree	Avoiding frequent and rapid changes in discharge through the dam will reduce the risk of bank erosion downstream related to changes in river stage (water surface elevation) and pore water fluctuations in the banks.
11-12	*and (iv) sediment passage to downstream with sediment sluices*	Disagree	Use of the sediment sluices will not ensure sediment passage to downstream as pressure flushing is effective only close to the power house intakes.

*Source: Xayaburi Dam Feasibility Report (2010)

ANNEX B. CUMULATIVE EFFECTS – TECHNICAL ASSESSMENT

B.1 Introduction

This annex contains background information that supports the main report as it relates to the review of the Xayaburi Dam's impact of sediment transport. This annex contains three main sections:

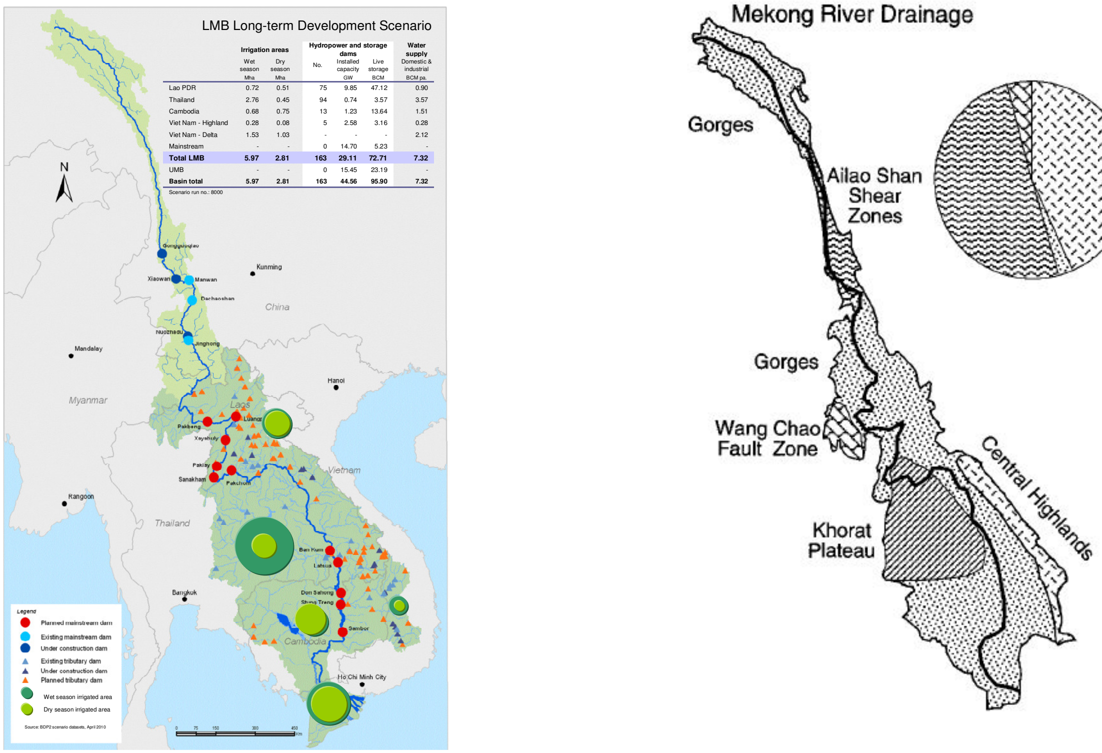
1. Sediment Yield
2. Transboundary Effects Assessment
3. Reservoir Sedimentation Management Options

B.2 Sediment Yield

Assessing potential transboundary effects due to the future presence of Xayaburi and other dams required an assumption regarding the magnitude and spatial distribution of sediment yield in the Mekong River Basin. Information to prepare an exact estimate of the spatial distribution of sediment yield is not available, nor was the amount of time required to execute such an analysis. Various authors, including Walling (2005, 2008), Walling and Fang (2003), and Wolanski *et al*. (1996) estimated the sediment yield for the Mekong River at the Delta. These estimates range from 120 to 180 Mt/yr. For purposes of this analysis it was assumed that the total sediment load in the Mekong River amounts to about 160 Mt/yr (Kummu and Varis 2006). The spatial distribution of sediment sources and the relative amounts of sediment yielded by each were estimated using research by others.

Clift *et al*. (2004) provides an overview, from a geologic perspective, of the principal sediment sources in the Mekong River Basin. From that study it appears that there are two principal sediment sources, plus one smaller source of sediment (Figure B.1). The Ailoa Shear Zone in China and the Vietnamese Central Highlands are the two most important sources of sediment. The Ailoa Shear Zone, combined with the Tibetan Highlands (which provides only a small portion of the overall sediment load) contributes about 43% of the total Mekong River sediment. The other major source, i.e., the Vietnamese Central Highlands, produces about 52% of the total sediment load; while the Wang Chao Fault Zone produces about 5%. Based on the assumed value of 160 Mt/year for the total Mekong River Basin and the source identification by Clift *et al*. (2004), it is assumed that the sediment discharge from each major source is as shown in Table B.1.

When relating these sediment sources to the existing and planned projects in the Mekong River Basin, it is noted that the Ailoa Shear Zone and the Tibetan Gorges are essentially upstream of the Manwan Dam. This provides an approximate way to quantify the sediment load to the Chinese dams. Downstream of the Chinese border the first source of sediment, the Wang Chao Fault Zone, is located upstream of Pakbeng Dam site. The estimated sediment load to the planned six mainstream dams in Laos is, therefore, predominantly determined by whatever sediment load passes the China border added to the sediment load originating from the Wang Chao Fault Zone. Downstream of Pak Chom Dam site the next sediment source, i.e., the Vietnamese Central Highlands, is the principal contributor of sediment to the dams in the lower part of the Mekong River, commencing with Ban Kum Dam site. This means that the sediment load to these dams can be estimated as the sum of the amount of sediment passing the last of the six dams in Laos and the sediment originating from the Central Highlands.



LMB Long-term Development Scenario

	Irrigation areas		Hydropower and storage dams			Water supply
	Wet season Mha	Dry season Mha	No.	Installed capacity GW	Live storage BCM	Domestic & industrial BCM pa.
Lao PDR	0.72	0.51	75	9.85	47.12	0.90
Thailand	2.76	0.45	94	0.74	3.57	3.57
Cambodia	0.68	0.75	13	1.23	13.64	1.51
Viet Nam - Highland	0.28	0.08	5	2.58	3.16	0.28
Viet Nam - Delta	1.53	1.03	-	-	-	2.12
Mainstream	-	-	0	14.70	5.23	-
Total LMB	**5.97**	**2.81**	**163**	**29.11**	**72.71**	**7.32**
UMB	-	-	0	15.45	23.19	-
Basin total	**5.97**	**2.81**	**163**	**44.56**	**95.90**	**7.32**

Scenario run no.: 8000

Source: BDP2 scenario datasets, April 2010

Figure B.1. The Mekong River Basin showing mainstream dams and sediment yield by source (from Clift et al. (2004)).

Table B.1. Assumed sediment yield from principal sediment sources in the Mekong River Basin for purposes of assessing transboundary effects.

Location	Geology / Region	% of Sediment	Total Load (Mt/yr)	Notes	Other Estimates
Upstream of Manwan Dam	Ailoa Shear Zone and Tibetan Gorges	43%	69.0	Largest portion of sediment load originates from shear zone.	90 to 100 Mt/yr*; 45.8 Mt/yr**; 85 Mt/yr***
From Manwan Dam to Pak Chom Dam	Wang Chao Fault Zone and rest of catchment	5%	8.0	Wang Chao Fault Zone contributes slightly more than the entire low sediment yield catchment. Rough estimate places it at about ten times the specific sediment yield of the low-yield part of the catchment (rough ratioing of areas).	10 to 25 Mt/yr*
Downstream of Pak Chom Dam	Central Highlands, Khoral Plateau and rest of catchment	52%	83.0	Central Highlands is second largest sediment source to Mekong. Khoral Plateau is assumed to contribute very low loads.	30 to 72 Mt/yr*

Notes:

* SYKE. 2010. Origin, fate and impacts of the Mekong sediments. Finnish Environment Institute.

** Fu, K. and He, D. 2007. Analysis and prediction of sediment trapping efficiencies of the reservoirs in the mainstream of the Lancang River. Chinese Science Bulletin, Science in China Press, Springer.

*** You, L.Y. 1999. A study of temporal changes of river sedimentation in Lancang River Basin. *Sci.Geogr. Sin.* (in Chinese), 54 (supp.).

B.3 Transboundary impacts assessment

The base case and five alternative future views of development in the Mekong River Basin were assessed. The alternative future views are known as the Definite Future 2015, Definite Future plus six Lao PDR dams, and three scenarios of the Foreseeable Future. Each of these is described in the following sub-sections. Section B.3.3 summarizes the results and relates the impact of Xayaburi Dam to the rest of the systems of proposed dams.

B.3.1 Approach

It is noted that the sedimentation assessment is based on available information and previous work by others. The Brune curve (see e.g., Annandale (1987)) was used to estimate the amount of sediment captured by each dam. The combined effect of sediment trapping by multiple dams was estimated using a mass balance approach. The amount of sediment that might originate between dams was estimated by simple proportioning. This was necessary for assessing the sedimentation in the reservoirs planned for Cambodia. The assumed proportioning is based on judgment due to time and data limitations.

B.3.2 Baseline Case and Alternative Future Views

B.3.2.1Scenario 1: Baseline – 2000

The Baseline – 2000 Case consists of the three existing mainstream dams in China plus fifteen Tributary Dams in the part of the Mekong River Basin downstream of the China border (the Lower Mekong Basin (LMB)). The estimated amount of sediment trapped in the three Chinese reservoirs is shown in Table B.2. The second column in the table contains the estimated amounts of sediment flowing into the different reservoirs. It is noted, as indicated before, that the Manwan Dam is located at approximately the lower end of the Ailoa Shear Zone, which produces almost all the sediment originating in China. Therefore, the amount of sediment flowing into Dachaoshan Reservoir was estimated as the total sediment yield of 69 Mt/yr less the amount of sediment estimated to deposit in Manwan Reservoir (41.6 Mt/yr). A similar estimate is made for the amount of sediment flowing into Jinghong Reservoir.

Table B.2. Baseline case: estimated average annual amount of sediment trapped by Chinese reservoirs.

Dam	Sediment Load from Catchment (Mt/yr)	Cumulative Sediment Load from Catchment (Mt/yr)	Based on Fu and He Approach			
			Trap Efficiency	Trap (Mt/yr)	Through (Mt/yr)	Sum Trap (Mt/yr)
Manwan	69	69	0.603	42	27	42
Dachaoshan		27	0.571	16	12	57
Jinghong		12	0.543	6	5	64

The trap efficiency estimate for Manwan Dam is based on measurements reported by Fu and He (2007). Based on these measurements, an equation for the Brune curve proposed by Fu and He (2007) was calibrated to calculate the amount of sediment that may be trapped by Dachaoshan and Jinhong Reservoirs. It is noted that the gross storage (i.e., the sum of the active and the dead storage) of Manwan Reservoir (gross storage volume for Manwan Reservoir was obtained from Fu and He (2007)) was used in this review to calibrate the equation proposed by Fu and He (2007). This value was used because it more accurately estimates the residence time than when using the active storage volume. It is also the approach followed by Brune to calculate residence time.

The sediment trap efficiency equation that was found when using the Manwan Reservoir gross storage volume for calibration is:

TE=1−??0.064??????V/Q????

where *TE* = trap efficiency; *V* = gross reservoir storage volume (km^3); *Q* = mean annual flow into the reservoir (km^3/yr); and *V/Q* = residence time (yr).

The rest of the table is self-explanatory, showing the amount of sediment trapped per year and the amount of sediment passing through the dam. The last column contains the cumulative amount of sediment stored in the three reservoirs on average per year.

For assessment of the Tributary Dams, it is noted that they could potentially affect discharge of sediment from two sources, i.e., the Wang Chao Fault Zone and the Vietnamese Central Highlands. None of the Tributary Dams are downstream of the Wang Chao Fault Zone. This means that none of the Tributary Dams will reduce sediment yield into the Mekong River from the Wang Chao Fault Zone. This sediment will, therefore, continue to flow into the Mekong River unhindered.

The only significant reduction in sediment load to the Mekong River due to the presence of Tributary Dams is from dams located immediately downstream of the Vietnamese Central Highlands, For the Baseline Case only five or so Tributary Dams are located downstream of the Central Highlands. It is also noted not all rivers draining the Central Highlands contain dams for the Baseline Case. The total estimated amount of sediment trapped by the fifteen Tributary Dams in the LMB is about 13 Mt/yr (Table B.3). Of the fifteen dams, only three were deemed to have significant trap efficiency (Kummu *et al.* 2009).

Table B.3. Estimate of approximate amount of sediment trapped in reservoirs with significant trap efficiency for the Baseline Case.

Dam	Trap Efficiency	Annual Flow (km^3/yr)	Annual Flow (m^3/s)	Assumed Sediment Load (Mt/yr)	Trapped Mass of Sediment (Mt/yr)
Nam Ngum	0.91	20.4	647	5.1	4.6
Se Kong	0.29	9.98	316	2.495	0.7
Se San	0.73	41.12	1,304	10.28	7.5
Total:			2,267	17.875	12.9

Note: Average sediment concentration, assume: 250 mg/l

B.3.2.2Scenario 2: Definite Future – 2015

The Definite Future – 2015 view consists of all eight planned and existing mainstream dams in China and twenty-six Tributary Dams downstream of the China border. Assuming that all the Chinese dams are in place, an estimate of the upper limit of the amounts of sediment that may be retained by each of the Chinese dams is shown in Table B.4.

Should all the Chinese dams be in place at once, an estimate of the time for the cascade of reservoirs to become filled with sediment is shown in Table B.5. The reservoirs are deemed to be filled with sediment when the total storage, i.e., both the dead and live storage, has been replaced by sediment. Only after the dams have been completely filled with sediment will the sediment delivery downstream resemble natural conditions. The table indicates that the expected time for the entire cascade to fill with sediment will likely be very long, on the order of hundreds of years. The amount of sediment trapped by the twenty-six Tributary Dams is estimated at about 23 Mt/yr (Table B.6).

Table B.4. Definite Future – 2015: estimated amounts of trapped sediment for proposed and existing mainstream dams in China*.

Dam	Sediment Load from Catchment (Mt/yr)	Cumulative Sediment Load from Catchment (Mt/yr)	Based on Fu and He Approach			
			Trap Efficiency	Trap (Mt/yr)	Through (Mt/yr)	Sum Trap (Mt/yr)
Gongguoqiao	23	23.0	0.499	11.5	11.5	11
Xiaowan	46	57.5	0.911	52.4	5.1	64
Manwan		5.1	0.603	3.1	2.0	67
Dachaoshan		2.0	0.571	1.2	0.9	68
Nuozhadu		0.9	0.904	0.8	0.1	69
Jinghong		0.1	0.543	0.0	0.0	69
Ganlanba		0.0	0.000	0.0	0.0	69
Mengsong		0.0	0.000	0.0	0.0	69

Note: *MRC indicated that construction of the Mengsong Dam may be postponed indefinitely. It has been included in this analysis for purposes of being complete.

Table B.5. Definitive Future – 2015: estimated indicative times for reservoirs in the Chinese cascade to fill with sediment.

Dam	Gross Reservoir Volume (km^3)	Time to Fill Reservoirs with Sediment (yr)
Gongguoqiao	0.51	51
Xiaowan	19.80	500
Manwan	1.01	500+
Dachaoshan	0.94	500+
Nuozhadu	24.60	500+
Jinghong	1.14	500+

Ganlanba	0.24	500+
Mengsong	0.24	500+

Table B.6. Approximate estimate of amount of sediment trapped by tributary dams for Scenario 2 (Definite Future – 2015).

River	Catchment Area (km^2)	Mean Annual Flow (km^3 • yr^{-1})	Active Volume (km^3)	Gross Volume* (km^3)	No. Of Dams	Retention Time (year)	Trap Efficiency (Brune)	Sediment Yield (Mt/yr)	Sediment Trapped (Mt/yr)
Nam Chi	49,067	29.52	0.002	0.004	3	0.000	0.00	7	0
Nam Kam	3,506	4.67	0.000	0.000	1	0.000	0.00	1	0
Nam Mang	1,788	3.17	0.045	0.090	1	0.028	0.62	1	0
Nam Mun	70,827	4.58	0.002	0.004	3	0.001	0.00	1	0
Nam Ngum	17,169	20.73	4.700	9.400	1	0.453	0.90	5	5
Nam Ou	26,130	19.48	0.016	0.032	3	0.002	0.00	5	0
Nam Phuong	3,420	5.41	0.000	0.000	1	0.000	0.00	1	0
Nam Theun	14,894	15.36	0.015	0.030	1	0.002	0.00	4	0
Se Done	7,730	7.11	0.001	0.002	2	0.000	0.00	2	0
Se Kong	28,766	29.59	0.649	1.298	1	0.044	0.69	7	5
Se San	18,684	41.12	0.794	1.588	5	0.039	0.67	10	7
Sre Pok	31,079	28.99	0.951	1.902	3	0.066	0.75	7	5
Total:			7.175	14.350	25			52	23

Note: Average suspended sediment concentration assumed: 250 mg/l; *Assumed as twice the active volume.

B.3.2.3Scenario 3: Definite Future plus Six Lao PDR Dams

The Definite Future plus Six Lao PDR Dams consists of all the China main stream dams, the 26 Tributary Dams and the six main stream dams that are planned for the Lao PDR. The estimated amounts of sediment to be trapped by the China main stream dams and the 26 Tributary Dams remain as shown in Table B.4 and Table B.6. The estimated amounts of sediment to be captured by the six Lao PDR dams are shown in Table B.7.

It is noted that the median Brune curve was used to estimate the trap efficiency of the facilities for the six reservoirs in Laos. This is done for reasons of being conservative in estimating the effects of reservoir sedimentation on both the facilities and for determining the remaining sediment load in the river. The estimated average annual remaining sediment load in the Mekong River just downstream of the last Lao PDR main stream dam, taking account of the dams in China and the six dams in Laos, is about 0.7 Mt/yr.

B.3.2.4Scenario 4: Foreseeable Future Scenario (i)

Foreseeable Future Scenario (i) contains all planned and existing mainstream dams in China and seventy-one Tributary Dams downstream of the China border. The sedimentation characteristics of the Chinese dams are exactly the same as those indicated for Definite Future – 2015 (Table B.4).

Appropriate information for estimating the sediment trap efficiency of the seventy-one Tributary Dams were not available to the reviewer at the time when this review was executed. From maps showing the locations of existing and planned dams in the Vietnamese Highlands it is estimated that between 60% and 70% of the sediment producing area is controlled by dams. The amount of sediment captured by these dams was therefore set equal to 65% of the total sediment load from the highlands, which is believed to be reasonable due to the cascading effect of many of the reservoirs.. This amounts to 54Mt/yr of sediment retained by the seventy-one reservoirs.

B.3.2.5 Scenario 5: Foreseeable Future Scenario (ii)

Foreseeable Future Scenario (ii) contains all planned and existing mainstream dams in China, six mainstream dams in Lao PDR, plus the seventy-one Tributary Dams. As before, the results for the Chinese dams are found in Table B.4 and Table B.5, and the estimated amount of trapped sediment for the seventy-one Tributary Dams remains at 54 Mt/yr. For the six mainstream dams in Laos Table B.7 shows the estimated average annual amounts of sediment that is expected to be trapped by the six dams in Lao PDR.

For the six mainstream dams in Laos the sediment load is the sum of the sediment flowing into the Mekong River from China and the sediment load that originates from the Wang Chao Fault Zone. No Tributary Dams are located between the Wang Chao Fault Zone and the most upstream of the six Lao PDR dams, i.e., Pak Beng Dam. Table B.7 shows the estimated average annual amounts of sediment that is expected to be trapped by the six dams in Lao PDR.

Table B.7. Foreseeable Future Scenario (ii): estimated amounts of trapped sediment by six mainstream dams in Lao PDR.

Dam	Sediment Load from Catchment (Mt/yr)	Inflowing Sediment (Mt/yr)	Median Brune Curve			
			Trap Efficiency	Trapped (Mt/yr)	Flow Through (Mt/yr)	Cumulative Trapped (Mt/yr)
Pak Beng	8.038	8.038	0.450	3.6	4.4	3.6
Luang Prabang		4.422	0.521	2.3	2.1	5.9
Xayabury		2.117	0.483	1.0	1.1	6.9
Paklay		1.093	0.334	0.4	0.7	7.3
Sanakham		0.729	0.002	0.0	0.7	7.3
Sangthong-Pakchom		0.727	0.000	0.0	0.7	7.3

B.3.2.6 Scenario 6: Foreseeable Future Scenario (iii)

Foreseeable Future Scenario (iii) contains all planned and existing mainstream dams in China, six mainstream dams in Lao PDR, five Cambodia dams, plus seventy-one Tributary Dams. The estimated effects of the Chinese dams and the seventy-one Tributary Dams remain unchanged for this scenario, as before. Assuming that all the mainstream dams in the LMB are in place, the estimated average amounts of sediment to be trapped in those reservoirs are presented in Table B.8. The estimated sediment load originating from the Vietnamese Central Highlands, as affected by some of the seventy-one Tributary

Dams, is the difference between the estimated sediment yield from the Central Highlands (83 Mt/yr) and the assumed amount of sediment trapped by the Tributary Dams (54 Mt/yr). The assumed distribution of the inflow of the remaining sediment into the lower LMB dams (from Ban Kum Dam downstream) is as shown in Table B.8. It is noted that some of the reservoirs in the lower LMB are so small that their trap efficiency is essentially deemed to be zero, leaving Sambor as the only dam that is expected to capture significant amounts of sediment in this part of the river.

Table B.8. Foreseeable Future Scenario (iii): estimated amounts of trapped sediment by eleven mainstream dams in the LMB.

Dam	Sediment Load from Catchment (Mt/yr)	Inflowing Sediment (Mt/yr)	Median Brune Curve			
			Trap Efficiency	Trapped (Mt/yr)	Flow Through (Mt/yr)	Cumulative Trapped (Mt/yr)
Pak Beng	8.038	8.038	0.450	3.6	4.4	3.6
Luang Prabang		4.4	0.521	2.3	2.1	5.9
Xayabury		2.1	0.483	1.0	1.1	6.9
Paklay		1.1	0.334	0.4	0.7	7.3
Sanakham		0.7	0.002	0.0	0.7	7.3
Sangthong-Pakchom		0.7	0.000	0.0	0.7	7.3
Ban Kum	14.53	15.3	0.000	0.0	15.3	7.3
Latsua	3.63	18.9	0.000	0.0	18.9	7.3
Don Sahong	3.63	22.5	0.000	0.0	22.5	7.3
Stung Treng	3.63	26.1	0.000	0.0	26.1	7.3
Sambor	3.63	29.8	0.450	13.4	16.4	20.7

B.3.3 Summary Results – Impact on Sediment Transport to Delta

A summary of the assessment results is shown in Table B.9, which compares the natural sediment load at the Delta (without development) to the Baseline Case and four alternative future views. The table presents average annual sediment loads and trapped sediment and, as such, is indicative of anticipated impacts. The time available for this review prevented consideration of system dynamics. However, the information provided in Table B.9 can be used for decision making and to determine the relative impact of Xayaburi Dam, which is the prime focus of this review.

Various studies on the trap efficiency of the reservoirs in the Mekong River have been performed and the accuracy of the estimates remain questionable (see e.g., Kummu *et al.* (2010)). This review, therefore, does not claim absolute accuracy. The intent with the analysis was to understand the relative impact of the various projects and to obtain some idea of the relative magnitude of the impact that the construction of dams might have on sediment yield in the Mekong River.

By acknowledging that the estimates made during this study are not accurate, another table is provided containing expected impact ranges (Table B.10). These estimates reflect the reviewer's uncertainty and are partly based on the calculations and partly on professional judgment.

As indicated in Scenario 2 (Definite Future – 2015), the effect of the Chinese dams on the sediment load in the Mekong River is expected to be substantial for several hundreds of years, once all the dams are in place. The anticipated amount of sediment to be removed from the Mekong River by the Chinese dams ranges from roughly about one third to almost one half of the total amount of sediment flowing on average into the Mekong Delta (Table B.10).

Table B.9. Summary sediment balance for baseline case and five alternative future views.

Sediment Source	Geology / Region	Natural Sediment Load (Mt/yr)	Trapped Sediment in Reservoirs											
			Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
			Baseline – 2000 (Mt/yr)		Definite Future – 2015 (Mt/yr)		Definite Future – 2015 + 6 Lao PDR Dams (Mt/yr)		Foreseeable Future Scenario (i) (Mt/yr)		Foreseeable Future Scenario (ii) (Mt/yr)		Foreseeable Future Scenario (iii) (Mt/yr)	
			Main	Tributary	Main	Tributary	Main	Tributary	Main	Tributary	Main	Tributary	Main	Tributary
Upstream of Manwan Dam	Ailoa Shear Zone and Tibetan Gorges	69	64		69		69		69		69		69	
From Manwan Dam to Pak Chom Dam	Wang Chao Fault Zone and rest of catchment	8					7				7		7	
Downstream of Pak Chom Dam	Central Highlands, Khoral Plateau and rest of catchment	83		13		23		23		54		54	13	54
Sub-total Trapped:			64	13	69	23	76	23	69	54	76	54	89	54
Total Trapped:			77		92		99		123		130		143	
Total Sediment Load to Delta:		160	83		68		61		37		30		17	

Table B.10. Ranges of estimated effects for the baseline case and five future views partly based on analysis and partly on expert opinion.

			Trapped Sediment in Reservoirs											
			Scenario 1		Scenario 2		Scenario 3		Scenario 4		Scenario 5		Scenario 6	
			Baseline – 2000 (Mt/yr)		Definite Future – 2015 (Mt/yr)		Definite Future – 2015 + 6 Lao PDR Dams (Mt/yr)		Foreseeable Future Scenario (i) (Mt/yr)		Foreseeable Future Scenario (ii) (Mt/yr)		Foreseeable Future Scenario (iii) (Mt/yr)	
Sediment Source	**Geology / Region**	**Natural Sediment Load (Mt/yr)**	**Main**	**Tributary**	**Main**	**Tributary**	**Main**	**Tributary**	**Main**	**Tributary**	**Main**	**Tributary**	**Main**	**Tributary**
Upstream of Manwan Dam	Ailoa Shear Zone and Tibetan Gorges	45%	35-40%		40-45%		40-455		40-45%		40-45%		40-45%	
From Manwan Dam to Pak Chom Dam	Wang Chao Fault Zone and rest of catchment	5%					5%				5%		5%	
Downstream of Pak Chom Dam	Central Highlands, Khoral Plateau and rest of catchment	50%		5-10%		10-15%		10-15%		20-30%		20-30%	10-35%	20-30%
	Sub-total Trapped:		35-40%	5-10%	40-45%	10-15%	45-50%	10-15%	40-45%	20-30%	45-50%	20-30%	55-85%	20-30%
	Total Trapped:		40-50%		50-60%		55-65%		60-75%		65-80%		75-100%	
	Total Delta Sediment Load:	100%	50-60%		40-50%		35-45%		25-40%		20-35%		0-25%	

It is noted that the combined effect of the tributary and mainstream dams in the LMB is expected to further remove between 35% and about 60% of the total amount of sediment available in the Mekong River. Although each of the individual facilities might only remove a small portion of the sediment flowing in the river, their combined effect is significant. This anticipated effect emphasizes the importance of responsible design and operation of all facilities.

The above facts require Lao PDR, Thailand, Vietnam, and Cambodia to construct and manage the existing and planned dams and reservoirs in a sustainable manner. This is necessary to ensure that adverse effects to the Mekong Delta are minimal by allowing as much of the sediment in the river as possible to flow to the Delta. This can best be accomplished if all the dams are constructed with the objective to pass sediment through their reservoirs. As such, it is possible to concurrently ensure infrastructure and natural resource sustainability, and minimise compensation payment to transboundary interests.

The estimated amount of sediment that might be trapped by Xayaburi Dam is on the order of about 1.0 Mt/yr. From an overall perspective this is a small amount of sediment. However, as previously indicated, when combined with the effects of other dams it jointly contributes to removing significant amounts of sediment from the Mekong River. By designing and operating Xayaburi Dam in a manner that will minimise the amount of sediment trapped by the facility it will contribute to reduce the effect on the remainder of the Mekong River and the Delta.

B.4 RESERVOIR SEDIMENTATION MANAGEMENT OPTIONS

B.4.1 Introduction

The World Bank commissioned development of the Reservoir Conservation (RESCON) approach to promote sustainable management of water resource infrastructure, particularly as it relates to reservoir sedimentation (Palmieri *et al*. 2003). The RESCON approach recommends adopting a ***life-cycle management and design approach*** in lieu of the conventional design life approach to infrastructure development. Adopting a life-cycle management and design approach provides sustainability benefits to both infrastructure and natural resources.

In the case of the infrastructure, the benefit of sustainable management is that it substantially increases the time period during which the infrastructure can be productively used, potentially in perpetuity. The benefit to the natural resource, particularly the river downstream of a dam, is that successful implementation of reservoir sedimentation management techniques (required to sustainably manage the infrastructure) can significantly reduce adverse impact normally associated with dams, such as adverse impacts to river geomorphology and nutrients.

Although a design life approach may be suitable for some kinds of civil infrastructure, such as roads, it is not deemed appropriate for large infrastructure systems, such as dams. The reason for this is that refurbishment of simpler infrastructure, such as roads, is relatively simple. At the end of their design life re-surfacing is fairly easy, ensuring the use of the infrastructure for periods longer than its design life; possibly in perpetuity.

However, in the case of dams such refurbishment is often not that simple, particularly not when the reservoir upstream of the dam is substantially filled with sediment at the end of its design life. From an operational point of view, it is very difficult to remove sediment from a reservoir, once filled with sediment. Decommissioning of such facilities provides serious challenges. Refurbishing reservoirs at the end of their design life, once filled with sediment, is not as straightforward as refurbishing other civil infrastructure, such as roads. It is for this reason that the World Bank promotes adopting a life-cycle management approach to design and operation of dams and their reservoirs, rather than the conventional design life approach (Palmieri *et al*. 2003).

The life-cycle management approach aims at designing and operating infrastructure in a manner enabling sustainable use. This means that the design should incorporate elements enabling maintenance for ensuring, in the ideal case, perpetual use of the infrastructure. With reservoir sedimentation the principal threat to dams and reservoir infrastructure sustainability, it means that dam designs should incorporate elements that will enable operators to implement and optimize reservoir sedimentation management in the long term.

Reservoirs upstream of dams fulfill many roles that are compromised when filled with sediment. Important roles include provision of storage and stilling basin functions. Depending on the project objectives, storage may be required for diurnal peaking, for seasonal balancing of water availability, and for long-term, multi-year carry-over storage. Additionally, reservoirs upstream of hydroelectric facilities can fulfill an important role in reducing the sediment concentration of water entering the power house intake. This reduces abrasion damage to turbines.

Once a reservoir is substantially filled with sediment, it can neither fulfill its storage role nor its role in reducing the sediment concentration of water entering the power house. This means that peaking abilities are compromised and that wet components of turbo-machinery are more exposed to the effects of abrasion damage. However, by regularly removing deposited sediment through reservoir sedimentation management techniques it is possible to retain a substantial amount of the original reservoir volume in perpetuity. Retaining most of the reservoir storage volume enables the infrastructure to fulfill its intended purpose in a sustainable manner for extended periods of time; preferably in perpetuity.

Apart from the need to sustainably manage water resource infrastructure (dams and their reservoirs) as it relates to sediment, it is also necessary to sustainably manage the natural resource, i.e., the river in which the dam and reservoir is built. The reduction of the amount of sediment that is passed through to the river downstream due to the presence of dams and their reservoirs can have significant adverse geomorphologic effects. In the case of the Mekong River, such effects can include increased bank erosion, increased river instability, and significant adverse effects to the Mekong Delta. Retention of sediment in the reservoir can also reduce the amount of nutrients in the river downstream of the dam.

By passing most of the sediment through the reservoir and preventing substantial loss of storage capacity due to reservoir sedimentation, it is concurrently possible to reduce the environmental impacts on the downstream river. By passing as much sediment through the reservoir and dam as can be practically achieved, it is possible to minimise adverse geomorphologic impacts and to maximize the amount of nutrients passed downstream. Reservoir sedimentation management, correctly implemented, therefore satisfies the needs of both natural resource and infrastructure sustainability.

B.4.2 The RESCON Approach

The RESCON approach (Palmieri *et al*. 2003) principally enables decision making as to whether sustainable water resource infrastructure management (reservoirs in particular) can be implemented on a particular project. The approach provides at a pre-feasibility level a means to identify reservoir sedimentation management techniques that are technically feasible and economically optimal. The RESCON analysis procedure compares the design life approach to the life-cycle management approach and identifies the economically optimal solution that is also technically feasible. The economic analysis considers intergenerational equity when identifying the economically optimal project approach.

The reservoir sedimentation management techniques considered by the RESCON approach include draw down flushing, hydro-suction, dredging, and dry excavation. Routing of sediments is not specifically listed in RESCON, but it is possible to analyze it by viewing it as a special kind of flushing.

The software does not allow analysis of pressure flushing, which is normally used to clear sediment in the area immediately in front of intakes.

Flushing and routing differ in purpose. Flushing aims at re-entraining already deposited sediment and discharging it in an unobstructed manner through the dam (Figure B.2). Routing, on the other hand, aims at maximizing the sediment transport capacity of the water flowing through the reservoir to enable passing as much of the incoming sediment through it as possible (Figure B.3).

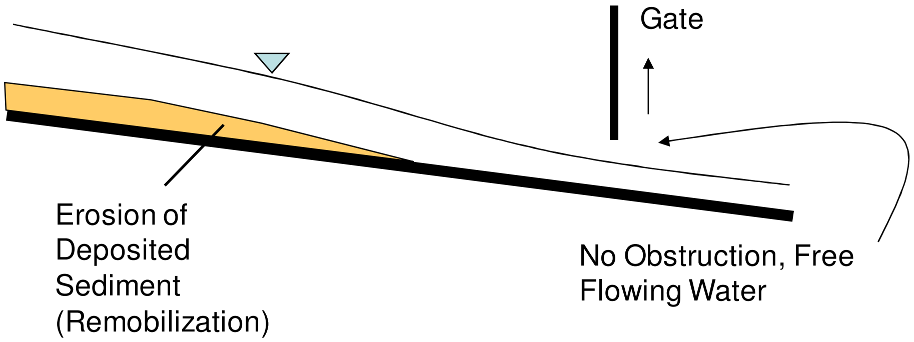


Figure B.2. The concept of flushing: drawing down the water surface elevation at the dam to create river-like flow conditions in the upstream reservoir that will re-entrain already deposited sediment and discharge it downstream of the dam. The flow conditions at the dam require that the flow and sediment passes the dam in an unobstructed manner.

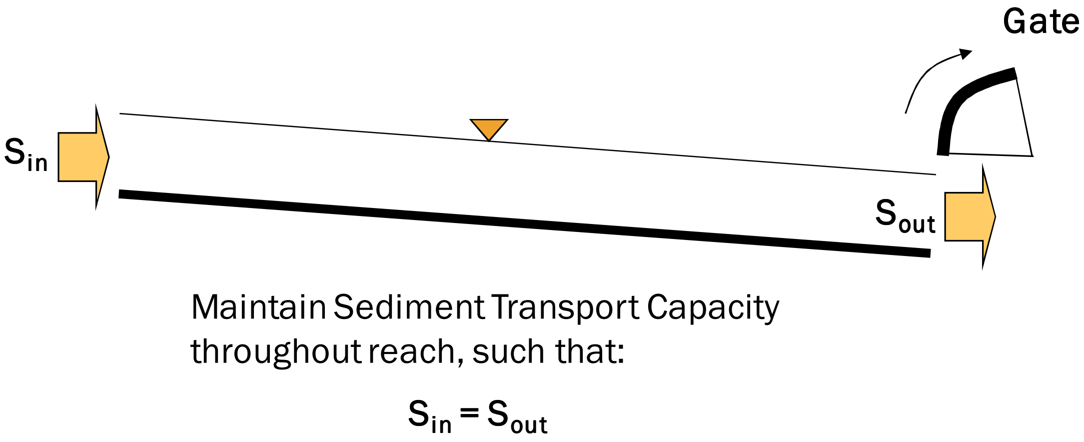


Figure B.3. Routing aims at maximizing the sediment transport capacity of the water flowing through the reservoir with the objective of passing as much of the incoming sediment through the reservoir as possible, without deposition.

To implement flushing, one aims at creating river-like flow conditions in the reservoir by drawing the water surface elevation at the dam down as low as possible and freely discharging the water downstream through the dam. The discharges associated with flushing are, therefore, usually smaller than what is possible with routing.

While the objective of routing is to maximize sediment discharge through the reservoir, the magnitude of routing flows are usually higher than flushing flows, as is the water surface elevation at the dam. For example, it may be possible to implement flushing by passing high flows through the dam spillway.

B.4.3 Preliminary Design Guidelines

The MRC-PDG lists a number of reservoir sedimentation management techniques. Pages 18 to 21 of the MRC-PDG describe sediment management measures that may be employed to avoid or mitigate potential sediment impacts. These include:

Upstream of the reservoir:

- *Sediment traps* (paragraph 110) – structures constructed in the river upstream of the reservoir to capture part of the sediment load.

In-reservoir:

- *Sediment routing* (paragraphs 99 through 101) – operating the dam to transport as much of the sediment load as possible through the reservoir for discharge downstream by maintaining high sediment transport capacity during the period when the sediment concentration and discharge are highest.
- *Sediment bypass channel* (paragraph 102) – *to* convey sediment around the reservoir and discharge it downstream. This means releasing sediment-laden water and impounding sediment free water.
- *Reservoir flushing* (paragraphs 103 through 108) – re-mobilizing previously deposited sediment in the reservoir and discharging it downstream of the dam. This is only feasible if river-like flow conditions can be re-created in the reservoir by drawing down the water surface elevation using low-level outlets that have the ability to pass free surface flows at very low elevations at the dam.

Localized sediment deposition:

- *Pressure flushing* – flushing deposited sediment through low-level conduits to keep intake structures clear and minimise the amount of sediment that passes through the turbines. This technique is usually implemented by maintaining a high water surface elevation at the dam (i.e., no need for reservoir draw down), while concurrently opening the low-level outlets.

Downstream of the dam:

- *Sediment augmentation* (paragraphs 112 through 115) – introducing sediment into the river downstream of the dam to replace the sediment trapped in the upstream reservoir and by so doing reduce the extent and intensity of adverse impacts caused by 'sediment hungry' water.

It is noted that most of the sediment management techniques recommended in the MRC-PDG can be analyzed with the RESCON approach. The only techniques that cannot currently be analyzed by the software are bypassing, pressure flushing, and sediment augmentation downstream of the dam. However, these were not found to be limitations as it relates to the assessment of Xayaburi Dam and Reservoir, as indicated in the next section.

B.4.4 Feasible Techniques for Xayaburi

The SEG reviewed the candidate sediment management techniques proposed in the MRC-PDG and concluded that the techniques feasible for implementation at Xayaburi Dam are routing, reservoir flushing, and pressure flushing. Routing and reservoir flushing could be used in tandem to reduce local and transboundary effects. Pressure flushing is only able to reduce the local effects of sediment accumulation immediately in front of the power house intakes.

Sediment traps upstream of the reservoir are not deemed feasible because of the high sediment load in the river and its high discharges. Such facilities, should they be constructed, would be major dams in their own right, which makes this approach infeasible.

Sediment bypassing is not deemed feasible due to its anticipated high cost. Implementation of this technique at Xayaburi Dam would require the use of a diversion structure upstream of the dam for diverting flows into a diversion tunnel that will run along the reservoir for discharging sediment during high floods downstream of the dam. Most of the bypass tunnels previously used to accomplish this goal are on the order of a few kilometers long. Examples include Asahi and Miwa Dams in Japan, that both have diversion tunnels that are on the order of about 3-km long. Xayaburi Dam would require a 100-km long tunnel, which is viewed as infeasible.

Sediment augmentation downstream Xayaburi Dam is not deemed feasible because the reservoir is too long. In order to accomplish such a goal is will be necessary to use a number of dredges throughout the reservoir to entrain deposited sediment and pump it downstream of the dam. The length of Xayaburi Dam makes this approach prohibitive.

The potential success for implementing routing and flushing at Xayaburi Dam was determined using the RESCON software.

The potential success for implementing pressure flushing at the power house intakes was already determined by the Developer by performing hydraulic model studies.

B.4.4.1 Routing and Flushing Criteria

Atkinson (1996) investigated a number of case studies of reservoirs where flushing was implemented, with and without success. Through this research, a number of criteria were established indicating the chances of successfully removing sediment from reservoirs by means of flushing. The criteria are presented in Table B.11.

Table B.11. Criteria for assessing potential flushing success in reservoirs (Atkinson 1996)

Criterion	Required
SBR	> 1
LTCR	preferably > 0.35
Guidelines	**Suggested**
DDR	> 0.7
FWR	> 1
TWR	~ 1
SBR_d	> 1

The criteria are defined as follows:

Sediment Balance Ratio (SBR) – the SBR is the ratio between the estimated amount of sediment that can be transported by the flushing flows through the reservoir divided by the average amount of sediment discharging into the reservoir. When this ratio is greater than 1, it implies that the amount of sediment that can potentially be removed from the reservoir is at least as large as the average amount of sediment discharging into the reservoir. Through the research it was found that if the SBR is greater than 1, it indicates that flushing might be feasible.

Long-term Capacity Ratio (LTCR) – the LTCR is the ratio between the estimated reservoir volume that can be retained in the long term when implementing a flushing strategy divided by the original reservoir volume. Atkinson (1996) set the limit for the LTCR at about 35%. It means that he considered flushing operations as having accomplished success if it was possible to maintain about 35% of the original reservoir capacity in the long term.

Draw Down Ratio (DDR) – the DDR is the ratio between the operating water level and the water level that can be accomplished with the flushing flows. It is expressed in terms of the height above the lowest level at the dam. The RESCON team viewed this as an additional guideline pointing towards potential success, but not a mandatory criterion. Atkinson (1996) found that if the DDR is greater than 0.7 it improves the chances of flushing success.

Flood Width Ratio (FWR) – the FWR is the ratio between the estimated bottom width of a flushing channel that might develop in the deposited sediment and the width of the natural river channel. If the FWR is less than 1, it means that the bottom width of the flushing channel is narrower than the width of the natural river channel. This then implies that it will not be possible to evacuate all sediment from the bottom of the original river channel. If the FWR is greater than 1, it means that the estimated width of the bottom of the flushing channel can be wider than the original river channel bottom width. Therefore, it may be possible to remove most of the sediment from the bottom of the channel.

Top Width Ratio (TWR) – the TWR is the ratio between the estimated top width of the flushing channel and the top width of the original natural river channel. Therefore, if the TWR is greater than 1, it means that most of the sediment that may have deposited on the overbanks of the original river channel may be removed by flushing. This indicates additional potential for success when implementing the flushing technique.

Sediment Balance Ratio at Maximum Draw Down (SBR_d) – the SBR_d is the ratio between the amount of sediment that can be transported through the reservoir when the maximum possible draw down has been achieved, divided by the amount of sediment that flows into the reservoir on average. As such, this guideline provides an indication of what might be possible. For example, an existing dam might not have low-level outlets. So, this guideline provides an indication as to whether flushing might be possible if a low-level outlet is installed at the lowest level. If the SBR_d is greater than 1, it provides additional information as to whether flushing might be successful.

B.4.4.2 Flushing Parameters for Xayaburi Dam

For the flushing simulations, it is assumed that the Developer will install low-level gates that can freely discharge the flushing flows through the dam, without obstruction. The invert of the gates is assumed at 230 m and the water surface elevation is set roughly equal to the tailwater elevation associated with the selected flushing discharge (using the rating curve provided by the Developer). The flushing discharge was set equal to 3,955 m^3/s for a duration of 5 days. It is recognized that the total flushing operation will last longer than 5 days, allowing time for draw down and refilling. An example of the input used in the RESCON analysis is shown in Table B.12.

Table B.12. Example of input data used to assess flushing potential at Xayaburi Dam.

(a) reservoir geometry

Parameter	Units	Description	Value
S_o	(m^3)	Original (pre-impoundment) capacity of the reservoir.	1,300,000,000
S_e	(m^3)	Existing storage capacity of the reservoir.	1,300,000,000
W_{bot}	(m)	Representative bottom width for the reservoir – use the widest section of the reservoir bottom near the dam to produce worst case for criteria.	600.0
SS_{res}		Representative side slope for the reservoir. 1 Vertical to SS_{res} Horizontal.	2.0
EL_{max}	(m)	Elevation of top water level in reservoir – use normal pool elevation.	275.0
EL_{min}	(m)	Minimum bed elevation – this should be the riverbed elevation at the dam.	230.0
EL_f	(m)	Water elevation at dam during flushing – this is a function of gate capacity and reservoir inflow sequence. Lower elevation will result in a more successful flushing operation.	243
L	(m)	Reservoir length at the normal pool elevation.	96,000
H	(m)	Available head – reservoir normal elevation minus river bed downstream of dam.	45.0

(b) water characteristics

Parameter	Units	Description	Value
V_{in}	(m^3)	Mean annual reservoir inflow (mean annual runoff).	125,229,456,000
Cv	(m^3)	Coefficient of Variation of Annual Run-off volume. Determine this from statistical analysis of the annual runoff volumes.	0.12
T	(ºC)	Representative reservoir water temperature.	20.0

(c) sediment characteristics

Parameter	Units	Description	Value
ρ_d	(tonnes/m^3)	Density of *in-situ* reservoir sediment. Typical values range between 0.9 -1.35.	1.20
M_{in}	(metric tonnes)	Mean annual sediment inflow mass.	2,000,000
Ψ	1600, 650, 300, 180	Select from: 1,600 for fine loess sediments; 650 for other sediments with median size finer than 0.1 mm; 300 for sediments with median size larger than 0.1 mm; and 180 for flushing with $Q_f < 50\ m^3/s$ with any grain size.	650
Brune Curve No	1 2 3	Is the sediment in the reservoir: (1) highly flocculated and coarse sediment, (2) average size and consistency, and (3) colloidal, dispersed, fine-grained sediment.	2
Ans	3 or 1	This parameter gives the model a guideline of how difficult it will be to remove sediments. Enter "3" if reservoir sediments are significantly larger than median grain size (d_{50}) = 0.1 mm or if the reservoir has been impounded for more than 10 years without sediment removal. Enter "1" if otherwise.	1
Type	1 or 2	Enter the number corresponding to the sediment type category to be removed by hydrosuction dredging: 1 for medium sand and smaller and 2 for gravel.	1

(d) removal parameters

Parameter	Units	Description	Value
HP	1 or 2	Is this a hydroelectric power reservoir? Enter 1 for yes; 2 for no.	1
Q_f	(m^3/s)	Representative flushing discharge. This should be calculated with reference to the actual inflows and the flushing gate capacities.	3,955
T_f	(days)	Duration of flushing after complete draw down.	5
N	(years)	Frequency of flushing events (whole number of years between flushing events).	1

With respect to the future supply of sediment flowing into the reservoir from upstream, two flushing situations are presented:

1. Situation 1: Sediment inflow is assumed at 69 Mt/yr as the upper limit; representing no reduction in sediment supply due to upstream trapping; and
2. Situation 2: Sediment inflow is assumed at 2 Mt/yr, representing the sediment impacts of trapping upstream.

For Situation 1, the reservoir will substantially fill with sediment in about 50 years with no flushing. With flushing, it is estimated that about 70% of the original reservoir volume can be retained in the long term. It is noted from Table B.13 that both the SBR and LTCR are greater than the criteria, indicating the flushing will likely be feasible.

Table B.13. Flushing parameters for Situation 1: sediment load = 69 Mt/yr.

Criterion	Required	Calculated
SBR	> 1	**7.29**
LTCR	Preferably > 0.35	**0.69**
Guidelines	**Suggested**	**Calculated**
DDR	> 0.7	0.70
FWR	> 1	1.34
TWR	~ 1	0.85
SBR_d	> 1	11.71

For Situation 2, the reservoir will require several hundred years to fill with sediment even if no flushing is implemented. It is also noted from Table B.14 that the criteria indicating potential flushing success have been met. The long-term capacity ratio remains the same for both situations. The only difference is that the long-term stable condition will take longer to be reached in Situation 2 than is the case for Situation 1.

Table B.14. Flushing parameters for Situation 2: sediment load = 2 Mt/yr.

Criterion	Required	Calculated
SBR	> 1	**251.42**
LTCR	Preferably > 0.35	**0.69**
Guidelines	**Suggested**	**Calculated**
DDR	> 0.7	0.70
FWR	> 1	1.34
TWR	~ 1	0.85
SBR_d	> 1	404.01

In summary, the RESCON analysis indicates that reservoir flushing is likely feasible at Xayaburi Dam. Final assessment requires more detailed investigations and design, to be performed by the Developer.

B.4.4.3 Routing Parameters for Xayaburi Dam

For the routing assessment, it was assumed that the water will be released through the current spillway. The magnitude of the routing flow was set at 10,000 m^3/s for a duration of 5 days. It is possible that the routing duration can be limited to 5 days because no draw down is required when implementing routing operations. The routing parameters for the two situations are presented in Table B.15 and Table B.16.

Table B.15. Routing parameters for Situation 1: sediment load = 69 Mt/yr.

Criterion	**Required**	**Calculated**
SBR	> 1	**14.50**
LTCR	Preferably > 0.35	**0.40**
Guidelines	**Suggested**	**Calculated**
DDR	> 0.7	0.38
FWR	> 1	2.13
TWR	~ 1	0.85
SBR_d	> 1	51.66

Table B.16. Routing parameters for Situation 2: sediment load = 2 Mt/yr.

Criterion	**Required**	**Calculated**
SBR	> 1	**500.09**
LTCR	Preferably > 0.35	**0.40**
Guidelines	**Suggested**	**Calculated**
DDR	> 0.7	0.38
FWR	> 1	2.13
TWR	~ 1	0.85
SBR_d	> 1	1,782.20

It is noted from the tables that both criteria are met and that two of the guidelines are not met. Our interpretation based on this information is that routing is a feasible sediment management technique. The analysis indicates that only about 40% of the original storage volume will be retained when implementing routing.

B.4.5 Recommendation

From the analysis, it is concluded that both flushing and routing are potentially feasible reservoir sedimentation management techniques. If flushing is implemented, more sediment will be removed than when routing is implemented. Long-term stable conditions for flushing are expected to tend to about 70% of the original reservoir volume, while it is expected to trend towards 40% of the original reservoir volume for routing.

Importantly, it is noted that the estimates for reaching stable conditions vary and depends on the level of upstream development. The time to reach stable conditions can vary from several decades to several hundreds of years. Therefore, the decision as to whether flushing or routing should be implemented may not be completely based on infrastructure sustainability only. It is important to consider the needs of resource sustainability when making such decisions. It is also pointed out that considerable uncertainty exists as to how much sediment might be captured by the Chinese dams.

It is our opinion that given the uncertainty and the needs for both infrastructure and natural resource sustainability that it is prudent to prepare a design that provides future generations of operators with the opportunity to manage sediment in the most effective way possible. Our recommendation is that the design of Xayaburi Dam should allow for both flushing and routing. If such a design is prepared it provides current and future generations to manage the reservoir in the most sustainable manner, while concurrently contributing to create conditions that will assist in maintaining a sustainable resource.

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ANNEX C. MODELLING

C.1 Introduction

The Mekong River Commission Secretariat (MRCS) Modelling Team developed a hydrodynamic model (in the ISIS software developed by Halcrow Water) for the Mekong mainstream between Chiang Saen and Pakse in 2006-2007. The modelling was aimed at mobile-bed sediment modelling and used the navigation chart survey combined with land topography to extract cross sections every 4 km. The model calibrated satisfactorily for major gauging sites. The utility of the model developed was recognised by Compagnie Nationale du Rhone (CNR) who used the data from an ISIS model to create a version with Hydrologic Engineering Center - River Analysis System (HEC-RAS) for the mainstream hydropower optimisation studies. For the studies performed for the Procedures for Notification, Prior Consultation and Agreement (PNPCA), it also offers an off the shelf facility that can be quickly used to study changes in flows, water levels, velocity and possibly sediment transport, and some water-quality parameters. A 1-km spacing model is close to finalisation and results will be updated to this standard.

Three-dimensional (3-D) modelling of three specific deep pools (near Luang Prabang, Midway to Xayaburi, and near the dam) is also underway and will be added to later updates of this Annex.

The Aims of the studies described here are:

1. To simulate and illustrate, using a fixed-bed hydrodynamic model limited to Chiang Saen to Xayaburi, the effect on water levels and velocity on the upstream pond should a level of 275 m be closely applied throughout the year at Xayaburi. The outputs of water level and velocity for a series of steady-state flows (1,000, 2,000, 5,000, 10,000, and 15,000 m^3/s) are shown in the expected area of backwater influence (including the river at Luang Prabang, around 100 km upstream of Xayaburi).
2. To simulate with a mobile-bed model the likely deposition of coarser sand/gravel size sediments (diameters larger than 63 microns) and in a separate simulation the likely deposition of finer sediments that make up the bulk of the sediment load at Xayaburi (diameters 2 to 63 microns). The effectiveness of the main spillway gates in flushing sediment deposits is also investigated through four flushing simulations:

    - Flushing Simulation I: Base case condition – operation at 275 m throughout the year opening gates as required to maintain level (turbines closed at this time);
    - Flushing Simulation II: Base case condition as per design with flushing of a few days per year (assumed 7 days occurring in July) as indicated by the Developer;
    - Flushing Simulation III: Alternative design of spillway gate with invert reduced closer to existing bed level (221-m sill level for gate assumed but 230 m may be sufficient – current design is 254 m) Fully opening the lowered spillway gates for 7 days as per Scenario II; and
    - Flushing Simulation IV: As Scenario III but opening lowered spillway lgates throughout August each year.

    These simulations were run for a period of 15 years using the recorded natural flows for the period 1985-2000. The recorded flow series and sediment rating curve were used, i.e. without modification to represent reductions in sediment input to the reservoir due to sediment trapping behind Chinese dams upstream. The Lancang dams will have effects on flows and sediment flux but are unlikely to affect the overall indication of results of the simulation, though future work could be undertaken specifically to try to take into account the effect of changes to the incoming sediment load.

3. In addition, a model run was completed to simulate the construction period where spillway gates are constructed and fully open and the river is closed by a cofferdam on the turbine house side of the river. It is expected that this situation will occur for a number of years during construction with potential for impact on sediment and fisheries especially during the dry season as river levels at the dam are raised 15 to 20 m.
4. Modelling of deep pools – using 3-D software (recognising the limitations of 1-D representation for complex features).

C.2 Results – Chiang Saen to Xayaburi Simulation of the Backwater and Velocity Effects of Raised Water Level

A fixed-bed hydrodynamic model of the 450-km reach from Chiang Saen (2,364 km) to Xayaburi (1,905 km) was extracted from the larger ISIS model to Pakse and modified to include the raising of water level at the dam to 275 m. This model was run for a series of steady flows and for the period 1985-2000. Luang Prabang is close to 100 km upstream of the site at 2,004 km. Note that river chainages are as used by the Developer and in earlier modelling but do not always coincide with those on navigation charts.

A comparison of velocities at each node in the model for steady flows of 1,000, 2,000, 5,000, 10,000 and 15,000 m^3/s are shown in Table C.1. The results show clearly a large reduction in velocity that occurs particularly in the dry season range of flow of 1,000 to 2,000 m^3/s, the backwater extending nearly 200 km at the lowest flow and velocity is halved at a location 140 km upstream (Figure C.1).

The effect on velocity of flow is similarly very high near the dam and still significant at Luang Prabang (location M2004). However, for the same flood event there remains a 0.4-m increase in flood level for the same event (at Luang Prabang). At a flow of 17,000 m^3/s Luang Prabang comes close to flood warning level and the Developer has indicated that gates would be fully opened near this flow to reduce the impact at Luang Prabang.

As it is clear that velocity decreases greatly far from the dam then there will be a tendency for siltation and settling of bed and suspended sediments. This has been simulated in the model as discussed in the next section. The siltation in the reservoir will raise flood water levels at Luang Prabang if not mitigated.

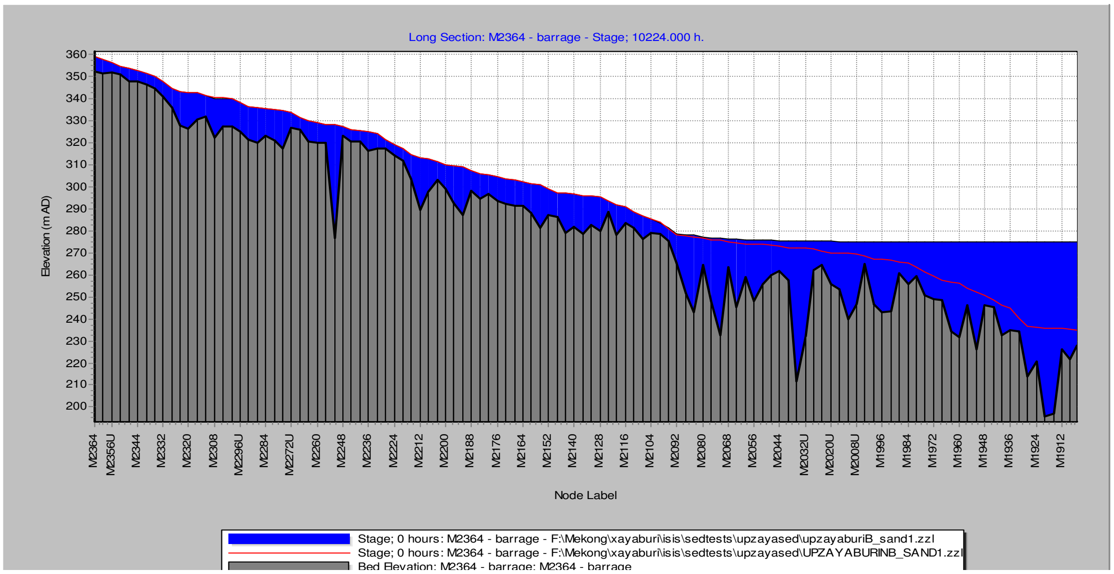


Figure C.1. Long section from Chiang Saen to Zayaburi for flow of 1,000 m^3/s (existing condition (red) and with dam showing 200 km zone of backwater influence (blue)).

Table C.1. Changes in section average velocities.

Section Average Velocities with and without Xayaburi Dam operating at 275 m AD

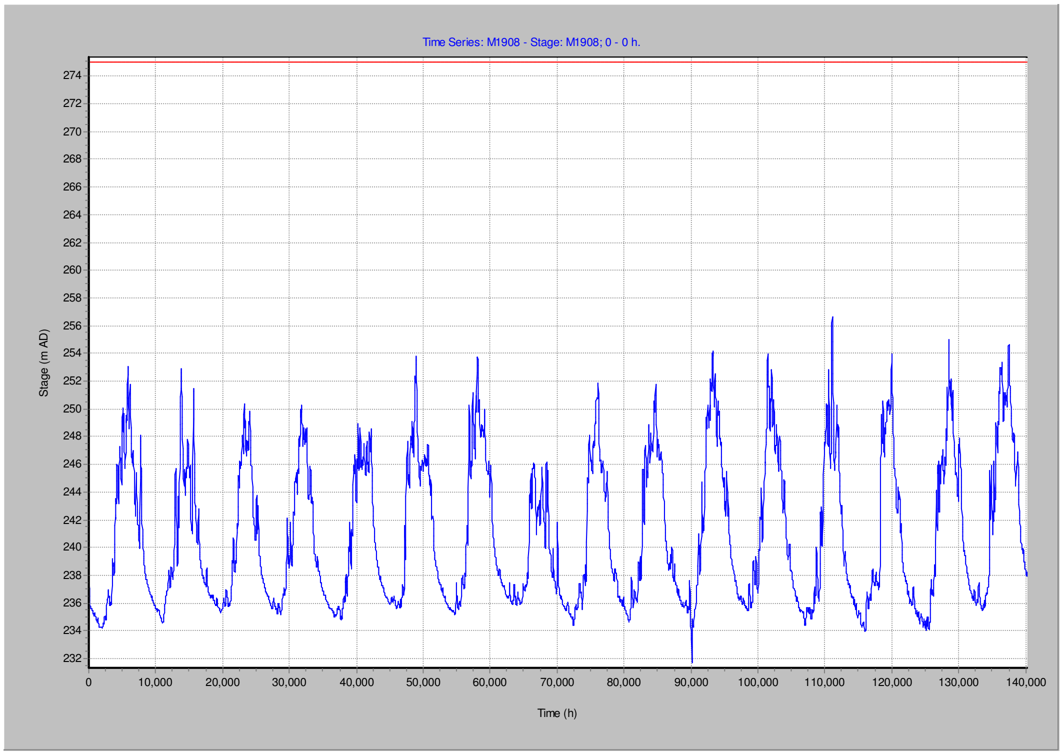
Velocities without and with Barrage for Specific Flows (locations indicate river distance in kilometers but note markers differ from Hydrographic Atlas see CNR Optimisation report)

Location	Velocity at 1,000 m^3/s			Velocity at 2,000 m^3/s			Velocity at 5,000 m^3/s			Velocity at 10,000 m^3/s			Velocity at 15,000 m^3/s			Notes
	Current	With Dam	V_d/V_b (%)	Current	With Dam	V_d/V_b (%)	Current	With Dam	V_d/V_b (%)	Current	With Barrage	V_d/V_b (%)	Current	With Barrage	V_d/V_b (%)	
M2100	1.065	1.066	100%	1.394	1.391	100%	1.835	1.829	100%							195 km upstream
M2096	1.745	1.728	99%	1.927	1.884	98%	2.1	2.085	99%							
M2092	2.213	1.834	83%	2.385	2.238	94%	2.526	2.492	99%							
M2088	0.789	0.65	82%	1.037	0.983	95%	1.469	1.447	99%							
M2084	0.419	0.36	86%	0.608	0.579	95%	0.979	0.966	99%							
M2080	1.843	1.195	65%	1.731	1.55	90%	1.808	1.745	97%							
M2076	0.572	0.477	83%	0.858	0.803	94%	1.267	1.233	97%							
M2072	0.295	0.258	87%	0.479	0.452	94%	0.849	0.834	98%							
M2068	1.767	1.056	60%	1.717	1.441	84%	1.759	1.69	96%							
M2064	0.462	0.349	76%	0.65	0.593	91%	0.987	0.956	97%							
M2060	1.061	0.713	67%	1.332	1.12	84%	1.75	1.67	95%							
M2056	0.363	0.299	82%	0.597	0.555	93%	1.146	1.116	97%							
M2052	0.61	0.407	67%	0.812	0.704	87%	1.286	1.226	95%							
M2048	0.547	0.368	67%	0.76	0.65	86%	1.242	1.175	95%							
M2044	1.156	0.587	51%	1.41	1.039	74%	2.017	1.809	90%	2.517	2.511	100%	2.961	2.981	101%	
M2040	0.639	0.313	49%	0.875	0.591	68%	1.377	1.148	83%	1.661	1.649	99%	1.961	1.969	100%	
M2036	0.157	0.119	76%	0.277	0.234	84%	0.569	0.517	91%	0.876	0.857	98%	1.126	1.113	99%	
M2032U	0.212	0.133	63%	0.331	0.258	78%	0.621	0.546	88%	0.884	0.857	97%	1.093	1.074	98%	
M2032D	0.214	0.134	63%	0.332	0.259	78%	0.623	0.547	88%	0.885	0.858	97%	1.094	1.075	98%	
M2028	0.803	0.256	32%	0.853	0.474	56%	1.116	0.873	78%	1.289	1.197	93%	1.453	1.397	96%	
M2024	1.618	0.246	15%	1.583	0.469	30%	1.363	0.909	67%	1.381	1.257	91%	1.533	1.463	95%	
M2020U	0.685	0.225	33%	0.91	0.443	49%	1.296	0.985	76%	1.721	1.578	92%	2.079	1.98	95%	
M2020D	0.692	0.227	33%	0.915	0.446	49%	1.298	0.987	76%	1.723	1.58	92%	2.081	1.981	95%	
M2016	0.701	0.18	26%	0.966	0.353	37%	1.181	0.776	66%	1.362	1.211	89%	1.586	1.489	94%	

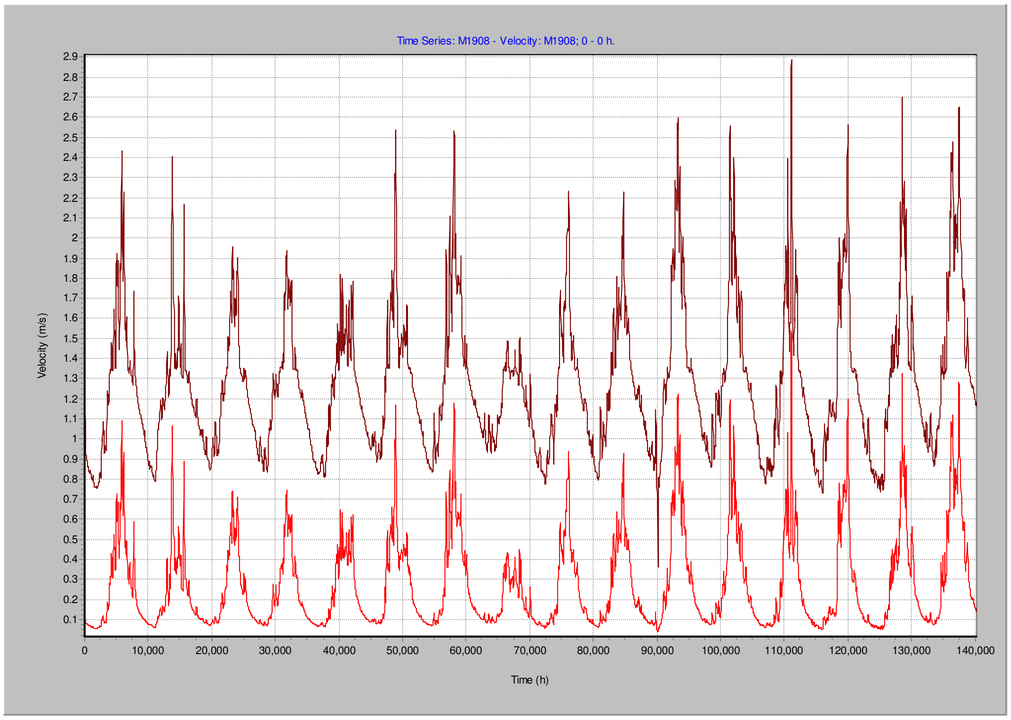
Location	Velocity at 1,000 m^3/s			Velocity at 2,000 m^3/s			Velocity at 5,000 m^3/s			Velocity at 10,000 m^3/s			Velocity at 15,000 m^3/s			Notes
	Current	With Dam	V_d/V_b (%)	Current	With Dam	V_d/V_b (%)	Current	With Dam	V_d/V_b (%)	Current	With Barrage	V_d/V_b (%)	Current	With Barrage	V_d/V_b (%)	
M2012	0.661	0.182	28%	0.919	0.359	39%	1.203	0.812	67%	1.507	1.322	88%	1.79	1.663	93%	
M2008U	0.359	0.149	42%	0.58	0.295	51%	0.972	0.683	70%	1.319	1.146	87%	1.589	1.463	92%	
M2008D	0.363	0.151	42%	0.583	0.297	51%	0.974	0.685	70%	1.32	1.147	87%	1.59	1.464	92%	
M2006i	0.401	0.152	38%	0.622	0.3	48%	1.011	0.694	69%	1.357	1.168	86%	1.629	1.49	91%	Luang Prabang
M2004	0.45	0.154	34%	0.671	0.303	45%	1.057	0.704	67%	1.398	1.189	85%	1.674	1.519	91%	Luang Prabang
M2002i	0.514	0.155	30%	0.737	0.307	42%	1.113	0.715	64%	1.447	1.213	84%	1.725	1.552	90%	Luang Prabang
M2000	0.616	0.157	25%	0.838	0.31	37%	1.19	0.726	61%	1.505	1.24	82%	1.784	1.59	89%	
M1996	0.368	0.147	40%	0.602	0.292	49%	1.052	0.698	66%	1.487	1.247	84%	1.851	1.665	90%	
M1992	0.348	0.101	29%	0.517	0.201	39%	0.809	0.479	59%	1.058	0.85	80%	1.282	1.123	88%	
M1988	1.073	0.155	14%	1.204	0.308	26%	1.516	0.736	49%	1.813	1.3	72%	2.076	1.706	82%	
M1984	0.432	0.1	23%	0.607	0.2	33%	0.924	0.484	52%	1.222	0.885	72%	1.456	1.197	82%	
M1980	1.348	0.138	10%	1.402	0.275	20%	1.655	0.668	40%	1.973	1.224	62%	2.223	1.651	74%	
M1976	0.957	0.088	9%	0.763	0.175	23%	1.017	0.429	42%	1.27	0.807	64%	1.496	1.119	75%	
M1972	1.506	0.121	8%	1.233	0.242	20%	1.557	0.595	38%	1.932	1.129	58%	2.263	1.578	70%	
M1968	2.34	0.133	6%	2.684	0.266	10%	2.709	0.657	24%	2.584	1.269	49%	2.938	1.805	61%	
M1964	0.527	0.091	17%	0.757	0.182	24%	1.267	0.451	36%	1.591	0.884	56%	1.961	1.287	66%	
M1960	0.585	0.077	13%	0.865	0.153	18%	1.285	0.381	30%	1.448	0.749	52%	1.758	1.093	62%	
M1956	2.824	0.091	3%	3.194	0.182	6%	2.794	0.452	16%	2.289	0.889	39%	2.562	1.3	51%	
M1952	0.546	0.085	16%	0.965	0.171	18%	1.575	0.425	27%	1.896	0.842	44%	2.275	1.243	55%	
M1948	1.013	0.067	7%	1.291	0.133	10%	1.58	0.332	21%	1.877	0.657	35%	2.154	0.969	45%	
M1944	1.521	0.065	4%	1.361	0.129	9%	1.392	0.322	23%	1.739	0.638	37%	2.075	0.944	45%	
M1940	1.42	0.062	4%	1.719	0.123	7%	1.661	0.308	19%	1.954	0.612	31%	2.213	0.908	41%	
M1936	1.879	0.061	3%	2.53	0.122	5%	2.624	0.304	12%	2.197	0.606	28%	2.349	0.901	38%	
M1932	2.764	0.061	2%	2.664	0.122	5%	1.538	0.304	20%	1.741	0.606	35%	2.067	0.904	44%	
M1928	0.619	0.039	6%	0.843	0.079	9%	0.902	0.197	22%	1.043	0.393	38%	1.245	0.587	47%	
M1924	1.28	0.075	6%	1.797	0.15	8%	1.758	0.375	21%	2.092	0.748	36%	2.525	1.119	44%	
M1920	0.254	0.046	18%	0.432	0.093	22%	0.659	0.232	35%	0.99	0.464	47%	1.287	0.695	54%	

Location	Velocity at 1,000 m^3/s			Velocity at 2,000 m^3/s			Velocity at 5,000 m^3/s			Velocity at 10,000 m^3/s			Velocity at 15,000 m^3/s			Notes
	Current	With Dam	V_d/V_b (%)	Current	With Dam	V_d/V_b (%)	Current	With Dam	V_d/V_b (%)	Current	With Barrage	V_d/V_b (%)	Current	With Barrage	V_d/V_b (%)	
M1916	0.287	0.05	17%	0.47	0.1	21%	0.701	0.251	36%	1.061	0.502	47%	1.387	0.752	54%	
M1912	0.485	0.039	8%	0.625	0.078	12%	0.691	0.195	28%	0.958	0.389	41%	1.211	0.583	48%	
M1908	0.873	0.074	8%	1.203	0.148	12%	1.365	0.369	27%	1.935	0.738	38%	2.459	1.107	45%	
barrage	0.646	0.036	6%	0.712	0.072	10%	0.727	0.179	25%	1.015	0.358	35%	1.281	0.537	42%	

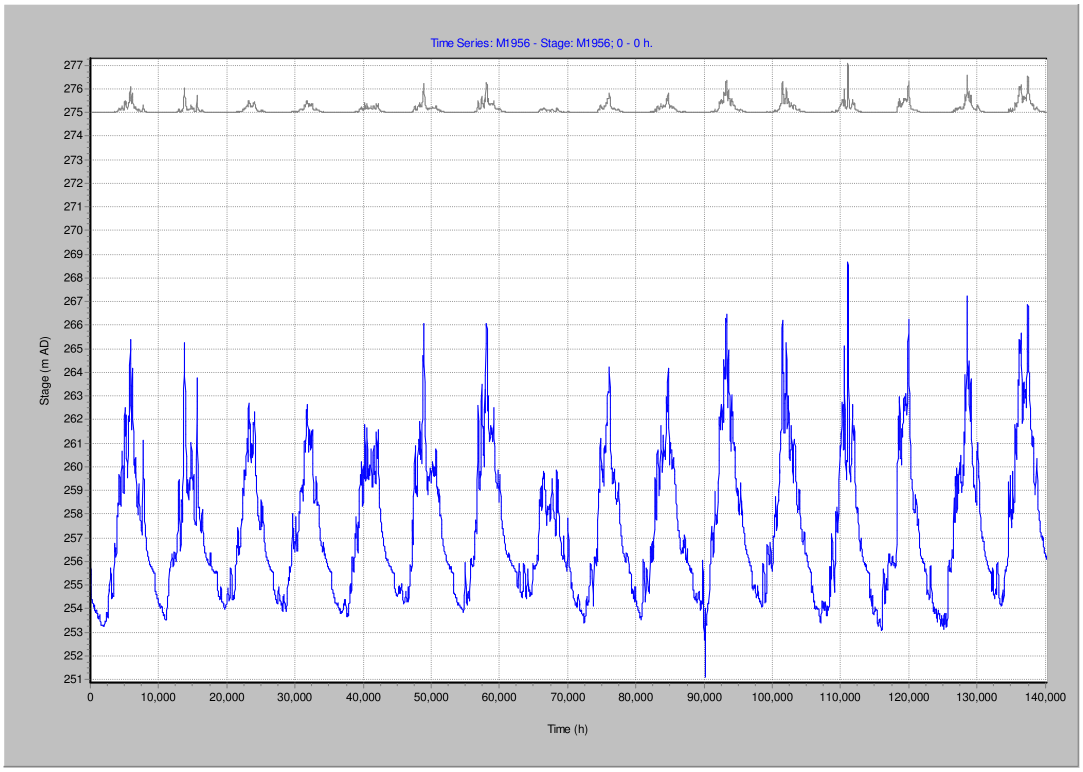
Note: V_d = velocity with dam; V_b = baseline velocity without dam.



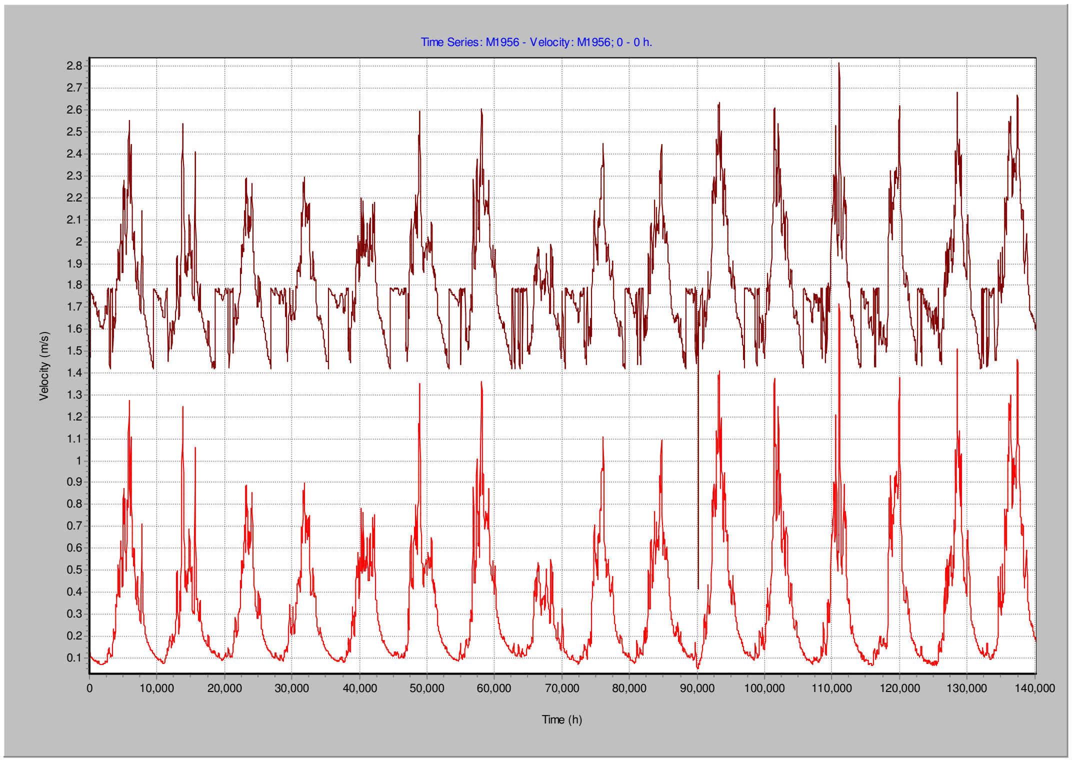
(a) water level 1 km upstream of Xayaburi for the period 1985-2000 flow series with and without dam



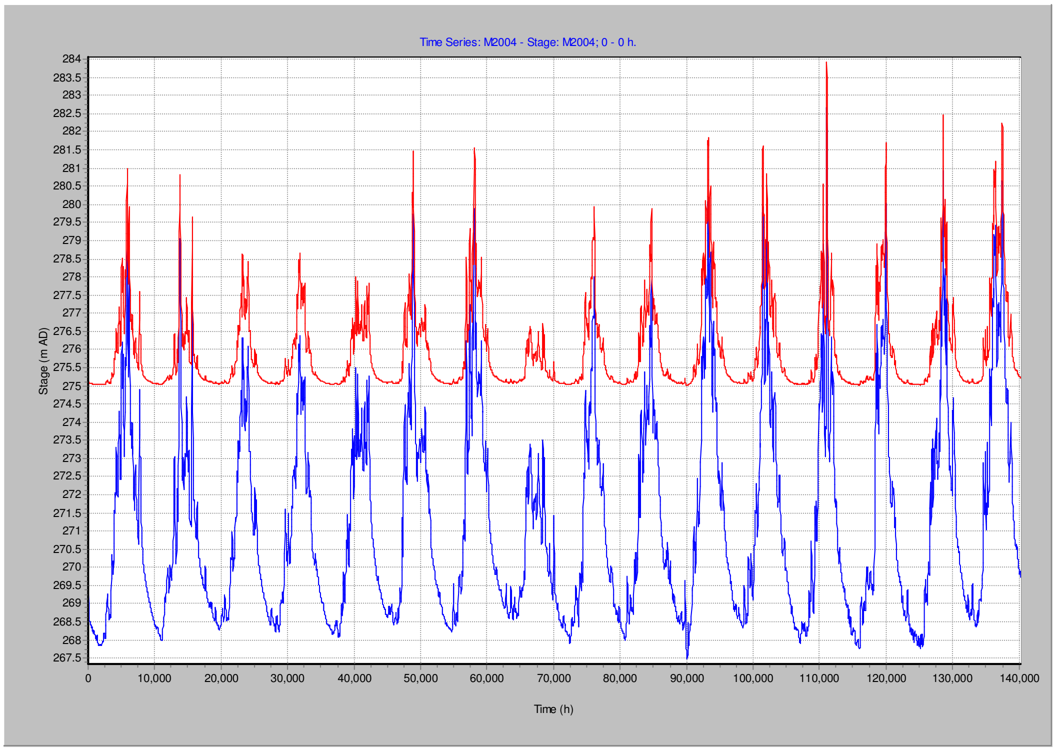
(b) velocity 1 km upstream with (brown) and without dam (red), 1985-2000 time series



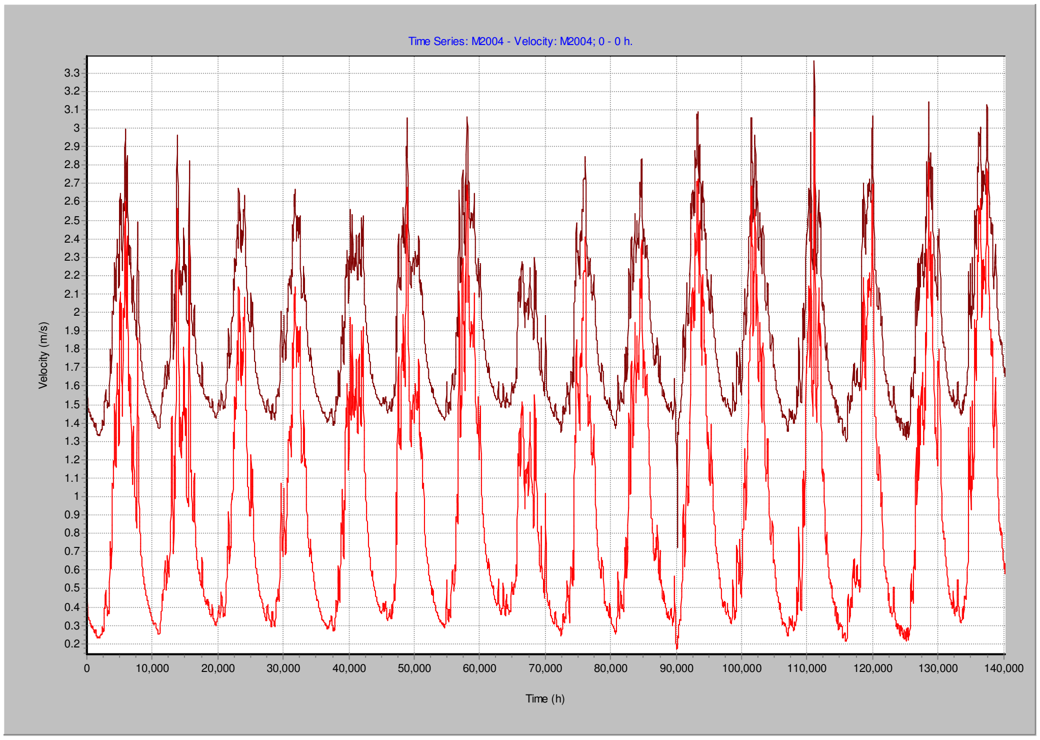
(c) water level 50 km upstream of Xayaburi for the period 1985-2000 flow series with and without dam



(d) velocity 50 km upstream with (red) and without dam (brown), 1985-2000 time series



(e) water level change Luang Prabang 100 km upstream of dam (note 7-m increase in dry season water level – MRC flood warning level is 285 m), 1985-2000 time series



(f) velocity change 100 km upstream at Luang Prabang (lower velocity with dam)

Figure C.2. Results from hydrodynamic model with dam constant level of 275 m showing water-level and velocity changes.

C.3 Chiang Saen to Xayaburi 1-D Mobile-bed Unsteady Simulation of the Effect of Gate Design and Operation on Likely Sedimentation for Silt and Sand/Gravel Fractions

The unsteady model used for the backwater simulations was set-up to investigate likely sediment trapping in the reservoir associated with different operating regimes, and potential options for passing or flushing sediment that would otherwise accumulate in the reservoir.

Flow regimes that were modelled using the 15-year natural flow sequence (1985-2000) were:

Simulation i: base condition (no dam),
Simulation ii: operation of dam continuously at 275-m pond level,
Simulation iii: operation of dam as proposed by Developer and 1 week opening of gates per year for flushing,
Simulation iv: as iii. but with lowered spillway sill elevation from 254 m to circa 230 m (1 week flushing per year),
Simulation v: as iv. but with spillway gates fully opened for a full month (August), and
Simulation vi: dam as proposed by Developer during construction with spillway gates all fully open, but no flow through power house side of the channel.

The effectiveness of the sand flushing gates below the turbines is likely to be only localized, as discussed elsewhere in this report. Once the reservoir pond is drawn down in level, the capacity of the long conduits of the sand flushing sluices will be very much less than their nominal capacity due to their small size and thus are not included in the simulation for the purposes of the sediment modelling but it is recognised that they may play some part in sizing of the lowered spillway gates.

The fine silt size sediment (< 63 µm) behaves differently to the larger sand and gravel size sediments and must be simulated using different transport, settling, and erosion formulae. Fortunately the ISIS sediment model is able to simulate this size fraction but what is required is an understanding of the sediment grading of material in transport. The data needed for this are being collected as a priority in the recently started MRCS Flow and Sediment measurement project but as yet there is no new information available. Both size fractions are clearly in transport primarily as a supply-limited wash load in the geologically constrained bed rock channel at Xayaburi.

To estimate the sand fraction at Xayaburi, a simulation of the alluvial reach between Vientiane and Nakhon Pranom for which bed size grading is known was undertaken. The sediment transport rate required to maintain stability in this alluvial reach just downstream of the bedrock-constrained reach upstream of Vientiane was then estimated from the long-term transport predictions given by the modelling. An indicative rating derived using the best estimate of bed material size grading and the Ackers White sediment transport equation in the model is shown in Figure C.3. This gives an average discharge of sand size sediment of around 2 Mt/yr.

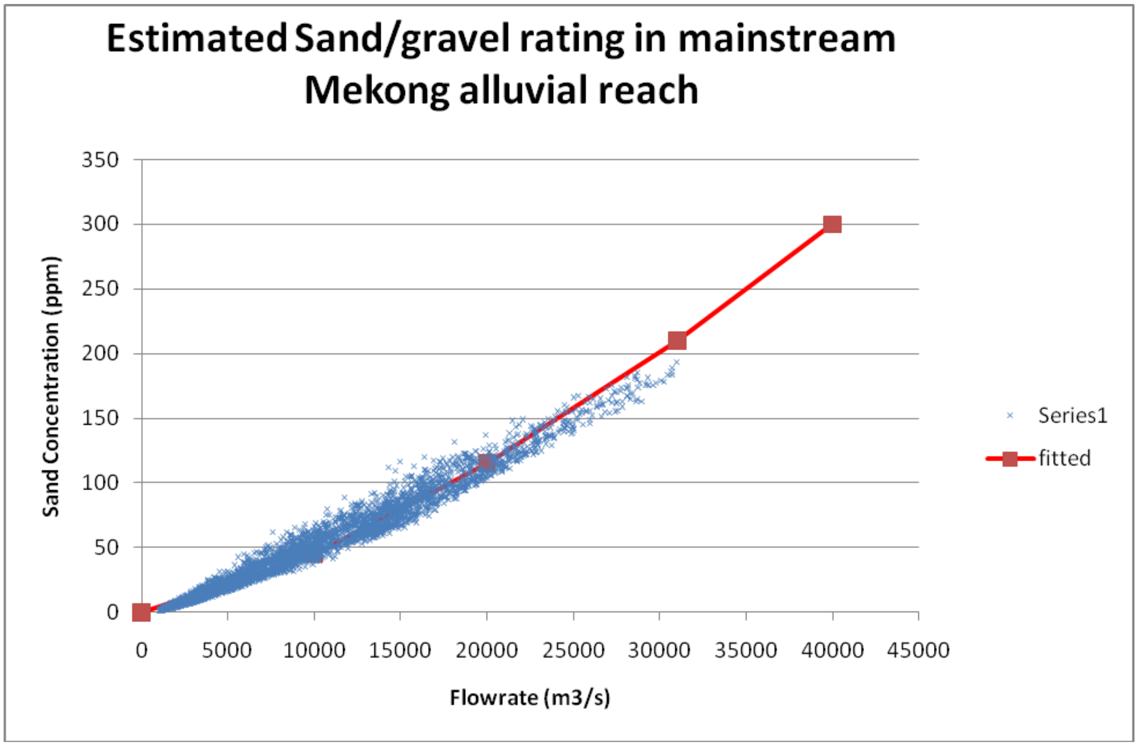


Figure C.3. Estimated rating curve for sand/gravel transport.

If this rating for the sand/gravel fraction is compared with the total suspended solids at Chaing Saen, then it can be seen (even allowing for the increase in flow between Chaing Saen and Vientiane) that a much higher total of fine material load is transported as shown in Figure C.4. It is possible that sand and gravel proportions are higher than estimated as the equilibrium transport is dependant on the size grading but this is unlikely to affect the overall behaviour simulated and can be refined in future work.

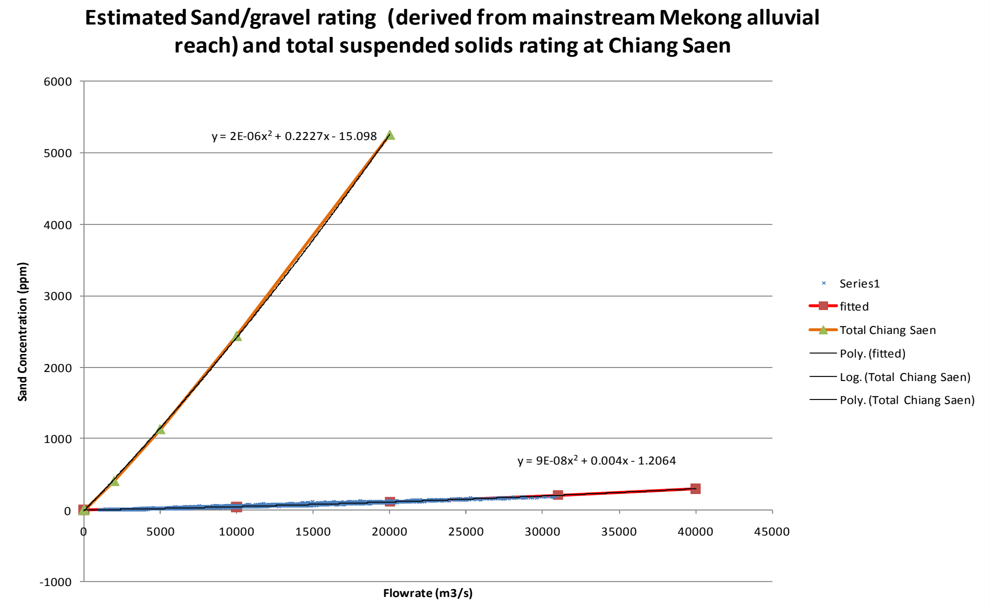


Figure C.4. Total suspended solids Chiang Saen compared with expected sand/gravel concentration at Vientiane.

Using the above relationships, the model from Chiang Saen to Xayaburi was run in mobile-bed mode with each model run separately for silt and for sand/gravel. In river sediment modeling, it is common to ignore the silt fraction as this commonly is purely a 'wash load' that does not utilise significant energy of the river and is supply limited. In this case, as the silt fraction is so much bigger than the sand/gravel loads, this is still a reasonable assumption that the different loadings behave differently without too much interaction though clearly the settlement of the fine loads in the quiescent conditions of reduced velocity behind the Xayaburi Dam is a primary concern and thus simulation of this part is needed. Of necessity, the existing bed was set at fixed and non-erodible in the model. Although there are some parts of the reach upstream of Xayaburi that have certain depths of sediment deposit on the rock bed, the thickness and composition of these is not known and is unlikely to significantly change model findings. The baseline condition is thus of little interest except to confirm that under natural conditions there is very little or no sedimentation at the cross sections for the loadings and hydraulic conditions modelled.

C.3.1 Simulation ii: Basic Operation of Xayaburi at 275-m Constant Head

This flow regime used in this simulation represents the Xayaburi Dam as currently designed in place and operating without any significant drawdown for reservoir flushing.

Under this condition, there is significant siltation upstream of a large proportion of both the silt and sand fractions. The model estimates that 96% of the sand/gravel fraction is deposited primarily in the reach, reducing mean annual load of sands and gravels from 1.9 Mt/yr to only 75,000 tonnes/year immediately downstream of the dam. The silt load is predicted to reduce from 70 Mt/yr to 23 million tonnes or 67% trapping. Within the 15-year series due to the rapid siltation and higher bed, the trapping reduces towards the end of the simulation period as can be seen in the concentration plot in Figure C.5.

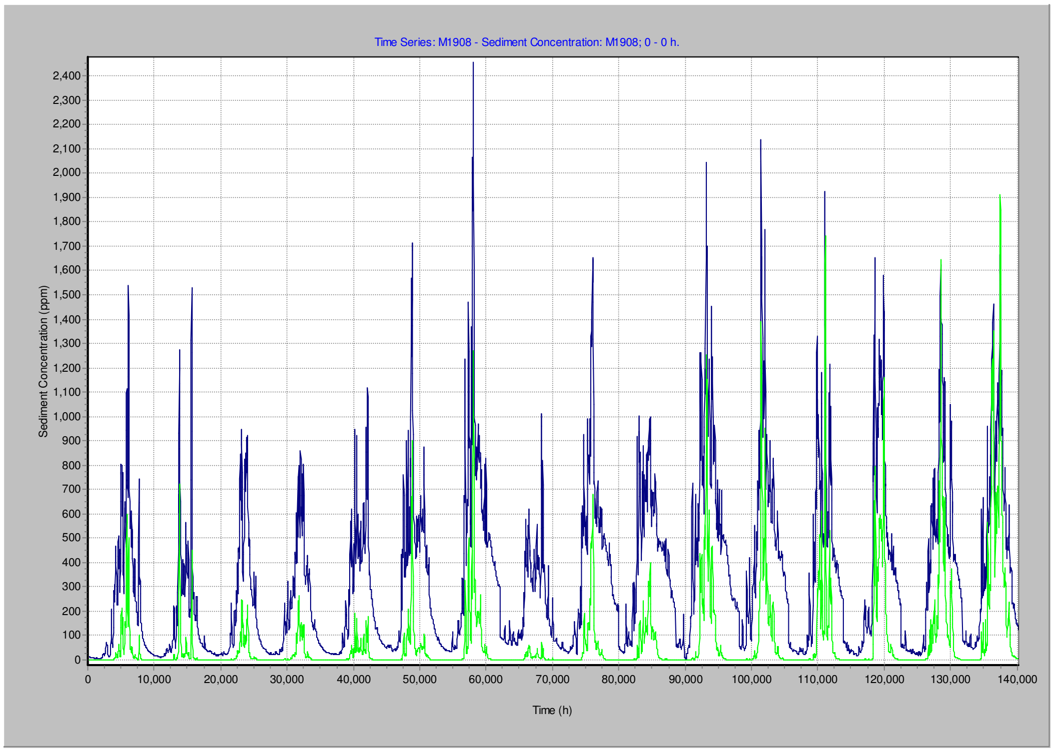


Figure C.5. Silt concentrations at Xayaburi Dam site (ppm) with (green) and without dam (black), Simulation ii, 1985-2000 time series.

The changes in bed level upstream are primarily due to the heavy deposition of silts that can be expected and these are deposited downstream of Luang Prabang in a progressive manner with the deepest siltation nearer the dam. Sand and gravel, however, can be transported to the mid reach as illustrated in Figure C.6.

The maximum depths of silt deposit exceed 10 m after 15 years and is particularly heavy in the pool areas. The density of fine silt deposits is assumed to be high (and similar to sand/gravel) in the simulation though in reality the density of deposited finer material is generally lower initially and takes time to consolidate. The fine deposits thus may 'fill up' the reservoir faster than simulated as a given mass of sediment may occupy a larger volume. Experience of the Lancang reservoirs would greatly help to determine such parameters though it can be noted that similar depths of deposit have been experienced near the Manwan and Dachauwan Dams. If sediment loads are reduced by the upper dams then siltation would be slower but show similar trends.

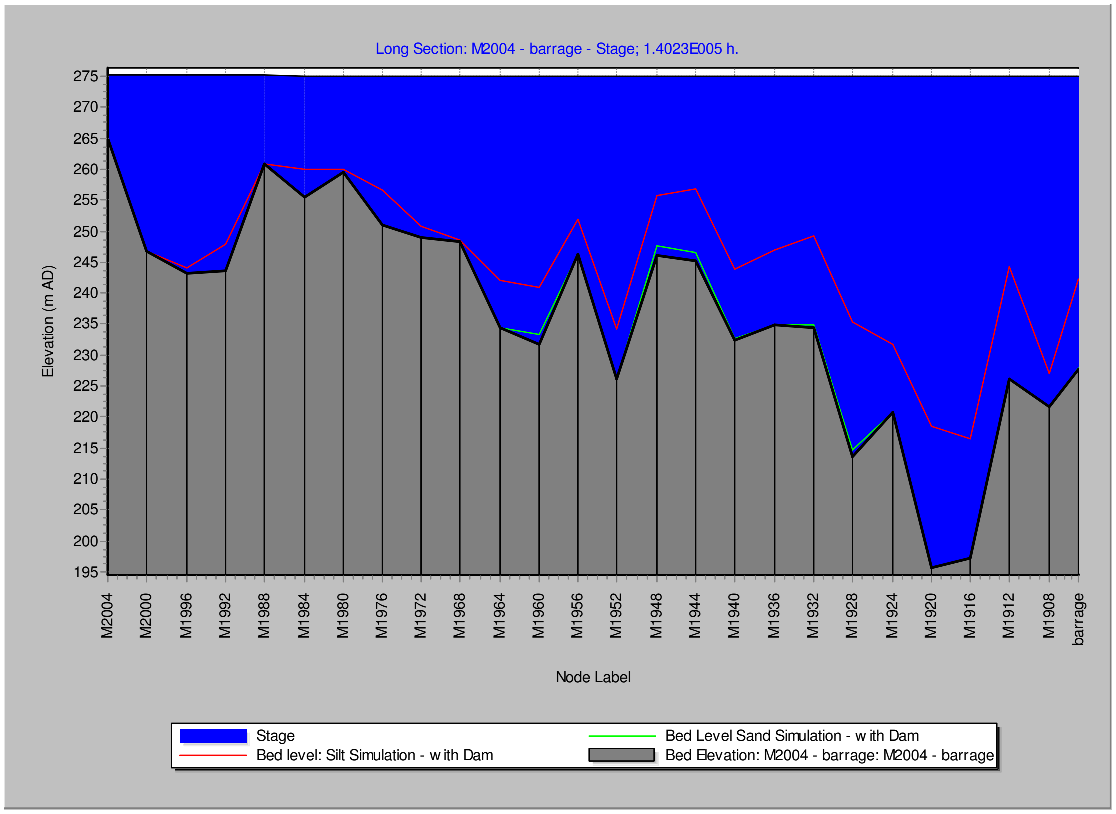


Figure C.6. Long section of predicted deposition of silt (red) and sand (light blue) fractions after 15-year Simulation ii: no flushing, Luang Prabang to Xayaburi. Note deposits of more than 10 m thickness near dam.

C.3.2 Simulation iii: Flushing for 7-day Period Using Developer Gates Fully Open

The effect of a yearly 7-day period of fully open gates during the wet season (July) was tested in the model. It is believed that this is the type of operation indicated by the Developer at meetings held. Again, this was simulated for silts and sand transport.

It was noted that drawing down the reservoir from 275 m to the level with gates fully open (around 260 m) takes time and is likely to add extra days each side of the flushing period together with a danger of creating a sudden drop in flow during the filling period as illustrated in Figure C.7.

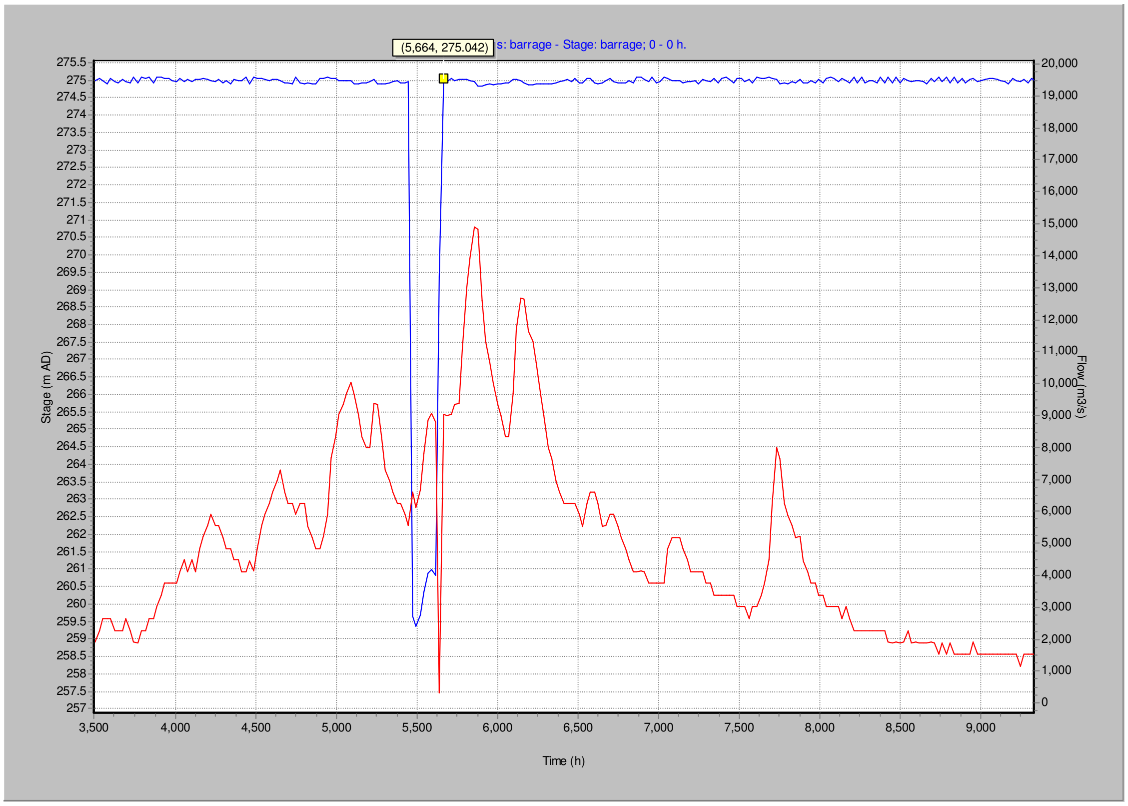


Figure C.7. Draw down of reservoir during 7-day flushing period with gates as proposed by Developer. One year of operation water level on left axis (blue) and flow on right axis (red).

The effectiveness of the operation can be judged by the change in silt accumulation as shown in Figure C.8. As can be seen, differences are not large and thus the effectiveness of the current gate design and potential flushing period cannot be expected to be effective.

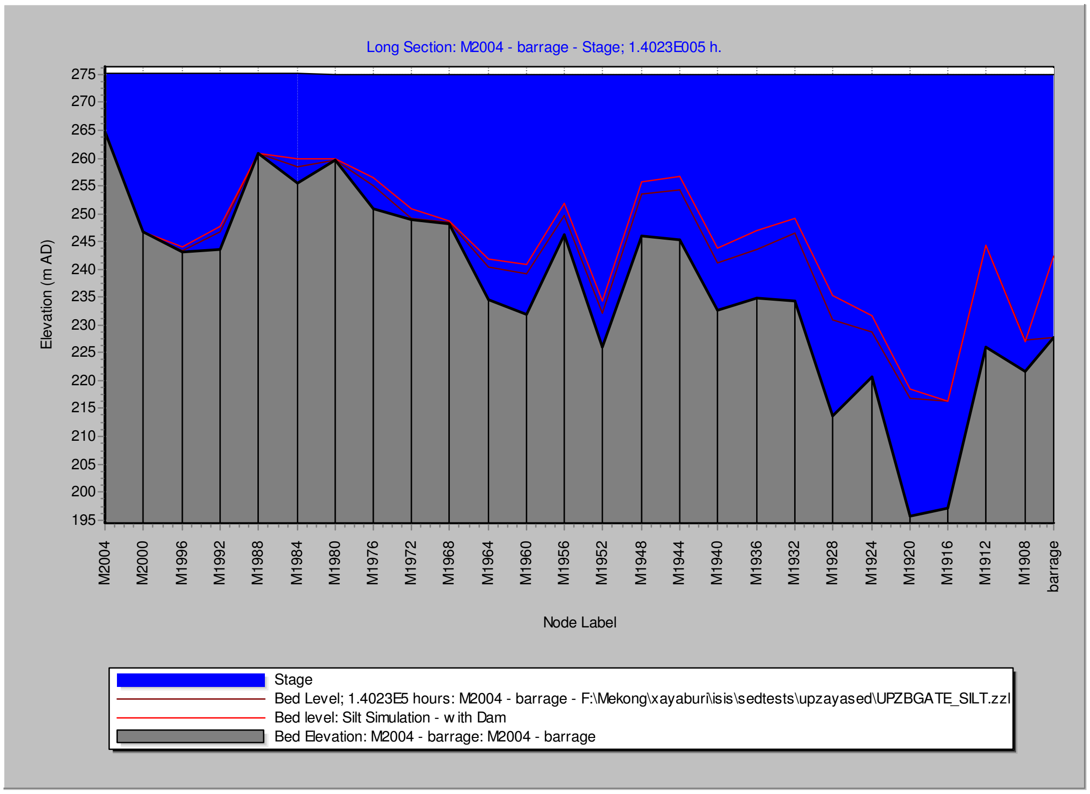


Figure C.8. Effect on bed levels of flushing 7 days per year using gates as Developer design (sedimentation predicted (brown) compared with sediment predicted in Simulation ii. (red)). Note slight reductions.

C.3.3 Simulations iv and v: Lowering Spillway gates and Extending Flushing Period

There are two potential issues affecting the effectiveness of possible flushing at Xayaburi:

1. the level of the spillway gates is significantly above the existing bed level, and
2. the period of time envisaged for flushing of a few days per year is constraining the movement of sediment.

Two further flushing situations were thus simulated: flushing design/operation iv. simply involves lowering the gate sill closer to the existing bed. There are practical issues with this solution that need to be considered carefully and a different gate design may be needed and flushing design/operation v. lowering gates **and extending the flushing period**.

Results of the bed levels obtained for the two simulations together, with those in others, are illustrated in Figure C.9. Although the operation of lowered gates for 1 week is more effective than the current design, it is only when the river is effectively allowed to pass largely unhindered for a significant period at high flows. For the purpose of the simulation, it is assumed that the gates are open in August each year and that the river is effectively returned each year to a near natural state during that period. There is some danger that a higher than normal sediment concentration at the beginning of the flushing could affect fisheries and this would need looking into further (Figure C.10).

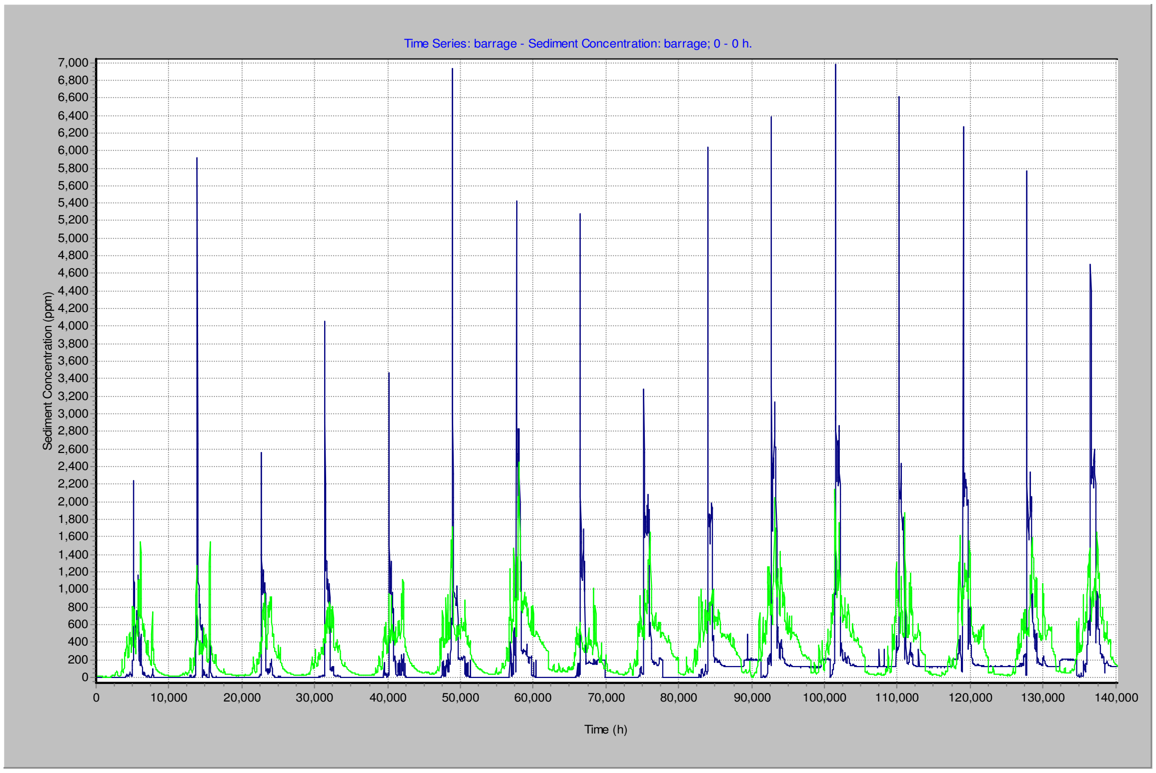


Figure C.9. Summary long profile Luang Prabang to Xayaburi Dam of predicted comparative sedimentation of silts after 15 years for each Simulation.

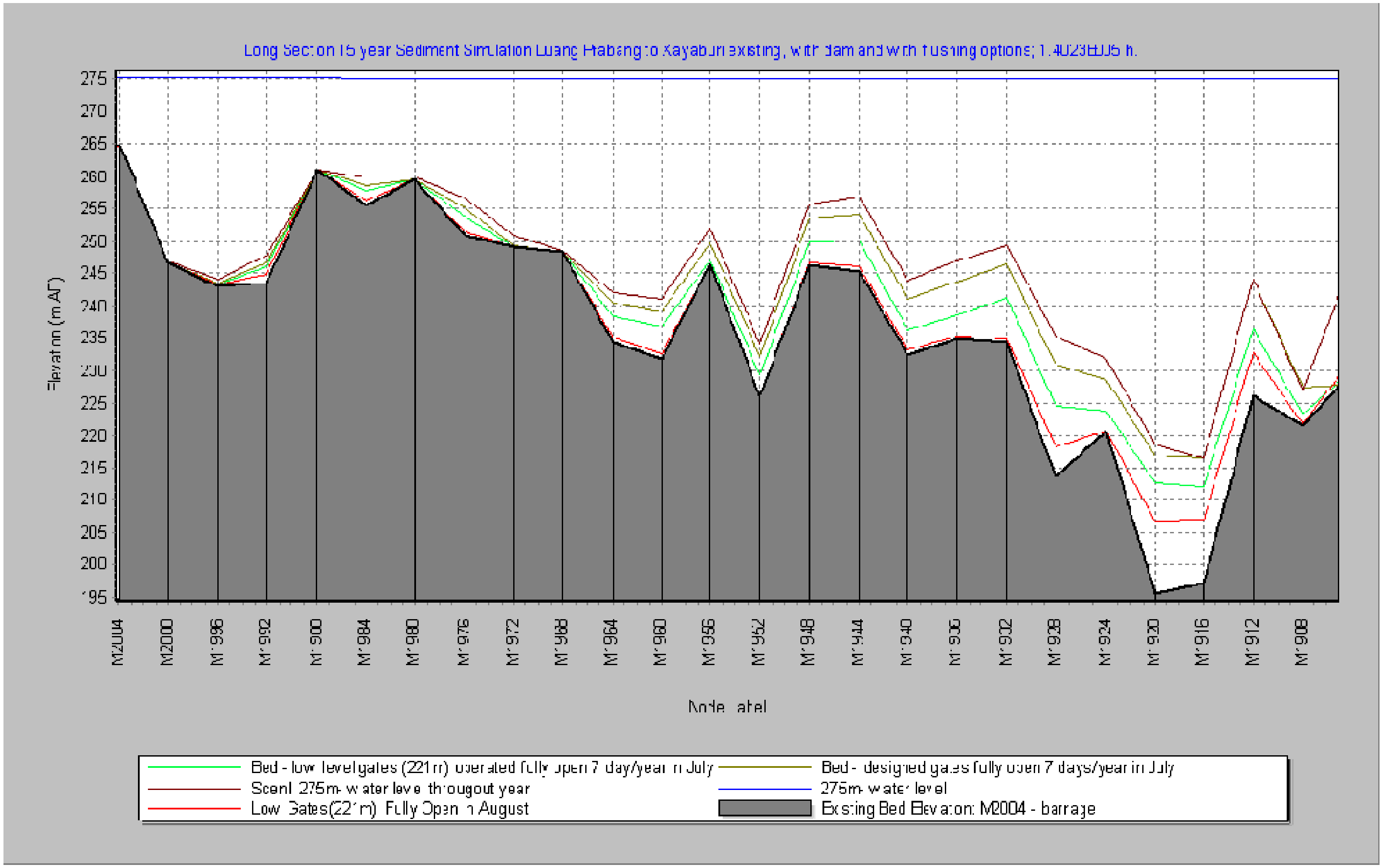


Figure C.10. Sediment concentrations at dam with flushing operation (Simulation v) compared with baseline showing higher peak concentrations at beginning of flushing period.

The trapping of sediment is greatly reduced to 11% for silts and 31% for sands/gravels.

In the longer term, a new equilibrium bed level will be reached, the lower the initial trapping percentage the closer this equilibrium will be to the natural bed level and ultimately the less risk of sediment issues in either the ponded part of the reservoir or downstream should there be a need to draw down the water level in the future for any reason such as changes in policy or on eventual decommissioning.

C.3.4 Flushing Design/Operation vi: Operation of Xayaburi with Developer Gates Fully Open (construction phase)

This Simulation illustrates that with the gates at a sill level of 254 m (30 to 50 m above current bed level), silt deposits can be expected during the construction phase for about 40 km upstream (Figure C.11).

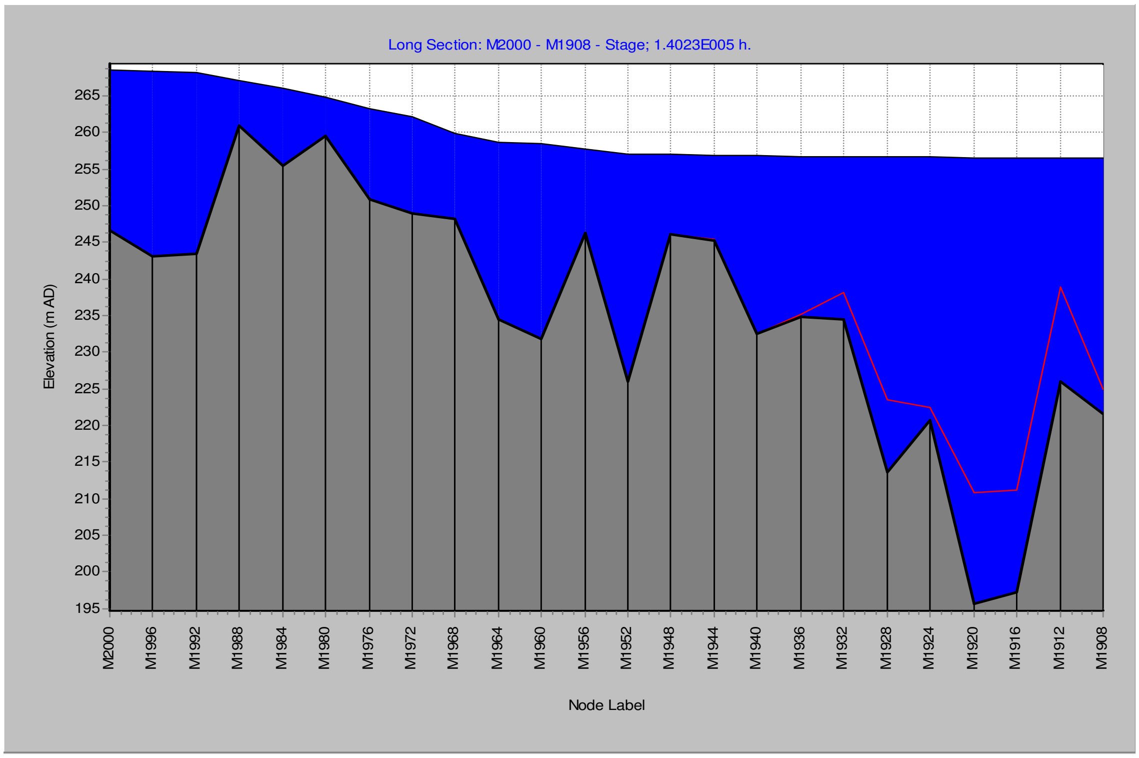


Figure C.11. Simulation vi. deposition (red) upstream of gates if left fully open.

C.3.5 Summary of Sediment Simulations

The results of the simulations illustrating options for sediment management are summarised in Table C.2. The simulation work highlights that:

- The design as submitted for PNPCA consideration will initially trap a large proportion of the sediment load as both sand and silt components at Xayaburi.
- It is possible to produce a design and sediment management plan that would greatly reduce the siltation rate. This would require changes in gate sill elevation so the reservoir pond could be reduced to natural levels during flushing and for the flushing to take place over a longer period (approximately 1 month, ideally August, when higher flows prevail regularly) during the wet season.

Actual rates of siltation will vary depending on upstream conditions and the lowering of spillway gates and flushing period needed could be refined by further design study and monitoring during operation. The model results, however, show clearly the potentially high trapping of the reservoir upstream of Xayaburi and the desirability of further study of sediment management.

Table C.2. Result of 15-year simulation.

Simulation	Sand/Gravel Load/Year		Silt Load/Year	
	% passed	% trapped	% passed	% trapped
i: Base condition	100%		100%	
ii: Dam as feasibility	4%	96%	33%	67%
iii: Dam 7-day opening	6%	94%	44%	56%
iv: Lower Gates 224 m Flush 7 day	27%	73%	61%	39%
v: Lower Gates 224 m Flush all August	69%	31%	89%	11%

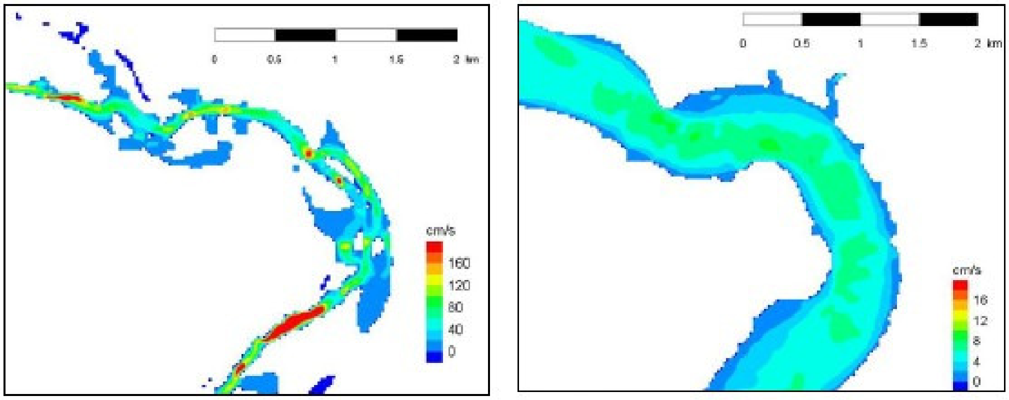
The 1-D modelling has also highlighted a number of other issues including:

1. **Draw down and refilling of the dam for flushing can take several days depending on the acceptable change in flow downstream.**
2. **Filling of the deep pools will occur in preference to other parts of the river system.**
3. **Significant siltation could occur upstream of the dam even during the construction phase if the current proposed gate design with a sill level of 254 m is used.**

C.4 3-D Modelling of Deep Pools

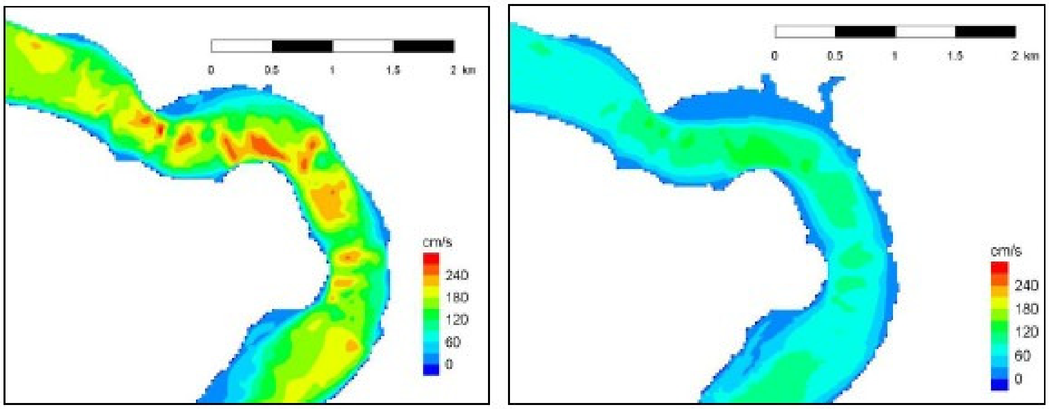
Simulation of changes in sediment movement and accumulation in three sample deep pools is being completed and will be reported fully but is not yet complete (February 6, 2011) due to corrections needed to the Digital Elevation Model (DEM) that affects the 3D model to a greater extent than the 1-D.

The modelling produced highlights the changes in velocity and sediment movement with and without the dam in place (Figures C.12 and C.13).



(a) baseline case (b) dam case

Figure C.12. Modelled near-bottom flow speeds. Dry season flow situation (February 20, 1995). Observe that the dam speed scale is order of magnitude smaller than for the baseline.



(a) baseline case (b) dam case

Figure C.13. Modelled near-bottom flow speeds. Peak flood flow situation (August 20, 1995).

C.4.1 Results – Chiang Saen to Nakhon Phanom Unsteady Simulation of the Potential Effect of Diurnal Patterns of Release

The Xayaburi ISIS model used in sediment simulations was extended to Nakhon Phanom (Figure C.14). A cycle of possible diurnal variation was simulated to examine whether changes would be expected to impact downstream and specifically across the border to Chiang Khan.

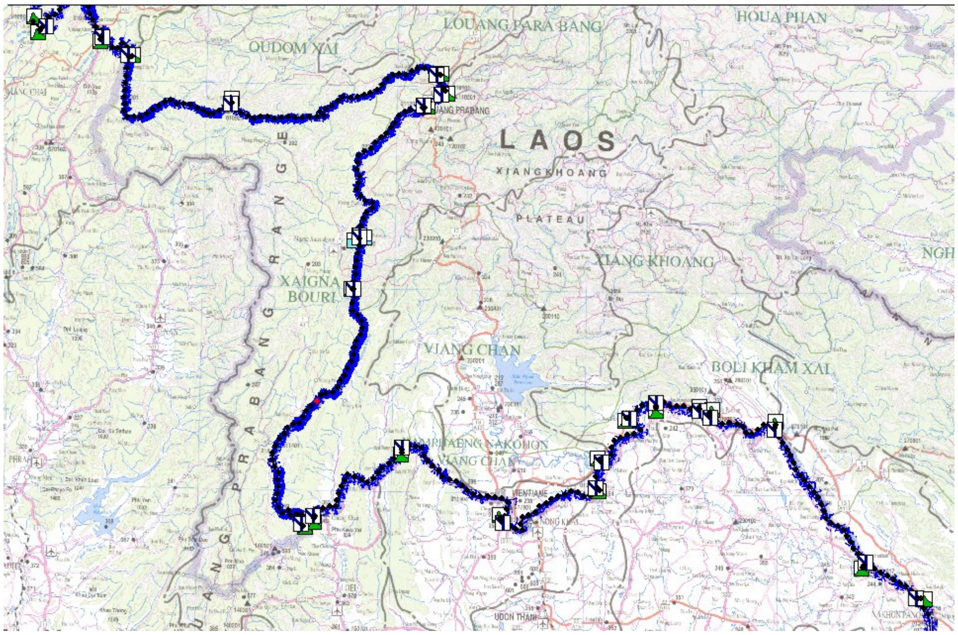


Figure C.14. Extent of model used for simulation of diurnal fluctuations.

The cycle of flow variation used is a simple increase for 4-hour periods of peak demand as shown in Figure C.15. The simulation was carried out for lower flows when it was expected that fluctuations are normally expected to have most impact. The cycle uses a low night flow of 1,060 m^3/s and a peak of 1,660 m^3/s is purely illustrative.

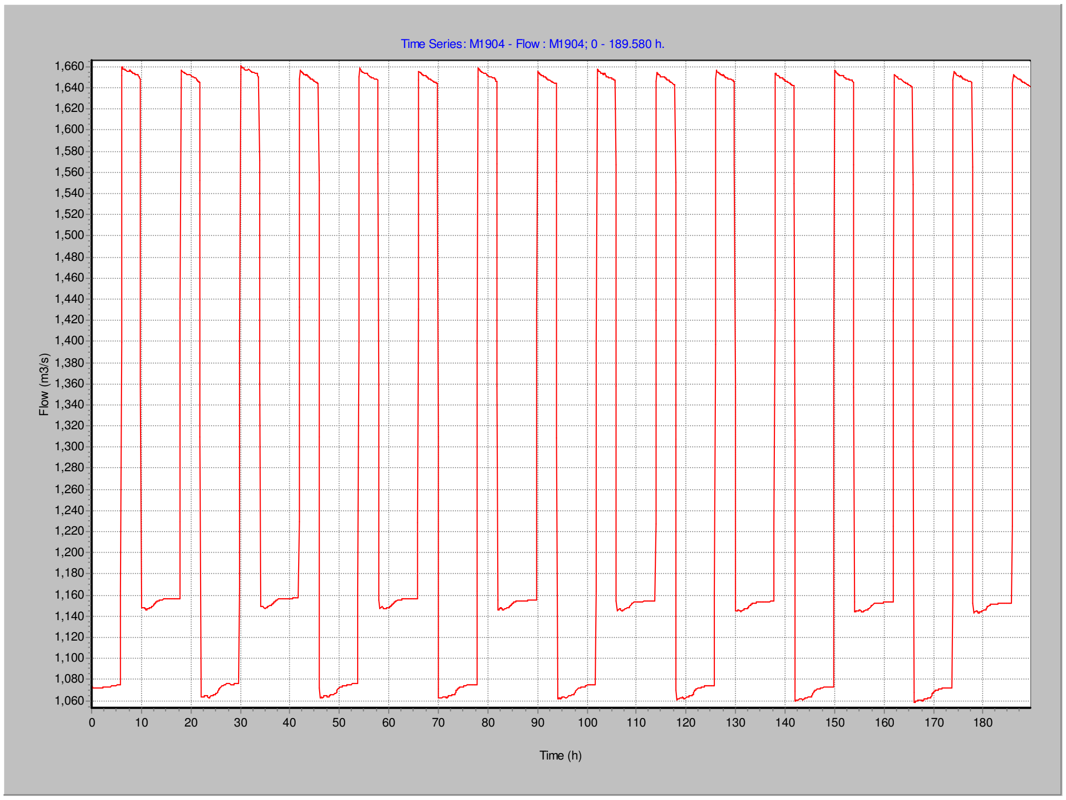


Figure C.15. Cycle of flow release simulated at Xayaburi.

The result of such a release pattern is for a 0.6-m variation in downstream water level and around 7-cm fluctuation upstream as shown in Figures C.16 and C.17, respectively.

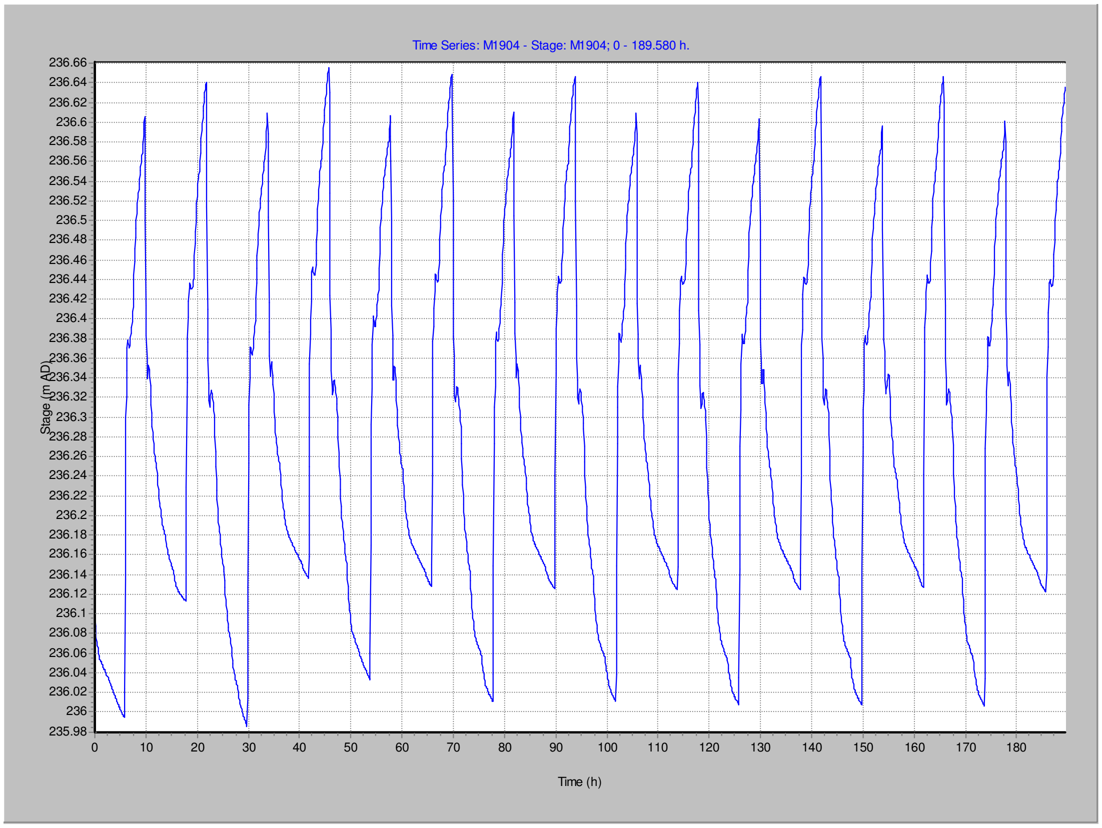


Figure C.16. Downstream variation in water level.

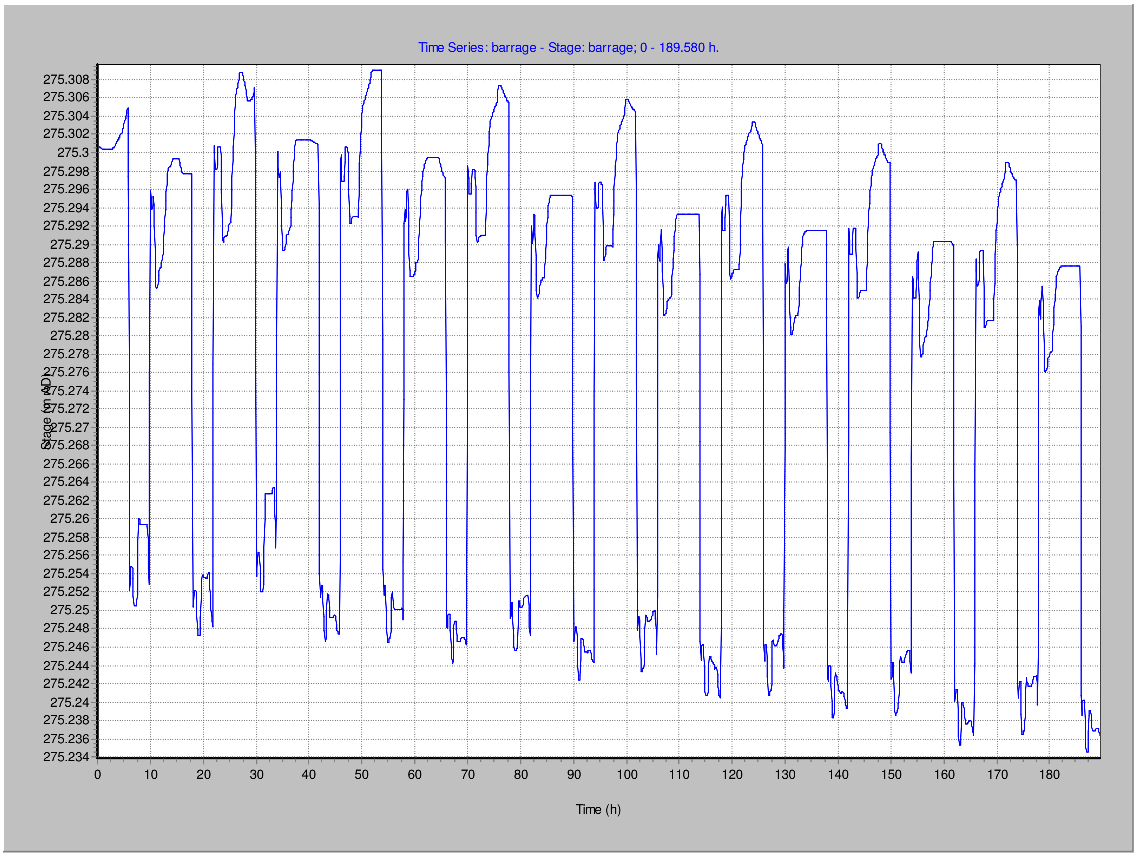


Figure C.17. Upstream variation in water level.

50 km from the barrage, the model indicates an initial drop in water level of 0.1 m when the cycling starts and then an equilibrium with variations of a few centimeters only as shown in Figure C.18.

At the border, around 200 km from the reservoir, such fluctuations are no longer clearly seen though there are some drops in level of around 4 cm, which is less than changes that occur naturally.

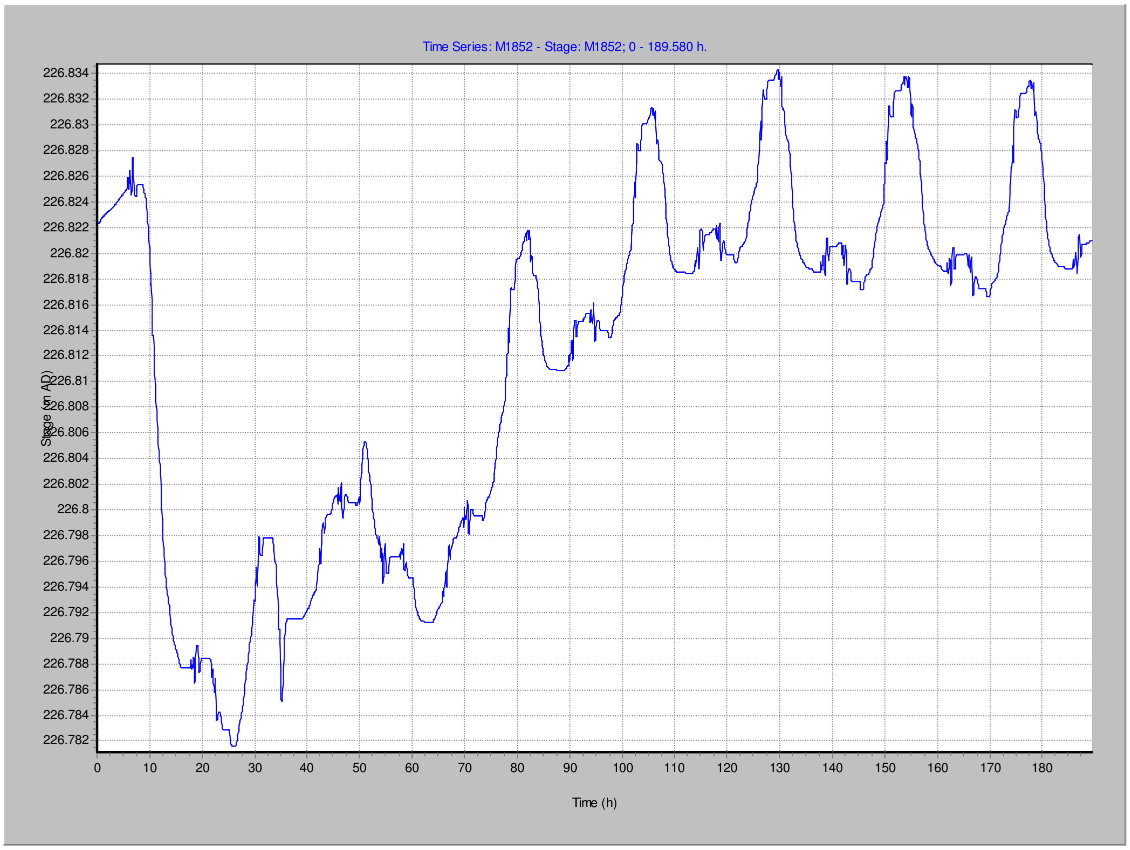


Figure C.18. Water level variation 50 km downstream of Xayaburi for assumed cycle.