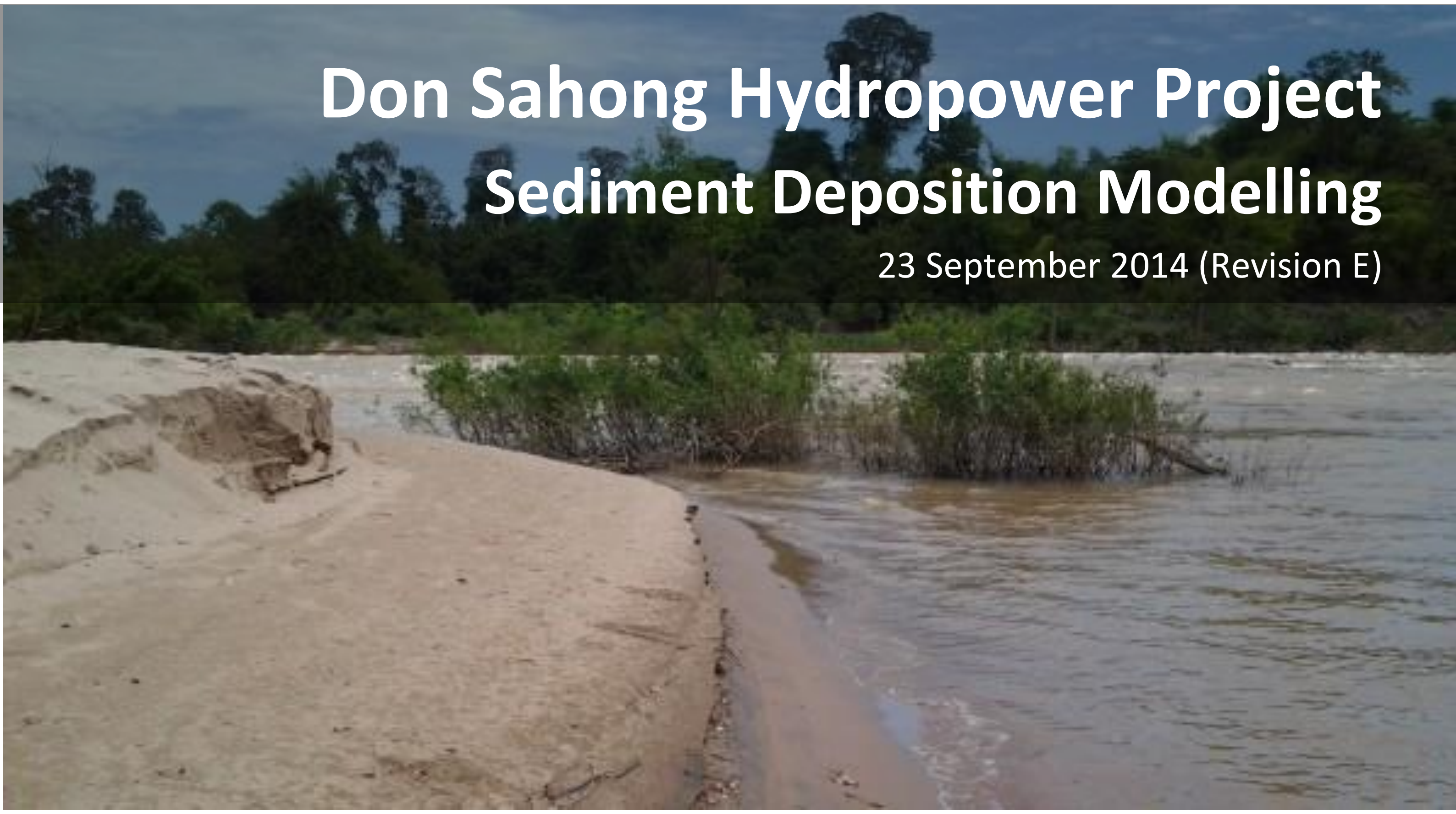
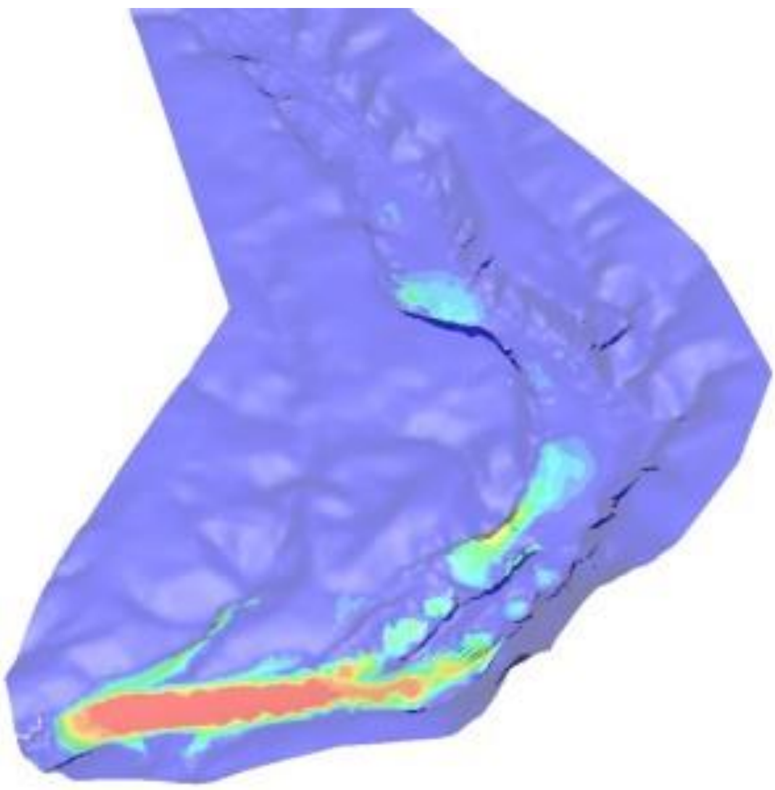
Don Sahong Hydropower Project

Sediment Deposition Modelling

23 September 2014 (Revision E)





EXECUTIVE SUMMARY

The Don Sahong Hydropower Project (DSHPP) is a proposed run-of-river hydropower scheme on the Hou Sahong branch of the Mekong River in Lao PDR. This report documents the results of sedimentation modelling of the DSHPP head pond, quantifying expected sediment deposition volumes. This study supersedes the previously published sedimentation study reported in the Hydrology, Hydraulics and Sedimentation Studies Report (AECOM, 2011).

The modelling study investigates the effects of sedimentation on station operation to inform scheme design and the need for sediment management provisions. The study assesses changes to sediment passage downstream, and demonstrates compliance with the MRC Preliminary Design Guidelines on sediment transport and river morphology.

The Mekong River carries a significant sediment load, of some 150 million tonnes of suspended load annually at Pakse. Almost the entire annual load is carried during the wet season from June to November. The quantities and properties of sediment modelled were based on published literature, and a site sampling campaign which included collection of suspended sediment and bed load samples to provide direct evidence of transported particle sizes.

The sedimentation modelling was based on an existing *Telemac* computational model of the head pond and upstream river branches. The *Telemac-2D* hydrodynamic code was directly coupled with the *Sisyphe* sediment transport and morphodynamic module. Deposition effects were investigated by modelling the continuous operation of the station over five years. Two cases were modelled, the first representing the bulk of the sediment load with the suspended transport of fine silt (d_{50}=10 μm), the second representing bed load with a medium-sized sand (d_{50}=0.3 mm).

With DSHPP only passing a small proportion of the Mekong flow during the wet season, only around 5% of the Mekong sediment load will enter the DSHPP head pond. A fraction of the suspended sediment will settle during the wet season, the majority of which is re-entrained as the head pond level drops as the wet season recedes. Almost all of the coarser bed load entering the head pond over the first two years of operation is expected to be retained. Thereafter, an inter-annual equilibrium is reached whereby a portion of the settled sediment is naturally flushed through the station under normal operation as the head pond depth decreases in the dry season, with a similar volume re-deposited in the rising wet season the following year.

The model predicts that in this equilibrium condition, the deposited mass of suspended sediment fluctuates between 0.4 and 1.2 million tonnes, while the coarser bed load deposits reach around 2.5 million tonnes. Combining the two cases, and given the natural year-to-year variation in hydrology and sediment load, it is expected that the mass of sediment trapped in the head pond will fluctuate between around 2 and 4 million tonnes depending on river conditions. The maximum amount trapped is equivalent to about 3% of the annual Mekong sediment load at Pakse.

The proposed DSHPP may be considered ‘transparent’ with respect to sediment transport, with the modelling estimating no change in the regional sediment balance after the first few years of operation.

As the modelling predicts that deposited sediments will not significantly decrease headwater levels at the station, the proposal for sediment flushing (AECOM 2011) to maintain operational performance is no longer required or proposed.

Bathymetry of the head pond should be surveyed annually during scheme operation, and suspended sediment concentrations upstream and downstream of the head pond should be monitored. The data collected should be compared with the modelling results to verify the conclusions presented in this report.

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1 INTRODUCTION

Mega First Corporation Berhad (MFCB) has engaged SMEC New Zealand Ltd (SMEC) to undertake numerical modelling of sediment transport, deposition and entrainment in the proposed Don Sahong Hydropower Project (DSHPP) head pond. The modelling builds on previous hydraulic modelling undertaken by SMEC[1], extending and superseding the earlier sedimentation studies by AECOM[2].

1.1 Background

Sediment is carried by the Mekong River, suspended in the flow and as bed load, with transport rates depending on sediment availability and flow velocities. Reduction in velocities as a result of the DSHPP head pond formation will see an increase in deposition of sediment or 'sedimentation' of the head pond. Computational modelling of sediment transport and sedimentation allows for the quantification of environmental effects related to sediment, including changes in sediment delivery to the river downstream, and localised deposition.

The DSHPP sedimentation study by AECOM (2011) identified the approximate volume of sediment that would enter the head pond, and the likely volumes of deposition based on assumptions on sediment grading and simple empirical relationships. This preliminary study proposed periodic flushing flows to manage the deposited sediment volume to around 2 million tonnes.

Subsequent preliminary computational modelling of sedimentation using SMEC's *Telemac* model and assumed sediment parameters[3] identified that deposition within the head pond quickly tended toward an inter-annual equilibrium condition. Sediment was shown to be flushed through the station with normal operation as the high wet-season head pond levels receded, and specific flushing flows would not be required. The amount of sediment deposition was shown to be strongly dependent on the assumed sediment grain sizes.

A site sampling campaign was initiated in 2012 to provide measurements of transported sediment particle sizes across the range of flow conditions, on which the current modelling is based. A separate report[4] provides a summary of the site sampling campaign methodology and results.

1.2 Purpose of Modelling

The modelling reported herein uses the most up-to-date understanding of site flows and transported sediment to:

- Inform the engineering design and O&M considerations of the DSHPP scheme, including the effects of sediment deposition on operation (e.g. effect on station

[1] SMEC (2014) *Don Sahong Hydropower Project, CFD Hydraulic Model Study*, Revision C, May 2014.
[2] AECOM (2011) *Don Sahong Hydropower Project, Design Studies: Hydrology, Hydraulics and Sedimentation Studies Report*, RPPG 0014_B, Revision B, October 2011.
[3] *Earlier revisions of the current report.*
[4] SMEC (2014) *Don Sahong Hydropower Project, Sediment Sampling Campaign*, Revision C, July 2014.

head, volume of sediment through the turbines) and the need for flushing flows or other sediment management provisions.

- Quantify the expected rates of sediment deposition, and assesses changes to sediment passage downstream.
- Demonstrate that scheme conforms to the MRC Preliminary Design Guidelines[5] (MRC PDG) with regard to sediment transport and river morphology. These are concerned particularly with the trans-boundary effects of the scheme on sediment transport downstream. A table summarising how the DSHPP scheme design addresses each applicable MRD PDG paragraph is included as Appendix A.

This report details the results of modelling runs of the DSHPP Reference Design with typical operation. Results include sediment deposition volumes and patterns, and effects on operation.

This report supersedes the sedimentation studies described in the 2011 AECOM report, with a more comprehensive and updated literature review, use of site measurements of sediment transport rates and characteristics, and the use of detailed numerical modelling.

[5] Mekong River Commission (2009) *Preliminary Design Guidance for Proposed Mainstream Dams in the Lower Mekong Basin*, Final Version, 31 August 2009.

2 BACKGROUND INFORMATION

The Mekong River is known to carry a significant suspended sediment load, but details on the quantity and composition of this sediment load are relatively limited[6]. Knowledge of the quantity of sediment transported by the river is clearly directly relevant to estimates of sedimentation volumes. Composition of the transported sediment, particularly the grain size distribution is similarly important in modelling the physical processes of erosion and deposition.

The closest location from which historical sediment data have been collected on the Mekong is at Pakse, some 160 km upstream of the DSHPP site. Sediment data collection was initiated at Pakse in the early 1960s, but was discontinued and not reinstated until the 1990s.

Recognising the limitations in available sediment data, MFCB initiated a site sediment sampling campaign in 2012, with suspended sediment and bed load sampled across a range of different river flow conditions. A report has been produced by SMEC summarising the sampling objectives, methodologies and results[7].

The available sediment data is further described and interpreted for the purposes of the current modelling in the sections below.

2.1 Pakse Suspended Sediment Data

A sediment sampling programme was initiated on the lower Mekong River in 1960 as part of the Lower Mekong Project funded by the US Agency for International Development and coordinated by the Harza Engineering Company. The sampling network covered a number of sites in Thailand and Lao PDR, including Pakse, some 160 km upstream of the DSHPP site.

The sampling was based on existing US practice, used standard US-designed isokinetic samplers and involved depth-integrated sampling of several vertical profiles in order to derive an estimate of the mean suspended sediment concentration (SSC) in the cross section.

Sampling was carried out frequently over the first three years, then discontinued, and re-established in 1997 with approximately monthly samples taken. From the limited available data, the mean annual suspended sediment load at Pakse is about 150 Mt.

Particularly frequent suspended sediment sampling was undertaken at Pakse in 1961, from which the seasonal variations in suspended sediment can be interpreted. The SSC and discharge data from 1961 are reproduced in Figure 1. 1961 was a reasonably wet year, with the flood peak having a 5-10 year return period. The annual sediment load calculated from these data for 1961 is 166 Mt[8].

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[6] E.g. Walling, D.E. (2009) *The Sediment Load of the Mekong River*, in *The Mekong: Biophysical Environment of an International River Basin*, Campbell, I. (editor), Elsevier.

[7] SMEC (2014) *Don Sahong Hydropower Project, Sediment Sampling Campaign*, Revision C, July 2014.

[8] Walling, D. E. (2008). The changing sediment load of the Mekong River. *AMBIO: A Journal of the Human Environment*, *37*(3), 150-157.

Important features evident in Figure 1 include:

- Most of the suspended sediment is transported in the wet season (June-Nov).
- Suspended sediment concentration does not show a singular correlation with discharge, for example the same flood discharge in August and October has quite different sediment concentrations.
- Suspended sediment concentrations are generally higher earlier in the flood season, likely reflecting the greater availability of deposited sediments earlier in the season, and perhaps the different seasonal flow inputs (e.g. snowmelt from the Tibetan Plateau earlier in the season bringing higher loads of fine sediment).

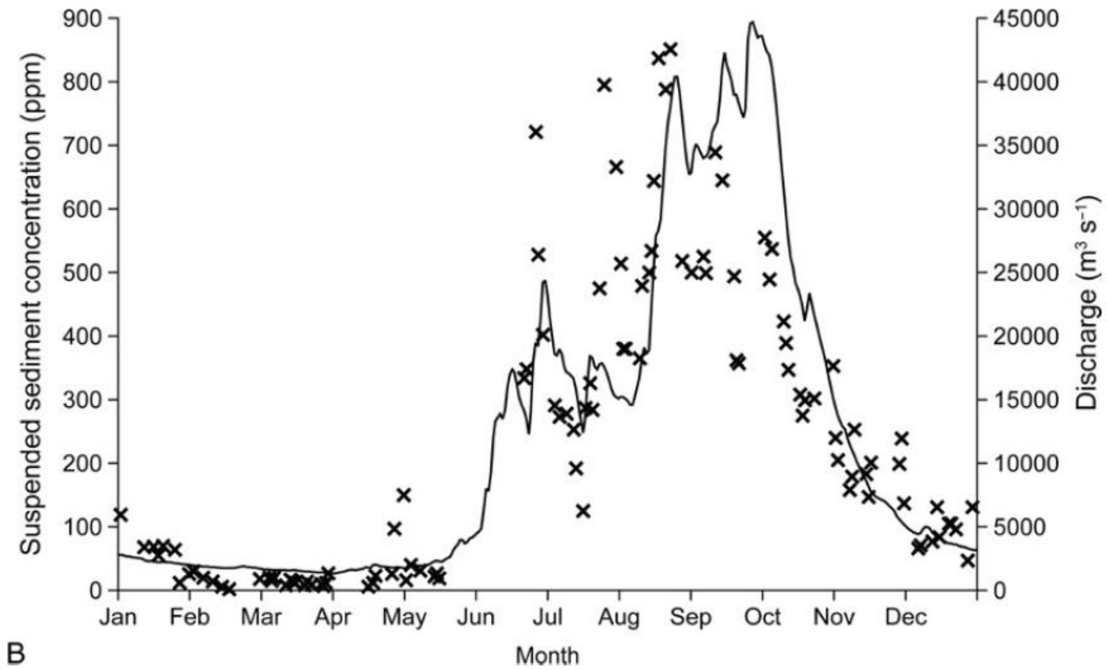

Figure 1: The record of water discharge and the measured suspended sediment concentrations for the Mekong River at Pakse for 1961 (reproduced from Walling, 2009)

Since 1985, monthly suspended sediment levels have also been recorded at Pakse as part of the MRC Water Quality Monitoring Network (WQMN). The Total Suspended Solids (TSS) has been measured, using a bottle dipped just below the surface rather than a true sampler. A comparison of the two data sets shows that the TSS data may significantly underestimate the average sediment concentration[9].

The 1961 SSC data is the most comprehensive set of suspended sediment measurement at Pakse. Since this time, however, there have been significant changes in land-use and intensification within the catchment, together with the construction of dams in the Lancang River (Upper Mekong), which will have altered the input of sediments to the river system.

[9] Walling, D. E. (2008). The changing sediment load of the Mekong River. *AMBIO: A Journal of the Human Environment*, *37*(3), 150-157.

A significant research effort has focussed on quantifying changes in sediment transported in the Mekong due to the construction of upstream dams[10,11,12]. Although the trapping of sediments by reservoirs is a well-known and understood phenomenon, there is no clear evidence in the measured data of a reduction in suspended concentration in the Lower Mekong[13]. This may be due to a balance of increased sediment input due to catchment land-use changes, or a 'buffering' effect of sediment input from bank and in-channel erosion. Even if not yet measurable, it must be considered likely that long-term the volume of sediment carried by the Mekong at the DSHPP location will decrease due to the presence of upstream dams

2.2 Grain Size Distribution

The MRC Strategic Environment Assessment Sediment Baseline paper[14] reports that little information is available on the grain size distribution of sediment transported by the Mekong, with the best estimates based on one distribution curve measured at Pakse. This curve, shown in Figure 2, gives a median grain size (d_{50}) of about 0.1 mm, being fine to very fine sand. The origin of these data is unclear.

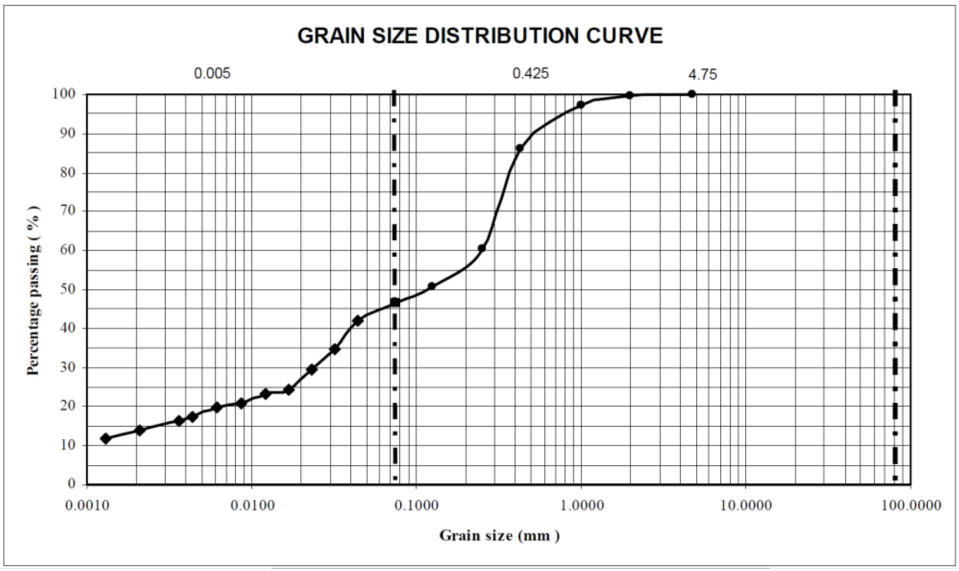

Figure 2: Grain size distribution at Pakse attributed to Carling, 2009 (reproduced from MRC, 2010)

[10] Lu, X. X., & Siew, R. Y. (2006). Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. *Hydrology and Earth System Sciences Discussions*, 10(2), 181-195.
[11] Kummu, M., & Varis, O. (2007). Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River. *Geomorphology*, *85*(3), 275-293.
[12] Xue, Z., Liu, J. P., & Ge, Q. (2011). Changes in hydrology and sediment delivery of the Mekong River in the last 50 years: connection to damming, monsoon, and ENSO. *Earth Surface Processes and Landforms*, 36(3), 296-308.
[13] Walling, D. E. (2008). The changing sediment load of the Mekong River. *AMBIO: A Journal of the Human Environment*, *37*(3), 150-157.
[14] MRC (2010) *Hydrology & Sediment Baseline Assessment Working Paper*, MRC SEA for Hydropower on the Mekong Mainstream.

The grain size distribution of TSS samples collected at Pakse as part of the MRC Water Quality Monitoring Network has reportedly been analysed, but results are not publically available[15] and have not been made available to MFCB.

From the review of available data, it was recognised that there are gaps and uncertainties in the knowledge of transported sediments at DSHPP site. To supplement historical data and to enhance the knowledge of transported sediments at the site, MFCB initiated a campaign of sediment sampling.

2.3 DSHPP Site Sampling Campaign (2012-2013)

The site sampling campaign involved six visits across different river flow conditions, focussed around the 2013 wet season. For each visit, samples of suspended sediment and bed load were taken at multiple cross-sections at the DSHPP site. A summary report has been prepared by SMEC documenting the sampling objectives, methodologies and results[16].

The average suspended sediment concentrations measured for each visit are shown in Figure 3 together with the Mekong (at Pakse) discharge, superimposed on the 1961 measurements.

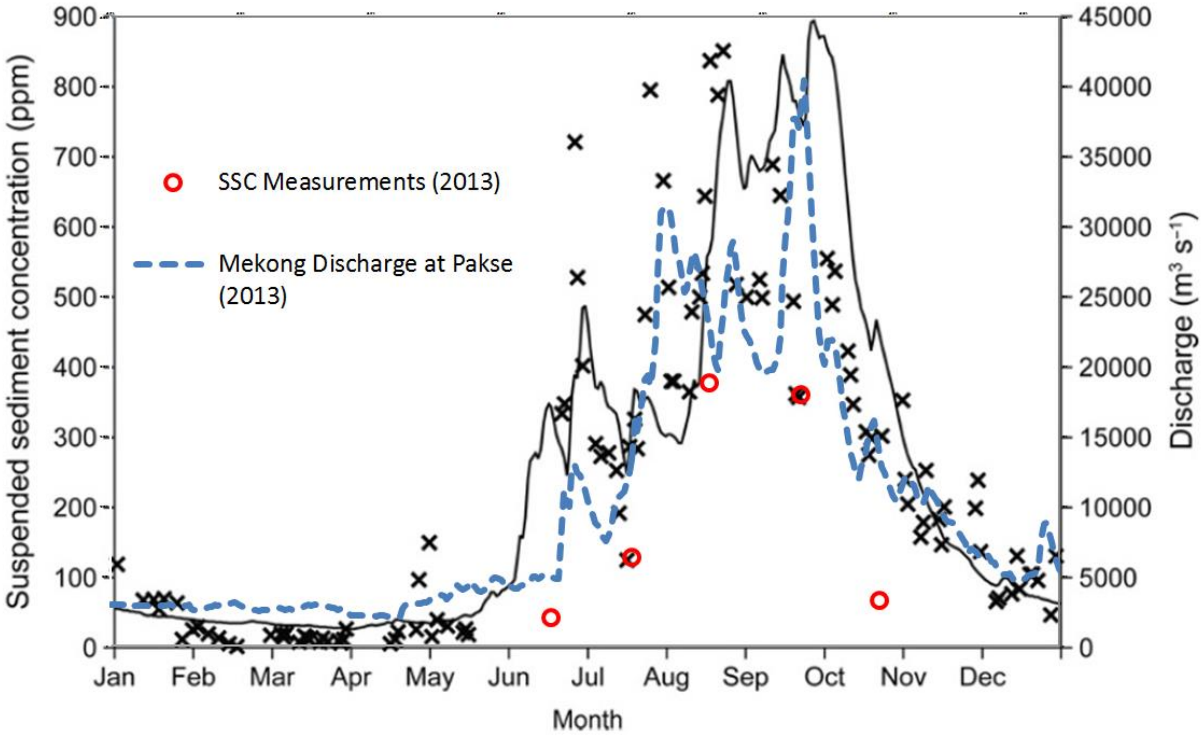

Figure 3: Average suspended sediment concentration measured at site and Mekong at Pakse discharge for 2013, superimposed on comparable data measured at Pakse in 1961

[15] MRCS (2014) Pers. comm.

[16] SMEC (2014) *Don Sahong Hydropower Project, Sediment Sampling Campaign*, Revision C, July 2014.

Important features evident in Figure 3 include:

- The highest SSC, measured in August 2013, was 375 mg/L, significantly lower than the highest SSC values reported from 1961 (approx. 850 mg/L).
- For both years, the highest SSC values were observed in August, not correlated with the peak flow rate which was observed in late September both years.
- The 2013 measurements from July, August and September very closely match measurements taken at similar times of year in 1961.
- The peak flood flows from both years are similar, although the wet season volume in 1961 was significantly greater.

Although it appears that the 2013 measurements show significantly lower overall suspended concentrations than the 1961 data, this could be related to the relatively low sampling frequency (i.e. higher concentrations were potentially present between sampling visits).

Particle-size distribution curves of the sampled suspended sediment, averaged across all sections for each visit are shown in Figure 4, comparing distributions for the different times of the season.

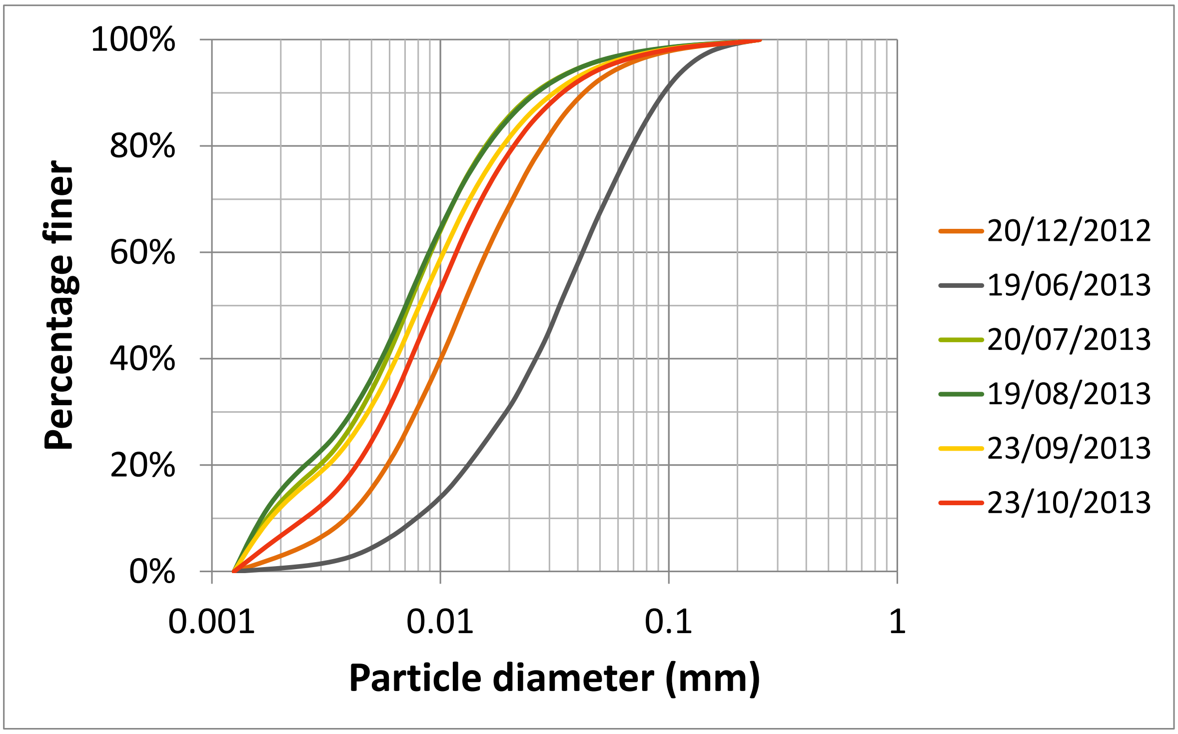

Figure 4: Particle size distribution of suspended sediment samples, averaged across all cross sections for each visit

Through the middle of the wet season (July-September), when the bulk of sediment is transported, the samples showed very similar grain size composition, with a median grain size (d_{50}) of approximately 8 μm. The median suspended grain size is seen to become coarser as the wet season recedes (October, December) and to be significantly coarser at the end of the dry season (June 2013).

Bed load sampling in the project area was not able to accurately quantify bed load transport rates. This was due to the uneven and irregular riverbed profile throughout the area, and deficiencies in the sampling methodology. There was however a clear increase in bed load transport rates observed at higher flow conditions (August and September 2013 visits).

The bed load sampling did obtain representative samples of the bed load material, allowing particle size analysis by sieving. Average particle-size distribution curves for each sampling visit are shown in Figure 5.

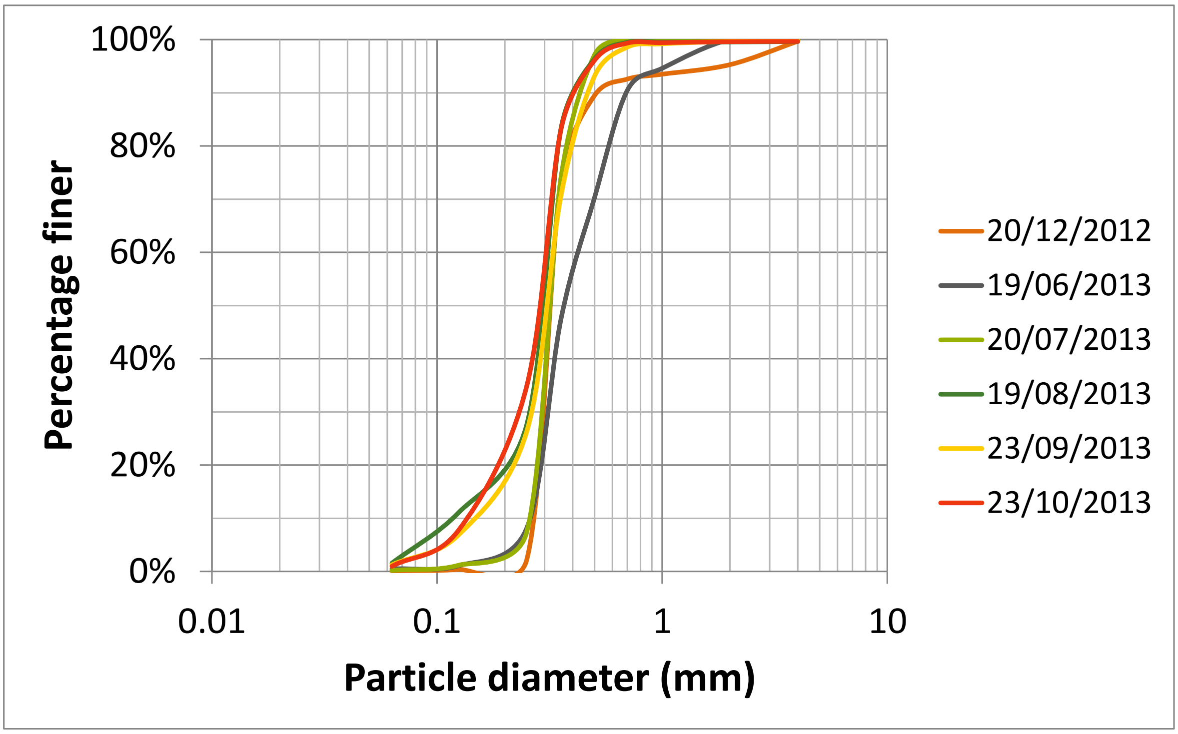

Figure 5: Particle size distribution of bed load samples, averaged across all cross sections for each visit

Excluding the December 2012 and June 2013 visits, from which only small volumes of sediment were recovered, the bed load composition is very similar across the sampling campaign, with a median grain size (d_{50}) of 0.3 mm.

2.4 River Setting

In the Siphandone area, the Mekong River composes a bedrock-constrained anabranching network with an alluvial overprint[17,18]. The islands are rock-cored and capped with alluvial material, and active alluvial deposits exist on the river banks and margins. Surveyed bathymetry shows an irregular riverbed with steep changes in elevation, displaying a deeply incised thalweg in places, in others being relatively shallow. Site observations confirm the irregular craggy nature of the riverbed, at rapids and outcrops exposed at lower river flow conditions.

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[17] Gupta, A and Liew, S, (2007) The Mekong from satellite imagery: a quick look at a large river, *Geomorphology*, 85 (3–4), 259–274.

[18] Van, P (2010). *Hydraulic modelling and flood inundation mapping in a bedrock-confined anabranching network: the Mekong River in the Siphandone Wetlands, Lao PDR*. PhD thesis, University of Southampton, UK, 305 pp.

For the purpose of modelling it has been assumed that the surveyed river bathymetry, which makes up the initial model bed elevations, represents non-erodible bedrock. This means that river morphology, in the sense of changes to the shapes of islands and channels, is not explicitly modelled. The geological setting and potential for channel movement was considered in earlier studies (e.g. through inspection of old aerial photographs) and the evidence indicated that the river morphology in the region was quite stable. The channel system and falls formed by the Great Fault Line are dominated by rock formed of meta-sediments which has a high degree of resistance to erosion and scour, at least as far as time scales relevant to engineering structures are concerned. Water levels upstream of the diversion are generally controlled by the series of rapids formed by shallow rock formations, and the rocky river bed at these locations has already proven itself to be resistant to erosion over time.

2.5 Sediment Parameters Adopted for Modelling

The continuous operation of the station over a number of seasons was modelled with varying flow and sediment inputs, to represent the changing natural conditions.

Due to software limitations, stable runs were only achievable using a single representative grain size. The overwhelming majority of sediment transported is silt-sized, though it was expected that the coarser transported fractions evidenced in the bed load samples would account for a relatively significant proportion of deposition within the head pond.

To investigate the deposition of both the high-volume suspended load and the highly-trappable bed load fractions, the model was run twice with different sediment parameters. The parameters, based on site measurements and experience, are tabulated below.

Table 1:Sediment parameters adopted for modelling

	Suspended Sediment case	Bed Load case
Median diameter, d_{50}	10 μm	300 μm
Sediment density, ρ_s	2650 kg/m³	2650 kg/m³
Settling velocity, ω_s	1 mm/s, (cf. 0.09 mm/s from Stokes' Law) conservatively increased to account for possible floc formation	44 mm/s, from Van Rijn formula[19]
Density of deposited sediment	600 kg/m³ (dry mass per unit volume)	1590 kg/m³ (dry mass per unit volume)
Deposition/Erosion	Zyserman and Fredsoe equilibrium concentration formula[20]	Van Rijn bed load transport formula[21]

[19] Rijn L.C. van, (1993) *Principles of Sediment Transport in Rivers, Estuaries and Coastal Seas*. Aqua Publications.
[20] Zyserman J.A. and Fredsoe J. (1994) Data analysis of bed concentration of suspended sediment, *Journal of Hydraulic Engineering, ASCE*, Vol. 120, 9, pp 1021-1042.

For the suspended sediment case it was assumed that suspended sediment concentration is determined by the time of year. This is based on the 2013 site sampling as well as the published 1961 SSC data, for which the highest concentration does not correlate with the highest discharge. Whilst water discharge would be expected to have a strong influence on suspended sediment transport, the time-of-year assumption is considered appropriate given the very regular seasonal flood patterns observed in the flow record (i.e. it implicitly accounts for flow effects).

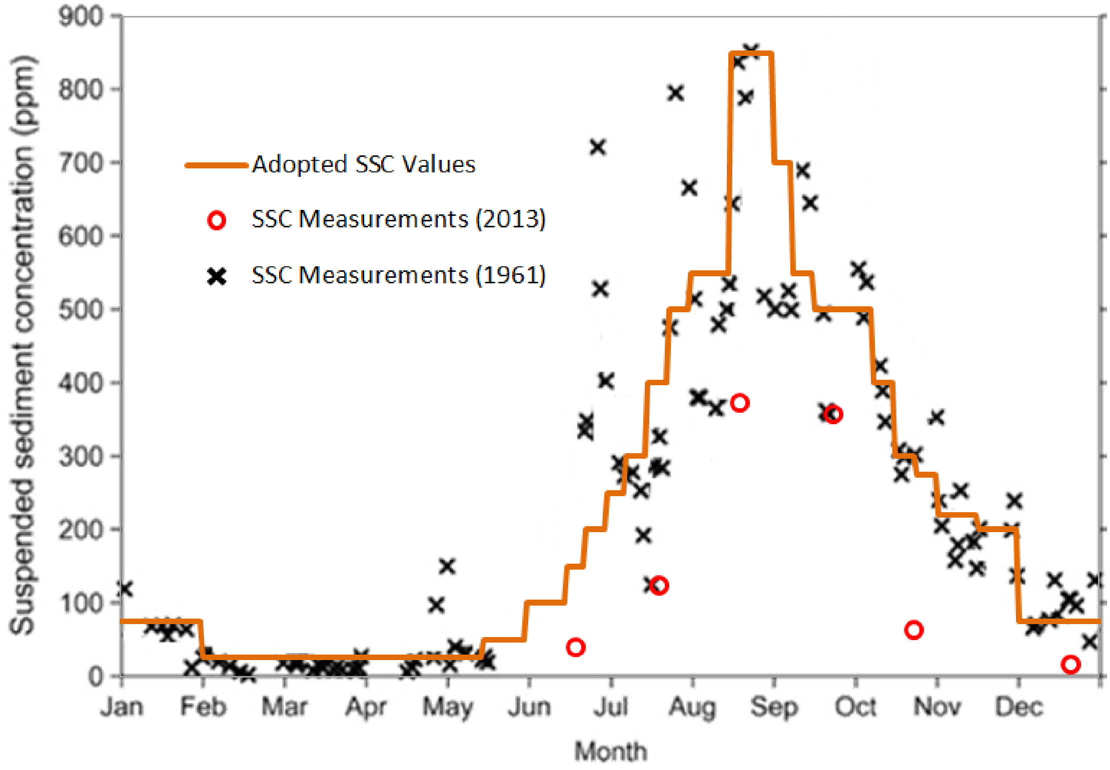

Figure 6: Measured SSC data from site (2013) and Pakse (1961) and the SSC values adopted for modelling

The suspended sediment concentrations adopted for modelling, varying by week-of-the-year (hence the stepped appearance) are shown in Figure 6. These are, conservatively, significantly higher than the concentrations measured at site, given that the site measurements may have missed the highest concentrations. Applying these concentrations to the Pakse daily discharge series (1925-2013) gives an average annual suspended sediment load at Pakse of 136 Mt, matching well with other estimates[22].

The same concentration is applied at each inflow boundary to the model. Site sampling did not show any discernable differences between the different channels, and it can be expected that the silt-sized sediments being considered would be well mixed by the relatively swift velocities predominant in the wider project area.

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[21] Rijn L.C. van, (1984). Sediment transport - Part I : bed load - Part II : suspended load, *J. Hyd. Div., Proc. ASCE*, 110, HY10, 1431-56, HY11, 1613-41.

[22] E.g. Walling, D.E. (2009) The Sediment Load of the Mekong River, in *The Mekong: Biophysical Environment of an International River Basin*, Campbell, I. (editor), Elsevier.

For the bed load case it was assumed that the sediment input at the boundaries is equivalent to 10% (by weight) of the input in the suspended sediment case. This simple assumption is commonly made when considering bed load flux[23], given the inherent difficulties in measuring bed load in the field. Monitoring of bed load transport is very limited on the Mekong[24], though a recent study estimated the total annual bed load to be 1.6 to 1.8 Mt at Kratie[25], i.e. around 1-2% of the suspended load. At the DSHPP site the common assumption of 10% of the suspended load is expected to be considerably conservative, given that the channel is bedrock-constrained, i.e. 'sediment-starved' in terms of coarser bed material.

[23] E.g. Milliman, J. D. and Meade, R. H. (1983). World-wide delivery of river sediment to the oceans. *Journal of Geology* 91, 1-21.
[24] Bravard, J.P. et al, (2013) An assessment of sediment-transport processes in the Lower Mekong River based on deposit grain sizes, the CM technique and flow-energy data. *Geomorphology,* 207, 174–189.
[25] Koehnken, L. (2012). *IKMP discharge and sediment monitoring program review, recommendations and data analysis. Part 2: Data Analysis and Preliminary Results*, MRC, Phnom Penh, Cambodia.

3 MODELLING METHODOLOGY

3.1 Model Domain

The modelling builds upon the *Telemac* 2D and 3D models developed by SMEC to verify the DSHPP diversion conditions. The model domain is identical to the 'Headpond Model' used in previous *Telemac* CFD modelling[26], as shown in Figure 7. The model includes inlet excavation as defined by the Reference Design, including retention of a 'skimming wall' at the Hou Sahong inlet to reduce the ingress of the coarsest fraction of transported sediments into the head pond.

The existing *Telemac* model was run in 2D mode, directly coupled with the *Sisyphe* sediment transport and morphodynamic module. Hydrodynamic results from *Telemac* are used by *Sisyphe* to model sediment transport and deposition, from which the updated bed elevations are continually fed-back to the hydrodynamic model throughout the model simulation.

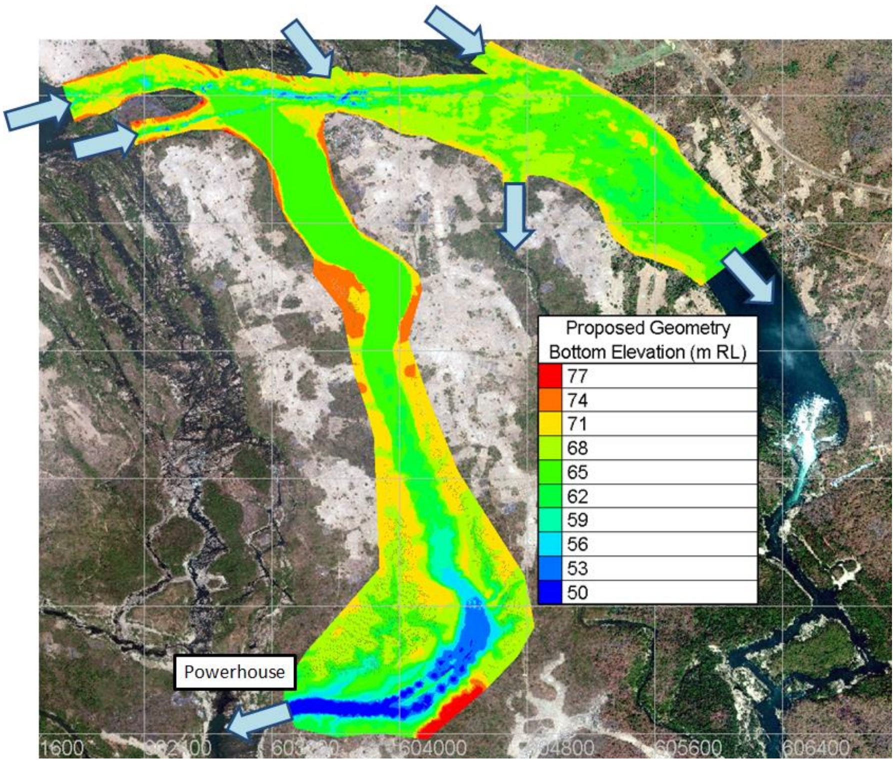

Figure 7: Telemac model domain, with colour scale representing non-erodible bathymetry. Arrows indicate flow boundaries.

Flow rates imposed at each boundary were based on the most recent correlations between flow rates at Pakse and in the various channels at site, developed in computational hydraulic model studies[27]. Hou Sahong discharge represented normal station operation, with station flow maximised up to 1,600 m³/s whilst maintaining at least 800 m³/s discharge out of Hou Phapheng.

[26] SMEC (2014) *Don Sahong Hydropower Project, CFD Hydraulic Model Study*, Revision C, May 2014.
[27] SMEC (2014) *Don Sahong Hydropower Project, Extended Computational Hydraulic Modelling,* Revision A, in preparation.

3.2 Model Cases

As described above, stable runs were only achievable using a single representative grain size. The overwhelming majority of sediment transported is silt-sized, and so the initial model case was run with a silt-sized sediment (d_{50}=10μm). It was expected that the coarser transported fractions evidenced in the bed load samples would account for a relatively significant proportion of deposition within the head pond, and so a subsequent model case was run separately with a fine sand-sized sediment (d_{50}=300μm).

3.3 Model Runs

Deposition effects were initially investigated by modelling the continuous operation of the station over three years. To simulate the natural variation in river conditions, flow inputs to the model were based on the recorded daily Mekong River at Pakse flows for 2001 to 2003. 2001 and 2002 could generally be described as wetter-than-average, both in terms of maximum flood discharge and total annual volume of water discharged, whilst 2003 is slightly dryer-than-average in both respects. Selection of these years was deemed to be conservative for the purpose of assessing effects, with transported sediment volumes over the period being higher than average. Historical flows were adjusted to the 'Definite Future' hydrological scenario[28], to account for the effects of upstream regulation. This adjustment results in slightly lower flood flows and higher dry season flows than in the historical measurements. Resultant sediment loads are slightly lower than they would be if the historical hydrology series were adopted unadjusted, consistent with expectations of upstream storage effects.

Flow conditions for the three-year duration were divided into representative fortnightly or weekly simulations, which were run sequentially beginning on 1st January of Year 1. The initial bed level was set to be non-erodible, though all subsequent changes to bed elevation caused by deposition were erodible depending on flow conditions, and deposited volumes were maintained between simulations. Each simulation adopted steady flow conditions, assuming no significant change during the two week simulation period in the dry season or one week period in the wet season.

After three years of simulated station operation and associated sediment deposition, it appeared that an equilibrium condition was being approached. To further investigate the development of an equilibrium condition, the final year of simulation was then repeated twice more, giving a five-year period of simulation for each model case.

3.4 Morphological Acceleration Factor

To achieve reasonable computer run-times, a morphological acceleration factor was used, which simply increases depth change rates by a constant factor[29]. In effect, running an 8.4 hour simulation with a morphological factor of 20 results in an actual simulated time period of 168 hours or one week.

[28] See AECOM (2011) *Don Sahong Hydropower Project, Design Studies: Hydrology, Hydraulics and Sedimentation Studies Report*, RPPG 0014_B, Revision B, October 2011.
[29] Knaapen, M. and Joustra, R. (2012) *Morphological Acceleration Factor: Usability, Accuracy and Run Time Reductions*, XIXth Telemac-Mascaret User Conference, Oxford, UK.

The quasi-steady flow conditions and the use of a morphological acceleration factor provide improved reliability and flexibility in carrying out the modelling, although introduce further simplifications of the actual physical processes. Comparison of preliminary runs without these simplifications showed no appreciable difference in deposited sediment volumes. The uncertainties introduced by these simplifications are assessed to be of a lesser degree than uncertainties associated with sediment loads and particle sizes, and within the limits of accuracy inherent in numerical sediment modelling.

4 RESULTS

The results of model simulations are reported in the sections below, including deposition volumes and patterns within the DSHPP head pond, effects on the station headwater levels and effects on the river downstream. Initial model runs using the median suspended particle size from site sampling (10 μm) showed that only a small fraction deposited within the head pond. A second model case was subsequently run with bed load transport using the median grain size from site bed load samples (300 μm). Results from both runs are reported, together with a combined result.

4.1 Suspended Sediment Deposition in Head Pond

The cumulated mass of suspended sediment entering, settling in, and passing through the DSHPP head pond is shown for the 5 year simulation in Figure 8.

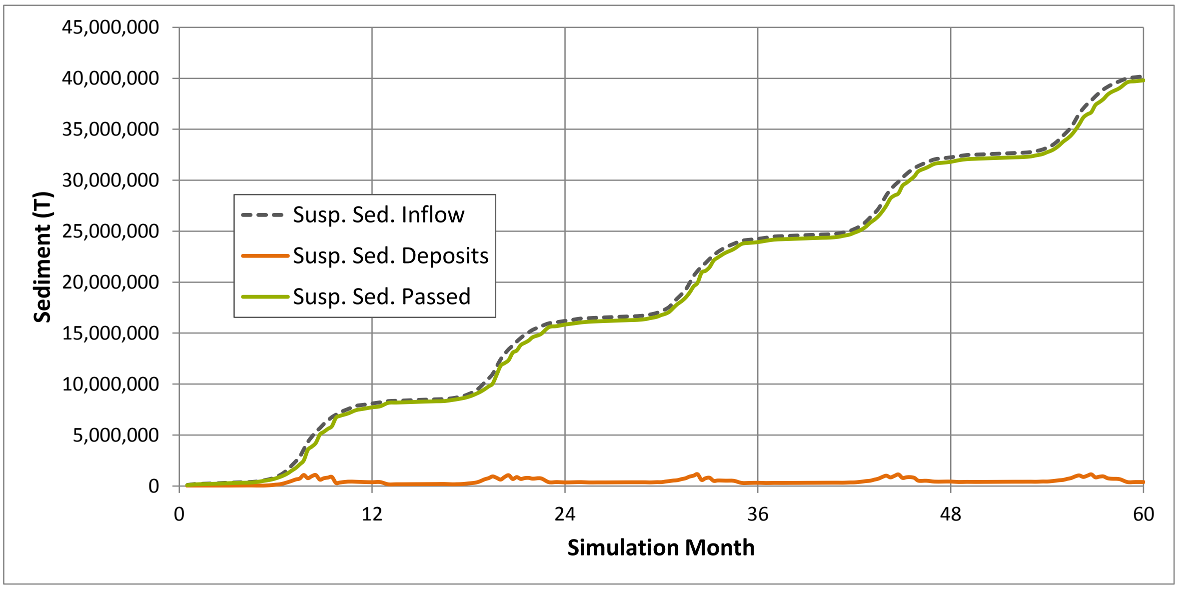

Figure 8: Cumulative mass of suspended sediment in DSHPP head pond, inflow, deposited, and passed through station

Only a small fraction of the suspended sediment entering the head pond will deposit. The modelled deposition (shown in more detail in Figure 9) is seen to quickly reach a quasi-equilibrium state over the first two or three years of operation. Generally, sediment deposits in the wet season when the head pond depths are high, and erodes as the wet season recedes.

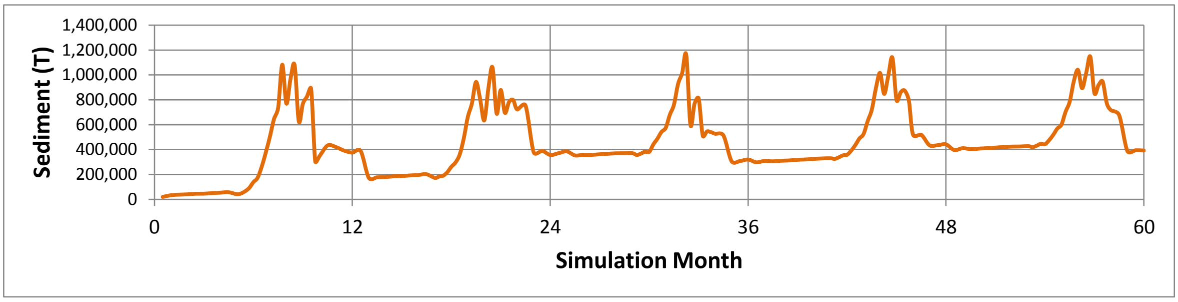

Figure 9: Cumulative mass of suspended sediment deposited in DSHPP head pond

It is noted that only around 5% of the Mekong suspended sediment load is modelled to enter the DSHPP head pond. The vast majority is transported by the large wet season flows in the channels to the west of the scheme. The maximum deposited mass of around 1.2 million tonnes is miniscule in relation to the Mekong sediment load of around 150 million tonnes annually (i.e. some 3,750 million tonnes over a 25 year concession period).

By the third year the annual mass of sediment deposition and re-entrainment appear to be balanced, though subsequent year-to-year variability in the amount of retained sediment would be expected due to the natural annual variability in wet-season flood peaks and sediment loads.

Deposition occurs in areas of the head pond where velocities are lowest. This is generally on the margins of the natural channel and in 'over-bank' areas outside of the natural channel (Figure 10). In these areas, the greatest volumes of deposition occur in the deepest spots. The natural Hou Sahong channel itself, which maintains a strong current conveying the majority of flow when inundated, remains largely clear of deposited fine sediment.

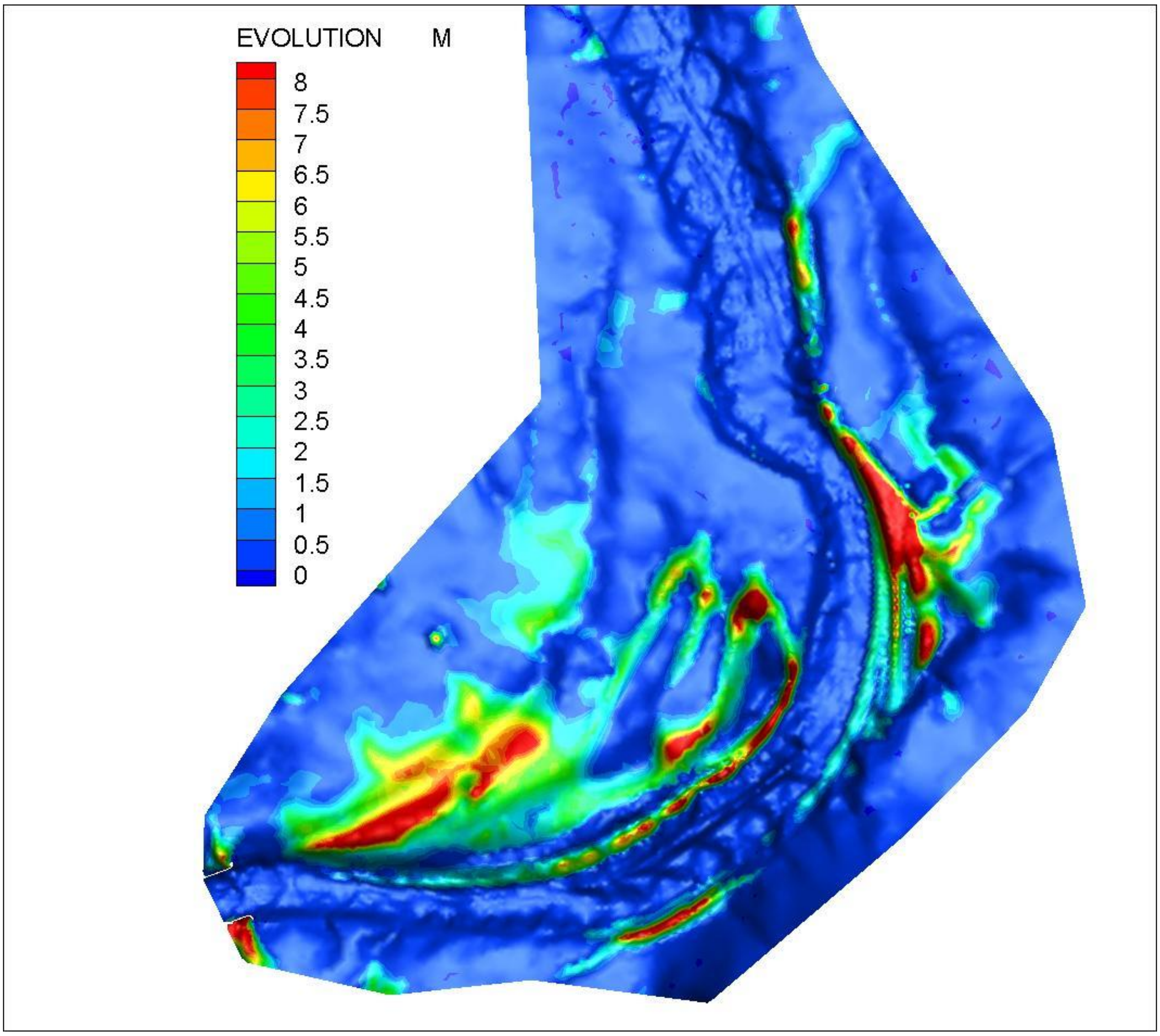

Figure 10: Pattern of suspended sediment deposition within the head pond, September Year 5, showing depth of deposition in metres.

As the wet season recedes, head pond water levels drop, and velocities increase as the station continues to operate at maximum discharge. Much of the deposited sediment is re-entrained, and passed downstream through the turbines. An equilibrium is quickly reached whereby the amount of sediment permanently deposited is constant year-to-year at around 0.4 million tonnes, whilst an additional 0.8 million tonnes is trapped during each wet season, and released as the wet season recedes.

4.2 Bed Load Deposition in Head Pond

From the second model case run, the cumulated mass of bed load entering, settling in, and passing through the DSHPP head pond is shown for the 5 year simulation in Figure 11.

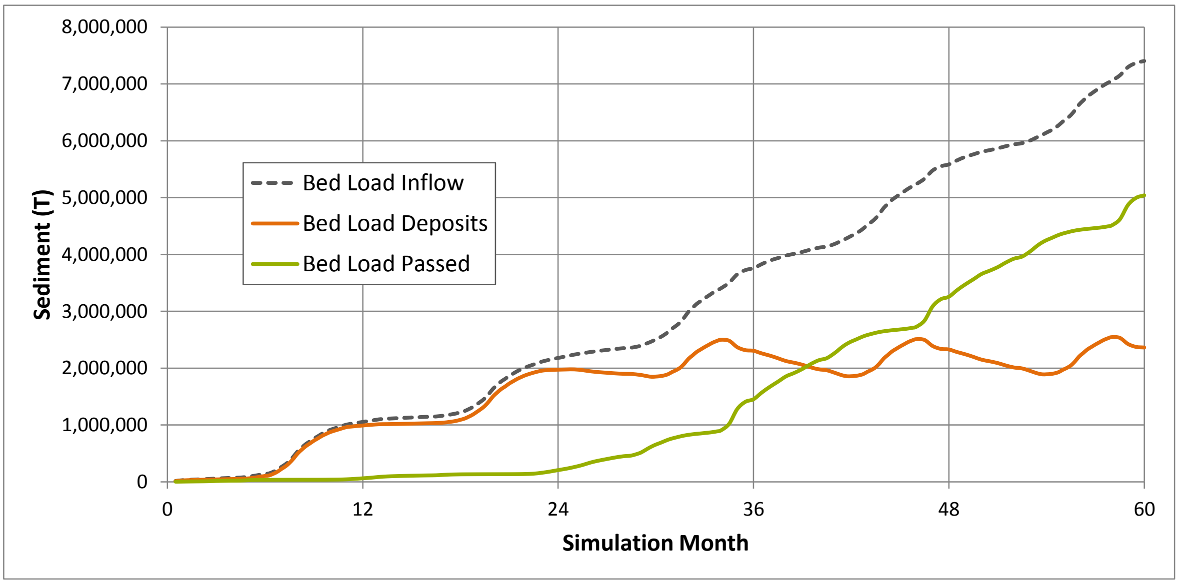

Figure 11: Cumulative mass of bed load in DSHPP head pond, inflow, deposited, and passed through station

For the initial years of operation, most of the bed load entering the DSHPP head pond is deposited. Once the total deposited mass reaches around 2 million tonnes, a quasi-equilibrium is reached whereby the amount deposited and the amount re-entrained and passed through the station over each year is approximately equal. Upon reaching this equilibrium the total deposited mass fluctuates between around 2 and 2.5 million tonnes. This mass of deposited coarse sediment is around twice the equilibrium mass of suspended sediment deposited, and again is small in comparison to an annual Mekong sediment load of around 150 million tonnes. The majority of the Mekong bed load will be carried by the adjacent channels, unaffected by the scheme.

With the amount of bed load in the project area assumed for the model run, the model shows that the annual mass of sediment deposition and re-entrainment is balanced by the fourth year of operation. As with the suspended sediment, year-to-year variability in deposited volumes would be expected with the annual variability in wet-season flood peaks and sediment loads.

Most of the bed load is carried within the main channel through the head pond (i.e. within the natural Hou Sahong channel) and deposited in the deeper downstream sections of the head pond. During the wet season when head pond depths are greatest deposition occurs over a greater length of the head pond, and as the wet season recedes, sediment in the shallower upper reach is flushed down the head pond and through the station.

Figure 12, depicting bed load deposition in the early dry season shows a 'tongue' of sediment that had been deposited in the previous wet season being flushed through the head pond.

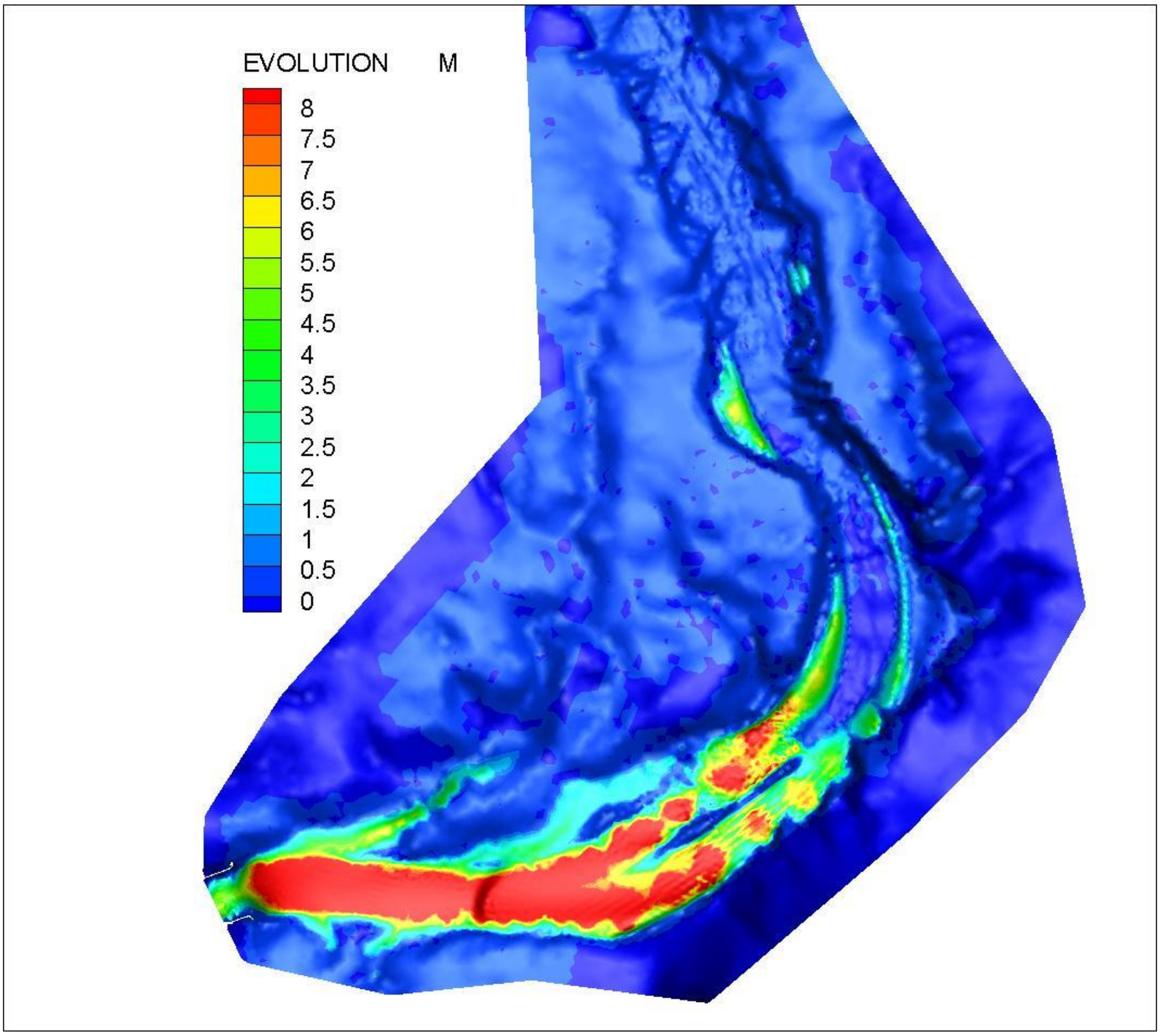

Figure 12: Pattern of deposited bed load within the head pond, January, Year 5, showing depth of deposition in metres.

4.3 Combined Sediment Deposition in Head Pond

In practice, sediment of a range of sizes will be transported into the DSHPP head pond concurrently. This range of sediments is represented by the two grain sizes modelled, and an interpretation of the model results must consider a combination of the two models.

As seen in Figures 10 and 12, the two different grain sizes modelled generally settle in different areas of the head pond, with the coarser grain being confined to the natural Hou Sahong channel, while the finer grain settles in low velocity areas in the shallower 'over-bank' areas of the head pond. Because of this, the two model results can reasonably be combined, neglecting any interaction due to the two sediments depositing in the same space.

To combine the two cases, model results were interrogated and at each model node the maximum deposited volume and mass from the two cases were extracted. An example of the combined deposited volume (as metres of deposition) is shown in Figure 13, while the deposited mass with simulation time is plotted in Figure 14. The deposited mass reaches a maximum of 3.3 million tonnes in the third year of operation, fluctuating between 2.2 and 3.3 million tonnes thereafter.

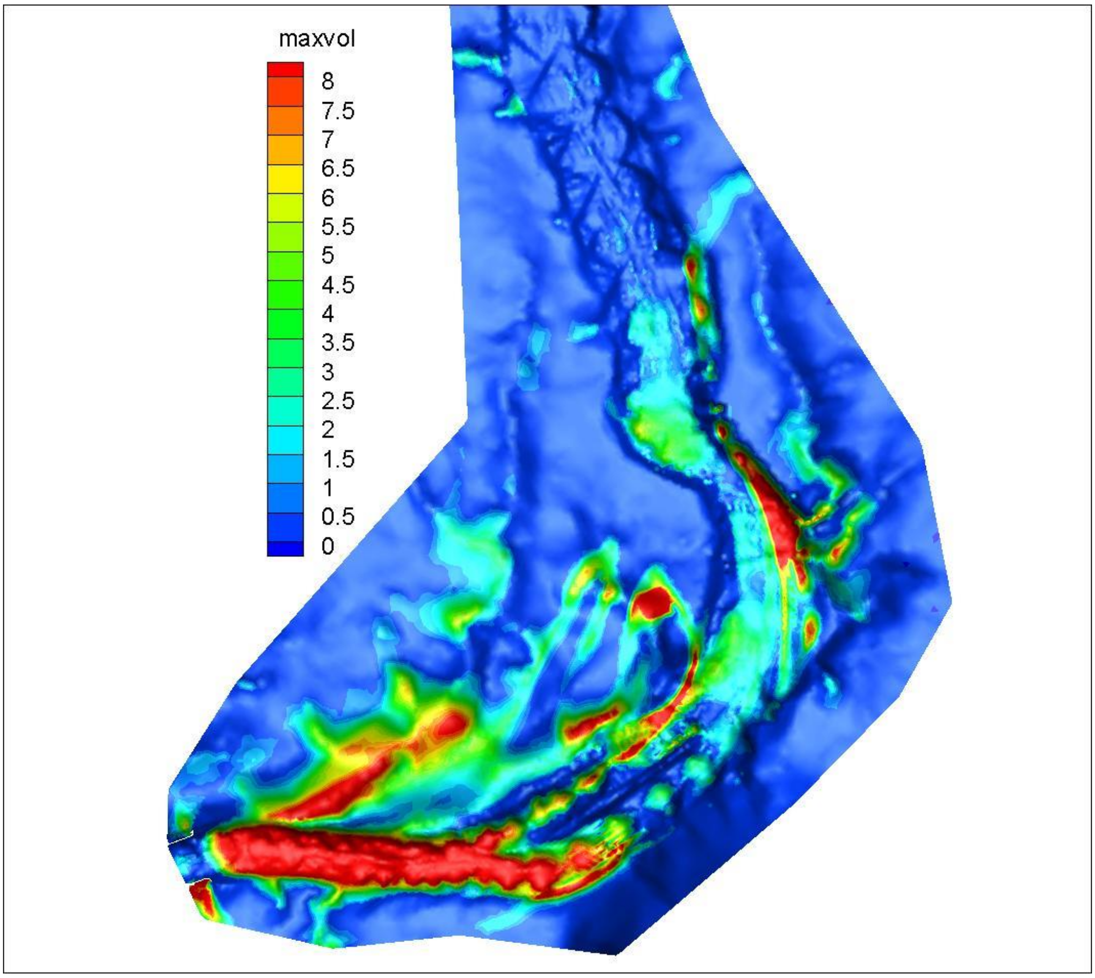

Figure 13: Pattern of combined deposition within the head pond, September, Year 5, showing depth of deposition in metres.

Figure 14: Cumulative mass of combined deposition in DSHPP head pond

4.4 Effects on Station Headwater Levels

Of major importance to the planned operation of DSHPP, and to the development of sediment management techniques, is an understanding of the effects of sedimentation on head loss through the head pond, and ultimately on headwater level at the station. Increased head loss and reduced headwater levels would result in a reduction in power output and thus a reduction in energy generation.

Head loss characteristics of the head pond change as sediment is deposited, flow area is reduced, and velocities are increased. Headwater level at the station is thus a function of prevailing Mekong River conditions (river levels upstream), station flow, and degree of sedimentation.

The modelled headwater levels at DSHPP station are plotted in Figure 15 against the Mekong flow condition, for the first three years of simulation for each model case.

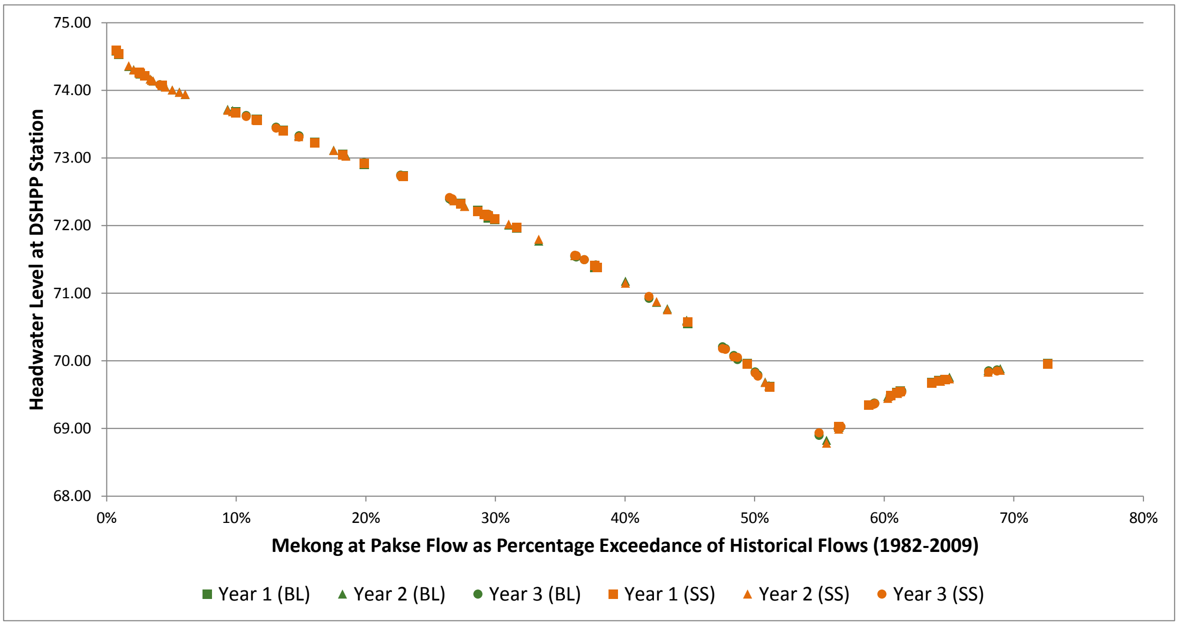

Figure 15: Station headwater levels from first 3 years of simulation for both model cases

There is no observable difference between headwater levels when the same flow condition is considered across different years (i.e. different degrees of sedimentation). Similarly, there is no observable difference between the suspended sediment and bed load model cases, with comparable results for the same flow condition being within 5 cm throughout the simulations. The lack of effect on headwater levels is attributable to the relatively small volumes of sedimentation compared to the head pond volume, meaning flow velocities are not significantly affected by sedimentation.

It is noted that the simulation does not cover the lower range of historically observed flow conditions (i.e. all flow conditions shown in Figure 15 are between 0% and 80% exceedance of historical flows). This is due to the 'Definite Future' hydrological assumption, for which these lowest dry-season flows are not predicted to occur, largely as a result of upstream regulation. Indeed, such flows (below 2,100 m^3/s at Pakse) have not been observed since 2010.

4.5 Effects on Downstream Sediment Load

The modelling estimates an insignificant change in the annual sediment load transported downstream of the DSHPP scheme. Over the first three years of operation, 3.3 million tonnes of sediment is estimated to settle within the head pond, compared with an annual load of around 150 million tonnes of suspended sediment and potentially 15 million tonnes of bed load.

Over subsequent years, there is no change predicted in the annual load delivered downstream, but there is a predicted change in timing of a portion of the load, with some sediment entering the DSHPP head pond being trapped during the wet season and released later in the year. The changes in sediment concentration in the Downstream Channel (combined Hou Xang Pheuak and Hou Sahong channels below station) as well as flow discharge with DSHPP operation are shown in Figure 16. The developed case is taken from the model results for simulation Year 5, combining both suspended load and bed load cases.

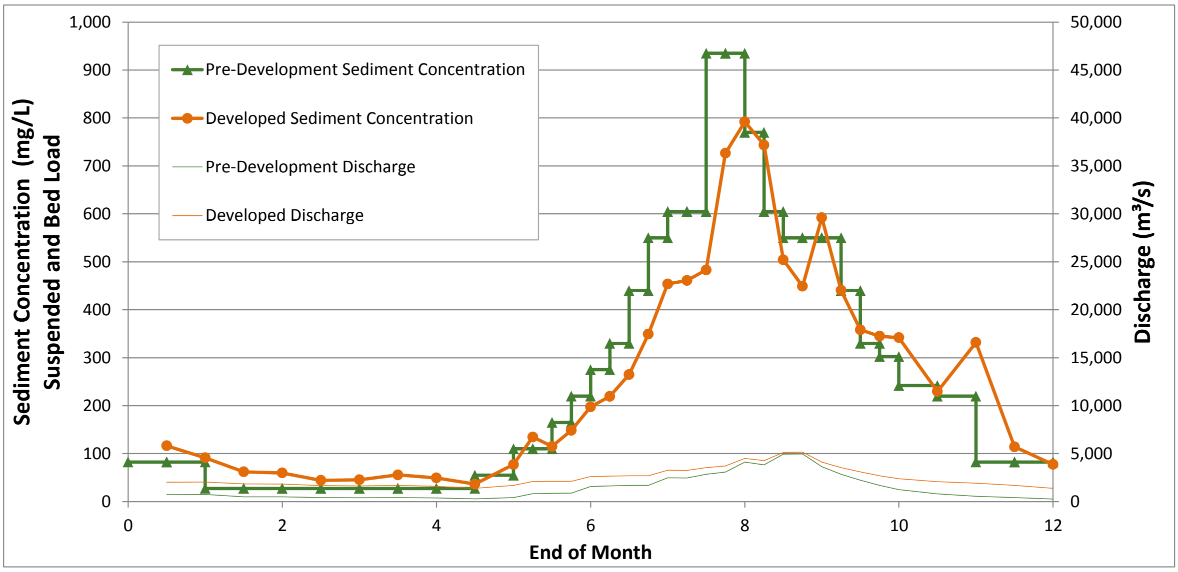

Figure 16: Sediment concentration and flow discharge in the Downstream Channel pre- and post- DSHPP development

Sediments are trapped in the DSHPP head pond in the rising and peak of the wet season (June-September), as evidenced by the reduced sediment concentrations released downstream. Sediment concentrations are conversely increased above pre-development levels for the same time-of-year in the receding wet season and through the dry season (October-April). In simplistic terms this change in timing of releases can be visualised such that with DSHPP in operation, the appearance of any given sediment concentration in the channel immediately downstream of Hou Sahong will lag some 2 weeks on average behind the concentration that is currently occurring in the pre-development case. Concentrations released downstream are always within the range of natural concentrations.

The majority of this lag in concentration modelled is associated with bed load, and is consistent with lag observed in bed load transport through the naturally-occurring

Mekong deep pools[30]. There are therefore not expected to be any significant environmental effects associated with the deposition and re-entrainment of sediment in the head pond. As noted above, conservative assumptions have been used throughout the modelling, particularly in regard to the volume of bed load, and changes in outflow concentration are expected to be less apparent than shown in Figure 16.

The change in concentration from station outflow will be a localised effect, as more than 90% of the Mekong sediment load bypasses the scheme through adjacent channels unaffected. Approximately 1 km downstream of the DSHPP station the Downstream Channel recombines with flows from the western channels, and downstream of this sediment concentrations will be much closer to their natural levels. There is therefore expected to be no noticeable trans-boundary impact on sediment transport.

[30] Conlan, I.A. et al (2008) *Sediment transport through a forced pool on the Mekong River: sand dunes superimposed on a larger sediment wave?* Conf. Marine and River Dune Dynamics, 1–3 April 2008, Leeds, UK,pp. 51–59.

5 DISCUSSION AND CONCLUSIONS

5.1 Modelling Summary

Computational modelling using the *Telemac* software package has been used to quantify the expected deposition of sediment within the DSHPP head pond. Estimates of deposition have been used to assess the trans-boundary impact of sediment trapping in the head pond. The downstream delivery of both fine and coarser sediments is an important environmental consideration. Finer particles carry nutrients downstream, while the supply of coarser sediments prevents additional erosion downstream.

Modelling results have also been used to assess effects on scheme operation, quantifying the volume of sediment expected to pass through the turbines, and the effect on headwater levels of sediment deposited in the head pond.

The modelling simulated scheme operation using information on flows and sediment properties measured at site. Two model cases were run representing two different sediment fractions – the plentiful silt-sized particles carried in suspension and expected to have a limited propensity to settle, and the medium-sized sand particles carried as bed load, which were conversely expected to have a high settling efficiency. Due to the practical difficulties in measuring bed load transport rates, the quantity of bed load was assumed as 10% of the suspended sediment load, a considerably conservative assumption.

5.2 Modelling Results

The modelling estimates an insignificant change in the annual sediment load of the Mekong downstream of the project, reducing to essentially zero impact after the first few years of operation. The proposed DSHPP may thus be considered 'transparent' with respect to sediment transport.

The model estimates that during the first wet season of operation less than 1% of the total Mekong suspended sediment load, approximately 1.2 million tonnes, will settle in the head pond. A majority of this sediment is re-entrained as the head pond level drops with the receding wet season, and an equilibrium is reached where the deposited mass fluctuates between 0.4 and 1.2 million tonnes through the seasons for subsequent years.

The model does not allow for consolidation of the settled fine sediment. In practice, the portion of this sediment that remains permanently trapped in the head pond (i.e. the 0.4 Mt identified above) would over time consolidate into a denser deposit. The mass of deposited sediment occupying this same volume would gradually increase, but remain insignificant in relation to the total Mekong sediment load.

In contrast to the fine sediment, almost all of the coarser bed load entering the head pond will be retained over the first two years of operation. Thereafter, an equilibrium is reached whereby further sediment settles in the wet season (up to a total of around 2.5 million tonnes) and is flushed out later in the year and through the dry season, as the head pond level drops.

Combining the two model cases, it is expected that by around the third year of operation, a total of around 3.3 million tonnes of sediment will have settled in the DSHPP head pond, and an inter-annual equilibrium condition will be achieved. A portion of the settled sediment will be flushed through the station by normal operation as the head pond drops in the dry season, with a similar volume re-deposited the following year. Given this process and the natural year-to-year variation in hydrology and sediment load, it is expected that the mass of sediment trapped in the head pond will fluctuate between around 2 and 4 million tonnes.

Scheme operation is predicted to alter the timing of sediment release to the channel immediately downstream, with a reduction in sediment concentration during the early and peak wet season, and an increase in sediment concentration in the receding wet season and dry season. This timing change can be visualised as a lag in sediment concentrations in this channel of approximately 2 weeks compared to the existing situation. The majority of this lag is associated with bed load, and is consistent with observation of bed load passage through naturally-occurring deep pools in the Mekong.

The deposited sediments do not build up to a level sufficient to cause any significant decrease in headwater level at the station. Active sediment management strategies are therefore unlikely to be necessary unless the volumes of sand passing through the station are a concern for turbine runner wear. Specifically, use of periodic flushing flows of above 1600 m^3/s to remobilise sediment deposited within the DSHPP head pond, proposed in earlier studies, is shown to be unnecessary and is no longer planned.

5.3 Sediment Monitoring

Given the inherent uncertainties in numerical modelling of sedimentation, deposition within the head pond as well as sediment concentrations in the project area should be monitored over the initial period of scheme operation and compared with the modelling results to verify the conclusions presented in this report.

The accuracy of morphodynamic model results (sediment transport and resulting bed evolution) is limited by numerous sources of uncertainty, including

- The accuracy of empirical sediment transport formulae,
- The sensitivity of sediment transport rates to hydrodynamic variables,
- The coverage and accuracy of bathymetric data,
- The accuracy of hydrodynamic modelling on the discretised model mesh.
- The representation of a range of sediment particle sizes by a single median size
- Future changes in sediment load
- ‘Cohesive’ effects associated with fine sediments including flocculation and changes in settling velocity, and potential consolidation of deposited mud with long-term changes in density and erodibility.

The head pond bathymetry should be surveyed at scheme commissioning to give a baseline data set. The survey should be repeated after the first wet season of operation, and repeated annually at a consistent time in the seasonal cycle, to identify any changes in deposited volumes. If head pond sedimentation is found to be greater than expected following monitoring, a mechanical dredging solution has been identified as technically feasible and could be implemented if required.

Suspended sediment concentrations should be continuously monitored upstream and downstream of the station, to confirm sediment loads and the effects on sediment loads of scheme operation. Monitoring could involve collection of water samples on a monthly basis, similar to the MRC WQMN programme. Discussion with MRC would be useful to potentially integrate the sample collection and analysis with the MRC programme.

Operational monitoring will also include visual inspection of the river banks in all areas influenced by the scheme. If required, river bank erosion control measures such as riprap or gabions should be included in scheme maintenance.

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APPENDIX A – COMPLIANCE WITH MRC PDG

Table A1 : Compliance with MRC Preliminary Design Guidelines for sediment transport and river morphology

PDG Paragraph	Is the clause applicable?	Compliance with PDG	Reference and comments
90-98. Background: General			General background information only.
99 -111. Background: Strategies to sustain reservoir capacity - Sediment routing - Sediment bypass - Sediment flushing - Mechanical removal - Sediment traps	Yes	n/a	Natural sediment bypass is provided by the adjacent channels, which pass over 90% of the Mekong sediment load. Of the suspended sediment that enters the head pond, the majority is shown to pass through the head pond without settling. Distinct sediment flushing flows are no longer proposed for DSHPP. Natural sediment flushing is shown to occur seasonally as the high wet-season head pond levels recede and head pond velocities increase. Mechanical dredging has been identified as feasible for the relatively small head pond, and could be implemented if required following monitoring.
112-115. Background: Mitigating downstream sediment starvation	Yes	n/a	The modelling demonstrates that there will be an insignificant change in the annual sediment load of the Mekong downstream of the project, reducing to essentially zero impact after the first few years of operation.
116-119. Background: Managing sediment in a cascade of dams	Yes	n/a	The modelling demonstrates that there will be an insignificant change in the annual sediment load of the Mekong, whether or not any further dams are constructed in cascade.

PDG Paragraph	Is the clause applicable?	Compliance with PDG	Reference and comments
			Contingency provisions have been included in the O&M budgets for sediment management
120. Mainstream dams should be designed to pass fine suspended sediment and coarse bed load material in a way that most closely mimics the natural timing of sediment transport dynamics in the river.	Yes	Yes	The majority of sediment will be passed naturally down adjacent channels, without any effect on timing. Of the suspended sediment entering the head pond, the majority will pass through the turbines with a negligible hydraulic residence time. The modelling demonstrates that some material is deposited within the head pond in the wet season, to be remobilized and flushed through the station as the head pond levels recede later in the season. This effect is considered to be minor.
121. Dams and intake structures should be designed to minimise the deposition and entrainment of sediment near the dam ensure long-term safe operation. Particular care should be taken to avoid sediment deposition that poses risks for the safe working of the flood passage capacity of the dam.	Yes	Yes	The station has a high capacity factor, meaning that the turbines will be operating near continuously, especially in the wet season. There is therefore no potential for a build-up of sediment to occur near the turbines which may affect turbine operation during flood periods. The turbines are specified to be capable of safely passing sediment. Flood passage capacity is provided by a) Turbine discharge, b) Bypass down adjacent channels, and c) Emergency un-gated overflow spillway. None of which will be effected by sedimentation.

PDG Paragraph	Is the clause applicable?	Compliance with PDG	Reference and comments
122. A sediment monitoring programme should be developed and implemented to routinely monitor reservoir sedimentation.	Yes	Yes	Monitoring of suspended sediment concentrations in the head pond and downstream, and periodic bathymetric survey of the head pond are proposed, to monitor sedimentation.
123. Sediment management strategies should be thoroughly evaluated and subject to independent expert review prior to implementation.	Yes	Yes	The sediment modelling shows that active sediment management strategies are not necessary at DSHPP. This modelling will be verified with ongoing monitoring during the scheme operation. Sedimentation studies, including the current document, are provided for the MRC Prior Consultation process including independent review.
124. Consideration to be given to alternative dam sites at the feasibility stage, with a view to select sites whose natural attributes, combined with the hydraulics of the river flow at the site best facilitate passage of sediment.	No		Alternative project locations have been considered by the Government of the Lao PDR (GoL). Alternative locations would not have better characteristics with regard to sediment passage.
125. Natural channel features, such as upstream bends focussing the bed load concentrations at one side during high flow periods, to be considered in design to reduce sediment problems at the proposed turbine intake locations.	No		Not applicable. The low-level turbine intakes occupy the entire width of the existing Hou Sahong channel. Excavation of the Hou Sahong inlet is designed to reduce bed load admission to the head pond.
126. The dam should be designed to allow for sediment routing and periodic drawdown to	Yes	Yes	Sediment routing is provided by the adjacent channels, with the inlet excavation designed to reduce bed load admission to the head pond.

PDG Paragraph	Is the clause applicable?	Compliance with PDG	Reference and comments
enhance sediment flushing.			The head pond has a seasonal range due to the prevailing Mekong level upstream that is sufficient to remobilize settled sediment.
127. Developers should employ the best possible technology for sediment investigation and modelling of sediment transport in 3-dimensional flow environments to assess how sediment deposition and downstream erosion problems can be minimised.	Yes	Yes	Computational modelling, as detailed in this model, has been employed to confirm the expected deposition volumes and patterns. Due to the confined and relatively small head pond, the natural configuration of the adjacent flow channels, and the correspondingly small volumes of sediment to be dealt with in the head pond, physical hydraulic models are not considered to be warranted.
128. Appropriate gates should be incorporated into dam design to allow sediment pass-through and periodic sediment flushing.	No		Low-level gates are not provided, as the turbine intakes are set at the lowest point of the headpond, and the turbines are specified to be abrasion-resistant, and be able to safely pass sediment.
129. Use of the bottom flow gates should be optimized to pass coarse sediment in both dry and wet seasons, also taking into account the need to avoid sediment problems with operation of turbine intakes	No		Low-level gates are not provided, as above.
130. Seasonal drawdown of the reservoir to MOL and opening of gates to allow sediment pass-through should be carried out when sediment concentrations and sediment transport rates are high.	Yes	Yes	DSHPP is a run-of-river scheme, and so draw down is dependent on the prevailing Mekong water levels and available flows. The head pond is drawn down to its lowest level twice each year during the shoulders of the dry season, where the Mekong level is relatively low, but

PDG Paragraph	Is the clause applicable?	Compliance with PDG	Reference and comments
			there is sufficient flow available for full station discharge. Sediment concentrations discharged from the station are still highest during the wet season.
131. Flushing of fine sediments should be routinely carried out each year. Reservoir should be drawn down every 2-5 years, depending on sediment modelling.	Yes	Yes	Modelling demonstrates that the head pond quickly reaches an equilibrium condition whereby the seasonal variation in head pond level each year is sufficient to remobilize settled sediments.
132. Where hydraulic flushing is not possible, or effective, alternatives to removing sediments accumulated in the reservoir should be considered.	Yes	Yes	An adaptive management philosophy is proposed, where the natural seasonal flushing is expected to be sufficient, but if shown by monitoring to be less effective than expected' mechanical removal by dredging will be undertaken.
133. Bottom-gates should be opened regularly to prevent accumulation of sediment directly behind the gates and ensure that gates can be opened in an emergency	No		Low-level gates are not provided, as above. The turbines have a high capacity factor, operating near continuously, especially in the wet season. There is therefore no potential for a buildup of sediment to occur near the turbines.
134 -135. To ensure environment-friendly sediment flushing a maximum allowable downstream sediment concentration, initially based on natural conditions, should be established and actual concentrations should be monitored.	Yes	Yes	Modelled sediment releases are within the naturally occurring range. Monitoring of suspended sediment concentrations in the Downstream Channel during scheme operation is proposed. Ongoing monitoring of suspended sediment concentrations upstream of the scheme is proposed, to allow natural conditions to be accurately defined.

PDG Paragraph	Is the clause applicable?	Compliance with PDG	Reference and comments
136. Monitoring and mitigation is needed of reservoir deposition and downstream scour	Yes	Yes	Ongoing monitoring of deposition is proposed. A monitoring plan is to be further developed, including discussion of the potential to cooperate/integrate with MRC monitoring.
137. Annual topographic and bathymetric surveys should be undertaken to establish rates of sedimentation	Yes	Yes	Annual survey is proposed during scheme operation, to be compared with a baseline survey taken at the time of scheme commissioning.
138. Natural deep holes in the reservoir reach should be monitored for infilling	No		There are no naturally-occurring deep holes within the reservoir reach.
139 -140. River banks should be monitored for erosion. The Owner should be responsible for erosion control.	Yes	Yes	River bank monitoring is proposed, with required remedial works to be the responsibility of the Owner.