Mekong River Commission
Basin Development Plan Programme, Phase 2

Assessment of basin-wide development scenarios

Technical Note 3

Geomorphological Assessment

(Work in Progress)

February 2010

Note to the reader

This series of technical notes is prepared to serve facilitation and discussion on the assessment of basin-wide development scenarios of the Mekong Basin by stakeholders in the basin countries. The assessment process is continuing and feedback on the initial findings is requested.

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List of Technical Notes

Technical Note 1: ***Synthesis of initial findings from assessments***
Technical Note 2: ***Hydrological assessment***
Technical Note 3: Geomorphological assessment
Technical Note 4: ***Environmental assessment***
Technical Note 5: ***Social assessment***
Technical Note 6: ***Economic assessment***
Technical Note 7: ***Power benefits assessment***
Technical Note 8: ***Agriculture impacts assessment***

Note: Technical note on Fisheries Assessment is being prepared. Only power point presentation is available

Table of Contents

Index of Tables

Index of Figures

EXECUTIVE SUMMARY

An assessment has been made of the potential geomorphological impacts of the basin-wide development scenarios in relation to the baseline conditions. Data are relatively scarce and the assessment has been made using a mixture of documentary review and expert opinion, supported by modelling of typical processes.

Geomorphological changes in the Mekong mainstream will be driven by current developments in the Definite Future Scenarios

The views reached are based on an understanding that approximately 40% of the sediments in the mainstream system are derived from the upper catchments in China, 40% from the 3-S basin in the LMB and 20% from other catchments in the LMB. The developments in the Definite Future Scenario, which include substantial development of dams in the Upper Mekong Basin in China and in the 3-S basin, indicate that substantial reductions in the quantity of sediment entering the mainstream system will occur. Further developments as envisaged under alternatives considered in the Foreseeable Future Scenarios (such as the LMB 20-Year Plan Scenario) will thus impact only on the remaining 20% of sediments entering the system from the other catchments.

The consequences of reductions in sediment entering the mainstream system, combined with only relatively small modifications to the geomorphologically significant wet season flows, are that the river will seek to restore the sediment balance. The river will do that, firstly by scouring existing sediments in the river and secondly, as these are cleared out by adjusting its slope and shape to one compatible with the reduced sediment load. The timing of these processes is difficult to predict with accuracy without further data collection and predictive modelling. The manner in which bed level changes happens will be constrained by the presence of rock beds and any future dams in parts of the river (which will determine minimum bed levels at specific locations).

In the Foreseeable Future Scenarios, the geomorphological changes at the regional scale are likely to be small

Given these understandings, the potential major changes to the morphology of the mainstream will be induced by current developments in the Definite Future Scenario, such that irreversible changes will occur. However, other than at specific locations where local effects can be expected, as a result of mainstream dams, for instance, in the medium term at a regional scale the morphological changes are likely to be small. The loss of impounded sediments in the upper reaches is being compensated by the take-up of existing deposits in the system. Effects on channel morphology will be noticed in upstream reaches first and in downstream reaches at later dates. Upstream effects may become evident in the Foreseeable Future Scenarios. **In the longer term (> 20 years), the river's shape will start to adjust more aggressively.**

Because the geology through which the river flows changes down its length, these impacts will be felt differently along the mainstream. In broad terms this can be characterised as follows:

- **Reach 1 — Chiang Saen to Vientiane**: This is a bedrock channel so no major changes in channel shape will occur but sediment will be flushed out from the channel in the Foreseeable Future Scenario.

- **Reach 2 — Vientiane to Nong Khai**: The channel is alluvial and readily erodible. Bed levels may begin to fall within the Foreseeable Future Scenario (next 20 years), and river bank stability may decrease locally.

- **Reach 3 — Nong Khai to Pakse**: The channel is alluvial upstream but has major bedrock bed level controls downstream. Consequently, channel change effects will be more evident in the alluvial sections but are not likely to be significant within the Foreseeable Future Scenario.

- **Reach 4 — Pakse to Stung Treng**: This is a bedrock channel so no major changes in channel shape will occur and sediment is not likely to be flushed out within the Foreseeable Future Scenario.

- **Reach 5 — Stung Treng to Kratie**: This is a bedrock channel so no major changes in channel shape will occur. However, the 3-S Basin is thought to supply large amounts of sediment to the main river at the confluence near Strung Treng. Due to dam construction in the 3-S Basin sediment inflow to the main river will decrease. Consequently, sediment is likely to be flushed out within the Foreseeable Future Scenario.

- **Reach 6 — Kratie to the Delta**: The channel is alluvial and readily erodible. Some sediment loss may occur immediately downstream of Kratie within the Foreseeable Future Scenario but sediment losses further downstream will be negligible within this timeframe. Projected local engineering works are more likely to induce medium-term effects on channel morphology rather than flow regulation by the existing and proposed dams.

Identified specific issues for the integrated economic, environmental and social assessment

The specific issues that the scenario assessment is required to address are as follows:

- **Bed erosion**: River bed erosion will cause the bed elevation level to fall. The impact will occur in upstream alluvial reaches first, with changes occurring downstream progressively later.
- **Bank erosion**: River bank erosion initially will be reduced owing to reduced flood peak water levels. However, in the long term (>20 years) bed level

incision may increase the risk of bank erosion. Bank erosion may be exacerbated immediately downstream of dams.

- **Mainstream dams**: The geomorphological changes will have no negative impacts on proposed mainstream dams in the LMB. A reduced sediment supply in time will mean less sediment to flush through structures. Nevertheless, a sediment management strategy will be required to pass sediment through the dams. However, main stream dams will have a local effect on channel morphology: 1) in the foreseeable future (next 20 years), dams induce local bed scour and increase river bank erosion immediately downstream of the dams, and 2) in the longer term (> 20 years), when the river would start to erode more aggressively, the dams would fix the river bed level at the dam locations.
- **Deep pools**: There are no negative geomorphological effects on deep pools due to the reduction in sediment supply, although pools in the vicinity of dams could be adversely affected by construction activity and by impoundment. Higher water levels in the dry season may increase the size of the refugia.
- **Sandbars**: The number and size of sand bars will decrease as the sediment supply is reduced. The effects will be seen in the Foreseeable Future Scenario (next 20 years) within Reaches 1 and 5 and at within progressively later time-frames downstream of these two reaches.
- **Floodplains**: The major floodplains are downstream in Cambodia and Vietnam. Consequently the impacts of the reduced sediment supply will not be noted within the Foreseeable Future Scenario (next 20 years). However, effects of engineering works such as flood embankments will have major impacts on the natural function of the floodplains.
- **Cambodian and Delta river channels**: The impacts of the reduced sediment load will not be noted within the Foreseeable Future Scenario. In the longer term, the reduction in sediment load would cause bed level reduction south of Kratie. However, engineering works, such as flood embankments, often may cause bed levels to increase. An additional complication is rising sea levels due to climate change which will affect the bed levels in the delta.

Issues for the countries to consider

It is recommended that the countries in the Lower Mekong Basin will consider the following issues in their development planning:

- **Design requirements of proposed mainstream dams**: Consideration is required to maximize the throughput of sediment in detailed designs and sediment management strategies. Hydropower operational regime may cause local bed scour and river bank erosion. Longer-term bed level reductions may cause problems with entry and exit to navigation locks.

- **Floodplain management strategies**: Consideration is required as to the balance between economic development through provision of flood protection and maintaining the natural functions of the floodplains. The latter importantly include floodwater storage, which reduces in-channel peak flows and so protects downstream infrastructure, such as at Phnom Penh and the delta. Significant flood protection in the Cambodian plains and the delta would cause major problems in terms of effective storage and conveyance of flood flows.

- **Channel stability**: Bed levels may begin to fall at Vientiane and immediately downstream within the Foreseeable Future Scenario, and river bank stability may decrease locally. These changes will put infrastructure at risk and there are implications for managing the international Lao/Thai border. Modelling would provide evidence of the degree of probable channel change and the timescales involved.

- **Delta integrity**: In the longer term (>20 years), the delta is at risk of erosion and inundation due to the combined effects of reduced sediment supply, increased storminess and rising sea levels. Modelling would provide evidence of the degree of probable morphological change and the timescales involved. Such results would aid prudent design of flood protection works etc.

- **Data collection**: Investment is required in basin-wide data collection and environmental monitoring with agencies using common agreed procedures. Such data are required for informed decision-making in the future.

1. REPORT SUMMARY

The regulation of the mainstem Mekong River by dams and the effect of dams on the tributaries will have measurable effects on the fluid discharge of the river and the annual flux of sediment transport. IQQM simulations of the future flows due to the Chinese dams, the definite future and the 20-year foreseeable future scenarios demonstrate that there will be reductions in peak discharge and water levels for the annual flood hydrograph. For the definite future, the discharge volume reduction will be between 17 and 10% for stations to the north of (and including) Vientiane, with lesser effects downstream. For the 20-year foreseeable future scenarios the figures are 18 to 15% reductions. However, the power of the river to transport sediment is usually indexed by the peak discharge and preliminary calculation shows that the capacity of the peak flow will be only reduced by a few percentage points. Consequently, the flux of sediment due to the power of the regulated peak flow regimen will not be reduced perceptively and it is not possible to distinguish significant differences in sediment flux due to the peak power of the river associated with any one future flow scenario. However, total annual sediment flux is not related solely to peak discharge and should be calculated by integration over the annual hydrograph. Consequently, more detailed studies of bed sediment entrainment and transport throughout the annual hydrographs for each scenario are required to better understand how the river responds to regulation (and climate change).

However, despite the sustained river power, sediment can be trapped within impoundments. The UMB with China dams, currently delivers for some 40% of the total load within the LMB. Depending on method used, it has been calculated that the China dams have already retained between 25% and 65% of the load from the UMB. The remaining 60% of the total load is assumed to be contributed from LMB tributaries and main river erosion. However, the tributary contribution of suspended load within the LMB is very poorly documented and, individually, each river often seems to contribute little load. Calculations indicate negligible additional load contributed by tributaries between Chiang Sean and Nong Khai. Limited study of the dams on the 3S Basin tributaries has shown that these dams within the central Highlands may trap as much as 37% of the suspended sediment load delivered to the tributary dam sites. Given the known and expected reduction in sediment delivery to the main channel, the effects of impoundments on the mainstem Mekong are of greatest concern with respect to sediment trapping. Proposed LBM mainstream dams will have variable, site specific effects on sediment retention and this retention will have to be considered in relation to specific construction and management design. In the Upper Mekong Basin, China is completing its hydropower cascade on the Lancang. The Manwan, Dachaoshan and Jinghong Dams are currently operational and these dams have already induced a measurable reduction in sediment supply to the LMB as far downstream as Vientiane. In particular, the Xiaowan and the Nuozhadu hydropower projects, close to completion, with 9,800 and 12,400 million m^3 of active storage, will result in significant further sediment retention and a consequent reduction in sediment supply to the Mekong mainstream.

Downstream of Vientiane there are few sediment sources (until the 3S Basin) and the majority of the sediment flux from Vientiane to Pakse is that passing Vientiane. Consequently, the flux of sediment past downstream stations (such as Pakse) will also be reduced within the next 20 years. Thus overall, given sediment trapping by dams, there will be a reduced flux of suspended sediment for both the definite future and the 20-year scenarios throughout the LMB.

Peaking in main river dam hydropower flow releases will depend on operational management but potentially can have significant impact on local channel stability, including bed levels and bank erosion downstream of each impoundment. The effects on channel stability require consideration in the design and management plans for each dam.

The channel upstream of Vientiane is largely bedrock-constrained such that the impact on the channel shape of a reduced sediment flux will be minor. However in the vicinity of Vientiane (and immediately downstream) the river bed is alluvial and there may be significant erosion of the river bed and associated destabilization of the river banks for the 20-year foreseeable future scenarios. This local situation should be modelled to ensure the implications for flood control and navigation are understood fully. In similar vein, a reduction in sediment load to the Cambodian Plain and the Delta will have implications for the stability of the main navigation channels in this lower region for the longer-term futures. Without modelling studies, it is difficult to determine over what time spans such effects may be evident, but using the Pearl River as an example of a regulated deltaic environment, changes may occur within 20 to 50 year time spans. It is recommended that the channel evolution within the delta region, due to reduced sediment flux and sand mining, should be modelled.

The impacts on the floodplains are difficult to determine with any certainty. Changes in the annual hydrograph according to IQQM simulations indicate negligible impacts in terms of capacity to deliver sediment to the floodplain surfaces, although reduced water levels during peak flows should mean a slightly lower depth of flooding and in principle less deposition of fine sediment on the floodplains each year. However, these impacts will be strongly affected by channel changes induced by changes in the total sediment flux, by flood protection measures utilizing levees and other flood control measures. In a similar vein the delta is at risk of no-longer receiving sediment from the Mekong to aid natural delta building, a problem that is being exacerbated by unregulated sand extraction from the river bed. Consequently, given global and regional sea-level rise the delta is at risk of seaward erosion and this situation requires a modelling study. It should be noted that there are no baseline data on floodplain sedimentation processes and a study of the baseline situation should be commissioned.

Within the baseline scenario, river bank erosion is locally of significance but is not a regional issue. However, the definite future and the 20-year plan foreseeable future flow scenarios and the effects of generalised water level fluctuations due to hydropower have little effect on the natural values of river bank erosion rates. The foreseeable future flow scenarios in fact show a trend of decrease in river bank erosion at the basin-scale. The uncertainty in respect of the deltaic environment means that detailed studies of river bank stability within the delta are desirable as river bank erosion could be exacerbated by channel changes within the delta for the foreseeable and longer-term futures. In addition, the predicted river bank erosion rates reflect only the effects of the changes in the IQQM flood hydrographs and do not account for enhanced river bed incision locally, as might occur near Vientiane and downstream of dams for the 20-year scenarios. Such local incision can increase bank recession rates considerably.

Deep pools are important for fish habitat and for river dolphins. It is not anticipated that the deep pools will be impacted, as a reduced sediment flux in future flow scenarios where the river power is sustained indicates that the river will still flush the pools during the wet season and the pools will not fill with sediments. Water levels in pools will be higher in the dry season potentially increasing habitat space. These situations could be modelled but the matter is not of the highest priority. The impact on sand bars and islands by the flow scenarios has not been considered specifically within this report. Sand bars and islands are of ecological significance and the islands have political importance due to international Thai/Laos border designations. Sand bars likely will be smaller in size and fewer in number due to increased dry season water levels and progressive flushing-out of the sediment within the LBM river system. The sediment cannot readily be replaced as mainstream dams will trap the supply to the main river. A study of the impacts of flow regulation on sand bars and islands is recommended.

1.1.MAIN RECOMMENDATIONS

- Detailed modelling of bed sediment entrainment and transport throughout the annual hydrographs for each scenario are required to better understand how the river responds to regulation (and climate change).
- The effects on channel stability require consideration in the design and management plans for each dam.
- The channel stability at Vientiane for the 20-year scenarios should be modelled to ensure the implications for flood control and navigation are understood fully.
- Channel evolution within the delta region, due to reduced sediment flux and sand mining, should be modelled for the 20-year scenarios.
- The uncertainty in respect of the deltaic environment means that detailed studies of river bank stability within the delta are desirable as river bank erosion could be exacerbated by channel changes within the delta.
- A study of the baseline floodplain sedimentation rates and processes should be commissioned with prognoses for the definite future and 20-year scenarios.
- A study of the impacts of 20-year scenario flow regulation on sand bars and islands is recommended.

2. TERMS OF REFERENCE

Main tasks

- Review data availability and identify any geomorphology and sedimentology related information and data gaps. Recommend further secondary data sources and identified appropriate means of collection and analysis to derive all outstanding data requirements
- Identify more vulnerable reaches of the river and a prediction of the extent of riverbank erosion over the next 20 years with respect to land lost as a results of hydropower developments and the proposed flood protection measures in the Mekong Delta
- Examine long term geomorphological processes in the Mekong River and assess the impact of channel movements resulting from hydropower and flood protection developments on riverbank erosion and deep pools
- Assist the International Environmentalist in describing and evaluating the trade-offs between the economic, social and environmental impacts associated with scenarios B2, B3, B4 and B5

The key results are presented in accordance with the flow scenarios detailed in Table 1. The full range of flow scenarios are as defined within section 2.1 ‘Basin Development Planning’.

Some subsidiary tasks not specified within the TOR are considered at the end of this report.

2.1. BASIN DEVELOPMENT PLANNING

The second phase of MRC’s Basin Development Plan Programme (BDP2) is designed to provide an integrated basin perspective through the participatory development of a rolling Integrated Water Resources Management (IWRM) based Basin Development Plan. The plan will comprise the following elements:

- ***Basin-wide Development Scenarios***, which will provide the information that Governments and other stakeholders need to develop a common understanding of the most acceptable balance between resource development and resource protection in the Lower Mekong Basin, taking into account developments in the upper Mekong Basin. The results will guide the formulation of the IWRM-based Basin Development Strategy.

- ***An IWRM-based Basin Development Strategy***, which provides a shared vision and strategy of how the water and related resources in the LMB could be developed in a sustainable manner for economic growth and poverty reduction, and an IWRM planning framework that brings this strategy into the various transboundary and national planning, decision-making and governance processes.

- ***A Project Portfolio*** of significant water resources development projects and supporting non-structural projects that would require either promotion or strengthened governance, as envisioned in the 1995 Mekong Agreement.

The preparation of the Plan will bring all existing, planned and potential water and related resources development projects in a joint basin planning process, through a combination of sub-basin and sector activities, and a basin-wide integrated assessment framework.

2.1.1. *Formulation and Assessment of Scenarios*

The formulated basin-wide development scenarios represent different levels and combinations of sectoral development and consider the many development synergies and trade-offs among the different water-related sectors, such as irrigation and hydropower synergies and hydropower and fisheries tradeoffs. Table 2 below summarizes the scenarios agreed by the countries.

Table 1: *Considered scenarios within Basin Development Plan Programme, Phase 2*

No.	Short Title	Full Title	Development Period	Interventions/Projects
Baseline situation				
1	BS	Baseline scenario	-	Year 2000 infrastructure including existing HEP dams
Definite future situation				
2	2015-UMD	Upper Mekong dam scenario	2000 - 2015	Baseline extended to include the full HEP cascade on the Lancang
3	2015-DF	Definite future scenario	2000 - 2015	2015-UMD plus 25 additional HEP dams in LMB and 2008 irrigation and flood measures
Foreseeable future situation				
4	2030-20Y	LMB 20-year plan scenario	2010 - 2030	2015 DF plus 11 LMB mainstream dams and planned tributary dams, irrigation, and water supply
5	2030-20Y-w/o MD	LMB 20-year plan scenario without mainstream dams	2010 - 2030	As above, excluding 11 LMB mainstream dams
6.1	2030-20Y-w/o LMD	LMB 20-year plan with 6 mainstream dams in Northern Lao PDR	2010 - 2030	As above plus 6 LMB mainstream dams in upper LMB
6.2	2030-20Y-w/o TMD	LMB 20-year plan with 9 mainstream dams	2010 - 2030	2030-20Y, excluding the two Thai mainstream dams
7	2030 – 20Y Flood	Mekong delta flood management scenario	2010 - 2030	Baseline plus 3 options for flood control in Cambodia and Vietnam Delta
Long term future situation				
8	2060-LTD	LMB long-term development scenario	2030-2060	2030-20Y plus all feasible infrastructure developments in LMB
9	2060–VHD	LMB very high development scenario	2030-2060	As above, extended to full potential infrastructure developments

First the development scenarios are assessed on a range of hydrological indicators to evaluate future water availability and use, and the flow changes caused by different levels of water use, taking into account the existing and planned developments in the Upper Mekong Basin. The scenarios for the foreseeable and the long term future will be assessed with and without consideration of climate change impacts. The results are then fed into the 'assessment of the transboundary economic, social and environmental impacts and IWRM requirements'.

In these assessments, the development scenarios are evaluated against 13 main indicators that can measure how well each scenario achieves the countries' objectives of economic development, social development and environmental protection. As well, a basin wide 'equity' indicator is included that measures the degree of 'equitable development' between each country that each scenario produces, taking into account benefits from existing water use and further planned investments in each country.

After basin-wide consultations on the assessment results, the countries will determine which development scenario would provide the most acceptable balance between economic, environmental, and social outcomes in the LMB, and would bring mutual benefits to the LMB countries. It is noted that in choosing a development scenario, the LMB countries are not committing to a particular set of projects (which are in any case subject to feasibility studies, EIAs etc.), but are identifying a development space within which they can plan and work. Conflicts and trade-offs may occur, but within the agreed vision and outcome of the IWRM-based Basin Development Strategy.

3. INTRODUCTION

The Mekong is a major world river and it is a dynamic feature in the landscape that adjusts naturally through time and space. The main drivers for channel adjustment, throughout the river's course, both in terms of size (capacity), altitude and lateral position of the river bed are variations in the annual runoff regimenn and the variation in the delivery of sediment to the river from land surface erosion. Thus riverbank erosion is a completely natural process and, although often unwelcome, and is not necessarily indicative of any problems within the hydrological system. The situation is made more complex by natural climate changes; for example the adjustments in hydrology that have followed the end of the Ice Age during a geological period of some 15,000 years - the Holocene. Major adjustments also occur at similar timescales within the river reaches closest to the sea. A major constraint in this latter respect is the natural changes in sea level that have occurred during the Holocene and which impact the lower reaches of the Mekong as it discharges to the sea. The Mekong Delta is an accumulation of sediment largely derived from river sediment flux with a subsidiary marine component. It is geological young (i.e. Mekong Delta is c. 8,000 years old) and it exists because of post-glacial sea level rise allowed accumulation between river and sea. Adjustments have also occurred throughout the LMB due to tectonic effects but mostly these have been extremely long-term effects operating over millions of years, of no immediate human consequence.

At the human time-scale (10s to 100s of years), the Mekong channel adjustments are increasingly affected by human intervention. Leaving aside direct intervention such as river training works, the river is (and will) respond to anthropogenic impacts which include changes in the hydrological cycle and delivery of sediment to the river induced by modified land-use. In addition, direct abstraction or augmentation of river flow can occur at the basin-wide scale. At the local scale, intervention such as dam construction to form impoundments, or run-of-river hydro-power schemes, have both local effects on river morphology as well as effects which can extend both upstream and downstream for 100's of km. Some effects of interventions are immediate (<2 years) whilst others can be protracted (10s of years) and subject to lag-effects, such that only later generations are effected by the changes in river regimenn. Added to these interventions at the basin-scale, there is now strong evidence for anthropogenic climate change at the regional scale, but this is not likely to be important for the next 50 years.

The Mekong River has been subject to natural changes during the Holocene. For example it has incised a few metres during this time period. However, the natural flow regimen, including sediment flux, has been very stable throughout the last century: flow and sediment flux being affected by the natural fluctations of the annual monsoon and occasional intrusions of typhoons and other storms and droughts. As will be explained below, the natural flow regimen of the mainstem is quite-well known due to adequate flow gauging records. The sediment flux however is poorly known. Adjustments in sediment flux as well as discharge adjustments are keys to understanding future channel changes and the impacts on human use of the LMB.

Consequently, this report considers: the variation in sediments concentrations and quantities at specific stations and as delivered to the delta area and the impacts on the Mekong river channel dynamics, especially river bank erosion. Consideration is also given to the general effect of dams on sediments.

4. SUSPENDED AND BEDLOAD SEDIMENT REGIMEN

There are currently few bedload data for the LMB and Adamson (2009) adopts a value of 3% of the total load based on limited studies within China, which value may not pertain for the LMB. USBR (1973) calculated bedload as 12.5% of the total load at Luang Prabang and Rutherfurd and Bishop (1996) report some 20 million tonnes of bedload per year for a reach near Vientiane. These figures are possibly too high as bedload in large rivers is rarely greater than 10% of the total load (see Table 2). Anonymous (2002) provides some bedload data for the Chaktomuk area, Phnom Pehn, but these data represent quite unusual confluence flow conditions and cannot be applied to other river reaches with any confidence. However, preliminary unpublished studies by Iwona Conlan indicate that the Mekong is relatively unusual such that a simple distinction between suspended load and bedload cannot readily be drawn without detailed considerations of both sediment grain size and discharge data. The active river bed, through the system, has little coarse material (less than 10% coarse sand and fine gravel), but rather consists of large quantities of fine sand which is readily suspendable. Thus there can be rapid exchange of sediment between the bed, the bedload and the suspended load as the force expended on the bed by this powerful river varies through time and space. Bedload is not considered further in this section 5.

The suspended sediment regimen of the mainstem Mekong in the MB has been reviewed by Adamson (2009), Fu et al (2007, Fu and He (2007), Lu and Siew (2005), Kummu and Varis (2004) and Walling (2005; 2008). Hårdén and Sundborg (1992) review the few data for tributary rivers. I have also considered briefly sediment data within the MRC HYMOS database, as appropriate, but timing constraints have prevented any detailed additional data analysis. In general, I concur with Adamson’s assessment and where I cite Adamson in the text below it is because I accept the analysis and assessments provided therein, unless otherwise stated.

Of these various studies, Adamson (2009) provides the most apposite assessment of the situation in regard to the changes in suspended sediment regimen consequent to the closure of the Manwan dam in China and the possible effects on the proposed cascade of dams in northern Laos. As noted by Adamson (2009) two suspended sediment monitoring programmes have been implemented over the years in the Lower Basin.

4.1. THE SUSPENDED LOAD DATA BASE

The first data source is the suspended sediment concentrations (SSC) data that have been monitored by the relevant Lao and Thai Line Agencies since the 1960’s and records at 70 locations are held at the MRCS. The measurement procedure involves depth-integrated sampling over several vertical profiles. Such a procedure, if properly conducted, should provide results of reasonable accuracy, such that the main source of errors in determining SSC would be (i) inadequate number of vertical profiles sampled and (ii) erratic sampling through time and poor sample handling. In order to characterise the annual cycle in SSC and to obtain an accurate annual estimate of total suspended sediment load (SSL), the temporal framework for sampling design needs to consider the temporal relationship between SSC and discharge variations throughout the annual cycle. The year to year variance in the existing record will reflect both natural variation and sampling error.

The second data source is the Water Quality Monitoring Network established by the MRC in 1985, which also includes mainstream sites in Cambodia and Viet Nam as well as a number on selected tributaries. The measurements include total suspended solids (TSS) data, though the data represent a bottle sample taken at 0.3 m depth, and are not representative of the fact that suspended sediment concentrations increase with depth. The data are likely to be significant under-estimates, while again there appears to be no experimental design in the sampling programme in relation to water discharge. The above issues have largely been noted prior by both Walling (2005; 2008) and Adamson (2009).

4.1.1. Conclusion and Recommendation

The analysis of Adamson (2009) is presently the most apposite for future planning and points clearly to the need for a well-designed and sustained sediment sampling and monitoring programme for the future management decision basis within the LMB.

The value of the existing data sets (especially WQMN) can be improved by target studies of the suspended sediment concentration throughout the water column to determine the actual vertical distribution of concentration for different seasons and for different water discharges. Such a short programme of work (completed within one year), using suitable equipment, could then allow the application of the Rouse equation which is a theoretical construct allowing estimation of the most-probable vertical concentration profile throughout the water column for given hydraulic conditions. The Rouse method could then be applied to enhance the historic data record.

There is a deficiency of data on the grain-size distributions of bed material, bedload and suspended load throughout the LBM. Some data exist scattered throughout the older literature, such as the 1960s dam site engineering assessments (e.g Pa Mong and Sambor). These data, although informative, cannot be related easily to the few more recent data pertaining to the baseline scenario because of the different methods used both to obtain data and to present the data in summary form. Very few data exist that represent the baseline i.e. post-1985 (e.g. an unpublished survey of bed and bank grain-size down the Mekong in May 2005 by Yamanashi University, and Conlan PhD). As well as instigating a routine well-designed sediment sampling programme throughout the LMB, that includes bed sediment sampling, it would be worthwhile to commission a literature review (mainly of hard-copy sources held within the MRC) to identify and tabulate existing sediment grain-size records. These data will be valuable for future sediment transport modelling exercises and to ascertain, latterly, if there have been any systematic changes in sediment grain-size over a 20 to 50 year period.

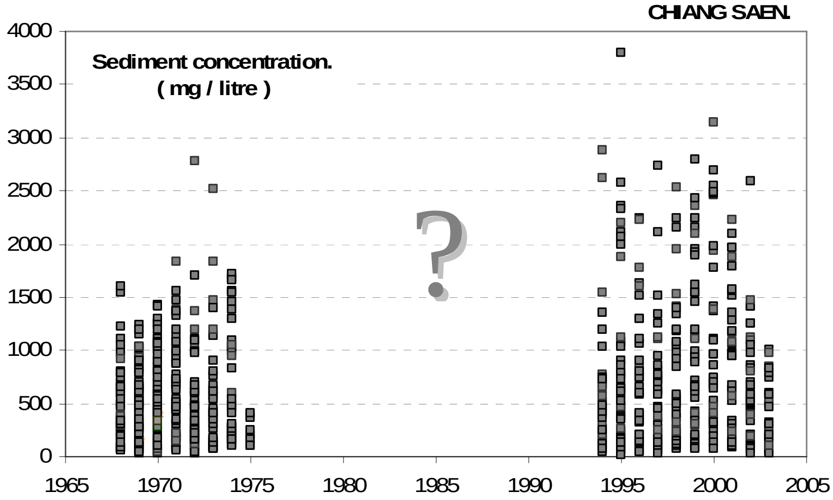
4.2. TOTAL SUSPENDED LOAD UPSTREAM OF VIENTIANE

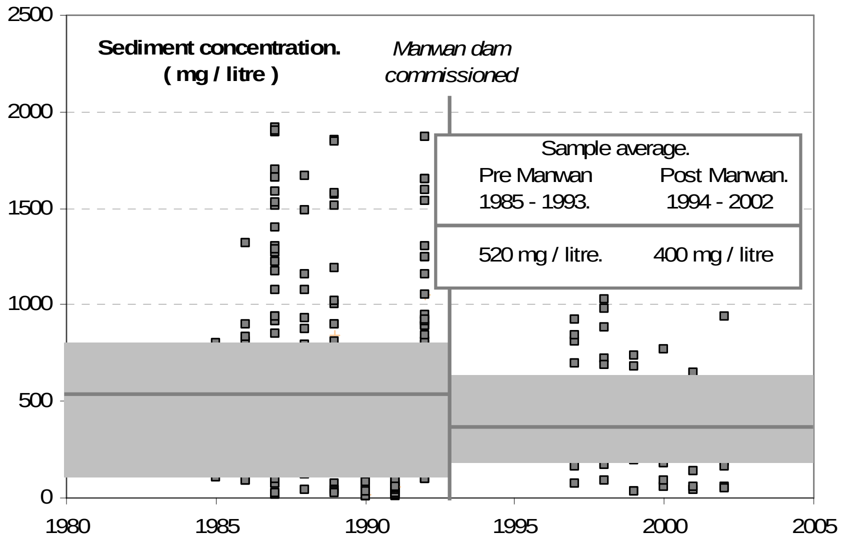
Using the above records, the several authors cited above have derived different estimates of annual load for two sampling stations in the LBM upstream of Vientiane and for one station at Vientiane as well as more limited assessments for the UMB. These difference estimates most likely are due to different ways of pre-processing the noisy data before statistical analysis. For example, the use of rating curves by both Lu and Siew (2006) and Walling (2005; 2008) will tend to smooth out temporal variability and provide different estimates of load in contrast to the overall mean.

Walling (2005) concluded that the construction of the major dams in China had had little effect on the SSL. This is not a conclusion shared by Lu and Siew (2005) or Kummu and Varis (2007) who indicate a 40 to 50% reduction in the mean annual SSL at Chiang Saen and Luang Prabang since the closure of Manwan dam in 1993. Notwithstanding the generally inadequate data available, it is probable that Walling’s conclusion is related to the method by which he processed the data. Given the absence of major inputs of suspended sediment from tributaries between the Manwan dam and the China-Laos border it is reasonable to concur with Adamson (2009) that closure of the Manwan dam in 1993 has had the effect of decreasing downstream SSCs and SSLs (Figures 1 and 2). The order of the change varies between 25 and 65% and, although the value of these estimates might be debated, the key point is that the range of the estimates demonstrates a probable and considerable sustained reduction in SSL coming from China. The size of this reduction is likely to have implications for bed level adjustments in northern Laos at least as far as Vientiane/Nong Khai. This issue is returned to in section 4.**5**.

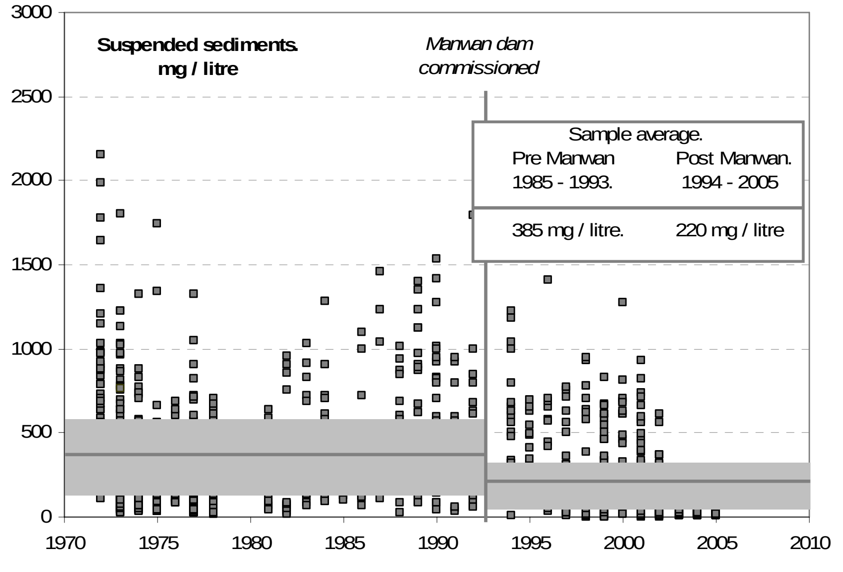
Coarser material, such as gravel and most sand, will be removed by the upstream storages and the suspended sediment passing the upstream China dams will be the finer fractions. Further the overall trend through time is likely to be delivery of finer suspended sediment to northern Laos. The operational regimen of the China dams, notably the issue of frequency and manner of flushing sediment from the impoundments may mean that slugs of sediment are introduced into the river in China from time to time. It is not possible to consider the effect on the Mekong in northern Laos of these pulsed inputs, without further detailed study of the operational regimen of the Chinese dams.

Downstream of Chiang Saen, Adamson (2009) notes that the larger tributaries, with their much lower concentrations and significant contribution to fluid flow, enter the mainstream between Chiang Saen and Luang Prabang and further dilute the reduced SSL coming from China. Axelsson (1992) recorded a less than expected rate of sediment-infilling of the Nam Ngum reservoir, which result tends to support the low sediment yield patterns for the northern tributaries. However, the recorded rapid reduction in SSCs in recent years, and the relatively small annual load at Nong Khai, compared with Luang Prabang and Chiang Saen, seem inexplicable in terms of dilution effects, as in this reach the tributary contribution is quite small. The trend is also counter to an increase in concentrations suggested by the TSS data for this station. In principle, this reduction in concentration and annual load might reflect a rapid and significant increase in recent deposition to the river bed between Luang Prabang and Nong Khai. However, given no measurably significant changes in the annual hydrograph over the same sampling period, such a rapid response in terms of deposition can be ruled out. Rather the efficacy of the SSC sampling programme at Nong Khai has to be questioned. The annual total suspended load (TSS) at Chiang Saen has been estimated as 67 x 10^6 tonnes per year and 109 x 10^6 tonnes at Vientiane by Pantula (1986) of which 6 to 8% might be organic (Pantula, 1986. The Chiang Saen estimate





Luang Prabang



Vientiane / Nong Khai

Figure 1: *Sample distribution of annual suspended sediment concentrations, pre and post the commissioning of Manwan Dam. Horizontal grey line is the sample mean and the grey shaded area represents the inter-quartile range. Source: Adamson (2009) unpublished*

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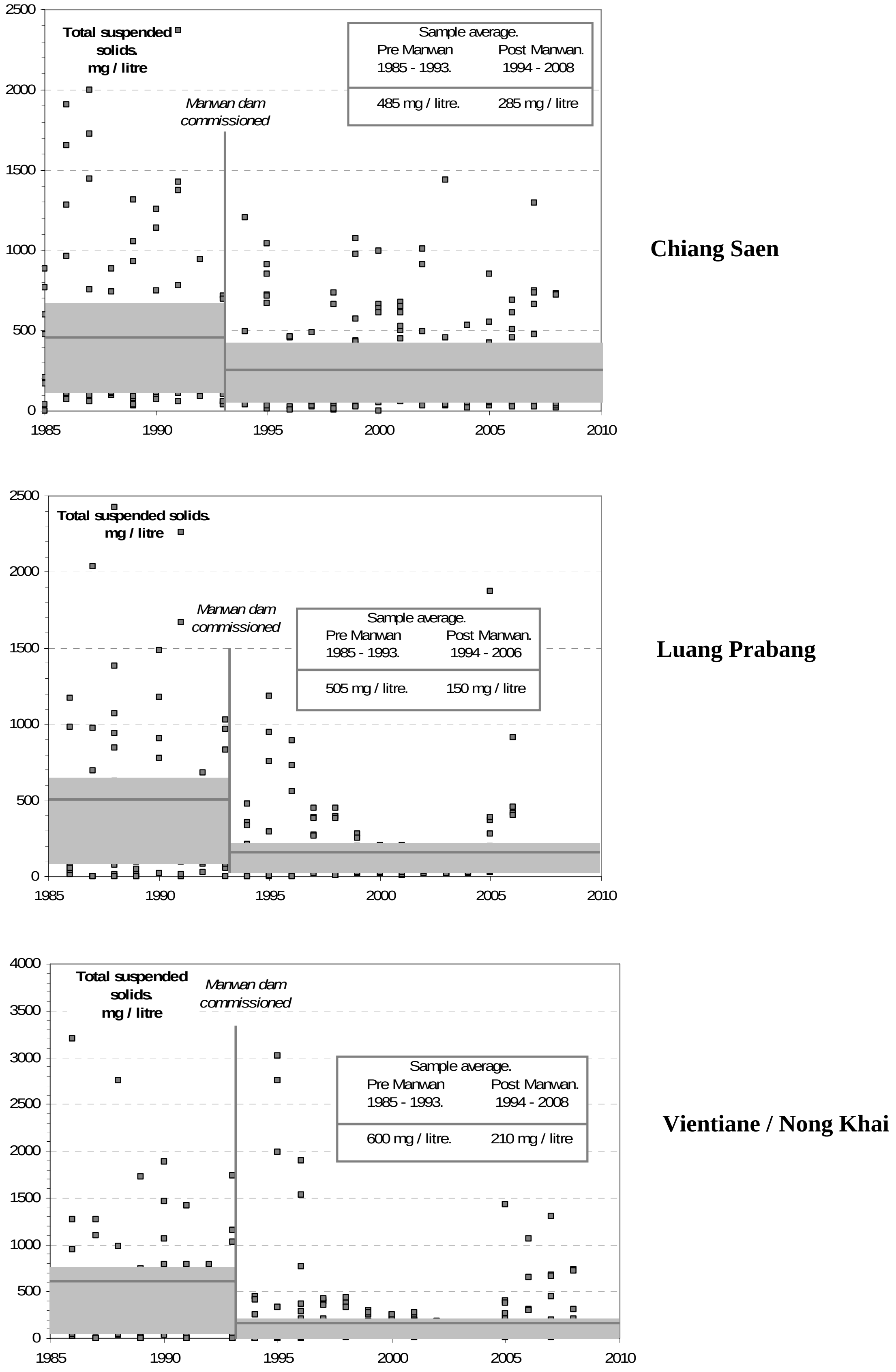

Figure 2: *Sample distribution of annual total suspended solids, pre and post the commissioning of Manwan Dam. Horizontal grey line is the sample mean and the grey shaded area represents the inter-quartile range. Source: Adamson (2009) unpublished*

is comparable with the HYMOS data (Table 2) but the Vientiane figure is at considerably at variance with Table 2.

Table 2: *Comparative estimates of the mean annual sediment loads between Chiang Saen and Vientiane / Nong Khai based on Wilander (undated) and those obtained using the TSS database – source: Adamson (2009)*

Monitoring site	Catchment area km^2	Mean annual discharge cumecs	Mean annual sediment load. 10^6 m^3 Wilander	Mean annual sediment load. 10^6 m^3 HYMOS SSC data
Chiang Saen	189 000	3 000	59	62
Luang Prabang	268 000	3 900	-	43
Vientiane / Nong Khai	299 000	4 600	58	28

4.2.1. Conclusion

There has been a considerable reduction in sediment load in the Mekong River upstream of Vientiane since the Manwan dam closure and this reduction in load may have implications for river channel stability. The imminent closure of the Xiaowan and the Nuozhadu impoundments will further reduce the load. The bed level may lower including in the vicinity of Vientiane. This issue is considered in section **4.5**.

4.3.TOTAL SUSPENDED LOAD DOWNSTREAM OF VIENTIANE

Walling (2005) provides estimates of the annual SSL between Vientiane and Pakse. The values he derives have to be considered in the light of the commentary provided by Adamson (2009). Nevertheless the same method was applied by Walling to all stations and thus although the absolute values may not accurately reflect the 'true' load, the relative values should reflect either adjustments in the downstream conveyance or station sampling deficiencies. Walling's best estimates of annual total load are: Vientiane – 102.7 10^6 tonnes; Nong Khai – 49.3 10^6 tonnes; Mukdahan – 160.8 10^6 tonnes; Pakse – 160.8 10^6 tonnes. The Nong Khai estimate is almost certainly incorrect (Adamson 2009) as noted above. Pantula (1986) provides an annual load of 132 x 10^6 tonnes 'upstream of' Khoné Falls but the origins of this estimate are unknown (probably from Harza reports) and must be based on Pakse data. There are no systematic historic data south of Pakse other than that reported within OTCA (1969). Hårdén and Sundborg (1992) refer to a long discharge record at Kratie but the discharge records at Kratie are unreliable due to a shifting channel bed and so no estimates of load are possible at this gauge. However, using OTCA (1969) data, Hårdén and Sunborg report 10 sequential years estimates of annual total load at Stung Treng which have a small variance (average annual load = 146 10^6 ; s.d = 44 10^6 ; s.e. = 14 10^6 tonnes). These data, if taken at face value indicate only slight dilution of the Mekong load (Pakse) by the major tributaries, Se Kong, Se San and Sre Pok rivers which join the Mekong at a shared confluence upstream slightly upstream of the Stung Treng gauge.

Adamson's (2009) analysis demonstrates from sediment mineral provenance studies that the Chinese Mekong may supply around 40% or more of the total load in the LBM main-stem river, which figure seems small in comparison with the load estimates given above. Adamson's provenance analysis also contends that there is only one other significant source area for suspended solids (the Central Highlands- specifically the 3-S Basin). Thus taking the figures for SSLs and total load outlined above as broad indicators of the direction of change, it is possible that the Chinese dams will effectively trap most of the SSL from China to the LMB. Sediment passing into northern Laos also will be retained effectively by the smaller cascade of dams proposed north of Vientiane. Further down the system, Kondolf et al (in prep) have calculated that dams within the central Highlands, such as on the Se Kong, Se San and Sre Pok rivers, may trap as much as 37% of the SS load delivered to the dam sites. However, as noted immediately above, the tributary contribution of suspended load is slight and dilution affects only SSCs and not the SSL throughout the LMB. Gauged tributary yields are at least an order of magnitude less than the main stem yield (Hårdén and Sunborg, 1992; Walling, 2005) and Hårdén and Sunborg further opined that the tributaries draining the Khorat Plateau supplied little suspended sediment to the mainstem. The sediment input from the large tributaries (e.g. Se Bang Hieng) draining the Annamite chain remain unknown but is probably small.

Adamson (2009) reports that the potential overall trapping efficiency of the Yunnan cascade when completed may be around 90%, which given the apparent limited additional inputs further downstream, would see sediment delivery to the Lower Mekong Basin fall dramatically. Although this could enhance the project life of main-stem dams and the northern Laos dam cascade in particular, it should be noted that Adamson estimates, albeit crudely, that the Lao cascade of five reservoirs may further reduce sediment concentrations in the mainstream by 80%. The figure is likely to be somewhat lower in reality due to systematic changes in sediment composition as the coarser constituents are removed and downstream trapping efficiencies decrease accordingly.

Gupta et al. (2002) and Walling (2005) were perplexed by the sustained and relatively constant SSL throughout the course of the Mekong south of Vientiane to Pakse; rather expecting a systematic increase in load as the basin area increases. Walling based his observation on a decrease in recorded average SSC values between Vientiane and Pakse (1500 to1000 ppm at Vientiane and 900 to 700 at Pakse) and attributed the maintenance in load to floodplain storage of sediment and possibly to in-channel storage of fine sand (Gupta et al.(2002). In contrast, Gupta et al. (2006) and Carling (2009) have commented on the lack of accommodation space on the floodplains for sedimentation. In fact, the Mekong is slightly incised throughout Laos such that overbank flooding is of very restricted extent and tends to be localised at tributary junctions, such that deposition of substantial quantities of sediment on the Laotian floodplains is not feasible. In the same vein, the region is tectonically stable and so there is no subsidence that could allow a systematic increase in sediment storage within the river channel and the few surveys of bed sediment thickness above the basement geology show a relatively thin cover. Ignoring possible sampling error, which might result in low or high values of SSC data, the ready explanation is that the discharge of the Mekong more than doubles between Vientiane and Pakse such that concentration values might be expected to decline downstream if the load is sustained at values commensurate with those recorded at Vientiane. Despite uncertainties, the data show clearly a sustained load throughout the course between Vientiane and at least as far as Pakse. The less reliable data for Cambodia nevertheless are consistent until Kratie. The simplest explanation is that there are no significant additions or deductions in total annual load between Vientiane and Kratie. Rather, a simple check on gauge data (Table 3) demonstrates that the river has more than sufficient force throughout to suspend all the fine silt-sand load and thus the river throughout Laos and northern Cambodia acts as a simple, stable conveyance channel, moving the load at Vientiane down to the Cambodian plains (Carling, 2009).

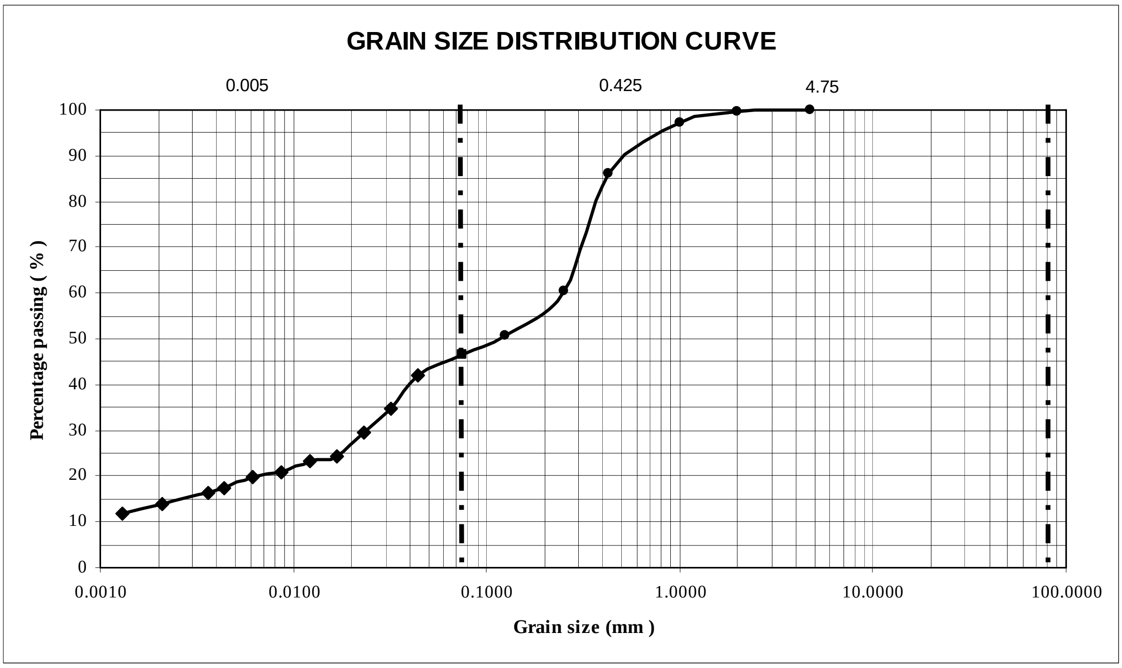

Figure 3: *Example bed material grain size curve from Pakse. Source: Unpublished data of Yamanashi University. NB: There is no gravel or coarse sand, 54% fine and medium sand, 26% silt and 20% clay*

4.3.1. Conclusion

The baseline suspended sediment load is sustained between Vientiane and Pakse and possibly as far as Stung Treng or Kratie because there are no significant additions or deductions in the load over these distances, the river remains powerful and acts as a simple conveyance channel for the imposed load. It may be expected that suspended sediment loads will decline downstream of Vientiane if the reduction in the load recorded at Vientiane is further conveyed downstream as in recent years. However the effects may be more delayed and less obvious than those expected to be observed in the next 20 years upstream of and in the vicinity of Vientiane. This issue is considered in section **4.4**.

4.4. TRANSPORT CAPACITY OF SUSPENDED LOAD DOWNSTREAM OF VIENTIANE

There are no systematic archived bed grain size data within HYMOS, however unpublished spot sample data (Harza reports and Conlan data) can be used to provide a demonstration that the river has sufficient force to readily transport the majority of the bed sediment. The example is given for Pakse (Figures 3 and 4), but it is expected that similar results would also pertain for gauges such as Vientiane and Mukdahan (Table 3). It is not possible to consider when sediment will move as a simple function of discharge. Rather, a standard method to estimate what grain sizes are moving as bedload and what is within suspension is to apply the Shields parameter as some function of flow conditions (here I use Particle Reynolds number). Particle Reynolds number increases as discharge increases and, for the non-specialist, can be seen simply as a surrogate for discharge. Thus as the Shields number for any given grain size increases, sediment of that size can be stationary (i.e. no motion: Figure 4), moving as bedload, or be in suspension. The curvilinear lines in Fig. 4 represent the threshold values of the Shields number for these three bed states as Particle Reynolds number (i.e. discharge) increases. The straight lines of data points show how the Shields value changes as discharge increases for different particle sizes. It is evident that these lines cross the curvilinear threshold curves.

Thus, Figure 4 presents the calculated Shields parameter values versus the Particle Reynolds number for Pakse. The symbols represent different grain-sizes from 7.5 x 10^{-5} m to 4.75 x 10^{-3} m (Figure 4). The coarsest bed material grains (4.75mm: 1% of the grain size distribution is coarser than 4.75mm) require a discharge of only 5,600 m^3s^{-1} to be entrained, with most bed material being moved as bedload or in suspension at much lower discharges. Notable all sediment less than 0.45mm (41% of the grain size distribution is finer than 0.45mm) is in suspension for discharges greater than 3,800 m^3s^{-1}. These two discharges are exceeded for 52% and 62% of the time each year. The 3,800 m^3s^{-1} value is typical of the transition from dry season flow to the transitional period. Consequently there is considerable transport of the coarser grain sizes for at least half of the year during the transition and monsoon periods with low flows being competent to move the finer components (i.e. fine sands and silts) most of the time.

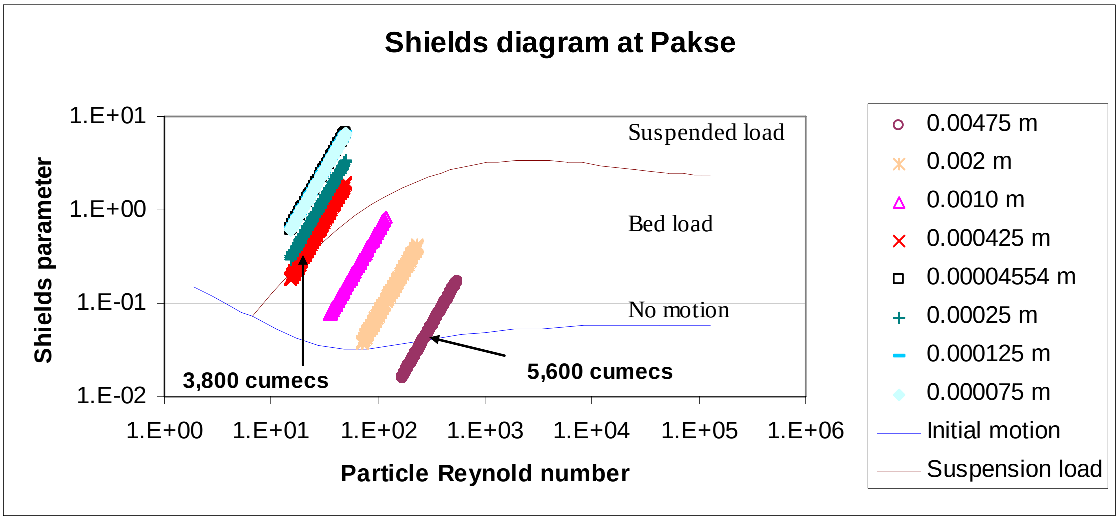

Figure 4: *Shields diagram at Pakse. See text for explanation*

Informal examination by the author of the river between Vientiane and Pakse (both in the field and from air photographs) show that the river is a 'relatively stable' single thread or divided channel, being incised with little evidence of palaeo-meanders. Preliminary unpublished work (Southampton University) between Stung Treng and Kratie suggest that the islands and sand bars are very stable, such that the available accommodation space for sediment deposition is already full. Thus, in terms of exchange of suspended load with the river bed there is only the annual deposition and resuspension cycle associated with the monsoon flood hydrograph which balances out year on year.

Table 3: *Value of the Shields parameter for maximum annual discharge conditions*

[*] The critical Shields parameter is for coarse sand. Values of the parameter greater than this critical value will ensure sand and finer sediments are in transport which is the case for mean annual flow and high discharges. MAWD = Mean annual water depth. SPMA = Shields Parameter for Mean Annual Water Level

Reach	Channel gradient	Max. Water Depth (m)	MAWD (m)	Shields Parameter max	SPMA	Critical Shields Parameter[*]
Vientiane (to Mukdahan)	0.0001	16	4.62	0.75	0.22	0.06
(Mukdahan to) Pakse	0.00006	19	4.45	0.54	0.13	0.06

The future flow scenarios are considered in Table 4. In this table the baseline values of the Shields Parameter (cited as 100%) for maximum water depth are reduced according to future flow scenarios. It is evident that with the recorded few percentage points reduction in each case the ability of the river to entrain sediment and then to transport sediment is not effected to any meaningful degree.

Table 4: *Percentage change in the Shields Parameter value for different future flow scenarios. Baseline water depth (WL) is for maximum recorded discharge. WL- is the expected drop in the maximum water level for future scenarios*

	Discharge Scenarios				
	Baseline	UMD	DF	LMB 20yr	Station
	WL	WL-	WL-	WL-	
	(m)	(m)	(m)	(m)	
	16	-0.48	-0.48	-0.76	Vientiane
SP%	100	97	97	96	
	19	-0.48	-0.48	-0.76	Pakse
SP%	100	99	99	96	

4.4.1. Conclusion and Recommendation

The simple, preliminary calculations indicate that the majority of the bed material of the Mekong River is transported during the transitional and monsoon period. The expected changes in the river hydrograph due to future flow scenarios will not significantly affect the ability of the river to transport the imposed sediment load during the next 20 years.

It is recommended that a detailed study is commissioned of the transport capacity of the river at several key gauging stations along the river. This will entail some field sampling of suspended and bedload to determine grain size distributions.

4.5. IMPLICATIONS FOR CHANNEL DYNAMICS UPSTREAM OF VIENTIANE

The implications for the Mekong River channel dynamics in northern Laos are complex but the most probable direction of change can be determined. First, it should be noted that the present flow regimen is capable of entraining into suspension at least 90% of the bed material grain-size distribution (Unpublished studies by Iwona Conlan, PhD thesis in prep). The bed material of the Mekong in northern Laos is unusual for a mountainous river in-as-much as there is little gravel, but abundant fine sand which is also found in quantity in suspension (Conlan, unpubl.), for example at Ang Nyay to the north of Vientiane which is one of Conlan's main sampling sites, close to the 1960s proposed Pa Mong dam site. The presence of substantial quantities of fine sand and lesser quantities of coarse sand in suspension and readily suspendable sand in the bed is at variance with Walling's (2005; 2008) and Adamson's (2009) supposition that the suspended load is silt and clay. The future flows regimens – China Dams, Definite Future Scenario (DFS), LMB 20-Year Plan Scenario – indicate a reduction in peak flood level during high flow (e.g. DFS = - 0.55m reducing to LMB 20yr = - 0.79m to -0.85m reflecting with or without dams) and a modest increase in the dry season flow levels (e.g. DFS = +1.04m increasing to LMB 20yr = +1.20m to +1.18m reflecting with or without dams); these data representing the average response for the four gauging stations: Chiang Sean, Luang Prabang, Chiang Khan and Vientiane. These effects should translate into only a slight reduction in capacity to carry sediment in suspension during the flood season and an increased likelihood of deposition to the bed during the dry season. In principle this adjustment could result in aggregation of the bed such that bed levels would rise. A rise in bed level would have implications for existing flood defences and navigation and would also impact on the future design of channel works. However, given the reduced load coming from China, in reality the river will remain sufficiently powerful to transport the reduced suspended sediment load AND pick up additional load from the river bed during the flood season. This prognosis would mean a progressive reduction in river bed level. In the reaches upstream of Vientiane, the reduction in bed level would be restricted to sand-filled rock-bed pools such that pools would be scoured out and thus deepen whilst sand bars would be reduced in size or eliminated. However the overall effect on bed level would be highly localised as there are numerous rock bars within the upper course of the river to prevent excessive bed degradation. The rock is erodible, but the rate of erosion will be negligible over the 20 to 50 year period under consideration. However close to Vientiane the river bed is alluvial, with between 5m and 15m of fill above bedrock near Friendship Bridge (OTCA, 1968), such that a significant lowering of the bed elevation and a resultant increase in river bank erosion may occur. It might be anticipated that flood levels would reduce as the bed level reduces but this supposition is conditional on the cross-sectional area of the channel remaining similar to that noted today. Should the cross-section narrow with incision, then capacity could be lost such that no over-all benefit would be noted in terms of a reduction in flood risk. The effects of incision also will have implications for the over-all stability of the river close to Vientiane, such that lateral and vertical instability should increase within the 20 to 50 year period and indeed significant effects might well be seen within 20 years. Management issues include under-mining of existing river bank protection works, positive and negative navigation effects and international boundary issues may emerge.

It is not possible to be more exact in determining the degree of channel change for each of the future scenarios, only to note that the degree of river incision and instability should increase for those scenarios with larger numbers of proposed mainstem dams in northern Laos. Thus the UMD/definite future scenarios will have less of an effect on the channel than the LBM 20 year plan with dams upstream of Vientiane.

4.5.1. Conclusion and Recommendation

It is recommended that modelling studies be undertaken to assess both the degree and rates of channel change in the vicinity of Vientiane given the anticipated changes in suspended sediment load and flow regimens. These studies would also determine the downstream extent of significant changes immediately south of Vientiane. Without model studies it is not possible to determine the effects of a reduction in sediment load on the river dynamics at considerable distances downstream of Vientiane. However, changes likely will be less but many local effects nevertheless still will occur as far downstream as Nakhon Phanom at which point the river becomes bedrock controlled. However these effects immediately upstream of Nakhon Phanom may not be of significance within the time-scale of 20 years but could be an issue within 50 years.

Deep pools are important for fish habitat and for river dolphins. It is not anticipated that the deep pools will be impacted anywhere in the LBM, as a reduced sediment flux in future flow scenarios where the river power is sustained indicates that the river will still flush the pools during the wet season and the pools will not fill with sediments. This situation could be modelled but the matter is not of the highest priority. As a rider, any deep pools close to or within a proposed impoundment would be affected by dam-construction and site-specific study would be required to determine the impacts.

4.6. IMPLICATIONS FOR CHANNEL DYAMICS DOWNSTERAM OF VIENTIANE

As noted in section 4.3 it is not possible to be explicit about the nature and timing of channel adjustments in the lower basin. In principle the direction of change in channel behaviour will be the same as reported within section 5.4 for upstream of Vientiane. However the changes will be muted and definitely protracted through time.

The first reason for the lesser degree of channel change are that effects of all the future flow scenarios on high water levels are slightly reduced in the lower basin downstream of Nakhon Phanom with more evident lesser increases in the dry season flow, in comparison with the upstream stations. The future flows regimens – China Dams, Definite Future (DF), LMB 20-Year Plan Scenario – indicate a reduction in peak flood level during high flow (e.g. DF = - 0.35m reducing to LMB 20yr = - 0.82m to -0.85m reflecting with or without dams) and a modest increase in the dry season flow levels (e.g. DF = +0.54m increasing to LMB 20yr = +0.23m to +0.18m reflecting with or without dams); these data representing the average response for the four gauging stations: Nakhon Phanom, Mukdahan, Pakse and Kratie.

The second reason for muted and protracted change is that the distance between the upper stations and the lower stations (Vientiane, 1580 km, Nakhon Phanom 1220 km and Kratie 545km from the sea) means that the river can eroded and transport bed material and river bank material to make up the expected deficit in the annual load coming from the UBM.

It is not known how much bed material is available for transport in the alluvial reaches between Vientiane and Kratie and consequently without modelling studies it is not possible to quantify bed level adjustments and the time spans involved. However, river bank erosion rates can be calculated and this issue is addressed in a separate section of the report [Section **5**]. On balance, channel adjustments are only likely to be noticeable at local ‘hot-spots’ (e.g. Vientiane) and are otherwise likely to be minor over a 20 year time frame, especially north of Nakhon Phanom. In addition, given that the most of the system between Nakhon Phanom and Kratie is bedrock-constrained no notable adjustments in bed level can occur, although the sandy alluvial fill can adjust through time and is likely to decrease in volume. Given the lag effect imposed by the distance from the China dams, it is not likely that changes in the channel downstream of Kratie will be noted within the next 10 years or so, but may be noticeable, within 20 years and should be apparent within and beyond a 50 year time frame, especially for the case of the LMB 20 year plan with mainstem dams. The situation south of Kratie might be exacerbated by potential additional dam construction in the Central Highlands and mooted water diversions south of Kratie to the Tonlé Sap lake and within the Delta.

4.6.1. Conclusion and Recommendation

The issues related to planned and conjectured future dams in the Central Highlands and major water diversions; their sediment trapping efficiency and effects on discharges of water and sediment downstream of Kratie and within the Delta require closer attention.

Changes are likely will be less than noted at Vientiane but many local effects nevertheless still will occur. The effects immediately upstream of Nakhon Phanom are not likely to be of significance within the time-scale of 20 years but could be an issue within 50 years. However, given the economic importance of the Delta, specific modelling studies of channel change induced by changes in the sediment transport regimen are recommended for the lower Mekong south of Kampong Cham. This recommendation is reinforced by the presence of extensive sand mining noted in section **4.7**.

The SSC data (Hårdén and Sunborg, 1992) for Cambodia (Stung Treng and Kratie and Phom Penh, Shre Pok) are not recorded within the HYMOS data base; this issue should be addressed; the data are found within OTCA (1969).

4.7. IMPLICATIONS FOR THE DELTA, FLOODPLAINS AND THE DELTAIC COASTLINE

4.7.1. Baseline Scenario

Notably the concentration of TSS is higher upstream for a given discharge (e.g. at Vientiane) than it is downstream (e.g. Kampong Cham) (Fig. 5) but, as noted above, this largely reflects dilution effects as discharge increases downstream whereas suspended annual sediment load is fairly constant downstream. However the supply, storage and transfer mechanisms of TSS in the lower Mekong are poorly known.

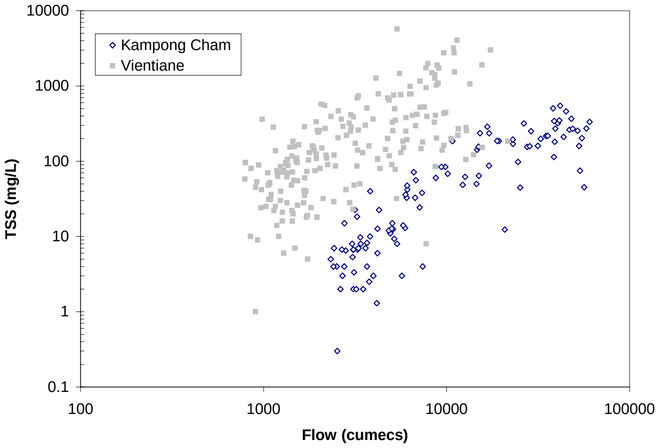

Figure 5: *Relationship between TSS and discharge (courtesy of MRC)*

The HYMOS data for the Tonlé Sap for the period 1950-1 to 1955-6 show around 4.5 to 6.0 x 10^6 tonnes per year entering the Tonlé Sap from the Mekong and around 3.0 to 6.7 x 10^6 tonnes per year passing into the Mekong from Tonlé Sap. The rate of sedimentation in the Tonlé Sap can therefore be estimated as less than 1mm per year. This is similar to estimates from the channels in the delta based on dredging volumes of less than 1mm per year. More recent water balance estimates have shown that the Tonlé Sap River tends to aggrade in the lower reach during the rising flow in the wet season and degrade during the falling stage (Anonymous, 2002). However, the Tonlé Sap is a unique ecosystem and the water balance and sedimentation due to future flow scenarios is being addressed by other MRC projects and so is not considered further in this report.

Sedimentation may be more significant at specific locations in the system, particularly near Snoc Trou where the Tonlé Sap joins the lake and around Phnom Penh (SMEC, 1998; Anonymous, 2002). Most investigations have considered local sedimentation issues (Azam, 1975; Chinnarabri, 1990; Hårdén and Sundborg, 1992; Wolanski et al., 1998; San, 1999) rather than assessing the basin-wide situation. A complex issue is the extensive (seemingly unregulated) large-scale extraction of sand for the construction industry north of Phnom Penh. This extraction will influence the present-day flux of sediment to the delta and may induce local channel instability close to Phnom Penh. The extraction was estimated as between 200,000 tonnes and 500,000 tonnes in 2001 (Anonymous, 2002) and it would be useful to obtain estimates of the trend in annual commercial extraction (by volume or weight) for further consideration.

Milliman and Syvitski (1992), Meade (1996) and (Syvitski et al., (2005) and Roberts (2001) estimated the total annual sediment load of the Lower Mekong River to be 160 x 10^6 tonnes and 150–170 x 10^6 tonnes respectively. These data seem to be for suspended sediment alone, as all seem to be based on MRC data for upstream locations and several authors appear to cite earlier derived estimates rather than provide revised values based on new data. Métivier and Gaudemer (1999) report a long-term (Quaternary) yield of 150 x 10^6 at the seaward limit. Only USBR (1973) make any estimate of total load (suspended load plus bedload) close to the delta head (Phnom Penh) using measured data. The USBR also made calculations of total load for some of the Laos gauging stations and all estimates are significantly higher than the suspended load estimates reported by Adamson (2009) and others recently. My best estimate in adjusting the USBR results in accord with the more recent SSC load estimates delivered to Kratie, is that the total load delivered to the head of the delta is no more than 170 to 180 x 10^6 tonnes. Nonetheless the total load remains high in comparison with other major rivers (Figs. 6 & 7) including rivers of a similar basin area.

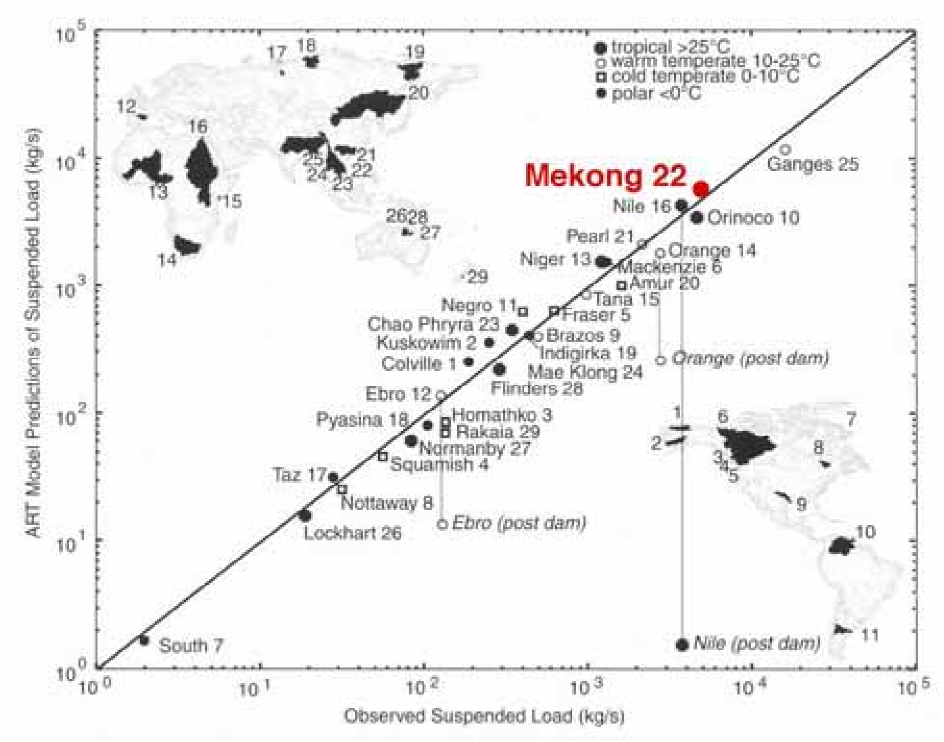

Figure 6: *Comparison of TSS load of Mekong with other major rivers (redrawn from: Syvitski et al,. 2005, for annual load of 160 million tonnes)*

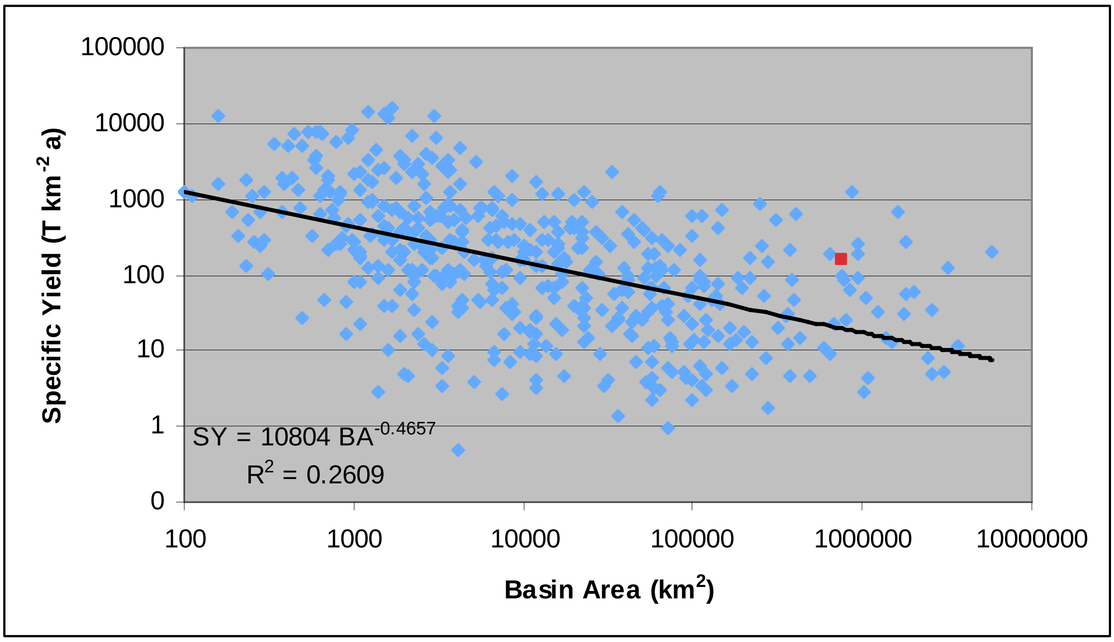

Figure 7: *Specific yield for 488 major river basins. The position of the Mekong River is shown as a red square. Data from on-line appendix of Syvitski and Milliman (2007)*

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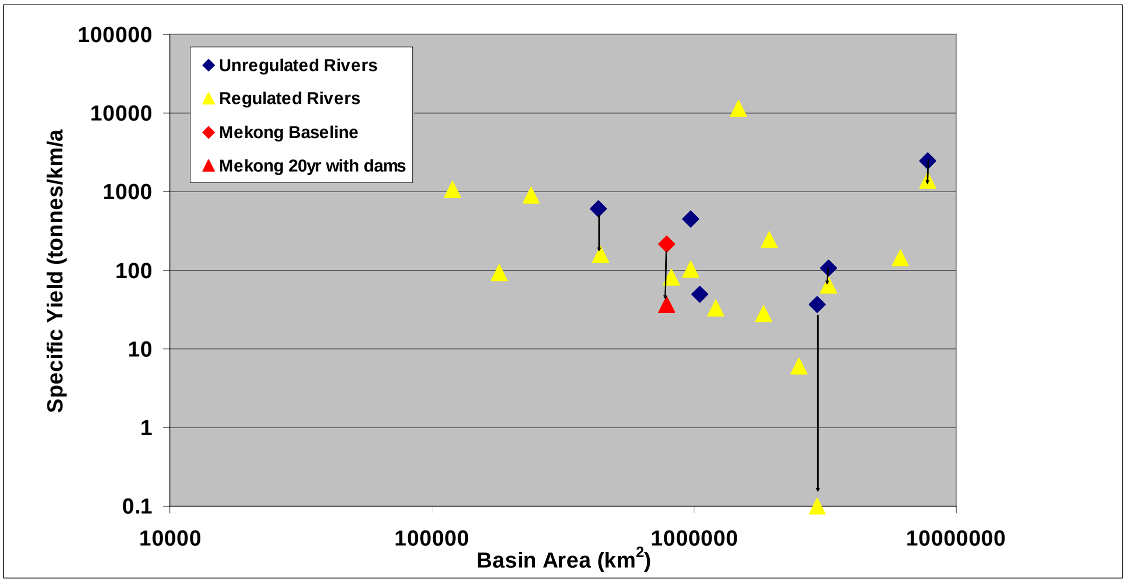

Figure 8: *Examples of specific yield to the coast for rivers of varying basin area and degree of regulation. Data from Hårdén and Sunborg (1992); the values for the Mekong are as given in the present text.*

4.7.2. 20 year Scenario with Dams

It is probable that there are no significant implications for the Delta for the Chinese Dams and the Definitive Future Scenarios and probably not for a 20 year framework although effects might be evident within 50 years. Any potential reduction in the delivery of suspended sediment to the floodplains due to reduced sediment supply from the UMB and the 3-S Basin will be balanced by scour of fine bed sediment in the Mekong in the near-future. The first effect to be noticed within the 20 year framework is likely to be a reduction in the concentration and grain size of the suspended sediment with a concomitant decrease in floodplain sedimentation rates. However, this will not have any immediate consequences.

The consequences of a 20 year future with full development of proposed dams can be addressed in general terms alone. As noted above the dams will trap considerable amounts of sediment if this sediment is not flushed continuously or periodically. Assuming the baseline total annual load of c. 100 x 10^6 tonnes at Vientiane is reduced by 90% by the Yunnan dams and the northern Laos cascade then the load at Vientiane would be reduced to 10 x 10^6 tonnes. If a baseline load of 160 x 10^6 tonnes (Pakse) is assumed to be delivered to the Cambodian Plain and Delta, then currently c. 60 x 10^6 tonnes are sourced from the tributaries of the LMB. According to Kondolf et al (in prep) some 37% of this load could be retained in future tributary impoundments given the 20 year scenario with dams. The tributary load thus is potentially reduced to 38 x 10^6 tonnes. The total load reaching the Cambodian Plains is thus:

100 x 10% + 60 x 67% = 48 x 10^6 tonnes

This is a very approximate calculation which nevertheless implies a reduction in load of two thirds in comparison with the baseline. If the alluvial river bed is assumed to be at equilibrium with the annual load; i.e. no significant erosion or deposition year on year and if the river sought to replenish its load to the baseline capacity (i.e. 160 x 10^6 tonnes) by eroding the bed, the question then is: "How long would it take to flush out all available sediment within the mainstem Mekong?". There are no evaluations of the thickness of readily mobile sediment within the bed of the river and so the quantity in store is unknown. Nevertheless, a very crude estimate can be obtained. Various reports, mainly by the Harza Company in the 1960s, provide engineering sections of the channel. From these sections e.g. (OTCA, 1968) it might be deduced that as little as an average of c. 5m of loose sandy fill is present. Assuming a 1km width of erodible bed and a total distance between Vientiane and the river mouth of 1580km then the total volume of stored sediment is 7900 x 10^6 m^3. Adopting a typical bulk density of 1.8 tonnes m^{-3}, the stored sediment represents 14,220 x 10^6 tonnes. Accepting this crude calculation, this lens of sediment would be flushed within 127 years if the river sought to maintain its current total load [i.e ((14,220 x 10^6 / (160 x 10^6 - 48 x 10^6)) = 127 years]. In reality there are complex issues related to river bed adjustments but significant bed erosion could occur within decades with impacts being noted in the Delta after several decades. Assuming the 20 year scenario with dams is a reality then after 2030 the full impact of a reduction in sediment load would come into effect and the 127 adjustment period would commence. Thus very major changes might be seen after a further 50 years, i.e. 2080. The decades leading to 2080 are within the purview of the present generation and morphological changes to the system definitely will effect the next generation.

In view of the uncertainty in estimating the degree of impact and the timeframe within which any impacts of reduced sediment delivery to the delta may occur, it is useful to review the situation that has occurred with other impoundments on large world rivers. Figure 8 gives three examples of significant reductions in load reaching the river mouths: the Ebro River, the Orange River and the Nile are the rivers in question. The Nile having the greatest loss with consequent impacts in the Nile delta and the suspended sediment load of the Mississippi has declined by 80% since impoundment began in 1850. All major river basins in the world have seen significant impacts on sediment yield and a variety of associated impacts on channel and coastal dynamics due to various regulatory controls on discharge, most notably impoundment (Walling and Fang, 2003; Walling, 2006). Notable, coastal wetlands have suffered due to reduction in sediment load; the most well documented being the Gulf Coast of the USA (Kesel, 1988; 1989; Mossa, 1996) with problems of subsidence and coastal erosion affecting economic and social use of the delta coastlines. Offshore effects can include a reduced organic sediment flux that reduces marine fisheries productivity (Halim et al, 1995) but this is disputed (Nixon, 2003).

The recent history of the Pearl River delta is a possible analogue for future changes in the Mekong delta including the timescales of adjustment. China adopted its 'open-door and market reform' policy in the 1970s since when the Pearl River delta has seen rapid economic development. Since 1998 the discharge in the Pearl River has tended to decline due to precipitation changes in the headwaters. Although, this control is not evident in the case of the Mekong, the Mekong will also be subject to some reduction in peak flows and possibly enhanced abstraction and water diversions in the lower reaches. Thus the direction of change is the same for both rivers. At the same time the Pearl has been subject to increased dredging, construction of levees and engineering works and uncontrolled sand mining. This activity has led to increased salinity intrusion and changes in the geometry of the distributaries. The sediment load dredged from the Pearl during 1980 to 1998 amounted to the total net sedimentation in the river within 70 to 125 years (Huang and Zhang, 2006). Although levée construction and dredging has reduced the high water levels at present (Lu et al., 2007) and thus reduced the incidence of floodplain flooding it is evident from the history of the Mississippi that over the longer term if illegal dredging is stopped then the bed elevation may rise such that the bed after many decades could be above the level of the floodplains. The effect of the construction of levées is two-fold. Firstly it provides a sense of security such that development of the floodplain accelerates but in addition should the levées fail the flooding is worse and the economic losses great. The construction of levées prevents annual silt deposition on the floodplains and this will reduce natural carbon sequestration. The silt maintains the elevation of the floodplain to counter natural consolidation, and the consolidation due to anthropogenic effects of tillage and soil degradation. For the Mekong delta a few data on floodwater suspended sediment concentrations and chemistry over the floodplain are provided by Anh et al., (2003). The silt brings natural nutrients which will have to be replaced by artificial fertilizers which increases the degree of pollution of runoff from the floodplains. In addition, the loss of annual flooding will severe effect any lagoon fish farming where the fish population and the nutrients are enhanced by natural flooding. Any brick industry using the local mud will also decline. As floodplain water stagnates the standing water may be associated with an increase in disease including malaria.

Although there are clear benefits from river regulation, similar adverse effects as those noted above can be expected on the Mekong over a time scale of 30 years. In particular, channel changes (induced especially by uncontrolled sand mining) might affect the distribution of flows in the distributaries; notably affecting the balance between the Bassac and the Mekong discharge and channel regimens with implications for navigation.

4.7.3. Recommendation

Given the anticipated reduction in total sediment load, modelling studies of bed level changes at key stations within the Cambodian Plain and the Delta should be commissioned. Particularly of concern are Chatomuk Junction (Quatre Bras) and the Van Nau pass.

The implications for a reduction in silt deposition on the delta plain are uncertain. In particular there are no baseline studies of deposition rates. A study of floodplain sedimentation rates and processes should be commissioned.

5. RIVER BANK EROSION

5.1. INTRODUCTION

Bank erosion is locally a social and economic problem throughout the LMB and a political issue along the border between Laos and Thailand. Lateral movement of the river is a completely natural process, which can be understood and predicted to some degree by specialist studies. In the absence of any revetment, erosion on one side of the river is balanced by deposition of sediments against the opposite bank such that the width of the river remains essentially the same although the lateral position of the main channel and the bank lines are changed. The zones of erosion or deposition tend to migrate upstream or downstream through time such that an eroding bank at one time may become a lateral accretion zone at another time and *vice versa*. Direct human intervention or unintentional activities can affect these processes. Examples are:

- Artificial infilling one side of the channel will accelerate erosion on the opposite side of the river.
- Construction of revetment along one bank alone can cause changes in the flow patterns and the patterns of erosion and deposition such that there are implications for the alignment of the opposing bank line.
- Extraction of aggregates can redirect the direction of the main flow causing changes in the patterns of erosion and deposition.

5.2. BASIC DATA

Rutherfurd and Bishop (1996) and Rutherfurd et al (1996) considered chiefly the reach of the river near Vientiane and noted that this reach lay in a transitional regimen between braided and meandering. Using hydrographic charts and cross-sections surveyed at gauging stations, Rutherfurd and colleagues deduced approximate planform adjustments and adjustments in bed level through time and related these to a simple bank stability model. Channel stability has also been considered near Vientiane (Kummu et al., 2007) and Kampong Cham (Uyen, 1989a and b) for various periods between 1961 and 2005 and for the Bassac River (Mansell, 2004). More recently, major studies have been undertaken of the channel stability in the Vientiane (JICA, 2004) and the Phnom Penh areas where, for the latter area, bank recession rates are locally 10m per year (Anonymous, 2002) and subject to considerable engineering study with a view to management and stabilization (Olesen, 2000).

Small data bases are held by the Lao Inland Waterways Administration and by the Thai Department of Public Works and Town and Country Planning, Ministry of the Interior. These data are summarised below:

<u>Lao PDR</u>

N = 77 locations

Average annual recession rate = 2.12m

Standard deviation = 2.04m

Maximum value = 9m

There are no data on length of river actually impacted by erosion. However the database includes data on the length of river considered worthy of bank protection. For planning purposes the table includes estimates of the cost of bank protection for the period 2005 – 2010 for a total length of 48km. For the period 2005 to 2025 the total length is 113.85km. These lengths might be taken as indicative of the proportion of the river subject to significant bank erosion on the Lao (eastern) side of the river.

Thailand

Data are provided as ranges of the values for each location so I have calculated the average and standard deviation based on range mid-point values.

N = 158 locations

Average annual recession rate = 2.26m

Standard deviation = 0.78m

Maximum range value recorded = 9m.

The total length of river bank impacted by bank erosion is recorded as 88.92km

The data from Lao and Thailand are consistent. However in all the riparian countries, there is no definitive information on how the data were collected in each country but I was informed that in urban areas direct measurements were made in the field whilst in rural areas local people were interviewed. Local people often report excessively high estimates of bank erosion rates, e.g. 200m/a. The absence of any very high data values in the tabulations gives me confidence that the data are from direct measurement or, if from verbal reports, they have been edited to exclude grossly large estimates.

The reach between Stung Treng and Kratie has been surveyed by Southampton University and the Royal University of Phnom Penh (unpublished). Bank erosion sites have been mapped and erosion rates determined by interviewing local people within 13 communes (Fig. 9) but all these sites are minor and of local significance only. The average annual river bank recession rate for the 13 locations was 1.78 m a^{-1} (s.d. = 0.86 m a^{-1}; s.e. 0.24 m a^{-1}). River bank erosion becomes significant in the vicinity of Kratie where the river is alluvial and the details are given below.

Some erosion locations within Lao PDR and Cambodia have been considered as potential demonstration projects within FMMP_C2 (Anonymous, 2008). They are:

1. Lao PDR: Bokeo erosion control (for which there are baseline data for six sites; Anonymous, 2008).

2. Cambodia: Kratie erosion control. The FMMP consultant team visited Kratie, and concluded that the river bank within the town is reveted and other eroded sections are just minor and they are agricultural land. Therefore the consultant team did not consider Kratie as a potential demonstration project for phase 2. However, erosion can occur sporadically with little evidence for several years and then rapid recession. The erosion of the left bank in Kratie Province occurs along a 6km reach from Sambok at km 572 to Ph Thmar Krae Kraon and Ph Russei Cha at Km 566, and along a 15 km reach from Kratie (km 572) to Prek Te (km 557). There are no data on recession rates.

Table 5: *Selected locations and bank erosion rates in LMB*

Location	Erosion Rate (m a^{-1})	Comments
LAOS		
Bokeo	3 – 200; data for 6 locations	MRC Flood Management & Mitigation Programme
Vientiane	0.8-1.2	Kummu et al (2007)
Souvannakkhomkham	0.3	
Namdhum	10 – 30	
Pakse	0.46	Southampton University
CAMBODIA		
Kratie	No data, but reported problems	MRC Flood Management & Mitigation Programme
Campong Cham/Phnom Penh	10	Chaktomuk Junction (Quatre Bras)
VIET NAM		
Mekong delta	> 10 to less than 5	Southern Institute of Water Resources Research

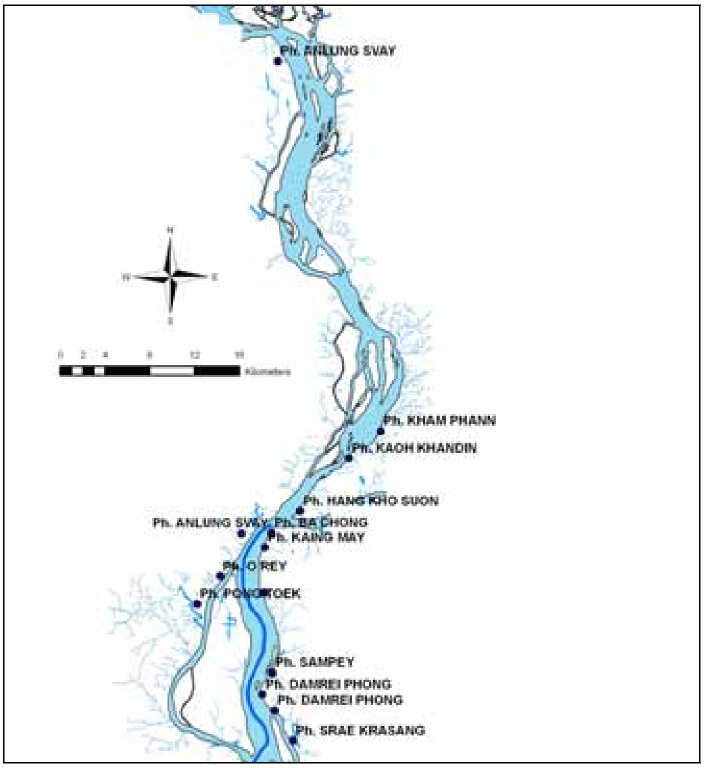

Figure 9: *Locations in northern Cambodia between Stung Treng and Kratie where bank erosion has been recorded by the Royal University of Phnom Penh*

Figure 10: *Map of river bank erosion in the Mekong delta. Reaches subject to erosion rate > 10 m/year are in red colour, from 5-10 m/year are in purple and <5m/year are in pink. Source: Southern Institute of Water Resources Research*

Figure 10 is a map of erosion in the Vietnamese portion of the Mekong delta. Comparing data in Table 5, Figures 9 and 10 it is evident that in terms of annual erosion rate the greatest losses of land are within the Mekong delta.

Several reports contain information on near-bank velocity field, bed and bank sediment grain-size, stratigraphy and bank failure mechanisms. These kinds of data are required for modelling river bank erosion and determining erosion rates. Bank recession through mass collapse occurs mainly during the annual flood recession (JICA, 2004). In the Bokeo province of northern Laos, banks often contain gravel layers, but south of Vientiane river banks throughout the LMB system superficially often appear to be homogeneous in vertical section when considering the silty fine-sand grain-size and stratigraphy, but subtle differences do occur and these translate into distinctive differences in bank profile and erosion mechanisms. Dr Stephen Darby (Southampton University) has developed a bank erosion model specifically for the Mekong River within the LMB (Darby et al., in submission). The model is physically-based, meaning that some geotechnical and river flow data are required to run the model but there is no empiricisms in the model construction and no requirement for prior calibration. However, the model has been run using data collected by Southampton University and the outputs have been compared with historically mapped erosion rates close to Vientiane and found to compare favourably. The basic model structure is described below, following which the model is used to predict future bank erosion under different flow regulation scenarios.

5.3. MODEL OF RIVER BANK EROSION

Bank erosion rate is simulated using a simple equation of form: E = k(TAUC-TAU) where E is instantaneous erosion rate (ms^{-1}), TAU (Pa) is the applied fluid shear stress (see below), TAUC (Pa) is the critical shear stress required to initiate erosion and is a coefficient describing the erodibility of the bank material (units of $m^2s\ kg^{-1}$). Instantaneous rates of erosion are determined at daily time steps (to give overall amount of retreat in a day), with the annual amount of retreat then determined via summation across the year. Methods of parameterising TAU, TAUC and K are discussed below.

Key to the analysis is the specification of the annual flow hydrograph (at daily time steps) for each of the four key scenarios (baseline, Chinese dams, Definite Future, and 20 yr Development Plan). Flow hydrographs for the 15 year period 1986-2000 (based on observed precipitation inputs for this period) were provided by Thanapon Piman (MRC) for each of these scenarios. The 15 year flow records for each scenario were then used to create a mean annual hydrograph for each scenario. Flow hydrographs for the 15 year period 1986-2000 (based on observed precipitation inputs for this period) were provided by Thanapon Piman (MRC) for each of these scenarios.

Flow data for each of the scenarios were obtained through use of the IQQM model with outputs at Pakse and Vientiane gauges. The three 'future' scenarios were obtained by perturbing the 1986-2000 baseline model with the future dam/water demand scenarios, but retaining the 1986-2000 precipitation series.

The critical shear stress (TAUC) and bank material erodibility (K) parameters were obtained via direct measurements using a CSM instrument (Tolhurst et al., 1999). Data for the Pakse reach are based on a single sample site near Pakse, data for Vientiane reach are from the Ban Hom study site. For full details see Darby et al. (in submission).

Flow discharge is linked to applied fluid shear stress using methods as detailed in Darby et al. (in submission). In summary, for each study site measurements of bank roughness parameters and outer region flow velocity are used to determine the skin friction component of shear stress exerted on the banks, using the methods of Kean and Smith (2006a & b). By repeating the analysis for a range of flow discharges, a calibration function of form either TAU = a*LN(Q)-b (Pakse) OR TAU = a*Q^b (Ban Hom) is developed, where a and b are site specific parameters (Figure 9 of Darby et al. in prep illustrates these functions for the Pakse and Ban Hom study sites. Details of the fitted parameters are also summarised below. Full details of the bank roughness and outer region flow velocity data used in the Kean and Smith modelling for each site are given in Darby et al. (in submission).

5.4. PREDICTED RIVER BANK EROSION FOR DEVELOPMENT SCENARIOS

The model described within Section **5.3** was applied to predict bank erosion at Vientiane and Pakse using (i) geotechnical data obtained by Southampton University at each site; (ii) flow velocity data supplied by Iwona Conlan; (iii) simulated future flow annual hydrographs as defined by the IQQM, as supplied by Thanapon Piman.

Table 6: *Mean Annual Rate of Bank Erosion Calculated Using the Model of Darby et al., (in review)*

Mean Annual Rate of Bank Erosion (m a^{-1})

	Development Scenario			
Reach	**Baseline**	**Upper Mekong Dam**	**Definite Future**	**20 Year Development Plan**
PAKSE	0.46	0.40	0.39	0.34
VIENTIANE	1.68	1.62	1.62	1.50

Mean Annual Rate of Land Loss (Hectares/km of bank line a^{-1})

	Development Scenario			
Reach	**Baseline**	**Upper Mekong Dam**	**Definite Future**	**20 Year Development Plan**
PAKSE	0.046	0.040	0.039	0.034
% CHANGE		*-11.8*	*-15.0*	*-25.5*
VIENTIANE	0.168	0.162	0.162	0.150
% CHANGE		*-3.6*	*-4.0*	*-10.7*

The analysis has been completed for the future trends in bank erosion (under the baseline + 3 development scenarios) for two locations on the Mekong: At Pakse and at Ban Hom (one of our study sites located between Vientiane City and Friendship Bridge).

The results are based on the hydraulic bank erosion model that is forced by flow discharge variations which prior work has shown to the main control on river bank erosion, mainly related to cutting-out of the toe of the river banks which leads to slumping. Mass failures (e.g. due to changes in seepage) are not directly accounted for, but this is unlikely to be a limitation for reasons argued in Darby et al (in submission). Prior work has also shown that changes in suspended sediment supply are not important and consequently it is the future hydrograph shape rather than the sediment load of the river that is significant to predict future bank erosion rates. However, a reduction in sediment load could result in incision of the river bed such that the river banks would be higher and the seepage gradients altered. The effects of bed incision on river bank erosion can be addressed in conjunction with the recommendation in sections **4.5.1.**, **4.6.1.** and **4.73**.

All future scenarios see a reduction in simulated bank erosion, at both sites for the next 20 years. This result is because the future scenarios assume reductions in the higher flows that drive bank erosion. The scenarios however do not consider the impacts of climate change, which should be accounted. The study by Kiem et al (2008) shows increasing high flows under future climate change, at Pakse. This would - in the absence of other factors, force increases in bank erosion. It remains unclear whether the net, combined, impacts of climate change and future development (as in these scenarios) would lead to an increase or decrease in bank erosion within a 20 year purview. This uncertainty highlights the need to explore these issues.

While both study sites see a drop in bank erosion in these scenarios, the difference in the magnitude of the drop between the sites highlights the site specific nature of the magnitude (if not direction) of response. Site specificity derives from the interaction between local hydrograph shape and bank material characteristics.

5.4.1. Recommendation

The predictions of bank erosion for future flow scenarios as presented above are robust being based on site-specific data. It is recommended that a similar analysis is undertaken for key sites within Cambodia and especially within the Vietnamese delta where recorded bank erosion rates are very high and the economic and social impacts are already high. This work programme would require some fieldwork.

These work package recommended above should include the effects of climate change over a 20 and 50 year timeline with a commentary on the longer-term implications of climate change beyond 50 years.

Existing national data sets on river bank erosion are collected using different protocols. It is recommended (i) that the MRC develop a consistent quality-checked data base and (ii) that a single river bank erosion model be adopted for MRC use and a data collection strategy developed to produce appropriate parameter data.

6. EFFECT OF DAMS ON THE MEKONG RIVER CHANNEL

6.1. EFFECTS OF RUN-OF-THE RIVER DAMS

The 11 proposed low head dams for the mainstem within the LMB will have heads of between 6m and 35 to 40m and so the largest may form reservoirs up to 100 to 150km in length due to the low channel gradient. The report by the MRC (2009) succinctly summarises the issues related to sedimentation and scour in respect of dam and fish pass design and operation. As recommended by MRC (2009) site specific models of channel sedimentation and scour will be required for each dam site. A more general estimate though can be developed prior.

6.1.1. Upstream effects

Run-of-river schemes notionally have no deadwater storage but significant backwater effects are noted in the dam designs for the impoundments upstream of Vientiane. These will cause localised aggregation and localises scour of the bed level within the impoundments. Other than the issue of bed aggradation due to sediment storage within the impoundment, the upstream effects of impoundments on river channels are poorly documented but can be spatially extensive in high-dam low-gradient systems. Generally progressive aggradation of the channel bed is to be expected. The aggradation profile within the impoundment can be determined using modelling studies. Classically this is described as a progressive delta front moving from the upstream end of the impoundment downstream towards the dam. However, this is most usual where there is substantial coarse bed sediment present. Where the bed sediment is fine and the power of the river is great, then the aggradation can occur over a substantial length of the impoundment following dam construction. Usually the bed also fines in grain-size downstream (and through time) and the overall bed gradient within the impounded reach will reduce. This aggradation has implications primarily for any major tributary which joins the main-stem in the impounded reach. Aggradation of the tributary junction will affect the tributary stream as far upstream the point where the backwater curve intersects the original bed profile. However this aggradation can result in increased local flooding at the confluence, especially when the tributary is in flood and the impoundment is full. Usually live storage is lost immediately and later dead storage is lost. Live storage is lost continuously for at least half the life of a project.

6.1.2. Downstream effects

Downstream impacts of dams are well documented through case studies, theory and flume studies. Brandt (2000) and Grant et al. (2003) comprehensively review the effects of impoundments on river channel morphology. Grant et al. (2003) developed a conceptual and analytical approach to determine the direction of change in response to channel regulation by dams. It is a simple model that uses two key variables to elucidate the direction of change. The first variable, S^*, is the ratio of the sediment load supplied below the impoundment to that above the dam. The second variable, T^* is the change in the frequency of sediment transporting flows pre and post dam construction.

Thus: $S^* = S_{below}/S_{above}$

and,

$$T^* = T_{pre}/T_{post}$$

The value S^* thus describes the amount of change in the sediment load. Sediment load can be determined from existing monitoring data, from additional surveys or from theoretical calculation. The value T thus describes the fraction of time that flows are greater than a critical value for sediment transport (e.g. the critical Shields parameter value in section **4.4**) such that T^* describes the change in the frequency of sediment transporting flows. The range of sediment transporting flows can be approximated using hydrological time series of data and from model studies of future flow scenarios. Estimates of the frequency of sediment transporting flows, both pre and post dam, then requires an estimate of how often the sediment transporting flow is equalled or exceeded on the daily flow duration curve, both natural and regulated. The T^*/S^* values for each impoundment can be plotted on a response domain (Fig. 10) to show the magnitude and type of effect expected (Grant et al., 2003) and the trajectory of change through time. Additional work will be required to address the sediment storage in each impoundment once the geometry of the impoundment and operation regimen are known. Nevertheless given the comments made within section **4.4** (Table 4), the transporting power of the regulated river will not be significantly different from the unregulated river regimen such that the fractional change in the frequency of sediment transport will be low. S^* will almost certainly decrease below a value of 1 due to sediment storage within the impoundments but as these are run-of-river impoundments the value need not be very low (i.e. $S^* \neq < < 1$) if sufficient consideration is given to sediment flushing. Consequently the impacts of main-stem dams are likely to local and subtle. Generally the changes imposed by the basin-wide reduction in sediment supply are likely to be more significant that the local effects of dams and the impact of dams will drive change in the same direction as implied for the basin-wide scenarios reported in section **4.5**. Thus local bed scour may occur below dams, with local increase in bank erosion and loss of any prominent sand bars (and erosion of islands) with a concomitant slight coarsening of the bed material. Bed material coarsening will not be significant because run-of-river dams should pass significant quantities of the natural size range of bed sediments and because the bed substratum generally does not contain much coarse sediment to form coarser lag deposits.

Brandt (2000) utilizing a very similar approach to that of Grant et al. (2003), developed a channel adjustment model consisting of nine potential trajectories of change that depend on the balance between supplied sediment load, transportation capacity and transportation power. Given the expected minimal change in transportation power in the Mekong river and a sediment load that will be less than the capacity of the flow to transport it, the Mekong would be classed as a ‘Case 4’ in Brandt’s 9-class schema. Case 4 is typified by channel degradation and channel widening which concurs with the expectation derived above using the Grant et al. (2003) methodology.

Consideration also needs to be given to the impacts of dam construction activity. These effects can be counter to the long-term adjustments consequent upon dam closure.

Increased sediment transportfrom the dam site leads to temporary channel bed aggradation and fining of the bed (Davey et al., 1987) which can be highly deleterious to the aquatic ecosystem.

The final consideration required is the time-scales of adjustments that might follow impoundment.

Slope changes: Minor bed coarsening downstream on an impoundment was noted as a probable response and this would occur immediately but progressively following dam closure. Coarsening of the bed can be associated with a change in bed gradient but Chien (1985) opined, from flume and field studies, that slopes changes are usually minimal. However the direction of change is likely to be a reduction in slope immediately below the dam, as the bed is unlikely to armour such that slope reduces in order to reduce transport capacity to match the incoming sediment load.

Cross-sectional changes: Changes in the cross-sectional shape depend on the balance between incision and bank erosion rates. Incision tends to drive bank erosion but this is mediated by the relative erodibility of the bed material versus the bank materials. In the Mekong the loose bed material is highly erodible and degradation will occur immediately. The bank materials are less erodible and so bank alignment adjustments would follow bed scour, if at all. Bank erosion may not occur depending on the detailed geotechnical properties of the local river banks. Of a large number of rivers investigated by Williams and Wolman (1984) half showed major width adjustments within 1.5 to 2 years of closure with an assumed adjustment in the river bed elevation over a similar time-scale, with depth adjustments reaching 50% of their final elevation within 7 years. However, there was considerable variance in the data with some systems taking decades to adjust. Periods of aggradation can punctuate the degradation and incision may cease if bedrock is reached, which is a possibility in many reaches of the Mekong: e.g. Vientiane. Thus adjustments downstream of impoundments can occur exceedingly rapidly. Modelling studies considering river bed degradation and river bank adjustments in conjunction could clarify the nature and time scales of adjustments.

Planform changes: Planform change refers to the plan-view style of the river channel: whether single straight channel, meandering single channel or multi-thread channels, for example. River bank erosion might locally cause a lateral shift in the location of the channel but this would be constrained by river bed incision and is likely to be minor. The reduction in sediment load also will tend to maintain a single channel so that it is not anticipated that the channel below a dam would become multi-thread, the latter channel form usually be associated with an increase in sediment load and significant increase in channel slope, neither of which are anticipated in the case of the Mekong River.

Bedform changes: The type and size of bedforms on the river bed, such as ripples or dunes, is dependent on the size of the bed sediments. At present much of the river bed is characterised by sand dunes with hieghts up to 1m or greater. These dunes have not been studied in the Mekong but are likely to be present under regulated regimen although less prominent if the grain-size of the bed material coarsens. Bedforms adjust immediately to changes in flow regimen and thus will adjust immediately after dam closure. Dunes can impede navigation and may require dredging or the use of flow guide vanes to control their development.

Tributary response to main stem changes: The main effect of dams on tributaries is related to the degradation of the bed level in the main channel and channel widening of the main channel. Both of these adjustments will lower the main channel water level and progressive bed scour can occur within the tributary mouth that also migrates up the tributary. Significant adjustments can occur in the geometry of the confluence as a result. The importance of the response will depend on the size of the tributary relative to the main stem and the distance of the tributary from the dam. Those tributaries joining the main-stem close to the dam will be effected most and those distally the least or not at all.

Variability with distance from the dam: Where dam construction is associated with likely bed degradation as is the case for the Mekong, the downstream scour is usually greatest near to the dam, at least initially with a progressive shift in the locus of scour downstream through time. This has important implications for the design of locks and fish passes to maintain accessibility for transit of ships and fish. Greatest scour may occur between zero and 70 channel widths downstream and most usually between 20 and 70 channel widths.

Effects of sediment flushing: A thorough treatise on reservoir flushing is given by Morris and Fan (1997) but the effects on river morphology downstream of dams is poorly documented. Perhaps the best documented case is that of the Cachi Reservoir in Costa Rica (Brandt and Swenning, 1999) the results of which study are broadly generic. Sediments released during flushing usually are at a much higher concentration than that which would pertain naturally. In the case of the Cachi Reservoir concentrations were 32 times as great as pre-impoundment monitored concentrations. Thus deposition tends to occur as concentrations cannot be sustained by the pulsed flushing flow dissipates downstream. The distribution of fine sediment downstream will depend on the local channel and flow characteristics at the time of the release, but the quantity is proportional to the amount flushed from the impoundment. Most material is sourced from the lower-lying portions of the impounded channel, initially close to the dam but progressive erosion works upstream during the flushing process along the former course of the channel and consequently flushing does not remove marginal areas of deposition within the impoundment. Fine sediment can be deposited across the river bed and also on the river banks if water levels are sufficiently high. However, in the former case the deposition is largely temporary, acting a source for future high flows. Thus the geomorphological effects are small whereas the major impacts of fine sediment deposition can be on fish and invertebrates which naturally have variable tolerances to sediment concentration levels both in the water column and on the bed.

6.2. EFFECTS OF HEP FLUCATUATIONS ON RIVER BANK EROSION

The operation regimenn of the run-of-river mainstem dams has yet to be determined. However I was asked to consider the effects of 1m to 2m water level fluctuations imposed on the ambient hydrograph by operational releases. The analysis, reported in Tables 7 and 8, has been done using data for Pakse and Vientiane to compare with Table 6 and all four future scenarios have been considered. A ±1m or ±2m fluctuation in the river stage is probably unrealistically high and translates into significant discharge fluctuations. The translation of stage into discharge was accomplished using the rating curves for each station such that the magnitude of the discharge fluctuation therefore varies as a function of the ambient discharge. The process implies that there would be bigger daily fluctuations during flood stages in contrast to base flow. This seems to me unrealistic - hydropower dams are likely to have a regular discharge release that will transform to variable water level fluctuations. Consequently, the present simulations are crude but perhaps helpful nonetheless. The key finding is that the fluctuations generate more erosion. It is not really the fluctuations that are responsible, only the fact that you are adding more erosive flows, and that the cumulative effects offset the reduced flows in the oscillation. Thus the decreases in erosion rate envisaged under the development scenarios are less with fluctuations than without. In two - but only two - specific scenarios the effect is to change the direction of response, albeit marginally.

Table 7: *Mean Annual Rate of Bank Erosion Assuming ±1m daily fluctuation in water level due to HEP generation. Calculated Using the Model of Darby et al., (in review)*

Mean Annual Rate of Bank Erosion (m/yr) [With +/- 1m daily water level fluctuation]				
	Development Scenario			
Reach	**Baseline**	**Upper Mekong Dam**	**Definite Future**	**20 Year Development Plan**
PAKSE	0.50	0.45	0.43	0.38
VIENTIANE	1.80	1.79	1.78	1.68
		Mean Annual Rate of Land Loss (Hectares/km of bank line/yr)		
	Development Scenario			
Reach	**Baseline**	**Upper Mekong Dam**	**Definite Future**	**20 Year Development Plan**
PAKSE	0.050	0.045	0.043	0.038
% CHANGE		*-10.5*	*-13.6*	*-24.0*
VIENTIANE	0.180	0.179	0.178	0.168
% CHANGE		*-0.3*	*-0.8*	*-6.2*

Table 8: *Mean Annual Rate of Bank Erosion Assuming ±2m daily fluctuation in water level due to HEP generation. Calculated Using the Model of Darby et al., (in review)*

Mean Annual Rate of Bank Erosion (m/yr) [With +/- 2m daily water level fluctuation]

	Development Scenario			
Reach	**Baseline**	**Upper Mekong Dam**	**Definite Future**	**20 Year Development Plan**
PAKSE	0.55	0.50	0.49	0.43
VIENTIANE	1.95	1.99	1.98	1.88

Mean Annual Rate of Land Loss (Hectares/km of bank line/yr)

	Development Scenario			
Reach	**Baseline**	**Upper Mekong Dam**	**Definite Future**	**20 Year Development Plan**
PAKSE	0.055	0.050	0.049	0.043
% CHANGE		*-8.9*	*-11.6*	*-21.4*
VIENTIANE	0.195	0.199	0.198	0.188
% CHANGE		*1.7*	*1.3*	*-3.4*

6.2.1. Recommendation

The effects of dam operational releases require further site specific consideration once operational procedures are known.

6.3. SUMMARY OF KEY GEOMORPHOLOGICAL IMPACTS

The regulation of the mainstem Mekong River will have measurable effects on the fluid discharge of the river and the annual flux of sediment transport. However, the power of the river will remain sufficient to transport sediment under regulated flow regimens.

The sustained power and reduced supply of sediment from upstream (UMB) means that sediment will be picked up from the river bed so that erosion of the river bed may occur at some locations within 20 years.

Much of the channel upstream of Vientiane is bedrock such that the impact on the channel of a reduced sediment flux will be minor. However in the vicinity of Vientiane there may be significant erosion of the river bed and associated destabilization of the river banks within the next 20 years.

A reduction in sediment load to the Cambodian Plain and the Delta will have implications for the stability of the main navigation channels in this lower region, although the time scales of change are not clear.

The impacts on the floodplains are difficult to determine. Changes in the annual hydrograph according to IQQM simulations indicate negligible impacts in terms of capacity to deliver sediment to the floodplain surfaces, although reduced water levels during peak flows should mean a slightly lower depth of flooding and in principle less deposition of fine sediment on the floodplains each year. However, these impacts will be strongly affected by channel changes induced by changes in the total sediment flux, by flood protection measures utilizing levées and other flood control measures.

The delta is at risk of no-longer receiving sediment from the Mekong to aid to natural delta building. Consequently, given global and regional sea-level rise the delta is at risk of seaward erosion although the time scales are not clear.

River bank erosion is locally of significance but is not a regional issue. The future flow scenarios and the effects of water level fluctuations due to hydropower have little effect on the natural values of river bank erosion rates. The future flow scenarios in fact show a decrease in river bank erosion. That being said, the uncertainty in respect of the deltaic environment means that river bank erosion could be exacerbated by channel changes within the delta.

Deep pools are unlikely to be effected by flow regulation expect in the immediate vicinity of impoundments.

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