Origin, fate and impacts of the Mekong sediments
Origin, fate and role of Mekong sediments

December 2010

Juha Sarkkula, Jorma Koponen, Hannu Lauri, Markku Virtanen

With significant contributions by Matti Kummu from Aalto University (former Helsinki University of Technology)
# Table of Contents

1 **BASIC CONCEPTS**
   - 1.1 WATERSHED ................................................................. 6
   - 1.2 SEDIMENT MOVEMENT IN WATER BODIES............................ 6
   - 1.3 COHESIVE SEDIMENTS ..................................................... 8
   - 1.4 SETTLING, SEDIMENTATION AND RESUSPENSION ...................... 8
   - 1.5 "SEDIMENT HUNGRY WATER" ............................................ 10
   - 1.6 GRAIN SIZE AND SEDIMENT TRANSPORT .............................. 10
   - 1.7 PHYSICAL PROCESSES AFFECTING SEDIMENT CONCENTRATIONS .... 11

2 **SEDIMENT MODELLING** .................................................................. 13
   - 2.1 SEDIMENT MODELLING COMPONENTS ................................... 13
   - 2.2 WATERSHED EROSION MODELLING ..................................... 14
   - 2.3 SEDIMENT MODEL CALIBRATION .......................................... 17

3 **SOURCES OF THE MEKONG SEDIMENTS** ..................................... 22
   - 3.1 ESTIMATED SEDIMENT LOADS ............................................. 22
   - 3.2 SIMULATED SEDIMENT LOADS ............................................. 25

4 **SEDIMENTATION IN THE TONLE SAP SYSTEM** .............................. 30
   - 4.1 NATURE OF THE TONLE SAP SUSPENDED SEDIMENTS .............. 30
   - 4.2 ESTIMATED TONLE SAP SEDIMENT LOAD FROM MEKONG AND TRIBUTARIES ........................................... 31
   - 4.3 TSS CONCENTRATIONS IN LAKE AND FLOODPLAIN .................. 33

5 **SEDIMENT TRAPPING BY THE HYDROPOWER DAMS** .................... 38
   - 5.1 MEKONG HYDROPOWER DEVELOPMENT ................................ 38
   - 5.2 DAM TRAPPING MODELLING ............................................... 39
   - 5.3 MODELLED CHINESE AND TRIBUTARY DAM SEDIMENT TRAPPING ........................................................................ 41
   - 5.4 LOWER MEKONG MAINSTREAM DAM IMPACTS ....................... 43
   - 5.5 ESTIMATED SEDIMENT TRAPPING ........................................ 45
   - 5.6 CHINESE EXPERIENCES ON SEDIMENT TRAPPING ................... 47
   - 5.7 MORPHOLOGICAL IMPACTS OF SEDIMENT TRAPPING .............. 49

6 **MAIN CONCLUSIONS ABOUT SEDIMENT TRAPPING AND MORPHOLOGICAL CHANGES** ........................................................................................................... 50

7 **KNOWLEDGE GAPS AND ADDITIONAL CONSIDERATIONS** ............. 51

REFERENCES .................................................................................. 52
Illustration Index

Figure 1. Non-cohesive sediment transport and net suspended flux at bed boundary. ........ 7

Figure 2. Cohesive sediment transport and net suspended flux at bed boundary. ........... 7

Figure 3. Forces acting on a grain in a flow (Collinson & Thompson 1982). ................. 9

Figure 4. TSS profiles for each indicated measurement day in Vientiane – Nong Khai section of the Mekong River. Depth is relative to the maximum depth. (Sarkkula et. al. 2007). ........9

Figure 5. Sediment sampling in cross sections. In each cross-section three locations with three depths each were measured. The depths were surface, 0.2 H_{max} and 0.8 H_{max} (H_{max} = maximum depth)................................................................. 10

Figure 6. The Hjulström diagram, showing the relationship between the velocity of a water flow and the transport of loose grains. Settled particles require more energy for start movement than keep on moving when already in motion. Clay particles require high velocities when compacted because of the cohesive nature of clay sediments. (W.H. Freeman et. al. 1986) .......................................................... 11

Figure 7. Morgan, Morgan and Finney watershed erosion model concept (Wageningen University, 2007). ................................................................................................................................................................. 15

Figure 8. Comparison of measured (red dots) and modelled (black line) sediment values in Chiang Saen near the Chinese border for the years 1994-1996. Above load and below concentrations. For location see Figure 11. Measured sediment loads in the figure are calculated by multiplying observed concentration with modelled flow. ...................................................... 18

Figure 9. Comparison of measured (red dots) and modelled (black line) sediment loads in Chiang Saen for the years 1997 - 2000. .................................................................................................................... 19

Figure 10. Comparison of measured (red dots) and modelled (black line) sediment loads in Mukdahan. For location see Figure 11. ............................................................................................................. 20

Figure 11. Location of main sediment stations (Chiang Saen, Luang Prabang, Nong Khai, Mukdahan, Khong Chiam) used in the study. (Wang et. al. 2009) ....................................................................................... 23

Figure 12. Variations of the (a) water discharge and (b) suspended sediment load along the Lower Mekong River. The five stations are Chiang Saen, Luang Prabang, Nong Khai, Mukdahan and Khong Chiam from left to right. Note that the solid and empty symbols represent the pre-dam and post-dam periods, respectively. (Wang et. al. 2009) ........................................ 25

Figure 13. Location of the model timeserie points (Chiang Saen, Pakse, Kratie) used in simulating the sediment loads. .................................................................................................................................................... 26

Figure 14. Proportion of Central Highlands eroded sediments compared to the total Mekong erosion during the last 8 million years (upper pie-chart). (Clift et. al. 2004) ............................... 28

Figure 15. Location of the mountainous Central Highland areas in the 3S basin (circle). Yellow to red colour shows areas which are over 1 km high. MRC 2 km resolution IWRM-model. ........................................................................................................................................ 29

Figure 16 Undisturbed grain size sample analysis from the Preak Leap site in the Tonle Sap River. WUP-FIN monitoring results analysed by the Canada Center for Inland Waters. ........ 30

Figure 17 Sonicated sample analysis from the Preak Leap site in the Tonle Sap River. Observe break-up of flocs present in into smaller particles. WUP-FIN monitoring results. .. 31

Figure 18 Annual TSS flux into and out from the Tonle Sap Lake (1997-2003). ................... 32

Figure 19 Tonle Sap flood volumes in 1997 - 2003.................................................................. 32
Figure 20. TSS concentrations in open lake and flooded forest (Sarkkula et al. 2004). Data is compiled from WUP-FIN floodplain and lake measurements.

Figure 21. Tonle Sap lake proper (blue color) and surrounding floodplain (green color). Observe ring road around the floodplain.

Figure 22. Tonle Sap Lake sedimentation rate estimates based on core sample analyses. (Penny, 2002; Penny et al., 2005; Tsukawaki, 1997).

Figure 23. Highest sedimentation areas.

Figure 24. Simulated net sedimentation in 1997 (top), 1998 (middle) and 2000 (bottom). Each year the simulation period is from May to end of April. 1200 - 1600 g/m² yearly sedimentation rate represents about 1 mm sediment depth increase. Observe low sedimentation in the lake proper due to high sediment resuspension during low water periods.

Figure 25. Location of the existing and planned tributary (left) and mainstream (right) dams. (Kummu et. al. 2010)

Figure 26. Empirical Brune curve showing sediment trapping efficiency as a function of capacity-inflow ratio.

Figure 27. Sediment load (g/s) in two scenarios: a) baseline (black line), b) 20 year dams with no mainstream dams (red line).

Figure 28. Yearly sediment loads (million tonnes/y) in two scenarios: a) baseline (black line), b) 20 year dams with no mainstream dams.

Figure 29. Modeled impact of different lower mainstream dam trapping efficiencies on sediment loads. The trapping efficiencies are percentages of the theoretical maximal values.

Figure 30. The confidence intervals for basin trapping efficiency (TE) calculations. The TE with the negative and positive confidence interval are presented in the upper right corner. (Kummu et. al. 2010)

Figure 31. The temporal development of the basin trapping efficiency for each of the existing and planned mainstream dam locations (some of those are named in the graph) and basin outlet (A = 816 000 km²). See Figure 1 for the location of the mainstream dams. (Kummu et. al. 2010)

Figure 32. Temporal variations in total water and sediment flux into the ocean from nine major Chinese rivers in the past five decades. (Chu et. al. 2009)
1 BASIC CONCEPTS

1.1 WATERSHED

A "fluvial system"-concept is useful in characterising the Mekong Basin sediment processes. An idealized fluvial system consists of Zone 1, the drainage basin as a sediment and runoff source; Zone 2, the main river channels as a transfer component; and Zone 3, the alluvial floodplains, fans, deltas, etc., as zones of deposition. Zone 1 can be further divided into upland areas, lateral areas, and small stream channels. Considered together, these three elements form the watershed.

Watersheds can be eroded by wind, flow, ice and vegetation. In the Mekong region soil particles are detached, transported, and deposited primarily by raindrop impacts, by runoff on the soil surface and runoff in river channels, lakes and reservoirs. Cumulative net sediment load can be estimated from the river channels by measuring sediment concentrations and discharge and multiplying these together.

1.2 SEDIMENT MOVEMENT IN WATER BODIES

Sediment movement in a water body can be divided into three types:

1. bed load (saltation, rolling and sliding of bed material)
2. suspended bed material load
3. wash load.

Suspended load is the portion of the total sediment load that is transported in suspension by average flow and turbulent fluctuations within the body of flowing water. It includes suspended bed material load and wash load. Bedload is portion of the total sediment load that moves on or near the streambed. The wash load is composed of fine particles in contrast to coarser suspended bed material load. Wash load is limited by upstream sediment supply whereas suspended bed material load depends on channel hydraulics. The division is pragmatic because in sufficiently slow flow conditions also wash load would behave like suspended bed material flow. The importance of the suspended bed material and was load separation is that the sand/gravel fraction can be part of the suspended load and can be sampled in the TSS (total suspended solids) monitoring. In general it can be assumed that the suspended load is all fine material.

In the Ganges and Brahmaputra/Jamuna there is about 50/50 sand/wash load split which is probably typical of major Himalayan Rivers. The Mekong, especially in the lower Mekong, has very probably a higher wash load.

Carling (2010) points out based on work by Iwona Conlan (unpublished) that bedload in large rivers is rarely greater than 10%, but Mekong may be an exception because its active river bed has little coarse material and consists mostly of fine sand. It should be emphasised again here that the remaining 90% is not necessarily only fine sediments but also coarser suspended bed material.

In the current model implementation no distinction is made between the suspended bed material and was loads. This is because of lack of suspended
sediment grain size data. Modelling needs to be developed further when the data becomes available through the MRC/IKMP sediment monitoring programme.

Figure 1. Non-cohesive sediment transport and net suspended flux at bed boundary.

Figure 2. Cohesive sediment transport and net suspended flux at bed boundary.
In Figure 1 and Figure 2 the transport and net-suspended flux at bed boundary are presented for non-cohesive and cohesive sediment transport, respectively.

1.3 **COHESIVE SEDIMENTS**

Important difference in sediment transport characteristic between coarse and fine-grained sediment can be attributed to cohesion effects. Cohesive forces act at very small distances and are affected by clay mineralogy, ion content and composition, pH and temperature. In general, sediment is described as being cohesive if the particle diameter is less than about 60 μm. Practically all Tonle Sap Lake bottom sediments are cohesive, with the exception of few sand dunes.

Three significant differences between cohesive and coarse-grained sediment transport are listed as follows (Teeter et al., 2001):

- **Cohesive sediments are only transported in suspended state.** Coarse-grained sediments are also transported in quasi-contact with the bed as bedload. Because of cohesive forces movement of cohesive sediment particles is restricted in respect to each other unlike that of sand where grains can move quite freely. Fluid muds are an exception to this rule.

- Flocculation increases settling velocities of suspended cohesive sediments by many orders of magnitude and is responsible for deposition.

- Cohesive sediment beds undergo settling and self-weight consolidation. When rapid deposition occurs, deposits are light and have little hydraulic shear strength. Cohesive beds can be uniform or vertically stratified by density and strength.

1.4 **SETTLING, SEDIMENTATION AND RESUSPENSION**

**Settling** is downward movement of sediments in water column. Smaller the grain size the smaller settling velocity is. **Sedimentation** is the act or process of depositing sediment from its suspension in water. Net sedimentation occurs when the bed shear velocity is smaller than the critical shear stress needed for resuspension. In case of cohesive sediments flocculation affects strongly the particle size and settling velocity. Sediment and turbulent flow characteristics affect flocculation. Sediment concentration can in turn impact flow characteristics. General cohesive sediment settling characteristics are not well understood, and in most cases the properties are strongly site specific.

Figure shows how a particle (piece of rock, pebble, sediment grain) is resuspended from bottom. The effect is similar to what keeps aeroplanes and birds flying, that is the velocity over the particle is lower than upstream and downstream of it and according to the Bernoulli principle there must be a reduction of pressure over the particle. This provides a lift force which can entrain the particle in the moving fluid. Also vertical turbulent fluid fluctuations can lift up the particle.
A vertical sediment distribution has its peak normally near the bottom. This is because settling transfers sediment particles from surface to bottom. In the Mekong mainstream the flow is usually fast and turbulent and mixing is efficient in comparison to the settling. Because of this the vertical suspended sediment profiles don't differ very much on the surface and near the bottom (Figure 4, Figure 5 shows sampling locations). However, very near bottom the suspended and bedload difference is not clear and concentrations can rise sharply.
Figure 5. Sediment sampling in cross sections. In each cross-section three locations with three depths each were measured. The depths were surface, 0.2 $H_{\text{max}}$ and 0.8 $H_{\text{max}}$ ($H_{\text{max}}$ = maximum depth).

1.5 "Sediment hungry water"

The expression "sediment hungry water" should be always presented in quotes. The expression has been used to illustrate the impact of sediment trapping on the downstream sediment balance: erosion will initially increase downstream of dams because sediment supply is reduced whereas the flow capacity for resuspension and erosion is generally not reduced. This results in net erosion and some compensation of the decreased sediment load. But this doesn't mean that water would become literally more hungry and gross erosion would increase.

It is important to understand in Mekong conditions that:

- the active bottoms are largely sand and they can't compensate for the finer sediments which are important for as fertilisers of the floodplains and agricultural areas
- even assuming same bottom and suspended sediment composition, the net erosion cannot fully compensate decreased sediment input to the system (this can be easily illustrated by assuming sedimentation and erosion originally in balance and in a new situation eliminating all external inputs to the system)
- the net erosion will decrease with time and the river system will obtain a new equilibrium with long-term balance between erosion and sedimentation.

1.6 Grain size and sediment transport

The Hjulström diagram (Figure 6) shows the relationship between grain size (horizontal axis), flow velocity and transport mode. Deposition occurs on the right lower corner of the diagram where flow can't move sediment particles. The upper part of the diagram indicates flow velocities which are able to sustain erosion and suspended transport. In between the two areas flow can sustain bedload transport. High speeds required to erode consolidated finer particles (mud) are explained by the cohesive properties of the fine sediments.

Flow velocities are on the order of meters/s. According to the diagram these speeds are able to sustain particle transport between clay and pebbles and even cobbles.
Figure 6. The Hjulström diagram, showing the relationship between the velocity of a water flow and the transport of loose grains. Settled particles require more energy for start movement than keep on moving when already in motion. Clay particles require high velocities when compacted because of the cohesive nature of clay sediments. (W.H. Freeman et. al. 1986)

1.7 PHYSICAL PROCESSES AFFECTING SEDIMENT CONCENTRATIONS

The physical processes that impact both bed and suspended sediment concentrations are

1. Flood flow which is overland and river flow that fills up or drains the basin
   - brings in sediments both in suspension and as bedload
   - flushes out sediments during receding flood
   - transports sediments
   - causes bed resuspension through bed shear stress

2. Wind flow, that is wind induced lake, river and floodplain flow
   - redistributes material in the lake and floodplains by transporting it
   - causes bed resuspension through bed shear stress

3. Wave action
   - wave generated near bottom circular velocity causes bed resuspension through bed shear stress
4. Settling and sedimentation
   • redistribute material from water column to the bottom.
2 SEDIMENT MODELLING

2.1 SEDIMENT MODELLING COMPONENTS

A holistic sediment modelling includes all fluvial zones. Fluvial zones and corresponding sediment modelling components including MRC Modelling Toolbox models are listed in Table 1.

Table 1. Fluvial zones, model types and available.

<table>
<thead>
<tr>
<th>fluvial zone</th>
<th>model type</th>
<th>Toolbox model</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>watershed erosion and transport</td>
<td>IWRM</td>
</tr>
<tr>
<td>2</td>
<td>river channel processes: suspended load, bedload,</td>
<td>IWRM, 1D,2D,3D</td>
</tr>
<tr>
<td></td>
<td>bed erosion/deposition, bank erosion</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>lake and reservoir erosion and sedimentation</td>
<td>IWRM, 3D</td>
</tr>
<tr>
<td>3</td>
<td>floodplain transport and sedimentation</td>
<td>2D,3D</td>
</tr>
<tr>
<td>3</td>
<td>coastal transport, erosion and deposition</td>
<td>3D</td>
</tr>
</tbody>
</table>

The MRC Toolbox 3D model includes comprehensive modelling environment for sediments. It includes:

- flow generated shear stress
- waves and wave generated shear stress
- boundary layer shear stress formulation
- 3D sediment transport (suspended load)
- simple bedload formulation
- cohesive sediment model using simple density dependent parameterisation
- land use and vegetation dependent transport and erosion
- calculation of bed adjustment (bed elevation changes with sedimentation/erosion)
- classification of bank erosion risk based on horizontal and vertical near-shore velocities.

Darby bank erosion model has been initially coupled with the MRC 3D model (Darby et. al., 2008). MRC 3D sediment modelling has been presented in MRC reports "Technical feasibility of dredging the Tonle Sap Lake for navigation" (Inkala et. al. 2008), "Hybrid 1D/2D/3D model for river-reservoir-floodplain systems" (Koponen et. al. 2008), "WUP-FIN Model Report" (Sarkkula et. al. 2007), and earlier WUP-FIN reports.
MRC Modelling Toolbox enable description of practically all aspects of the Mekong sediment processes. Especially the Tonle Sap system has been modelled in detail and a lot of experience and information is available from it. Other important areas remain largely without applied work. Vietnamese and Cambodian Delta need to be modelled with combined 1D/2D/3D modelling system in order to describe sediment transport, floodplain sedimentation and Delta productivity. Coastal areas need to be modelled for sediment transport, deposition and erosion. Detailed reservoir sedimentation including short and long term behaviour are important for hydropower impact assessment, reservoir water quality and productivity assessment, long-term economic feasibility and reservoir sediment management planning. River morphological changes including erosion and maintenance of deep pools are important for navigation and fisheries. Although watersheds processes have been modelled there is great need for model verification and improved calibration of sediment fractions. All of these tasks are possible with the existing tools, but in many cases data collection, field surveys and sampling need to be conducted to support modelling.

2.2 Watershed Erosion Modelling

Watersheds can be eroded by wind, flow, ice and vegetation. In the current IWRM-modelling framework (see Sarkkula 2010) only precipitation and flow initiated erosion is considered. Soil particles are detached when the impact of raindrops or the erosive force of flowing water is in excess of the ability of the soil to resist erosion. Sediment particles are transported by raindrop splash and by overland flow. Deposition of soil particles occurs when the weight of the particle exceeds the forces tending to move it. This condition is expressed as sediment load exceeding sediment transport capacity.

Widely used simple empirical erosion formulation by Morgan, Morgan and Finney (1984) has been used in the IWRM-model. The advantages of the Morgan, Morgan and Finney model are:

- is suitable for the Mekong conditions (the model was developed to predict soil loss from hill slopes)
- is relatively simple, yet covers the advances in understanding of erosion process
- is physically based empirical model (Mix model)
- needs less data than most of the other erosion predictive models.

The model divides the erosion process into raindrop and surface runoff based components (Figure 7). The model compares the predictions of total detachment by rain drops (F) and surface runoff (H) with the transport capacity of the runoff (TC). It uses lower value of the two for actual erosion rate. The formulation is conceptually simple and corresponds to an intuitive understanding of the erosion process.
A revised MMF model has been developed that takes into account canopy height, leaf drainage and more detailed soil particle detachment by flow. The original MMF equations used in the IWRM-model are described below.

**Water phase**

\[ E = R \left(11.9 + 8.7 \log_{10}(I)\right) \]

- \( E \) = kinetic energy of rainfall (J/m\(^2\))
- \( R \) = daily rainfall (mm)
- \( I \) = intensity of erosive rain, mm/h.

IWRM-model calculates the surface runoff \( SR \). The standard annual formulation which is **not** used in the IWRM-model is:

\[ SR = R \exp\left(-\frac{R}{R_c}\right) \]

- \( SR \) = volume of surface runoff (mm)
- \( R \) = annual rainfall (mm)
- \( R_c \) = annual rain per rain day (mm) = \( R/R_n \), where \( n \) is the number of rain days in the year
- \( R_c \) = soil moisture storage capacity.
\( Rc = 1000 \text{ MS BD } EHD (E_a/E_p) \)

\( Rc = \) soil moisture storage capacity
\( MS = \) the soil moisture content at field capacity (\(\%\), w/w),
\( BD = \) the bulk density of the soil (Mg/m\(^3\)),
\( EHD = \) the rooting depth of the soil (m)
\( (E_a/E_p) = \) the ratio of actual to potential evapotranspiration.

**Soil phase**

\( F = 10^{-3} K KE \)

\( F = \) rate of soil detachment by rain drop (kg/m\(^2\))
\( K = \) soil detachability index (g/J)
\( KE = \) total energy of the effective rainfall (J/m\(^2\)).

\( KE = E^{0.05 A} \)

\( KE = \) total energy of the effective rainfall (J/m\(^2\))
\( E = \) kinetic energy of rainfall (J/m\(^2\))
\( A = \) percentage of rainfall contributing to permanent interception and stem flow.

The IWRM-model modifies \( A \) based on leaf area index which in turn depends on annual vegetation cycles for each land use class.

\( H = 10^{-3} (0.5 \text{ COH})^{1.5} SR^{1.5} \sin(S) (1-GC) \)

\( H = \) rate of soil detachment by surface runoff (kg/m\(^2\))
\( COH = \) cohesion of the soil surface (KPa)
\( SR = \) volume of surface runoff (mm)
\( S = \) slope (deg)
\( GC = \) fraction of ground (vegetation) cover (0-1).

\( TC = 10^{-3} C_f SR^2 \sin(S) \)

\( TC = \) the transport capacity of the runoff (Kg/m\(^2\))
\( C_f = \) crop or plant cover which can be adjusted to take account of different tillage practices and levels of crop residue retention.

The estimates of the soil particle detachment by raindrop impact, \( F \) and by surface runoff, \( H \) are added together to give a total detachment rate. This is then compared with the transport capacity of the surface runoff and the lesser of the two values is the annual erosion rate:

\( E = \min[(F+H), TC] \)

\( E = \) annual erosion rate (Kg/m\(^2\)).
\[ F = \text{soil particle detachment by raindrop (Kg/m}^2) \]
\[ H = \text{soil particle detachment by surface runoff (Kg/m}^2) \text{ and} \]
\[ TC = \text{the transport capacity of the runoff (Kg/m}^2) \text{.} \]

As indicated above the IWRM-model formulation differs in some points from the MMF-model. The differences are:

- IWRM-model includes formulation for snow-melt erosion
- surface runoff is obtained from the IWRM-model hydrological component
- vegetation state (leaf area index) modifies the total effective rainfall energy.

### 2.3 Sediment Model Calibration

Only the MRC dedicated mainstream sediment monitoring stations (HYMOS depth-integrated SSC) were used in the model calibration. The reliability of the SSC data has been discussed in detail by Walling (2005).

Sediment model calibration proceeded in two steps. During the first step model was calibrated based on observed and simulated total suspended sediment concentrations. The match was evaluated subjectively. Initially parameter \( A \) (percentage of rainfall contributing to permanent interception and stem flow) was calibrated together with \( K \) (soil detachability index). After that \( K \) was fine-tuned. In the second step \( K \) was calibrated using the Wang et. al. 2009 results (see next chapter) including total average China and upper Mekong sediment load.

Figure 8 shows comparison between the modelled and measured sediment loads (figure above) and concentrations (figure below) in Chiang Saen for the years 1994 - 1996. The use of sediment loads instead of concentrations is more justified because the loads include information about sediment amounts. The correspondence between the measured and modelled values is also better and more logical when using sediment loads.

Figure 9 shows Chiang Saen sediment load comparison for the years 1997 - 2000 and Figure 10 Mukdhahan comparison for the years 1994 - 2000. Station locations are presented in Figure 11.
Figure 8. Comparison of measured (red dots) and modelled (black line) sediment values in Chiang Saen near the Chinese border for the years 1994 - 1996. Above load and below concentrations. For location see Figure 11. Measured sediment loads in the figure are calculated by multiplying observed concentration with modelled flow.
Figure 9. Comparison of measured (red dots) and modelled (black line) sediment loads in Chiang Saen for the years 1997 - 2000.
Figure 10. Comparison of measured (red dots) and modelled (black line) sediment loads in Mukdahan. For location see Figure 11.

The comparison of the average modelled and estimated (see next chapter) loads from different parts of the basin are presented in Table 2. When looking at the results one has to keep in mind that the modelling and sampling based estimation of the loads doesn't at the moment detail sediment fractions. The suspended sediment load from the upper parts of the basin may contain coarse sediment fractions that are transformed to bedload in the lower parts (see next chapter). This is important in relation to the finer sediments (silt and clay) which probably contain most of the nutrients.
Table 2. Computed and estimated (see next chapter) average sediment loads from different parts of the basin. Modelling period is 1990 - 2000.

<table>
<thead>
<tr>
<th>Place</th>
<th>Annual average load million tonnes/year</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>estimated</td>
</tr>
<tr>
<td>China</td>
<td>99</td>
</tr>
<tr>
<td>3S</td>
<td>17</td>
</tr>
<tr>
<td>Kratie</td>
<td>165</td>
</tr>
</tbody>
</table>

The estimated and modelled loads are in line with each other, but this is to be expected from the selected calibration approach.

MRC DSF SWAT model has been previously tested for sediment modelling (Kittipong 2007). In the study the model area from the Chinese border to Kratie has been divided into 8 sub-areas which have been calibrated separately and boundary values have been obtained from observation based sediment rating curves ("The sediment rating curves at SWAT sub-model inlet points were derived from timely sampled Total Suspense Solids (TSS) data."). Because of this forcing the modelling approach is quite different from what has been used in the IWRM-model. In order to compare the models SWAT should be either set for the whole basin without the forcing or IWRM model should be divided and forced with the same data as SWAT.
3 SOURCES OF THE MEKONG SEDIMENTS

This chapter examines the source of sediments based on both analysis of observation data and basin-wide sediment modelling.

3.1 ESTIMATED SEDIMENT LOADS

Wolanski et. al. (2005) estimated that the Mekong sediment discharge is about 160 million tonnes per year. To place the Mekong in perspective with other major rivers, the Mekong River has a smaller drainage area than the Yangtze (41%), the Amazon (12%), the Mississippi (24%) and the Ganges-Brahmaputra (53%) rivers. However the Mekong River sediment load is about the same as that of the Mississippi, it is 85% that of the Yangtze River and it is 12% larger than that of the Amazon. The Ganges measurements show around half and half in the sand fraction and silt/clay fractions but less sand is expected in the Mekong. Hence the fine sediment transport probably is very high on a global scale relative to other rivers.

Wang et. al. 2009 used four different methods to estimate the annual sediment loads of individual years during 1962–2003 at five main stations along the Lower Mekong River (Figure 11). For the years with high quality data, a rating curve that was based on the measured SSC and water discharge for that particular year was used. For the years with limited data, three methods were used (see Wang 2009). The results of the study are presented below.
Figure 11. Location of main sediment stations (Chiang Saen, Luang Prabang, Nong Khai, Mukdahan, Khong Chiam) used in the study. (Wang et al. 2009)

**Upper Basin** - The sediment load at Khong Chiam, which is the nearest point to the Mekong estuary among our studied sites, ranged from 119 to 162 million tonnes/y ($10^6$ tonnes/year) during the four sub-periods with an average of 145 million tonnes/y during the entire period of 1962–2003. This is in line with previous estimates. For the mean annual sediment load at Pakse (41 km downstream to Khong Chiam), 147 million tonnes/y (Walling, 2005) and 128 million tonnes/y (Lu and Siew, 2006) have been estimated.

**Lancang** - The observed pre-Manwan dam sediment load at Chiang Saen is around 90 million tonnes/y, ranging between 90-110 million tonnes/y (see Figure 1). This is in line compared to results of Walling’s (2005; 2008) results.

**3S rivers** - No detailed SSC measurements are available for 3S area. It is, however, estimated by Kummu et al. in press, that the SL from the 3S basins is around 10 million tonnes/y. This might be an underestimate and the probable range for SL could be around 10-25 million tonnes/y. This is supported by the TSS measurements in various stations in Se San and Sre Pok. The issue needs, however, further analysis to give a more accurate estimation for the 3Ss SL.

Taking the above estimates together, it can be estimated roughly that:

- The average annual sediment load at Kratie is around 165 million tonnes/y (145 million tonnes/y at Khon Chiam + 20 million tonnes/y from the 3S)
- China contributes to this by 55 - 65 % (pre-Manwan situation)
- The 3S contribute to the load at Kratie by 5 - 15 %

23
• The rest of the watershed contributes to the Kratie load by 20 - 40 %.

Using the averages the contributions are: **China 60%**, **3S 10%** and **rest of the basin 30 %**. In average annual loads these translate to 99, 17 and 50 million tonnes/y respectively.
Figure 12. Variations of the (a) water discharge and (b) suspended sediment load along the Lower Mekong River. The five stations are Chiang Saen, Luang Prabang, Nong Khai, Mukdahan and Khong Chiam from left to right. Note that the solid and empty symbols represent the pre-dam and post-dam periods, respectively. (Wang et. al. 2009)

Figure 12 presents spatial variation of the water discharge and the sediment load. The feature that draws attention is the reduced sediment load between Luang Prabang and Nong Khai stations. The upstream watershed area changes relatively little between the stations but the suspended sediment load diminishes significantly. A logical explanation for this would be either differences in sediment measurement procedures between the stations or change of suspended solids grain size distribution. The upper part of the river with steeper slope and more narrow channel upstream may sustain coarser suspended solids than river downstream.

3.2 SIMULATED SEDIMENT LOADS

The basin-wide IWRM-model (see Sarkkula 2010) have been used to estimate sediment loads from different parts of the basin. For the baseline simulation none of the currently existing dams have been included in the simulations. This is important especially for the Manwan dam. The daily modelled discharges and total suspended sediment concentrations were multiplied with each other in Chiang Saen, Pakse and Kratie timeseries points. The Chiang Saen point gives load from China, Kratie total upper Mekong load and difference between Kratie and Pakse
approximate 3S load. The yearly cumulative loads are presented in Table 3 for the simulation period 1995 - 2000.

**Figure 13.** Location of the model timeserie points (Chiang Saen, Pakse, Kratie) used in simulating the sediment loads.
Table 3. Yearly sediment loads from different parts of the basin. No reservoirs included in the simulation. Calibration adjusted according to Wang et. al. 2009.

<table>
<thead>
<tr>
<th>Year</th>
<th>Total M tonnes</th>
<th>China M tonnes</th>
<th>3S M tonnes</th>
<th>Rest M tonnes</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>156</td>
<td>77</td>
<td>17</td>
<td>62</td>
</tr>
<tr>
<td>1991</td>
<td>159</td>
<td>89</td>
<td>14</td>
<td>57</td>
</tr>
<tr>
<td>1992</td>
<td>94</td>
<td>48</td>
<td>13</td>
<td>33</td>
</tr>
<tr>
<td>1993</td>
<td>133</td>
<td>80</td>
<td>11</td>
<td>42</td>
</tr>
<tr>
<td>1994</td>
<td>181</td>
<td>90</td>
<td>14</td>
<td>77</td>
</tr>
<tr>
<td>1995</td>
<td>176</td>
<td>96</td>
<td>14</td>
<td>65</td>
</tr>
<tr>
<td>1996</td>
<td>141</td>
<td>75</td>
<td>15</td>
<td>51</td>
</tr>
<tr>
<td>1997</td>
<td>190</td>
<td>102</td>
<td>13</td>
<td>74</td>
</tr>
<tr>
<td>1998</td>
<td>185</td>
<td>144</td>
<td>12</td>
<td>30</td>
</tr>
<tr>
<td>1999</td>
<td>207</td>
<td>124</td>
<td>18</td>
<td>65</td>
</tr>
<tr>
<td>2000</td>
<td>201</td>
<td>79</td>
<td>58</td>
<td>64</td>
</tr>
<tr>
<td>average</td>
<td>166</td>
<td>91</td>
<td>18</td>
<td>56</td>
</tr>
</tbody>
</table>

The total yearly Kratie load varies between 94 and 207 million tonnes/y. The average load is 166 million tonnes/y. This can be contrasted with the estimated value of 165 million tonnes/y. China variability is even higher - the annual loads range from 48 to 144 million tonnes/y. The average value is 91 million tonnes/y or 55% of the total upper Mekong load. This is very much in line with the estimated 90 million tonnes/y and 60%. 3S contribution is the same in the model and estimation.

Table reveals very large yearly sediment variability. The simulation period is too short compared to the very high variability to obtain reliable mean values and the model simulations should be repeated for a considerably longer period. Also the estimated average load can contain errors, and quite probably does. In any case the simulations provide useful insights for the sediment load behaviour.

It is interesting to contrast the contributions from different parts of the basin in the dry year 1998 and record wet year 2000. The dry and wet years are here defined in terms of the Kratie flow. For instance in 2000 the flow was average in the upper reaches of the Mekong. In the dry year overwhelming part of the sediment load, 78%, originated from China whereas in 2000 only 39%.

Carling (2010) assumes that 40% of the total Mekong load comes from the Central Highlands in Vietnam (3S). This is probably based on Clift et. al. (2004) geological study of the past 8 million year erosion of the Mekong basin (Figure 14). Clift's methodology is based marine sediment analysis. It is possible that model doesn't take sufficiently into account gorge incision driven by heavy precipitation and thus under-estimates the Central Highlands. Also the 5 km resolution of the model grid used in the simulations is a problem because it evens out slope gradients. On the other hand 40% seems too much in light of Figure 15 which shows the proportion of mountainous areas in different parts of the basin. In any case sediment monitoring needs to be based in the 3S basin to clarify the real sediment load and high resolution local erosion model needs to be set for the 3S.
Figure 14. Proportion of Central Highlands eroded sediments compared to the total Mekong erosion during the last 8 million years (upper pie-chart). (Clift et. al. 2004)
Figure 15. Location of the mountainous Central Highland areas in the 3S basin (circle). Yellow to red colour shows areas which are over 1 km high. MRC 2 km resolution IWRM-model.
4 SEDIMENTATION IN THE TONLE SAP SYSTEM

Sediments and nutrients bound to them are transported to the lower Mekong Basin. Part of the sediments end up enriching the floodplains and paddy fields providing basis for fisheries and agricultural productivity. Obtaining comprehensive picture of the sedimentation would require either considerable amount of observation data and/or detailed 2D or 3D model for the Cambodian and Vietnamese Delta. Proper modelling of the sediment fluxes is required for quantitative analysis and impact assessment. In addition to sediment processes sediment fluxes require modelling of the complex overland, floodplain and channel flow. At the moment such model exists only for the Tonle Sap and Plain of Reeds systems. Below results for the Tonle Sap are discussed as it is by far the most important fisheries area in the Mekong Basin.

4.1 NATURE OF THE TONLE SAP SUSPENDED SEDIMENTS

Figure 16 and Figure 17 show the measured suspended solids grain size distribution for undisturbed and sonicated samples obtained from the Tonle Sap river. Sonication breaks up sediment flocculates. The grain size distribution shows that the suspended sediments are mostly clay. The sediments are even finer in the Tonle Sap Lake. It should be noted that the samples are taken near the surface and near bottom there is much more suspended coarse bed material load. Also bed load may be quite significant in the Tonle Sap River.

Figure 16 Undisturbed grain size sample analysis from the Preak Leap site in the Tonle Sap River. WUP-FIN monitoring results analysed by the Canada Center for Inland Waters.
4.2 ESTIMATED TONLE SAP SEDIMENT LOAD FROM MEKONG AND TRIBUTARIES

The average annual suspended sediment flux into the Tonle Sap system from the Mekong and lake’s tributaries is around 5.1 million tonnes/y and 2.0 million tonnes/y, respectively. The annual outflow TSS flux from the lake back to Mekong is only 1.4 million tonnes/y. Thus, around 80% of the sediment the system receives from the Mekong River and tributaries is stored in the lake and its floodplain (Table 4). Here a year indicates a complete flood cycle starting on May.

Table 4. Annual TSS flux into and out from the lake system including the remaining amount of the sediment in the lake and floodplains.

<table>
<thead>
<tr>
<th></th>
<th>From Mekong</th>
<th>From tribs</th>
<th>To Mekong</th>
<th>Remaining</th>
</tr>
</thead>
<tbody>
<tr>
<td>1997</td>
<td>5.72</td>
<td>1.99</td>
<td>-1.22</td>
<td>6.49</td>
</tr>
<tr>
<td>1998</td>
<td>2.54</td>
<td>0.95</td>
<td>-0.79</td>
<td>2.70</td>
</tr>
<tr>
<td>1999</td>
<td>4.42</td>
<td>2.05</td>
<td>-1.49</td>
<td>4.98</td>
</tr>
<tr>
<td>2000</td>
<td>5.88</td>
<td>3.43</td>
<td>-1.82</td>
<td>7.49</td>
</tr>
<tr>
<td>2001</td>
<td>6.62</td>
<td>2.20</td>
<td>-1.67</td>
<td>7.15</td>
</tr>
<tr>
<td>2002</td>
<td>7.11</td>
<td>1.77</td>
<td>-1.61</td>
<td>7.27</td>
</tr>
<tr>
<td>2003</td>
<td>3.35</td>
<td>1.33</td>
<td>-1.08</td>
<td>3.60</td>
</tr>
<tr>
<td>Total</td>
<td>5.09</td>
<td>1.96</td>
<td>-1.38</td>
<td>5.67</td>
</tr>
</tbody>
</table>
The annual variation of the TSS flux into the lake is significant as it varies from 3.5 million tonnes/y (dry year 1998) to over 9 million tonnes/y (wet year 2000) as presented in Figure 11. The corresponding flood volumes are shown in figure Figure 12. Comparing figures it can be seen that sediment fluxes correlate closely to the flood volumes.

**Figure 18** Annual TSS flux into and out from the Tonle Sap Lake (1997-2003).

**Figure 19** Tonle Sap flood volumes in 1997 - 2003.
4.3 TSS CONCENTRATIONS IN LAKE AND FLOODPLAIN

Assuming that all the sediment remaining in the Tonle Sap system, i.e. 5.7 million tonnes/y (Table 4), would settle down to the permanent lake area of around 2500 km², it would mean a 0.00142 m (1.42 mm) thick layer of sediment (the density of the sediment is presumed to be 1600 kg/m³). If the sediment would settle down evenly to the entire floodplain and lake area of 13,000 km², the layer would be 0.27 mm thick. However, the sediment is not settled down evenly to the Tonle Sap system. Most of the sediment is trapped by the vegetation, including trees and scrubs, in the floodplain. This is illustrated by the Figure 20 which shows that TSS concentration is much lower in the floodplain than in the lake proper. The sedimentation occurs with the same rate both in the floodplain and the flooded forest, but there is much less resuspension in the floodplain due to the trapping effect of the vegetation. Vegetation also decreases considerably flow velocities and thus resuspension. The very high sediment concentration during the dry season, when the lake is very shallow, indicates active resuspension of the sediment in the dry season lake area. The lake proper area is shown in Figure 21 with blue color in and the floodplain with green color.

![Figure 20](image-url) TSS concentrations in open lake and flooded forest (Sarkkula et al. 2004). Data is compiled from WUP-FIN floodplain and lake measurements.
Figure 21. Tonle Sap lake proper (blue color) and surrounding floodplain (green color). Observe ring road around the floodplain.

The settling velocity has been impossible to determine exactly from the Tonle Sap water samples in laboratory, because velocity is very small. Both particle fall velocity equation and calibration of the settling velocity in the 3D flow and sediment model give about the same value 7 cm/d. In a laboratory setting sediment contained in Tonle Sap water settles down at an approximate rate of 1 m in 2 weeks, which also corresponds to the settling velocity from theoretical and model studies.

It is often claimed by local people and international organizations alike that the lake is rapidly filling up with sediment as a result of increasing sediment yields from the catchment. However, rapid rates of infilling often cited in the literature have not been demonstrated, and recent sedimentation studies using radioisotope dating (Figure 22) show that net sedimentation within the Tonle Sap Lake proper has been in the range of 0.1-0.16 mm/year since ca. 5500 years before present. Around 5500 years ago the current connection was created between the Mekong and Tonle Sap. The small sedimentation rate results to accumulation of only 0.5-0.7 m of sediment in the lake since the middle Holocene epoch.
Figure 22. Tonle Sap Lake sedimentation rate estimates based on core sample analyses. (Penny, 2002; Penny et al., 2005; Tsukawaki, 1997).

These data, and the model-based results (Sarkkula 2003), indicate that the rate of sediment accumulation within the lake is low and not accelerated with respect to the long-term sediment dynamics of the system. However, even though the overall net sedimentation within the Tonle Sap Lake is not threatening to fill up the lake, there can be local problems associated with high sedimentation and erosion rates. Most of the villages around the lake are located by the tributaries and the situation there is completely different from the average within the lake proper and calls for further investigations (Heinonen 2005). For instance settlements and fishing can be affected by high local sedimentation and erosion rates.

The model results show that most of the sediment settles down into the lake’s floodplain, Figure 24. This correlates well with the field data and core results made by Tsukawaki and Penny. The highest sedimentation rates are in Lake Chma, near river mouth and western part of the lake (Figure 23). Some places on the floodplain the simulated net sedimentation rates exceed 1.0 mm/a but in most places the rate is between 0.2 mm and 0.4 mm.

The above discussion applies to the lake proper (area of the dry season lake) conditions. However, around the Tonle Sap river and its vicinity there is large sedimentation of coarse material brought by the Tonle Sap river. This is probably largely flushed out when the flood reverses. Mostly the fine grained sediments enter into the lake and surrounding floodplains. The floodplains filter further coarse fractions.
Figure 23 Highest sedimentation areas.
Figure 24. Simulated net sedimentation in 1997 (top), 1998 (middle) and 2000 (bottom). Each year the simulation period is from May to end of April. 1200 - 1600 g/m² yearly sedimentation rate represents about 1 mm sediment depth increase. Observe low sedimentation in the lake proper due to high sediment resuspension during low water periods.
5 SEDIMENT TRAPPING BY THE HYDROPOWER DAMS

5.1 Mekong Hydropower Development

Figure 25 presents the existing and planned tributary and mainstream dams. In the mainstream dam scenario 10 mainstream dams below the China border were added to the China dams and the tributary dams. The included mainstream dams below China are:

- Pakbeng
- LBP
- Sayaburi
- Paklay
- Sanakham
- Pakchom
- Ban Koup
- Don Sa Hong
- Stungtreng
- Sambor.
5.2 DAM TRAPPING MODELLING

In the IWRM-model dam sediment trapping is calculated simply with the following methodology:

- reservoir net sediment settling rate is given separately for three sediment fractions (clay, silt and sand)
- reservoir sediment mass balance is formed based on sediment in- and out-flows and net sedimentation in the reservoir
- it is possible to give different trapping efficiency coefficient for each reservoir.

The approach requires knowledge about the net sedimentation rate for each reservoir. In the scenarios simulations it is assumed that the net sedimentation rate is the same as theoretical settling rate for each sediment fraction except for the mainstream dams below the Chinese border. Especially for the mainstream run-of-the-river dams net sedimentation rates need to be obtained either from detailed 3D
reservoir model applications, comparable existing dams and conditions or empirical/theoretical models. In this report a set of net sedimentation rates is examined.

Figure 26. Empirical Brune curve showing sediment trapping efficiency as a function of capacity-inflow ratio.

The model trapping has been compared with empirical results. Following table summarises comparison between empirical sediment trapping efficiencies by Brune (Figure 26) and model results. C:I is the ration between the reservoir volume (m$^3$) and annual cumulative flow (m$^3$).

<table>
<thead>
<tr>
<th></th>
<th>C:I 0.003</th>
<th>C:I 0.03</th>
<th>C:I 0.3</th>
<th>C:I 0.03 half depth</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bourne min</td>
<td>5%</td>
<td>60%</td>
<td>90%</td>
<td></td>
</tr>
<tr>
<td>Bourne max</td>
<td>35%</td>
<td>80%</td>
<td>100%</td>
<td></td>
</tr>
<tr>
<td>Clay</td>
<td>1%</td>
<td>11%</td>
<td>54%</td>
<td>25%</td>
</tr>
<tr>
<td>Silt</td>
<td>15%</td>
<td>60%</td>
<td>93%</td>
<td>99%</td>
</tr>
<tr>
<td>Sand</td>
<td>37%</td>
<td>93%</td>
<td>99%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Model results for silt and sand trapping efficiencies are rather well within the scope of the Brune curve. However the clay is trapped clearly less in the model than the range given by Brune. It should be noted that decreasing the reservoir depth (last column) clay sedimentation becomes much more efficient as has been also observed in practice: "shallow sediment-retention basins ... can operate much more efficiently than indicated by the [Brune] curve."
5.3 Modelled Chinese and Tributary Dam Sediment Trapping

The IWRM model has been preliminarily applied for the BDP scenarios. Only two scenarios were simulated: baseline and 20 year dams. The 20 year dams includes most probable future hydropower developments. China dams and tributary dams are included in the 20 year dam scenario. The mainstream dams below China are examined in the next chapter.

The impacts of the dams on sediment fluxes are illustrated in Figure 27 and Figure 28 for Kratie. The first figure shows daily variation of the sediment loads and the next one yearly total sediment loads. The yearly loads are also presented in Table 6. The average sediment load reduction is 46%. The largest reduction of 70% is in year 1998. This is also the year dry year when China contribution to the sediments is largest, 78% (Table 3).

**Figure 27.** Sediment load (g/s) in two scenarios: a) baseline (black line), b) 20 year dams with no mainstream dams (red line).
Figure 28. Yearly sediment loads (million tonnes/y) in two scenarios: a) baseline (black line), b) 20 year dams with no mainstream dams.
Table 6. Yearly sediment loads in Kratie in the baseline and 20 year China dams + tributaries scenarios.

<table>
<thead>
<tr>
<th>Year</th>
<th>Baseline</th>
<th>China+trib.</th>
<th>Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>1990</td>
<td>156</td>
<td>89</td>
<td>43%</td>
</tr>
<tr>
<td>1991</td>
<td>159</td>
<td>87</td>
<td>45%</td>
</tr>
<tr>
<td>1992</td>
<td>94</td>
<td>54</td>
<td>43%</td>
</tr>
<tr>
<td>1993</td>
<td>133</td>
<td>75</td>
<td>44%</td>
</tr>
<tr>
<td>1994</td>
<td>181</td>
<td>117</td>
<td>35%</td>
</tr>
<tr>
<td>1995</td>
<td>176</td>
<td>111</td>
<td>37%</td>
</tr>
<tr>
<td>1996</td>
<td>141</td>
<td>89</td>
<td>37%</td>
</tr>
<tr>
<td>1997</td>
<td>190</td>
<td>107</td>
<td>43%</td>
</tr>
<tr>
<td>1998</td>
<td>185</td>
<td>56</td>
<td>70%</td>
</tr>
<tr>
<td>1999</td>
<td>207</td>
<td>82</td>
<td>60%</td>
</tr>
<tr>
<td>2000</td>
<td>201</td>
<td>97</td>
<td>52%</td>
</tr>
<tr>
<td>Average</td>
<td>166</td>
<td>88</td>
<td>46%</td>
</tr>
</tbody>
</table>

According to the model results China dam cascade when finished traps 70% of the sediments (91 versus 28 million tonnes/y).

5.4 LOWER MEKONG MAINSTREAM DAM IMPACTS

The impact of lower mainstream dams is more difficult to judge as the net sedimentation rates and their time evolution are more difficult to estimate than in the case of the Chinese and tributary dams. Real sediment trapping efficiency should be studied with help of detailed 3D hydrodynamic and sediment models. Here only a range of possible impacts can be given.

Figure 29 presents average sediment load reductions for different lower mainstream dam trapping efficiencies. The efficiencies are percentages of the of the theoretical maximal values. When lower mainstream trapping efficiency is 0 only Chinese and tributary dams retain sediments. Sediment load reduction increases first sharply with small mainstream net trapping efficiency increase. After about 10% the load reductions don't increase as drastically. A saturation point is reached around 40%. After that about 90% of the Mekong sediments will be trapped by the dams.

It is expected that with time the mainstream reservoirs obtain an equilibrium state when average net sedimentation and erosion are in balance and average dam trapping is 0. The time scales for obtaining the equilibrium are difficult to assess without more detailed reservoir modelling. Even with sedimentation and erosion in balance it can be expected that sediment management, especially sediment flushing, will provide short sediment pulses instead of more constant natural sediment load and probably has consequences to the downstream agricultural and fisheries productivity. The high sediment concentrations can be harmful for fish and benthic fauna and other organisms.
Figure 29. Modelled impact of different lower mainstream dam trapping efficiencies on sediment loads. The trapping efficiencies are percentages of the theoretical maximal values.

Kummu et. al. (2010) provide a method for estimating probable reservoir trapping efficiency based on ratio of reservoir storage capacity and annual inflow. They have categorized the Mekong reservoirs and provide trapping efficiency envelope curves for them (Figure 30). It is an obvious step to use these values for the IWRM-model. The mainstream dam trapping efficiencies vary between 10% and 60%.
5.5 **Estimated Sediment Trapping**

Kummu et al. (2010) developed a method to calculate the basin-wide trapping efficiency (TE) of the reservoirs along the mainstream based on Brune’s method. This was then used to estimate the basin-wide TE of the existing and planned reservoirs.

**Existing reservoirs.** The existing reservoirs in the Mekong, and particularly those in the Lancang part of the basin, have already a significant impact on the sediment fluxes. The planned reservoirs would have potential to significantly increase this impact. The existing dams in basin have the potential to trap annually 34 - 43 million tonnes of sediment. The existing reservoirs have a basin TE of 15 - 18%.

**Future reservoirs.** Should all the planned dams be built in the sub-basins, the amount of trapped sediment would have the potential to reach 89 - 94 million tonnes/y of the total basin sediment load (SL) of 140 Mt/yr in Khong Chiam. Should all the planned reservoirs be built, this would increase to 51% - 69% (Figure 31).

**Time evolution.** Also the time evolution of the TE was studied. The following times were studied: existing reservoirs, year 2012, 2015, 2018, 2022 and all existing and planned reservoirs. The results are presented in Figure 31. There is not much change in TE from the existing reservoirs to the year 2012 but rather significant change from year 2012 to year 2015, when the largest reservoirs in the Lancang
are projected to be in operation. From 2015 to 2018 there is large increase
particularly in upper parts of the LMB. Year 2022 situation is rather similar
compared to all the reservoirs.

**Yunnan cascade.** The existing and planned mainstream dams in the Chinese part
of the river have the largest impact on the sediment load as approximately 50 -
60% of the basin sediment load originates from this stretch of the river. The three
existing reservoirs in that part of the basin have potential to trap annually
approximately 32 - 41 million tonnes of sediment. If the entire cascade of eight
dams were constructed, the TE would increase to 78% - 81% and potentially to 70
- 73 million tonnes/y, or more than 50% of the total basin sediment load would be
trapped annually.

The specific sediment yield (SSY) in the Lancang sub-basin is around three to four
times as high as the average SSY of the analysed sub-basins. Consequently, the
Lancang reservoirs have the potential to trap much more sediment than other
reservoirs with the same potential. Accordingly, even though the active storage
capacity of the Lancang reservoirs is only 24% of the existing and planned sub-
basin storage capacity, they have the potential to trap 78% of the estimated total
trapped sediments.

Because of this high heterogeneity of the sediment loads per unit area between
the sub-basins, the trapped SL percentage should be used for the calculations
whenever possible. The trapped sediment load (SL) calculations for the upper half
of the basin confirmed that there is a significant difference between the basin TE
and the total sediment trapped. At this stage, it was not possible to calculate the
trapped SL for the whole basin due to the limitations in the observed sediment
data. According to the preliminary estimations, the basin wide trapped SL for the
case when all the existing and planned dams are realised, would be closer to 90%
instead of the estimated 50% - 69% by using the basin TE protocol.

These estimates for sediment trapping, either 50% - 69% or even 90 %, can be
compared to the modeled values although the scenario definitions are not the
same in them. The modeled values range between 46 % to 90 % depending on the
efficiency of the lower mainstream dam sediment trapping. Thus they are in line
with the estimated trapping values.
Figure 31. The temporal development of the basin trapping efficiency for each of the existing and planned mainstream dam locations (some of those are named in the graph) and basin outlet ($A = 816,000 \text{ km}^2$). See Figure 1 for the location of the mainstream dams. (Kummu et. al. 2010)

5.6 CHINESE EXPERIENCES ON SEDIMENT TRAPPING

Major rivers with high sediment or water discharge act as natural integrators of surficial processes, including human activities within their drainage basins, and they are also the primary sources of terrestrial materials entering the oceans. The river-derived material flux has a tremendous effect on the wetlands, estuaries and coastal seas. This flux has been strongly affected by anthropogenic activities. There are numerous recent publications and reports on human impacts on river sediment flux. Chinese scientists have reported on the quantitative changes human activities have caused to the sediment flux from the major Chinese rivers

---

47
entering the western Pacific Ocean, including Yangtze, Yellow, Pearl, Songhuajiang, Liaohe, Haihe, Huaihe, Quintangjiang and Minjiang.

The total amount of the sediment flux from the above Chinese rivers has decreased from about 2000 million tonnes per year in the 1960ies to the present ca. 400 million tonnes per year, based on data during 2000-2007 (Figure 32). This massive reduction (80%) has taken place in a time when the total water discharge has stayed relatively stable. The main reason for the total sediment load reduction has been the trapping of sediments by dams and reservoirs (56%). Other reasons for the reduction have been soil and water conservation (23%), water consumption (15%) and in-channel sand mining (3%).

**Figure 32.** Temporal variations in total water and sediment flux into the ocean from nine major Chinese rivers in the past five decades. (Chu et. al. 2009)

Key references on the China rivers sediment loads are:


5.7 MORPHOLOGICAL IMPACTS OF SEDIMENT TRAPPING

This chapter focuses on morphological changes. The next chapter discusses the fine sediments, sediment bound nutrients and their environmental impacts.

Carling (2010) discusses the hydropower dam sediment trapping morphological impacts. He is mainly focusing on long term (>20 years) changes of the river channels and floodplains. They are connected to bed erosion, bank erosion, mainstream dams, deep pools, sandbars, floodplains and Cambodian and Delta river channels. In Delta "channel changes ... might affect the distribution of flows in the distributaries; notably affecting the balance between the Bassac and the Mekong discharge and channel regimens." This would have implications for navigation, aquaculture, irrigation, water quality, coastal fisheries, habitats etc.

Carling discusses the potentially very important coastal impacts: "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." Because of large data gaps especially in the Delta sediment processes, Carling states: "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." and "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."

River bank erosion will increase due to increased water level fluctuations. The wetting and drying of river banks and changing ground water levels will stress the banks and lead to increased erosion. The magnitude of fluctuations can be even 18 m as the Nam Theun 2 water level monitoring shows.

In addition to the river system sediment trapping naturally impacts the reservoirs themselves. For example, Manwan Dam has lost about 22% of the total storage capacity due to sedimentation during over its 11 first years of operation (Fu et. al. 2008). The Ubon Ratana Dam in Khon Kaen, is estimated to be almost 100 % efficient in sediment load capture and settles out also very fine particles (Mekong Committee, 1979). Naturally the reservoir sedimentation has great impact on the reservoir economic feasibility. Because of this reservoir sedimentation, sediment management and long-term dam impacts should be well understood before commissioning of any new dams. It would be most unfortunate that economically unviable projects would be commissioned in itself, but even more so if they would cause long-term irreparable damages to the environment and people’s livelihoods.
6 MAIN CONCLUSIONS ABOUT SEDIMENT TRAPPING AND MORPHOLOGICAL CHANGES

- Dam sediment trapping will decrease sediment input to the Cambodian and Vietnamese Delta around 50%, and possibly even 90% if mainstream dams are implemented.

- Although morphological changes linked to coarser sediments take time to be realised downstream, the fine suspended sediment impacts can be seen immediately.

- Downstream sediment load is quite sensitive to mainstream dam sediment trapping: only 5% mainstream dam efficiency compared to the maximal theoretical trapping causes trapped sediment to increase from 50% to 70%.

- In the long term river channels will suffer increased erosion and morphological changes due to trapping of coarser sediments and decreased bedload; the time scales or impact magnitude are difficult to estimate; more research is needed on this issue.

- In the Delta channel changes might affect distribution of flows the distributaries; this would have implications for navigation, aquaculture, irrigation, water quality, coastal fisheries, habitats etc.

- Coastal erosion will increase because sediment input to the coast will decrease; estimation of the magnitude of the impact requires further research.

- Delta has been formed quite fast in geological terms, this indicates possibility of relatively fast morphological changes in the Delta.

- There are no plausible compensation mechanisms for decreasing sediment input to the system; especially river bottom coarse sediments (sand and gravel) can't compensate for finer suspended sediments.

- Reservoir sedimentation has large consequences both in terms of impacts, reservoir economics (decrease of storage volume) and reservoir fish production; because of the large unknowns reservoir sediment modelling is needed.

- Reservoir sediment management (sediment flushing) will probably result in high sediment pulses that can be harmful to organisms and will have different impact downstream productivity than more even sediment input.

- Large water level fluctuations will stress river banks through wetting and drying and ground water level changes causing increased bank erosion.

The nutrient, productivity and socio-economic consequences of the hydropower sediment trapping are discussed in the DMS Productivity and Socio Economics reports.
7 KNOWLEDGE GAPS AND ADDITIONAL CONSIDERATIONS

The knowledge gaps related to sediments can be summarised as:

- Delta processes are poorly understood; there is need for systematic and comprehensive modelling and monitoring effort.
- Coastal areas need to be modelled for erosion, water quality and productivity.
- Detailed reservoir modelling is required for impact analysis, economic evaluation, fisheries production, guidance for sediment management, multi-purpose optimal operation etc.
- Sediment sources, especially the 3S, need to be verified.
- Sediment nutrient sources and fates need to be clarified with field studies and modelling.
- Suspended and bed load grain size changes need to be monitored and modelled.
- Long-term river morphological changes need to be estimated and modelled.
- Linkage between socio-economic analysis and modelling need to be strengthened.
- Economics of hydropower development require comprehensive and critical approach.

Nutrient and productivity related issues and knowledge gaps are discussed in detail in the DMS productivity report.
REFERENCES


