MRC Information & Knowledge Information Program (IKMP) & World Wide Fund for Nature (WWF)

SUMMARY REPORT of DECISION SUPPORT FOR GENERATING SUSTAINABLE HYDROPOWER IN THE MEKONG BASIN

Knowledge of sediment transport and discharges in relation to fluvial geomorphology for assessing the impact of large-scale hydropower projects

Draft 2, 14 November 2014
## Abbreviations and Acronyms

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<tr>
<td>ADCP</td>
<td>Acoustic Doppler Current Profiler</td>
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<tr>
<td>AFD</td>
<td>French Agency for Development</td>
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<tr>
<td>BTR</td>
<td>Bedload Transport Rate</td>
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<tr>
<td>CM diagram</td>
<td>Method used to interpret transport mode of sediments prior to deposition</td>
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<tr>
<td>DSMP</td>
<td>Discharge Sediment Monitoring Project</td>
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<tr>
<td>GIZ</td>
<td>Technical Cooperation of the Government of Germany</td>
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<tr>
<td>GS</td>
<td>Graded suspension (mode of sediment transport)</td>
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<td>GW</td>
<td>Gigawatt</td>
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<td>IKMP</td>
<td>Information and Knowledge Management Programme (of the MRC)</td>
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<td>French Global Environment Facility</td>
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<td>LMB</td>
<td>Lower Mekong Basin</td>
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<td>MRC</td>
<td>Mekong River Commission</td>
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<tr>
<td>SPM</td>
<td>Suspended articulate Matter</td>
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<td>UMB</td>
<td>Upper Mekong Basin</td>
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<td>WWF</td>
<td>World Wide Fund for Nature</td>
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Executive Summary

This report summarises sediment and geomorphic investigations completed by the Mekong River Commission (MRC), World Wildlife Fund (WWF) and associated organisations between 2009 and 2014. Funding for the majority of the research was generously provided by the Government of Finland and the French Global Environment Facility (FFEM), administered through the French Agency for Development (AFD). Additional assistance has been provided by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

The main investigations included:

- On-going suspended and bedload monitoring in the LMB and data analysis and interpretation of the results;
- An investigation into the distribution of sand in the Mekong channel and the transport mechanisms under which it was deposited and how these relate to the stream energy of the river;
- An quantitative survey of the volumes of aggregate extracted from the Mekong River, and the locations, longevity and trends within the industry;
- An examination of the morphological changes in the main channels in the delta between 1998 and 2008 to quantify changes in bed level and channel morphology;
- An analysis of changes to the delta front between 2003 and 2011 based on satellite imagery and field investigations; and,
- An analysis of temporal and spatial trends in the composition and distribution of the Mekong River plume in coastal waters.

The research investment was enhanced by piggy-backing additional, smaller research projects onto these investigations. Additional work included the *in situ* determination of suspended sediment particle size in the LMB, and modelling of potential bedload transport rates at a sub-set of the DSMP monitoring sites.

Overwhelmingly, the investigations have documented a river in the process of undergoing substantial changes with respect to sediment transport and sediment dynamics. Major findings include:

- The suspended sediment load of the river is presently estimated at ~72 Mt/yr compared to previous estimates of up to 160 Mt/yr. The large decrease is presumably attributable to the capture of sediment in the Lancang Cascade hydropower project and in other tributary dams;
- Sand comprises up to 20% of the suspended load of the river at (Kratie) and is transported as bedload, and as suspended load during periods of high flow. Much of the previously described imbalances in the sediment budget of the Mekong may be attributable to sand being transported via different mechanisms in different reaches of the river;
- Aggregate extraction in the LMB exceeded 50 Mt in the LMB in 2011/2012 with 90% of the extracted material consisting of sand, and over 80% of the extractions occurring in Cambodia and Vietnam. The magnitude of sand extractions in 2011 exceeded the estimated amount of sand being transported in the river in suspension and bedload by ~25Mt;
- The Mekong and Bassac channels in the delta have deepened considerably in the 1998-2008, with a net loss of ~200,000 m³ of material. The channel changes do not
correlate with channel hydraulics, and the results strongly suggest the channel deepening is related to sand mining and associated readjustment of the channel;

- The delta coast line has undergone extensive change between 2003 and 2011. Near the eastern river mouths, there has been net aggradation which is attributed to a reworking of coastal deposits under a regime of decreasing sediments. In the muddy southwestern sector of the delta erosion rates of -12 m/yr have been recorded. These rates need to be considered within the geomorphic history of this part of the delta, where accretion rates in excess of 20 m/yr have been documented in the recent geologic past. The southern Gulf of Thailand coastline has recorded erosion rates of -4 m/yr, while the northern coast line has shown fewer changes, with ~60% of the northern coast not recording any significant change over the study period;

- The concentrations and composition of the plume emanating from the Mekong is showing strong evidence of change, with Suspended Particulate Matter, turbidity and nutrient indicators showing decreasing trends. A long term trend of ~5% SPM concentration per year is observed in the pro-delta area and is attributed to the decrease of the Mekong river sediment output during the high flow season.

The decrease in sediment loads captured by each of these investigations is linked to a number of inter-related processes, including:

- Dam developments in the UMB (Lancang Cascade) trapping large volumes of sediment;
- Aggregate extraction for construction;
- Channel deepening directly and indirectly related to aggregate extractions which alters water levels and can increase water velocity and hence scour;
- Altered channel dynamics which affect the distribution of fine-sediment deposition and alter the salt water incursion patterns.

Collectively, the investigations show the Mekong is in a state of rapid change, and it is highly likely the present flow of the Mekong is not in a dynamic equilibrium with the sediment supply to the river. On-going adjustments to the decreasing sediment supply are likely to include bank erosion, bed incision and changes to the pattern and quantity of sediment delivered to the delta and the sea.

Future developments need to be considered within the context of this rapidly changing river, and a more robust understanding of sediments and sediment processes in the mainstream, tributaries, delta and coastal areas is needed.
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1 Introduction

This report summarises sediment and geomorphic investigations completed by the Mekong River Commission (MRC), World Wildlife Fund (WWF) and associated organisations between 2009 and 2014. Funding for the majority of the research was generously provided by the Government of Finland and the French Global Environment Facility (FFEM), administered through the French Agency for Development (AFD). Additional assistance has been provided by the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ).

In addition to the ‘core’ MRC and WWF investigations, the cooperative projects have provided a platform which has allowed the implementation and completion of additional investigations, thus enhancing and maximising the outcome and investment. The hydrological, sedimentological and geomorphic information which is now available will also provide the basis and input for many on-going and future research projects, investigations and management activities.

The summary presented in this report provides a synopsis of the present understanding of sediment and geomorphic processes in the Lower Mekong Basin (LMB), insights into the activities which are affecting sediment movement in the river, and how these activities are affecting sediment and geomorphic processes. Details about the investigations and additional interpretation of results can be found in the original reports (available from the responsible entity) and published papers by the original researchers.

1.1 Background to Investigations

1.1.1 Overview
The water resources of the Mekong River fuel the lives and economies of Southeast Asia. The monsoonal pattern of the region drives the flow regime and creates the unique hydrologic characteristics of the river: the annual wet and dry seasons which are well defined by the rapid rise and fall of the river, the reversal of the Tonle Sap system, the distribution and timing of tributary inflows and the movement of water on to and off of floodplains in the lower catchment. The monsoons and associated flow patterns also drive the delivery of sediments to the river, and transport of the material through the system. This interaction between sediments and the flow regime dictates the physical form of the river, creating the ‘skeleton’ of the channel, banks and flood plains.

The amount of sediment delivered to the Mekong is controlled by tributary flows and catchment characteristics and activities. Once in the river, sediment size dictates the rate and method of transport through the system. Very fine material is rarely deposited once it is suspended, and is generally carried through the system and into the sea where its nutrient content underpins marine ecosystems and commercial fisheries. Slightly coarser material may end up on flood plains and river banks where it serves to fertilise river bank gardens and floodplain farms.

Sands and gravels may take years to decades or longer to be transported through the system, being temporarily stored in the channel or on river banks or bars where it creates stable and resilient channels and river forms, providing important ecological habitats. Sand sized material is also critical for maintaining the stability of the Mekong River channels in the lower river and delta. The physical form of the river in conjunction with the river flow and tides controls the movement and distribution of fresh and saline waters in the area.
The physical attributes of the Mekong have been exploited to varying degrees through the catchment. The river provides drinking water, agricultural and irrigation supply and recharge for ground water aquifers. Waterways form the 'highways' and provide a means of transportation and communication in much of the basin. The flow patterns and materials in the river create a rich-mosaic of river forms and habitats which underpin the ecological diversity and high biological productivity of the system, upon which millions depend for protein, other food and livelihoods.

In the Upper Mekong Basin (UMB), upstream of the Chinese borderer, the mainstream has been harnessed through the development of a cascade of hydropower stations, which provide approximately 15 GW of power each year (Magee, 2012). Hydropower has also been developed in the tributaries in the Lower Mekong Basin (LMB), and a large number of additional hydropower developments are in various stages of development in both the LMB mainstream, and tributaries.

The sands, gravels and pebbles in the river are extracted and used for land filling and construction materials locally, and also provide the basis for an export industry.

Recognising that the present and planned development activities in the Mekong have the potential to alter the hydrological, physical and ecological attributes of the river, which in turn could have economic and social impacts, the Information Knowledge Management Programme (IKMP) of the MRC in cooperation with a variety of other organisations have completed a range of hydrological sediment and geomorphic investigations to better document and understand the processes operating in the catchment, and how these are being altered by present activities, and may be altered under future development scenarios.

Many of the results summarised in this report arise from investigations completed under a project entitled *Decision support system for generating sustainable hydropower in the Mekong Basin* with the explanatory sub-title *Knowledge of sedimentary discharges and flows in relation to fluvial geomorphology for detecting the impact of large-scale hydropower projects*, which was initiated in 2009 and involved funding and assistance from FFEM, AFD, and Finland. Although the title focusses on hydropower, the information gained through the investigations is relevant to a range of development and water management activities, and this report aims to provide an overview of the sediment and geomorphic processes operating in the Mekong rather than focussing exclusively on issues associated exclusively with hydropower.

### 1.2 Physical features of the LMB relevant to sediment investigations

This section presents a brief description of the geological and geomorphic attributes of the Mekong River. It is not intended to be an exhaustive review of background information, and other sources such as Campbell (2009) or other references in the text should be consulted for detail. The aim of the following summary is to provide a broad context within which the results of the sediment and geomorphological investigations can be presented and interpreted.

The geology of the LMB (Figure 9) is complex, but the course of the mainstream Mekong is largely confined and defined by Mesozoic sedimentary rocks, with intrusive and extrusive igneous units underlying highland areas. The Tibetan Plateau is comprised of Metazoic sedimentary rocks, with the middle reaches of the Mekong contain Palaeozoic and Mesozoic sedimentary rocks, and resistant intrusive igneous rocks (Lui et al., 2005). The lower reaches are characterised by extensive alluvial plains, with Mesozoic sedimentary rocks, and exposed igneous extrusive rocks (Lui et al, 2005).
The Mekong River Basin has been classified into seven broad physiographic regions or geomorphic provinces, including the Tibetan Plateau, Three Rivers Area and Lancang Basin, which form the Upper Mekong Basin, and the Northern Highlands, Khorat Plateau, Tonle Sap Basin and Mekong Delta which comprise the Lower Mekong Basin. These regions vary with respect to geologic and geomorphic characteristics, which directly affect sediment availability and transport.

The mainstream river channel in the UMB and the LMB between the Chinese border and near Vientiane is largely bedrock controlled (Figure 10), with varying levels of alluvial infill. Another extended reach of bedrock control occurs in the mid-LMB, where the river cuts through the Mesozoic sedimentary rocks. Alluvial reaches are limited to river reaches between Vientiane and Mukdahan/Savannakhet, and downstream of Kratie where the river emerges into the extensive Cambodian floodplain and Mekong River delta. The remaining reach, between the lower bedrock reach and the delta region contains a mix of alluvial and bedrock control.

The distribution of bedrock and alluvial control of the Mekong mainstream is important for understanding how the river will respond to potential flow or sediment changes in the future. Where the river channel is confined by bedrock, potential channel modifications are typically restricted to modifications of the inset sediment deposits (and associated vegetation), but the channel would be resistant to widening or deepening due to the presence of bedrock. Potential responses might include channel constriction if flood frequency is reduced (but no change to sediment supply) due to increased deposition, or removal of existing sedimentary deposits if sediment supply is reduced with no change to the flow regime. Although the channel dimensions may not be highly altered, changes to the distribution and characteristic of inset sediment deposits would affect the distribution and quality of ecological habitats. Similarly, in the multi-channel sectors of the river (eg. from Sankham to upstream of Vientiane, Sipandone and Stung Treng to Kratie) a reduction in coarse sediment supply would affect aquatic habitat and could have flow on effects for the associated fisheries and biodiversity of the region.

The alluvial reaches of the Mekong, between Vientiane and Mukdahan or downstream of Kratie have the potential to respond to hydrological or sediment budget changes through channel widening, bed incision, or channel contraction or bed aggradation. The predominance of bedrock controlled reaches in the upper LMB could result in a situation where flow or sediment changes in the UMB or upper UMB might lead to relatively minor changes locally, but induce larger scale responses downstream in the alluvial reaches.
Figure 9 – Left: Schematic geological map of the SE Asia continent Modified after Commission for the Geological Map of the World (Liu et al., 2005); Right: Physiographic provinces of the Mekong River Basin (MRC, 2010)
Figure 1.1. (left) Distribution of bedrock and alluvial reaches in the LMB. MRC (2010)

Figure 1.2. (right) Potential sediment production in the LMB based on GIS analysis using land cover, Watershed Classification and runoff (Koehnken, in Vogel, 2013).

The geology, rainfall patterns and intensity, and land use in each geomorphic province will govern the sediment contribution from the region. The MRC has recently investigated potential sediment contributions from sub-catchments using GIS layers of landscape attributes (elevation, relief, soils, Watershed Classification, Land Use) to estimate relative sediment contributions in the basin (Koehnken, 2012a). The modelled potential sediment production map (Vogel, 2013, Figure 1.2) shows that the northern highland geomorphic province in Lao PDR, and the mountains along the eastern boundary of the LMB are the largest potential contributors per unit area.

The presence and maintenance of deep pools in the Mekong mainstream in both the alluvial and bedrock reaches are important characteristics with respect to geomorphology and sediment transport. The pools are located in areas subject to high stream energy during high flows related to local hydraulic controls. The persistence of these deep pools or channels through the dry season indicates that scour and erosion during the wet season exceeds sediment deposition during the end of the wet season in the pools. The pools are also important in that they have been found to provide refuges and migration links for a number of important fish species (Poulsen and Valbo-Jorgensen, 2001; MRC, 2006).
2 Historical sediment information

Historically, sediment measurements in the Mekong have been limited to suspended sediment samples which have been made intermittently in the Mekong between 1960 to the mid-2000s as summarised in Table 2 (MRC data, Walling, 2005). Walling (2005) evaluated available monitoring results and identified 5 sites which he considered to have reliable results based on the number of available results for each monitoring year (n>20 or if total results for 2 successive years >20), and the statistical fit of a power curve to produce a sediment rating graph ($r^2>0.5$). The sites included in Walling’s analysis were: Chiang Saen, Luang Prabang, Nong Khai, Mukdahan and Pakse.

A mean annual total suspended sediment load from the river of 160 Mt/yr was frequently cited in the 1980s and 1990s based on the available historic sediment results. A sediment load of 80-100 Mt per year was attributed to the Upper Mekong basin which contributes less than 20% of the natural flow inputs (Walling, 2005, 2008). Analyses of sediment results pre- and post-dam construction in China have found varying impacts. Walling (2005) found no clear evidence of a reduction in sediment load at sites within the LMB following dam construction based on an analysis of results from 1960 to 2002, although the representativeness of some of the results was questioned as they were based on grab-samples collected at a low sampling frequency. In contrast, Lu and Siew (2005) found significant decreases in sediment load at the most upstream LMB monitoring site (Chiang Saen) in 1992 following filling of the Manwan Dam, but no statistical decline at sites located farther downstream.

The lack of reliable sediment transport measurements has led to indirect methods of sediment transport being used to estimate loads and evaluate the impact of dams on the mainstream in the UMB on sediment supply between 1962 and 2003 (Wang et al. 2009). The investigators found that the mean annual sediment in the Mekong probably increased during the period of dam construction (1986 – 1992) and decreased following initiation of dam operation (1993–2003) at Chiang Saen, although other catchment activities cannot be ruled out as contributing to these changes.

These uncertainties highlighted the need to improve knowledge regarding sediment information in the LMB.
Table 1 – Historic Suspended Sediment Concentration Data Held by MRC

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<th>Station Code</th>
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### Summary of IKMP & WWF Sediment Investigations

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2.1 Overview of investigations

The investigations completed by the MRC and associated organisation can be divided into four broad categories:

- The development and implementation of an LMB-wide system for measuring discharge and sediment transport and characterizing materials from the river bed in the mainstream;
- Understanding the relationship between flow, sediment transport and geomorphic characteristics of the river;
- Quantifying the scale of aggregate extraction in the LMB;
- Understanding the geomorphological stability of the delta and sediment distribution processes in the coast zone;

The first objective, development and implementation of a systematic project for measuring discharge and sediment transport has been designed, managed and implemented by the MRC and Member Countries and line agencies through the Discharge Sediment Monitoring Project (DSMP). The other areas of research were undertaken and managed by WWF.

A summary of the individual investigations synthesised in this report are shown in Table 2.
Table 2. Summary of sediment and geomorphology related research conducted by the IKMP -MRC and associated organisations, and references for reports and published papers

<table>
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<td>Sediment transport and geomorphologic characteristics of the river</td>
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<td>Prof Jean-Paul Bravard</td>
<td>Bravard, JP, Goichot, M, 2013a, Knowledge of sediment transport and discharges in relation to fluvial geomorphology for assessing the impact of large-scale hydropower projects</td>
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<td>Bravard, J-P, Goichot, M, Tronchère, 2013b, An assessment of sediment processes in the Lower Mekong River based on deposit grain-sizes, the CM technique, and flow-energy data, Geomorphology, <a href="http://dx.doi.org/10.1016/j.geomorph.2013.11.004">http://dx.doi.org/10.1016/j.geomorph.2013.11.004</a></td>
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<td>The scale of aggregate extraction in the LMB</td>
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## Summary of IKMP & WWF Sediment Investigations

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### Related Sediment Investigations

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3 Summary of MRC IKMP Discharge and Sediment Monitoring Project

3.1 Background
Systematic monitoring of the water resources of the Mekong River extends back many decades at some locations, providing long-term rainfall, river level and river discharge records for the basin. Sediment monitoring, however, has been much more sporadic in the catchment, with no long-term continuous records available. Part of the reason for this is the difficulty associated with the collection of accurate sediment samples due to the different modes of sediment transport in a river, and the spatial and temporal variability of sediment concentrations.

Sediment size and the flow regime dictate the method and rate at which sediment is transported through a river. The total sediment load of a river is divided between the suspended load, or wash load which is carried in the water column of the river, and bedload, which rolls or jumps along the bed. Whether material is transported in suspension, as bedload, or remains stationary in the channel is dictated by the flow regime, with sediment transport varying as the flow varies. The same grain-size may be transported in suspension, as bedload, or be deposited as flow rates decrease in a river, and go through the reverse sequence as water velocity again increases.

Due to the heterogeneity of flow in a river cross-section, the collection of accurate suspended sediment samples requires the collection of depth ‐ integrated, flow‐proportional samples across the river cross-section. Similarly, the collection of accurate bedload measurements requires samplers which can be reliably deployed on the river bed for sufficient periods to collect the material rolling or jumping past. To obtain an accurate picture of sediment movement in a river requires the collection of both of these sediment components, over a range of discharge rates and seasons.

The historical sediment monitoring results held by the MRC are limited to suspended sediment measurements (Table 1), which were collected using the best depth‐integrating equipment available at the time. Unfortunately, the depth and flow conditions in the Mekong River frequently exceed the operational limits of these early samplers, raising questions about the accuracy of these historic results. Historical bedload measurements are not available for the Mekong.

Recognising the need for accurate sediment transport information, the MRC through the IKMP initiated the Discharge and Sediment Monitoring Project (DSMP), which had the objective to provide the Member Countries with the equipment and skill set required to obtain high quality suspended and bedload sediment measurements at a sampling frequency adequate to understand sediment transport in the Mekong at a catchment scale, over time-scales relevant to the development and management of water resources.

In addition to quantifying the mass of sediment moving through the mainstream Mekong, it was recognised that understanding the grain-size characteristics of the sediment was also important.

3.2 Description of DSMP
The blueprint for the DSMP was developed by Conlan (2009), based on international best practice techniques for sediment transport measurement. Sediment monitoring sites for inclusion in the DSMP were selected based on the location of existing hydrologic monitoring sites, combined with the availability of historic information, and hydrologic and ecological importance. The DSMP monitoring locations are shown in Figure 3.1, with an enlargement
of the Chaktomuk confluence at Phnom Penh shown in Figure 3.2. Catchment areas are summarised in Table 3, with the parameters monitored at each site shown in Table 4.

The original design of the DSMP included the following components:

- Recording of water level at gauging sites on a daily basis;
- Discharge measurement using either an Acoustic Doppler Current Profiler (ADCP) or a current meter collected on a weekly, biweekly or monthly basis depending on flow rate;
- Collection of a depth integrated suspended sediment sample at each monitoring site using the Equal Discharge Increment approach;
- At a subset of sites on a subset of discharge and suspended sediment monitoring days, large volume depth integrated water samples are collected for the subsequent determination of particle grain size;
- At a subset of sites on a subset of monitoring days, bedload samples are collected at 5 to 10 points across the transect; and,
- Surveying of channel cross-section on a twice per year basis (wet season, dry season).

At the delta monitoring sites, where flow is bi-directional due to the influence of the tide, DSMP monitoring consists of the following:

- Hourly measurement of current velocity at 6 depths at a reference vertical;
- Conversion of current velocity to discharge using the established relationship between the reference vertical and cross-sectional discharge (calibrated several times per year using ADCP);
- Daily measurement of depth integrated suspended sediment at the reference vertical;
- Surveying of channel cross-section on a twice per year basis (wet season, dry season)

The DSMP was initiated in 2009, but due to time-lags associated with the procurement of equipment and training, monitoring at some sites did not commence until 2011.
Figure 3.1. DSMP monitoring locations in the Lower Mekong Basin (LMB). Monitoring of the Sekong River upstream of Mekong River at bridge was included in the DSMP in 2012-2013.
**Figure 3.2.** Confluence of the Mekong River with the Tonle Sap and Bassac Rivers showing DSMP monitoring locations.

**Table 3.** Summary of DSMP sediment monitoring locations, sub-catchment area entering between monitoring sites and accumulated catchment area upstream of monitoring site.

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Summary of IKMP & WWF Sediment Investigations

Table 4. Summary of DSMP monitoring design. SSC = Depth Integrated Suspended Sediment measurement (Suspended sediment concentration), SGSA = Sediment Grain Size Analysis.

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<td>Viet Nam</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
<tr>
<td>3S as Sekong Bridge</td>
<td>Cambodia (2012-13 only)</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td></td>
</tr>
</tbody>
</table>

*Country that reports the results to the IKMP. Sites located along the border of Thailand and Lao PDR are monitored cooperatively with Thailand responsible for processing the samples and reporting results.

Monitoring frequency under the DSMP is variable through the year, with four samples per month collected during the peak wet season (July – October), and two samples per month for the remainder of the year. The sediment grain-size analyses and bedload samples are also collected more frequently during the wet season (Table 5).

Table 5. Summary of monitoring frequency for discharge, suspended sediment (SSC), sediment grain-size (SGSA) and bedload sampling.

<table>
<thead>
<tr>
<th></th>
<th>Jan</th>
<th>Feb</th>
<th>Mar</th>
<th>Apr</th>
<th>May</th>
<th>Jun</th>
<th>Jul</th>
<th>Aug</th>
<th>Sep</th>
<th>Oct</th>
<th>Nov</th>
<th>Dec</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>SSC Discharge</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>34</td>
</tr>
<tr>
<td>SGSA Bedload</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>17</td>
</tr>
</tbody>
</table>

3.2.1 Limitations of the data set

The DSMP monitoring is completed by line agencies in each of the MRC Member Countries and reported to the IKMP on a semi-annual or annual basis. The monitoring is conducted across the four Member Countries by 10 hydrological teams, using different types of equipment. As in any large scale monitoring campaign, there are gaps and limitations in the resultant data set which need to be recognised. Limitations associated with the DSMP include:

- Some gaps exist in the data set, associated primarily with delays in the procurement of suspended sediment monitoring equipment, non-functioning equipment and contractual issues. These gaps have limited the time periods over which direct comparisons could be made between sites, but modelling techniques (such as sediment transport rating curves) have been used to derive sediment transport information which are temporally and spatially comparable;
• Discharge measurements are collected using current meters and Acoustic Doppler Current Profiles. At moderate to high flow rates (>~3,000 m³/s) results from these two sample techniques can differ, with the current meter technique recording up to 15% higher flow rates at peak discharge in the Mekong. This is a recognised phenomenon attributable to the movement of bottom sediments and can be corrected. However, the DSMP discharge results have not been corrected so flow and sediment fluxes at sites measured using ADCP are likely to be underestimated;

• Depth integrated suspended sediment samples are collected using at least four different samplers. The! samplers purchased through the DSMP (the D-96) are the recognised international standard for the collection of accurate depth integrated suspended sediment samples. Due to limitations of the sampling equipment used at some sites in Thailand and Lao PDR (D49, Nilsson – Uppsala sampler), there is a very high risk that samples collected at Mukdahan and Kong Chiam are over estimating sediment concentrations, whilst the results at Pakse have a high risk of underestimating suspended sediment values. Vietnam uses a locally designed and manufactured suspended sediment sampler, but no comparison between the sampler and the D96 is available to demonstrate its accuracy;

![Figure 3.3. Depth integrated suspended sediment samplers used in DSMP. Top left: D-96, 3L sampler appropriate for Mekong conditions; Top right: D-49, 0.75 L sampler operationally limited to 5 m depth, bottom left: Nilsson-Uppsala sampler, 1L sampler limited to 5 m depth; Bottom right: Vietnamese designed and constructed sampler, unknown operational limits.](image)

3.3 Major findings of the DSMP 2009 – 2013

The 2009 – 2013 DSMP dataset has been reviewed and analysed in Koehnken (2014) which should be consulted for more detail. The following summary provides a brief overview of the findings with respect to the hydrological, sediment transport and sediment monitoring results.

3.3.1 Hydrological Results 2009 – 2013

The discharge results from the DSMP have been used to update rating curves for the sites on the Mekong mainstream upstream of Phnom Penh (Someth et al., 2013). Using the
discharge results and rating curves, the 2009 – 2013 hydrologic years showed the following characteristics:

- The 2009 – 2013 DSMP monitoring years included considerable hydrologic variability, with 2011 being a very wet year, and 2010 and 2012 being dry years;
- Hydrographs from the DSMP monitoring sites show there is limited water input between the sites of Chiang Saen and Nong Khai, with a large increase in flow between Nong Khai and Nakhon Phanom. Additional step-wise increases in flow occur between Mukdahan and Pakse, and between Pakse and Stung Treng, reflecting the inflow of the Mun and 35 River systems, respectively;
- The discharge results show a good flow balance through the Chaktomuk bifurcation during both inflowing and outflowing periods of flow in the Tonle Sap (confluence shown in Figure 3.2);
- Flow results from Chiang Saen show a delayed onset of the wet season in 2009 and 2012 relative to the other flow years, and are consistent with the operation of the Lancang hydropower cascade in the UMB;
- The 2013 flow results show a prolonged ‘tail’ to the wet season, and elevated water flows during the dry season as compared to previous monitoring years. These characteristics are also consistent with operation of hydropower plants in the UMB.

**Results - Suspended Sediment concentrations**

- Suspended sediment concentrations at the DSMP monitoring sites typically range between 200 and 400 mg/l, with the higher values generally associated with the onset of the wet season;
- Suspended sediment concentrations at Mukdahan and Kong Chiam are higher than at other sites, but are likely reflecting the over sampling of the water column due to the limitations of the sampling equipment;
- Suspended sediment concentrations at Chiang Saen are increasing prior to the onset of high flows at the site, and showing a reduced relationship with flow rates, which is consistent with the operation of a cascade hydropower project in the UMB.

**Results - Suspended Sediment Loads**

- Suspended sediment loads in the LMB have been calculated by interpolating sediment loads between monitoring dates, and through the modelling of daily suspended sediment concentrations based on sediment rating curves and daily river discharge;
- Suspended sediment loads show variability between years, with 2011 (a very wet year) generally having the highest loads;
• The calculated suspended sediment loads at Chiang Saen range from 7.3 to 12.8 Mt/yr with an average of 10.8 Mt/yr over the 2009-2013 period. There is a doubling of sediment loads between Chiang Saen and Luang Prabang (average = 22 Mt/yr). Between Luang Prabang and Nong Khai, there is no increase in suspended sediment loads, with the results reflecting a loss of sediment through this reach;

![Annual Suspended Sediment Flux](image1)

![Annual Water Flux](image2)

• There is a large influx of water and sediment between Nong Khai and Nakhon Phanom, with average sediment loads in excess of 50 Mt/yr at the downstream site (although monitoring results are limited at Nakhon Phanom);

<table>
<thead>
<tr>
<th>Mt/yr</th>
<th>CS</th>
<th>LP</th>
<th>CK</th>
<th>NK</th>
<th>NP</th>
<th>MUK</th>
<th>KC</th>
<th>PK</th>
<th>ST</th>
<th>KT</th>
</tr>
</thead>
<tbody>
<tr>
<td>2009</td>
<td>14.86</td>
<td>20.29</td>
<td>14.73</td>
<td>11.08</td>
<td>50.72</td>
<td>88.87</td>
<td>63.60</td>
<td>64.00</td>
<td>84.16</td>
<td>80.70</td>
</tr>
<tr>
<td>2010</td>
<td>7.28</td>
<td>18.87</td>
<td>14.06</td>
<td>14.27</td>
<td>56.30</td>
<td>119.46</td>
<td>206.43</td>
<td>62.08</td>
<td>48.02</td>
<td>44.16</td>
</tr>
<tr>
<td>2011</td>
<td>12.84</td>
<td>22.79</td>
<td>18.73</td>
<td>35.52</td>
<td>*</td>
<td>114.20</td>
<td>166.14</td>
<td>70.81</td>
<td>95.93</td>
<td>98.46</td>
</tr>
<tr>
<td>2012</td>
<td>9.83</td>
<td>24.81</td>
<td>18.08</td>
<td>16.30</td>
<td>48.39</td>
<td>68.71</td>
<td>54.78</td>
<td>54.09</td>
<td>56.06</td>
<td>52.02</td>
</tr>
<tr>
<td>2013</td>
<td>9.11</td>
<td>24.56</td>
<td>20.48</td>
<td>16.97</td>
<td>62.02</td>
<td>91.09</td>
<td>91.24</td>
<td>77.75</td>
<td>99.72</td>
<td>87.16</td>
</tr>
<tr>
<td>Average</td>
<td>10.8</td>
<td>22.3</td>
<td>17.2</td>
<td>18.8</td>
<td>54.4*</td>
<td>96.5</td>
<td>116.4</td>
<td>65.7</td>
<td>76.8</td>
<td>72.5</td>
</tr>
<tr>
<td>Average no 2011</td>
<td>10.3</td>
<td>22.1</td>
<td>18.8</td>
<td>14.7</td>
<td>54.4*</td>
<td>92.0</td>
<td>104.0</td>
<td>64.5</td>
<td>72.0</td>
<td>65.0</td>
</tr>
</tbody>
</table>

Calculated suspended sediment flux in the LMB 2009-2013 based on sediment rating curves and average daily river flow. Shaded values are considered of low reliability due to the limitations of the suspended sediment sampling equipment. *No results available for flood year 2011

• Suspended sediment loads at Mukdahan and Nong Khai are much higher than recorded at the upstream or downstream sites which likely reflect a combination of the resuspension of bed material in this reach, and oversampling of the water column due to the use of undersized suspended sediment samplers;

• Sediment inflow from the 3S is estimated at 8.5 Mt/yr based on monitoring results from August 2012 – July 2013;

• Between Stung Treng and Kratie the suspended sediment loads generally decrease by 5% to 12%, which is attributable to loss of suspended sediment to the floodplain and / or bedload. The average suspended sediment load at Kratie for the 2009 – 2013 period is 72.5 Mt/yr;

• The magnitude of the sediment loads varies considerably between years, but the pattern of sediment delivery is uniform, with approximately 60% of the sediment load transported in August and September, and 80% of the load transported between July and October;
The majority of suspended sediment entering the Chaktomuk confluence in the Mekong remains in the mainstream Mekong and Bassac Rivers, with only about 10\% estimated as entering the Tonle Sap during the inflowing season.

**Results - Suspended Sediment Characteristics**

- Suspended sediment grain-size characteristics show changes within sites and between sites over the wet season. Overall, the results show a fining of grain-size with distance downstream;

- Grain-size results from Chiang Saen are limited to the wet season, and show the suspended load is dominated by medium and fine sands;

- At Luang Prabang, sand is also the dominant grain size during the wet season, with silt increasing in proportion in the dry season, whereas at Nong Khai, silt makes up a substantial proportion of the suspended load throughout the year;

- The suspended load at Pakse is dominated by sand, suggesting the large influx of sediments between Nong Khai and Pakse contains abundant sand sized material, and/or more sand is being carried in suspension;

- At Kratie, the suspended load is dominated by silt, with fine sand and clay also present. The clay increases in the suspended load downstream of Kratie, and is the predominant size fraction at the delta sites of Tan Chau and Chau Doc. At Kratie, it is estimated that the annual average load comprises \(~13\text{ Mt of sand, 41 Mt of silt and 13 Mt of clay;\}
• In the delta, the suspended sediment is dominated by silts and clay, indicative of a loss of coarse silt and sand from the suspended load to bedload.

**Bedload Transport of Sediment**

• Bedload is measured at three sites (Chiang Saen, Nong Khai and Kratie), and because of the difficulty in collecting reliable samples the results are considered an order of magnitude estimate only;

• The bedload is dominated by gravel, pebbles and coarse sand at Chiang Saen, fine and medium sand at Nong Khai, and coarse to fine sand at Kratie (Figure 3.6);

• Estimates of bedload transport rates for the three sites were: 1.6 Mt in Jul to Dec 2011 at Chiang Saen (interpolation), 1.3 to 4.1 Mt/yr at Nong Khai (ADCP bed movement estimate), and 1.2 to 2.1 Mt/yr at Kratie (bedload sediment rating curve). These ranges represent 3% to 15% of the suspended load at the respective sites (Table 6).

![Bedload Transport of Sediment](image)

*Figure 3.6. Grain-size distribution and mass of bedload transport based on monitoring results from Chiang Saen and Kratie in 2011 / 2012.*

<table>
<thead>
<tr>
<th>Site</th>
<th>Year</th>
<th>Interpolation MT/yr Time period</th>
<th>Bedload Rating Curve MT/yr</th>
<th>2012-13 ADCP Rating curve MT/yr (Jan – Dec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chiang Saen</td>
<td>2012</td>
<td>1.6 (Jul – Dec)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nong Khai</td>
<td>2011</td>
<td>1.1 (Jun – Dec)</td>
<td></td>
<td>2.1 – 4.1</td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>2.5 (Feb – Oct)</td>
<td></td>
<td>1.3 – 2.6</td>
</tr>
<tr>
<td></td>
<td>2013</td>
<td></td>
<td></td>
<td>1.4 – 2.9</td>
</tr>
<tr>
<td>Kratie</td>
<td>2011</td>
<td>2.1 (Jun - Dec)</td>
<td>1.9</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2012</td>
<td>0.7 (Aug – Nov)</td>
<td>1.2</td>
<td></td>
</tr>
</tbody>
</table>

**Bed Materials**

• An extensive bed material survey was conducted in 2011. The grain-size distribution of bed material reflected the flow regime at the time of collection, with fine material
present at sites during low flow, and coarser material present during the wet season;

- Notwithstanding the influence of the flow regime at the time of sample collection, bed materials generally showed a reduction in grain size in a downstream direction, with the percentage of gravels decreasing and percentage of silts increasing.

**Comparison of DSMP results with historic findings**

- The DSMP results show a substantial decrease in suspended sediment concentrations and suspended sediment loads relative to results collected in 1960 to 2003 (Figure 3.7);

- The average annual suspended sediment load measured at the most upstream site (Chiang Saen) in the LMB has decreased from ~85 Mt/yr to ~11 Mt/yr. This reduction is consistent with modelled sediment trapping in hydropower impoundments in the UMB (Kummu et al., 2010). Suspended sediment inflow from China now accounts for ~16% of sediment in the LMB as compared to about 55% historically;

<table>
<thead>
<tr>
<th>Source</th>
<th>Chiang Saen (Mt/yr)</th>
<th>Luang Prabang (Mt/yr)</th>
<th>Nong Khai (Mt/yr)</th>
<th>Mukdahan* (Mt/yr)</th>
<th>Pakse (Mt/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Walling (1961-2003)</td>
<td>84.7 (31 – 147)</td>
<td>76.8 (56 – 112)</td>
<td>72.3 (30 – 114)</td>
<td>107.3 (47 – 238)</td>
<td>147.4 (75 – 180)</td>
</tr>
<tr>
<td>DSMP (2009-2013)</td>
<td>22.3 (19 – 25)</td>
<td>18.8 (11 – 36)</td>
<td>96.5 (69 – 119)</td>
<td>65.7 (54 – 78)</td>
<td></td>
</tr>
</tbody>
</table>

*Likely reflects over sampling of water column. Included for comparison, but absolute values should be considered with caution

- At the most downstream site for which there are historical results (Pakse) average loads have decreased from ~147 Mt/yr to ~66 Mt/yr. Historical estimates of up to 160 Mt/yr for the entire basin appear to have decreased to an average of 72.5 Mt/yr, based on results from Kratie. When interpreting these changes it must be
recognised that the historic results were collected using suspended sediment samplers which likely overestimated sediment loads, and the present results from Pakse have been collected using a sampler which may be underestimating loads;

- The DSMP calculated sediment load of 8.5 Mt/yr for the 3S system is lower than baseline models which indicated sediment loads of about 17 Mt/yr, but consistent with predicted loads of 10 Mt/yr due to sediment trapping in reservoirs in the tributary (Carling et al., 2009);

- The reduction in sediment entering from China and from the 3S basin has led to sediment inputs from ‘Other’ tributaries now providing the majority (~70%) of the sediment load of the Mekong. Approximately 12 Mt/yr is entering in the reach between Chiang Saen and Luang Prabang, which represents about 17% of the present sediment load (although there is an apparent decrease between Luang Prabang and Nong Khai), with the remaining ~53% contributed by tributaries between Nong Khai and Pakse;

- Based on the DSMP sediment balance, almost 30% of the present suspended sediment load of the LMB is derived from upstream of Luang Prabang. The sediment load is characterised by sand (suspended) and gravels (bedload), and these coarser materials have the potential to be trapped in dams planned for the mainstream Mekong and sub-catchments in the area;

- These results do not include any consideration of sediment loss through other activities, such as sand mining, so attributing the reduction in sediment loads solely to hydropower trapping is likely an oversimplification.

**Recommendations arising from the DSMP review**

Recommendations arising from the review of the 2009 – 2013 monitoring results include:

- Improving field equipment to ensure the accurate collection of depth integrated sediment samples. This should focus on upgrading equipment at sites where old suspended sediment samplers remain in use, and upgrading the on-board power supply and winch mechanisms to achieve appropriate suspended sampling transit velocities (rate at which sampler is lowered and raised),

- Investigations into the use of new technology to reduce the time and costs associated with the physical collection of sediment samples, such as in situ particle size analysers, and the use of ADCP results for the estimation of bedload transport;

- Additional capacity building in the context of decentralisation to ensure sampling and analytical continuity, accuracy and consistency into the future;

- Additional analysis of the DSMP data set;

- Integration of the DSMP results with water quality results and the findings of other geomorphic and sediment related investigations in the LMB.

### 3.4 Bedload modelling based on DSMP monitoring results

Jianzhao (2014) used the DSMP monitoring results to develop a potential bedload sediment transport model for 8 of the DSMP monitoring locations (Luang Prabang, Nong Khai, Nakhon Phanom, Mudkahan, Khong Chiam, Pakse, Stung Treng and Kratie). A Bedload Estimation Application (BEA) was developed in C++ to model daily and annual potential Bedload Transport Rates (BTR). The model adopted a critical velocity approach for bedload transport, and inputs to the model included the following information from each site:

- A representative median grain-size ($D_{50}$) of the bed material;
The cross-section of each monitoring location (collected twice per year by the DSMP);

- The daily water level; and,

- The daily discharge volume.

All input data was site specific with the exception of the representative median grain-size for bedload. A value of 0.375 mm was adopted as D_{50}, which is the average of the median grain-size present at Mukdahan and Pakse. A uniform grain-size was adopted so the relative magnitude of potential sediment transport could be compared between sites.

The potential bedload transport rate was calculated at a daily time-step for the 2009 to 2013 period. Examples of the daily results (Figure 3.8) show there is an increase in energy with distance downstream, with Mukdahan and Kratie having similar rates even though Kratie is a much wider reach of the river. Differences between the sites are also attributable to local flow patterns. For example, at Kratie in late 2013 there was a high flow event, and associated increase in bedload transport, which was not apparent at the upstream sites.

![Figure 3.8. Estimated potential bedload transport rate (10^3 t/day) at Luang Prabang, Nakhon Phanom, Mukdahan and Kratie.](image)

Estimated annual potential Bedload Transit Rates (BTR) are summarised in Table 7, and compared graphically in Figure 3.9. Results at Nong Khai (1 – 2 Mt/yr) are similar to the DSMP estimates obtained using the bedload sampler or ADCP data. Potential Modelled transport rates at Kratie (5 – 16 Mt/yr) are higher than the DSMP estimates of 1 to 2 Mt/yr.

**Table 7. Estimated annual potential Bedload Transit Rates for the period 2009 to 2013.**

<table>
<thead>
<tr>
<th>Site</th>
<th>Annual Estimated Potential BTR for 2009 – 2013 (10^6 Mt/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2009</td>
</tr>
<tr>
<td>Luang Prabang</td>
<td>1.30</td>
</tr>
<tr>
<td>Nong Khai</td>
<td>0.92</td>
</tr>
<tr>
<td>Nakhon Phanom</td>
<td>4.32</td>
</tr>
<tr>
<td>Mukdahan</td>
<td>10.81</td>
</tr>
<tr>
<td>Khong Chiam</td>
<td>3.18</td>
</tr>
<tr>
<td>Pakse</td>
<td>5.90</td>
</tr>
<tr>
<td>Stung Treng</td>
<td>6.87</td>
</tr>
<tr>
<td>Kratie</td>
<td>9.79</td>
</tr>
</tbody>
</table>

Comparing potential transport energy at the sites shows that Mukdahan has consistently elevated rates, even though the river is wider at the downstream sites of Stung Treng and Kratie. This is attributable to the transport energy per unit distance in the cross-section...
being higher as compared to the other sites. These results are consistent with the increased occurrence of deep holes in the reach, which are indicative of high shear stress, and higher average flow velocity for a given river discharge as compared to the downstream monitoring sites (Figure 3.10). The underlying fractured bedrock and different lithology in this region as compared to downstream may also be contributing to differential erosion in the river reach.

Figure 3.9. Estimated annual potential BTR at the DSMP monitoring sites for 2009 – 2013.

Figure 3.10. Comparison of average flow velocity and discharge at Luang Prabang (LP), Nakhon Phanom (NP), Muakphan (Mk), Pakse (PK) and Kratie (KT). Average flow based on current meter or ADCP measurements.
4 Summary of WWF Investigations into sediment transport and the geomorphology of the Mekong River and delta

Prior to the DSMP, sediment monitoring in the Mekong was limited to the collection of suspended sediment samples, and the sediment load of the river was commonly described as being dominated by silts and clays. During low flow periods, however, the exposure of sand deposits in the river channel and on river banks and bars indicates that large quantities of sand are also transported by the river.

Sand and coarser materials are recognised as being important for the structural composition of river channels, banks and bars, and are responsible for creating the physical habitats associated with many ecological niches. Sand, gravel, and pebbles are also important as inexpensive construction materials and are playing an important role in fuelling the rapidly growing economies of south east Asia.

Understanding the sources, transport mechanisms and fate of sand in the Mekong is also directly relevant to hydropower development and management, as sand sized material and larger is effectively trapped within reservoirs. Mitigation measures may ultimately move the sediment downstream, however the timing and seasonality of sediment delivery generally differs from pre-dam patterns, which can also affect downstream sand related processes.

The WWF and its associated researchers identified a suite of investigative projects to enhance the understanding of the distribution, sources and transport mechanisms of sand in the river, and to explore how the exploitation of the resource is affecting the geomorphic characteristics of the river channel and delta (Table 2).

The first investigation (Bravard et al., 2013a & b) used satellite imagery, field observations and field measurements of the grain-size characteristics of exposed sand deposits down the length of the mainstream to establish the mode of transport (bedload, graded suspension, uniform suspension) immediately prior to deposition.

Alterations to the sand budget of the Mekong were investigated through a field based survey of sand and gravel extraction operations to arrive at the first estimates of the quantities of material being removed from the river (Bravard, et al., 2014). The survey also explored the longevity and stability of the operations to gain an understanding of the stability and sustainability of the underlying sand resource.

The third area of investigation focussed on the response of the delta to recent alterations to the sediment budget through investigations into changes in the morphology of the river channel (Brunier et al., 2014), the distribution of erosion and deposition along the delta front (Anthony, 2013a & 2013b), and trends in the characteristics of the Mekong plume in coastal waters (Loisel, et al., 2014).

Each of these research areas are summarised in the following sections. The references listed in Table 2 should be consulted for the full details of the investigation and a more in-depth discussion and interpretation of results.
4.1 An assessment of sediment-transport processes in the Lower Mekong River based on deposit grain sizes, the CM technique and flow-energy data

4.1.1 Research objective
The research objectives of Bravard et al., (2013a&b) including the following:
- Describing the distribution of sand deposit within the Mekong River channel;
- Ascertaining the flow conditions associated with the transport and deposition of sand in the LMB,
- Investigating the upstream to downstream variations of sediment load in space and time;
- Exploring the lack of relationship between the downstream increase in basin size and decreasing values of sediment concentrations and loads detected in the suspended load.

4.1.2 Methodology
Bravard et al., (2013a & b) applied a range of investigative techniques to ascertain sediment transport processes associated with sand in the Mekong. Field investigations included the mapping of sand deposits, including recording the maximum height of sand deposits relative to low water level in the river, and the collection of representative samples over the height of the deposits for subsequent grain-size distribution analyses. Samples were collected from the locations indicated in Figure 4.1. Measurements of the physical attributes of the river (cross-section, slope, flow regime) were collected or extracted from aerial imagery and used to calculate stream energy at the sand sampling sites using the following equation from Bagnold (1960):

\[ \omega = \frac{\Omega}{w} = \frac{rgQ_b S}{w} \]

Where:
- \( \omega \) is expressed in W·m\(^{-2}\);
- \( \Omega \) is the gross stream power
- \( R \) is expressed in 1000 kg·m\(^{-2}\);
- \( g \) is 9.8 m·s\(^{-1}\)
- \( Q_b \) is the bank-full discharge
- \( S \) is the average slope along the reach (m·m\(^{-1}\))
- \( W \) is the average width of the bank full channel (m)

The 1 in 2 year flood at established gauging stations was used as the bank-full discharge for this investigation. Interpolation was used to determine the stream energy at the monitoring sites located between the gauging locations.
The mode of transport was inferred through use of the CM method (Passega, 1957), which uses ratios between coarsest (C=D99) and median (M=D50) grain-sizes to deduce the hydraulics of the water column at the time of deposition. The methodology is based on how the distribution of sediment varies with depth in the water column under different flow conditions. A uniform suspension occurs when river energy is sufficiently high to distribute all suspended sediments evenly through the water column, regardless of grain-size. A graded suspension occurs when river energy is sufficient to uniformly suspend fine material throughout the water column, but larger particulates are limited to the lower water column or as bedload. Sediments deposited under different flow conditions show varying ratios between median grain-size (D50), and maximum grain-size (D99). These patterns are interpreted using CM diagrams, as summarised in Figure 4.2. Based on Passega (1977) CM diagrams have the following characteristics:

- Sands deposited during the recession of a flood fall within the N-O segment of the diagram (Figure 4.2c). During floods, turbulence is competent to support the coarsest particles (black triangles Figure 4.2a&b); when the turbulence decreases during the recession of the flood, the coarsest particles settle on the banks or on the bed, resulting in the coarsest and median grain-size of the deposit being similar, so the results plot parallel to C = M line, which is the line of perfect sorting). This good
correlation between C and M shows “the precision of the control of sedimentation by bottom turbulence”;

- Particles transported through rolling along the bed (bedload), in contact with the channel bed plot within the segment OP on the CM graph;
- Sand transported in suspension during a flood fine upwards through the water column, resulting in “graded suspension”. On the CM diagram, two types may be distinguished:
  - Segment PQ corresponds to a mix of rolled (bedload) particles and “graded” suspension. These deposits are typically present on the lowest areas of the banks.
  - Segment QR corresponds to pure graded suspension or GS, in the absence of bedload transport. Due to the graded nature of the suspended sand material deposited under these hydraulic conditions, deposits are usually composed of medium sized sand on the lower banks and fine sand on the upper banks.
- Results which plot within the RS sector of the CM diagram are characterised by a constant C value, reflecting the uniform nature of the coarsest material in the wash load being transported in uniform suspension, with variable M values reflecting different bottom velocities with the lowest values corresponding to the lowest water velocities. During the recession of a flood, as water velocity decreases, the CM characteristics of the deposited material move from S to R on the graph, due to the decrease in size of material which can be deposited, but no change in the maximum size of the material being carried in suspension.
- The last type of deposition is termed ‘decantation’ (T), which occurs in still water bodies existing over a floodplain, or in ‘dead arms’ or quiescent areas of water bodies. These deposits do not exist in the channel except in small shallow swales, for instance upstream of sand dunes.

![CM Diagram](image)

**Figure 4.2. The complete theoretical CM image after Passega (1957)**
4.1.3 Summary of results

Three examples of the field mapping and CM results are presented in Figure 4.3 to Figure 4.5 as examples of the information collected and interpretation of results from individual sites. The report and published paper should be consulted for a full presentation of the results.

The results from site 135, located in zone 1a (Figure 4.1) in the upper most reaches of the LMB show the following:

- Samples 0 and +3 m (sample references are relative to the height above observed low water level on the day of collection) are indicative of sorted medium sand deposited during the recession of the flood in a small cove along a large bar. Some silt is also present and probably reflects deposition as water levels decreased due to increased bed roughness caused by ripples;
- Samples +2, +4, +6, and +8 m show material deposited under a combination of bedload and suspended conditions, consistent with episodic flooding at these levels. Note that the value of C is similar at different elevations (750 - 820 µm), reflecting the maximum size of the material able to be transported as bedload, but that M values decrease with height due to finer material being transported (and deposited) higher in the water column.
- Samples +9 m, +13 m and +17 m have lower C values and an increased percentage of the silt component probably due to the effect of vegetation trapping and finer material carried in suspension at these high flow levels. Samples at this site were likely deposited by low frequency (high flow) floods.

![Figure 4.3. CM image of site 135, reach 1a.](image)

Results from site 372 (Figure 4.4), located downstream of Luang Prabang and upstream of Vientiane, show smaller grain-sizes relative to the upstream site and the following characteristics:

- Grain-sizes in the deposit decrease with distance above the low water level, with both C and M values decreasing with height;
- CM results are consistent with the material being deposited under conditions of graded suspension, except for sample +9 m, which contains slightly more silt than the other samples and is suggestive of deposition under conditions of uniform suspension;
- The sample collected from +9 m was visually consistent with older levee deposits and may not represent recent deposition;
The results from site 119 (Figure 4.5) were obtained from the river channel and a mid-stream bar in the alluvial reach between Paksane and Savannakhet in the central LMB. The CM results for this site are interpreted as follows:

- The coarse riverbed samples are indicative of bedload transport and deposition;
- The samples collected at the different levels of the sand bar have similar CM results, and are composed of fine sand deposited by processes at the transition between graded and uniform suspension (point S of the theoretical image);
- The energy regime in this reach reflects bedload transport of coarse sand and uniform suspension of finer sand (low turbulence / absence of turbulence) because there is no vertical gradient in the deposit (reflecting a lack of gradient in the water column).

The integrated information (Figure 4.6) shows the following longitudinal trends in the Mekong River based on the CM results:

- The characteristics of material carried in graded suspension are shown by the range of ‘C’ values (plot C). The maximum grain size being transported by the river ranges from 160 to 1000 μm, and changes with distance down the length of the river, with the following ranges observed:
  - 300 – 800 μm in reach 1a to 2
  - 190 – 360 μm in reach 4
  - 45 – 530 μm in reach 5
  - 250 – 380 μm in reach 6, and
250 – 400 µm in reaches 7 and 8;

- No evidence of uniform suspension was found in the steep reaches of the river;
- Sand was also found in historical levees, which raises questions about the previously suggested theory that sand is a recent phenomenon in the river associated with land use may not be accurate (see paper for full discussion);
- The maximum elevation of sand reflects local channel hydraulics. Maximum height decreases from 17 m to 5 m between reaches 1 and 2A, is in the range of 6 m to 9 m in reaches 4 and 5, and is limited to approximately 4 m at the Vietnamese border (plot D).

Figure 4.6. Summary of results from field investigations. ‘A’: CM results for each reach, ‘B’: the river profile, ‘C’: range of the coarsest percentile in each reach (C values); and ‘D’: maximum height of sand above low water level in the reach.

The sediment transport findings are compared with the stream energy calculations in Figure 4.7, and show that the changes in stream energy with distance downstream are consistent with the observed sediment transport mechanisms. The results show that the fine wash load is uniformly transported down the length of the Mekong in the LMB, as is sand as bedload. Sand transport varies between uniform and graded suspension downstream of Nong Khai, but is limited to uniform suspension in the river downstream of Stung Treng. The changes in energy are also reflected in bedload transport, where availability of material and low energy limits the transport of cobbles and gravel downstream of Nakhon Pharam.
4.1.4 Conclusions of investigation

The results of the investigations provide new insights into how and why the suspended sediment load of the LMB varies in a non-uniform manner with distance downstream. It is suggested that increases in river energy level near the sites characterised by elevated suspended sediment loads (Mukdahan, Kong Chiam) lead to the increased concentrations of material in suspension, and hence more sand is captured in suspended sediment samples. The change in transport process from bed load to graded suspension to uniform suspension can contribute to high variability in suspended sediment concentrations, and may lead to an apparent ‘imbalance’ in the sediment load if only one sediment fraction (e.g. suspended) is being considered.

In general, the research has documented that silt and clay travel as wash load with a very limited amount of this sediment fraction deposited upstream of Cambodia. Sand transits as suspended load and as bedload. In the upper mountain reaches, high turbulence during floods results in sand being transported in suspension, while sand is transported as bedload during lower energy conditions associated with rising and receding floods. Downstream of Vientiane, bedload is considered to be the dominant transport mechanism for coarse and medium-size sand, while fine material is transported in uniform or graded suspension during floods.

These findings are consistent with the results of the DSMP, which suggest that the suspended sediment monitoring equipment being deployed at the Mukdahan and Kong Chiam monitoring sites is over sampling the water column. Combining the findings of the two can account for the extremely high suspended sediment concentrations monitored at high flow; the increased energy in the reach is leading to relatively higher levels of suspended sediment as compared to reaches upstream or downstream, and the under sized sediment monitoring equipment is magnifying this phenomenon through over sampling.

4.1.5 Interpretation of results with respect to existing and future hydropower developments

Bravard et al., (2013 a&b) have interpreted the results of the investigation in the context of existing and potential hydropower developments in the Mekong. This interpretation includes the following:

- The field observations collected during the investigation did not include any clear evidence of sand erosion to the river banks between Chiang Saen and Luang Prabang or even farther downstream, although it is acknowledged that no inter-annual comparisons were included. The authors suggest that the area prone to bank
erosion at present is likely limited to the reach between the lowest Lancang dam and Chiang Sean, which was not able to be included in the study;

- With respect to the Xayaburi dam project, is it noted that whilst sluice gates to flush sediment are included in the project, that the technical conditions suggest that flushing may be only partly successful, and could create ecological conditions downstream of the dam that could be detrimental for fish and biological diversity in general;

- Sediment inputs from tributaries downstream of the Lancang cascade are of prime importance for the lower Mekong sediment balance, with the Nam Ou identified as a very important input that is presently undammed (although seven dams are planned for the tributary with projects in various stages of development);

- Downstream of Luang Prabang low quantities of sand are entering the river due to existing dams in tributary catchments;

- The potential impact of the 11 mainstream hydropower developments on sediment movement include:
  
  - Trapping of the coarse fraction of the suspended sediment, and changes to sediment transport processes due to a reduction in stream energy in the reservoir;
  - Deposition of fine-material in sheltered areas of reservoirs;
  - The retention of fine-material will promote the creation of cohesive deposits which will be more resistant to mobilisation under flushing flows;

In conclusion, it is suggested that the Mekong is a highly complex system and there remain high levels of scientific uncertainty regarding sediment transport in the basin. If dams are constructed on the main stream of the Lower Mekong, they will alter the equilibrium of sediment transport. It is recommended that additional studies be completed to strengthen the Mekong River commission’s role in technical guidance, and that there remains a need for the derivation of a reliable basin-scale sediment budget, which includes tributary inputs. It is also recommended that tributaries which contribute significant amounts of sand should remain free of obstructions to ensure an adequate supply of sand to the delta, with catchments contributing low amounts of sand targeted for hydro development. A final recommendation is to establish stronger international institutions to oversee activities which affect sediment transport in the Mekong, such as quotas for sand extractions, establishing rules and overseeing the coordinated flushing of reservoirs to promote the transfer of sand through the river.

4.2 Study of the sediment fluxes of the Lower Mekong River, September 25 to October 6, 2012

Dramais et al., (2013) completed field based measurements at the end of the 2012 wet season to measure the flux of sediment and the spatial distribution of both particle size and sediment concentration at three locations in different physiographic regions of the lower Mekong. The objectives of the work were to ascertain the magnitude and flux of sand transiting through the river to advance the understanding of sand transport in the river, and to trial the applicability of various technologies.

4.2.1 Methodology

At each monitoring location, water discharge was measured using an ADCP with GPS capabilities. ADCP longitudinal profiles were also collected to identify the presence and potential movement of dunes on the river bed.
In situ measurements of suspended sediment particle size were obtained using an AQUAscat particle size analyser. Measurements were collected from three or four points in the cross-section, at four to seven depths. The instrument was deployed horizontally to minimise the potential for grain-size gradients in the measurement.

Water samples were collected from discrete depths using a Van Dorn water sampling bottle. In the field, the lack of sufficiently sized sample bottles precluded the collection of the entire 2L water sample collected using the Van Dorn bottle. Only half the sample was able to be retained, with 500 ml collected into each of 2 bottles. Accurately splitting samples containing sand sized material is recognised as extremely difficult (e.g. USGS research shows samples with average particle size >0.25mm cannot be accurately split, even using a dedicated churn or cone splitter (USGS, 1997). The authors acknowledge that sand may have remained in the sampler or not have been equally divided between the sample bottles, and this is a potential source of error.

One of the two 500 ml sub-samples was sent to Irstea Lyon for the determination of suspended sediment concentration. The other sub-sample was split into three subsamples, with two used for grain-size determination using the LISST, with the remaining sub-sample returned to France for additional grain-size determination. The splitting of this sample also presented challenges.

Bedload samples were obtained using a BL-84 style sampler at Luang Prabang and Kratie. The sampler was deployed for 2 minutes at each of five locations across the cross-section. The samples were dried and weighed, and the grain-size distribution of each sample was determined using a standard sieve stack. No bedload samples were collected at Kong Chiam due to concerns about losing or damaging the bedload sampler on the bedrock present in the river channel.

Data analysis include the interpretation of ADCP and AQUAscat profiles to estimate the proportion of fine (10 – 20 µm) and coarse (70-200 µm) sediment, and the modelling of bedload velocities using a range of approaches.

### 4.2.2 Results and Discussion

A summary of the field measurements and grain-size distribution results for the three monitoring sites is shown in Table 8. The discharge and suspended sediment varied considerably between the sites, but the distribution of fine and coarse grained sediments at each site was similar, with between 86 and 91% of the material considered to be fine-grained, with median grain-sizes of <15 µm (D50). Although the coarse grained material only accounted for up to 14% of the samples, it was present in higher proportions in individual samples collected at Kratie with suspended sediment concentration in excess of >500 mg/L, where up to 35% of the sample was composed of sand sized material.

<table>
<thead>
<tr>
<th>Site/date</th>
<th>Discharge (m³/s)</th>
<th>SSC Range (mg/L)</th>
<th>SSC Avg (mg/L)</th>
<th>Sed Flux kg/s t/d</th>
<th>%Fine (D50)</th>
<th>%Coarse (D50)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luang Prabang</td>
<td>4,812</td>
<td>118 - 174</td>
<td>155</td>
<td>746 kg/s 64,442 t/d</td>
<td>91% 14 µm</td>
<td>9% 70-230 µm</td>
</tr>
<tr>
<td>2/10/2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kong Chiam</td>
<td>9,025</td>
<td>104 - 195</td>
<td>140</td>
<td>1,265 kg/s 109,166 t/d</td>
<td>87% 9 µm</td>
<td>13% 64-115 µm</td>
</tr>
<tr>
<td>4/10/2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kratie</td>
<td>24,402</td>
<td>145-805</td>
<td>263</td>
<td>6,417 kg/s 554,490 t/d</td>
<td>86% 10 µm</td>
<td>14% 70-130 µm</td>
</tr>
<tr>
<td>28/09/2012</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The estimates of bedload transport at Luang Prabang and Kratie determined by extrapolating the collected samples to the width of the cross section (Table 9) show that the bedload at Kratie is finer-grained as compared to Luang Prabang, and that transport rates are low compared to the suspended sediment load of the river.

Table 9. Summary of bedload transport estimates based on field measurements.

<table>
<thead>
<tr>
<th>Site</th>
<th>Bedload Flux, kg/s</th>
<th>Bedload flux t/d</th>
<th>D_{50}</th>
</tr>
</thead>
<tbody>
<tr>
<td>Luang Prabang</td>
<td>5.5</td>
<td>477</td>
<td>0.60 mm</td>
</tr>
<tr>
<td>Kratie</td>
<td>146</td>
<td>12,600</td>
<td>0.38 mm</td>
</tr>
</tbody>
</table>

Other results from the investigation include:

- The longitudinal ADCP surveys at Kratie documented the presence of dune forms on the river bed, with wavelengths of 60 m to 150 m and heights of 2 m to 5 m. The ADCP backscatter profiles of these features were consistent with bedload movement of material not being uniform over the structures, with higher backscatter (e.g. sediment concentration) present along the crests of the dunes;

- The modelled distribution of sand in the cross-section using the ADCP backscatter signal strength calibrated with the collected suspended sediment samples (Figure 4.8) is consistent with the findings of Bravard et al., (2013) and the understanding of sediment transport in rivers, showing sand being preferentially transported near the bed of the river, and in surface waters with high velocities at Luang Prabang.
Summary of IKMP & WWF Sediment Investigations

Figure 4.8. ADCP discharge measurement from Luang Prabang (top) and estimates of the concentration of suspended sand at Luang Prabang obtained with Sedview by calibrating the backscatter data with the water samples.

4.2.3 Conclusions of investigations

The investigation demonstrated that multiple techniques can be integrated to directly measure or model the suspended sediment load, and grain-size distribution in the Mekong, and substantial quantities of sand sized material was present in the suspended load at all three sites at the end of the 2012 wet season. The results from the three physiographic regions show a fining of transported sediment downstream, although the relative contribution of fine (9-15%, D_{50} = 10 to 20 μm) and coarse material (D_{50} = 60 to 250 μm) was similar between the sites.

5 Geography of sand and gravel mining in the Lower Mekong River, First survey and impact assessment

The presence of sand and gravel in river channels is important for the integrity and physical structure of the river channel, underpinning ecological processes and biological productivity. The continued delivery of sand to river deltas is critical for maintenance of the structural stability of delta fronts, and for maintaining the balance between salt water intrusions and river water flows. In addition to the ecological function of sand and gravel, the material are also important contributors to the developing economies of third world countries, providing inexpensive materials for land filling and construction.

Channel extractions can affect river dynamics and ecosystems through channel incision. In the Pearl River basin, where 870 million cubic metres of sand were excavated between 1986 and 2003, impacts included the lowering of river channels, bank instability and threats to infrastructure, changes in the proportion of flow between various water courses, modification of saltwater intrusion levels, and a limit of freshwater supply (Bravard et al., 2013).

In many countries the practice has been banned or is highly regulated, with deleterious impacts requiring mitigation through the re-establishment of a balanced sediment budget.

In the Mekong, where channel and flow characteristics could potentially be susceptible to the range of impacts documented in the Pearl River, extractive activities are highly visible over the length of the river, however the magnitude of the extractions and impacts on the river channel have not been quantified. The quantity of material extracted from the
Summary of IKMP & WWF Sediment Investigations

channels represents a potentially major, yet unquantified part of the sediment budget of the Mekong River, and the WWF completed a field based survey to provide the first qualitative assessment of the practice in the basin.

5.1.1 Background of sand and gravel extractions in the Mekong
As summarised by Bravard et al., (2013), in lowland areas of Cambodia and Vietnam, landfill is widely used to reclaim land and to elevate roads and levees above flood level. In Phnom Penh, the districts close to the Mekong and the Bassac Rivers sand is used to raise land above flood levels, and to fill the wide-spread, naturally occurring depressions in the region, called “beng” in the Khmer language. This use consumes the largest volumes of sand drawn directly from the riverbed. Another major consumer of sand extracted from the riverbed is the road network in the delta, which has been significantly extended and flood proofed over the past decade. The demand for sand and gravel from foreign countries has triggered a large exportation business that has also led to more large-scale extractions. Singapore’s landmass has increased by 22% since the 1960s, partly thanks to river and offshore sand imported from different countries and the city is presently the largest importer of sand in the world (Global Witness, 2009). Since 2000, countries such as Vietnam, Indonesia and Malaysia have banned the exportation of river and offshore sand and the demand is shifting to countries with weaker institutional frameworks, such as Cambodia.

In 2009, Cambodia banned dredging after an international controversy following the dredging of the Tatai River, in the Koh Kong Province in South-West Cambodia. However, dredging of the Tatai River continued and supplied Singapore with 6.4 million cubic metres of sand per year, in spite of the rising cost of sand there. Concerning the Mekong River, in 2012, the Cambodian Prime Minister Hun Sen ordered government planners from the Ministry of public works, the Ministry of water resources and the national Mekong Committee to draw up a master plan to restore the silted Bassac River and shallow areas along the Mekong waterway. This initiative was based on the misconception that dredging would improve navigation conditions with a deeper channel and decrease the risks of bank collapse caused by areas that became shallower after the 2011 flood. As Mr. Hun Sen said, “We must use the river to save the river... We must think about the river as a whole. If we don’t resolve [the issues], we don’t know what could happen in the future.” Cambodia is therefore planning more dredging in order to sell sand to Singapore and China whose national production has been halted for environmental reasons, i.e. reasons that have not yet been taken into account on the Mekong. It was in this context that China made a soft loan to build a terminal in Kien Svay, Kednal province, 30 kilometres downstream of Phnom Penh, that has been used for exporting sand (Radio Free Asia Cambodian service, retrieved 09/03/2012, 22/01/2013).

5.1.2 Methodology
Field surveys were completed by the WWF in each of the Mekong Countries (Lao PDR, Thailand, Cambodia, and Vietnam) by four teams. The work took place during the 2011 or 2012 low-flow season (February to April 2011 for Laos, Thailand and Cambodia, and May 2012 for Vietnam). The teams conducted surveys based on individual questionnaires for each extraction site. Two types of survey questionnaires were submitted to contractors, depending on the size of the operation:

- Small operations with no interview. The survey included GPS location of the site, categories of sediment extracted (sand, gravel, pebbles), number of full-time staff working on site, types and number of vehicles operating on site (trucks, shovels and loaders, conveyor belts, bucket dredgers and suction dredges);
• Large operation with interview. The same data were collected and questions asked on the number of years of operation, the seasonal calendar of operation, preferential locations for specific size categories, sediment sizes selected by the company, an estimate of quantities produced annually per category, total quantity extracted each year, demand trend for each category of sediment extracted, changes in quantities extracted over the years, any changes noticed by the operator in the extraction depth (deeper dredging) and concerning in-channel features, an estimate of the increase or decrease in depth, monitoring of activity by local authorities, status of the concession and taxes.

On the Cau River in Vietnam, the method consisted of field observations, group discussions and consultation of experts on different topics such as financial feasibility and recommendations to mitigate the negative consequences of mining (Nguyen, 2011).

The results were collated and annualised, and plotted onto maps to provide a geographic understanding of the extractive industry (Figure 5.1). Where multiple operations precluded individual mapping at the basin scale, the quantities were combined, with the number of operations contributing to the total indicated. Volumes were represented on maps by circles proportional in size to the cube root of the annual extraction figures in cubic meters (Minvielle and Souiha, 2003). This method facilitated a visual representation of the results by avoiding disproportionate sizes of circles between small sites (very small or non-visible points) and very large sites (large circles) which vary by orders of magnitude in extractive volumes.

5.1.3 Results

5.1.3.1 Quantities and distribution of extracted material
The compiled survey results are summarised in Table 10 through Table 12, and in Figure 5.1, and indicate that a total volume of 34.48 million cubic metres or 55.2 million tons (density of 1.6 tonne per cubic metre of dry sand) of sediment were extracted from the Mekong main stem in Laos, Thailand, Cambodia and Vietnam in 2011. Of the total, 90% on average was sand which equates to approximately 31 million cubic metres, or 49.6 million tonnes in 2011.

Table 10. Volumes and percentage of grain-size categories per country.

<table>
<thead>
<tr>
<th>Country</th>
<th>Sand (&lt;2 mm)</th>
<th>Gravel (2 – 32 mm)</th>
<th>Pebbles (&gt;32 mm)</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lao PDR</td>
<td>904,100</td>
<td>10,000</td>
<td>454,500</td>
<td>1,368,600</td>
</tr>
<tr>
<td>Thailand</td>
<td>3,677,200</td>
<td>857,740</td>
<td>0</td>
<td>4,534,940</td>
</tr>
<tr>
<td>Cambodia</td>
<td>18,748,503</td>
<td>2,044,940</td>
<td>0</td>
<td>20,793,443</td>
</tr>
<tr>
<td>Vietnam</td>
<td>7,750,000</td>
<td>0</td>
<td>0</td>
<td>7,750,000</td>
</tr>
<tr>
<td>Total</td>
<td>31,079,803</td>
<td>2,912,680</td>
<td>454,500</td>
<td>34,446,983</td>
</tr>
<tr>
<td>Percent of total</td>
<td>90%</td>
<td>8%</td>
<td>1%</td>
<td>100%</td>
</tr>
</tbody>
</table>

Gravel and pebbles represent less than 9% of extracted sediment (Table 10) most of it being gravel (8%, nearly 3 million cubic metres). The low quantities of larger material (pebbles to cobbles) are attributable to two reasons. First, sand and gravel are easier to extract than the larger pebbles and cobbles and, secondly, this larger material is concentrated in the steep upper reaches, of the LMB, far from the cities where demand for construction material is low and transport costs are high.

The geography of sediment categories reveals that Cambodia was the largest extractor in 2011-2012, accounting for 60% of the extractions, with Vietnam (22%) and Thailand (13%)...
2\textsuperscript{nd} and 3\textsuperscript{rd} respectively. Extractions in Lao PDR accounted for only 4\% of the catchment total, although quantities may vary considerably between years in each country.

Interpreting the results spatially also shows that:

- Limited volumes are extracted in the mountainous Laotian reach upstream of Vientiane;
- Sand and pebbles are extracted from the long reach between Vientiane and Savannakhet reflecting the area of the river which transports pebbles and gravels as bedload (Bravard, et al, 2013 a & b);
- There are two clusters of extractive activity in the mid-reaches of the river, near the towns of Pakse and Kratie;
- Sand is the dominant material extracted in the lower basin.

The predominance of sand extractions in the lower catchment is evident when the results are stratified by river reach and grain-size class (Table 11). The longevity of operations in the lower catchment is also consistent with a sustained demand for materials near the most populated areas of the river catchment (Table 12, discussed in Section 5.1.3.3).

Table 11. Volume of extracted material by grain-size categories per river reach (locations shown in Figure 5.1)

<table>
<thead>
<tr>
<th>Reaches</th>
<th>1000 x m(^3)/yr</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sand</td>
</tr>
<tr>
<td>Upstream Vientiane</td>
<td>87</td>
</tr>
<tr>
<td>Vientiane-Savannakhet</td>
<td>4154</td>
</tr>
<tr>
<td>Savannakhet - Champasak</td>
<td>341</td>
</tr>
<tr>
<td>Cambodia upst. Kompong Cham</td>
<td>580</td>
</tr>
<tr>
<td>Kompong Cham - Vietnam border</td>
<td>18,160</td>
</tr>
<tr>
<td>Delta, Vietnam (+Bassac)</td>
<td>7,750</td>
</tr>
<tr>
<td>Total</td>
<td>31,072</td>
</tr>
</tbody>
</table>

On the local scale, extractions were generally observed occurring on the lateral bars and bank insets in the upper LMB, and from the channel itself where the river slope is low and river depth increases.

5.1.3.2 Extractive techniques

The techniques used depend on the seasonal pattern of flow and sediment mining. Upstream of Phnom Penh, gravel and sand are mined during the low-flow season, usually from December/January to May. High bars may be mined longer than low ones. Small extraction sites use mechanical shovels, tractors and light trucks, while bigger sites use pumping dredges and conveyors belts for extraction and have several large trucks. The activity depends on the accessibility of the site by trucks and mechanical shovels. Downstream of Phnom Penh, mechanical shovels operate from artificial levees in shallow areas, and, in deep areas, pumping dredges are the only means to mine sand. With the latter, extraction is possible all year long except during peak flooding. In the delta, sand is dredged with some limited amounts of small-size gravel, which probably originates from ancient layers below the present channel bottom. Due to the unknown depth of dredging, it was not possible to distinguish between the gravelly sand deposited recently and the fossil deposits of the Holocene delta.
Figure 5.1. Results of extractive industry survey. Size of circle is related to the cubic root of the extracted volume, and number next to circle indicates the number of operations included in the volume; bar graphs show distribution of material extracted at the site (sand, gravel, pebbles).

5.1.3.3 Length of operations
The survey results related to the length of present operations and trends in extracted volumes are summarised in Figure 5.1 and Table 12. Of the 118 operational sites 55 are two years old and 33 are three-years old. This implies that the best extraction sites shift along
the river with the operators shifting locations to mine the best sites and particularly the fresh flood deposits. The mobility of the extraction sites is likely reflecting the slow replenishment of mined areas. Conversely, where operations have remained stable for many years suggests that large volumes of material are stored in these areas relative to the quantities extracted and / or there is a high rate of replenishment compared to the extraction rate.

Table 12. Duration of extractive operations sorted by river reach (locations shown in Figure 5.1)

<table>
<thead>
<tr>
<th>Reaches</th>
<th>1yr</th>
<th>2-5 yrs</th>
<th>5-10 yrs</th>
<th>&gt; 5-10 yrs</th>
<th>&gt; 10 yrs</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upstream Vientiane</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vientiane-Savannakhet</td>
<td>3</td>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Savannakhet - Champasak</td>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cambodia-upst. Kompong Cham</td>
<td>3</td>
<td>4</td>
<td>11</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Cambodia- Vietnam border</td>
<td>3</td>
<td>14</td>
<td>18</td>
<td>2</td>
<td>12</td>
</tr>
<tr>
<td>Channels of the delta, VN</td>
<td>7</td>
<td>30</td>
<td>2</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total : 118</td>
<td>13</td>
<td>55</td>
<td>33</td>
<td>2</td>
<td>15</td>
</tr>
</tbody>
</table>

Trends in the operations show that extractions have generally increased over the past years in the reach between Savannaketh and the Cambodian-Vietnamese border, while extractions are decreasing in the different branches of the delta in Vietnam. Sediment decreases in Vietnam are likely due to more long-standing dredging operations which have depleted supply rather than a decrease in demand.

5.1.3.4 Evaluation of accuracy of the results

These results are based on declarations from the mining operators. It must be stressed that the study results provide a general estimate of the relative importance of extraction sites that may be considered reliable, however it is likely that the volumes are underestimated by an unknown factor. The discrepancy between reality and estimates may vary from one site to another and from a country to another.

Operators have concessions and usually pay fees depending on the amount extracted and may thus be inclined to minimise declarations where possible. Also, only the main stem of the lower Mekong and two channels of the delta, the Mekong (Tien) and Bassac channels (Hieu), were surveyed. The upper Mekong in China, the tributaries and the other channels in the Mekong delta were not surveyed.
Table 13. Summary of length of operations, and trends in extractive operations surveyed in the Mekong. Left column shows duration of activities, right column indicates trend.

5.1.4 Discussion of results
In the absence of a systematic long profile of the Mekong River at low flow, it is not possible to quantify the magnitude or extent of riverbed incision due to extractions. However, between Kratie and Phnom Penh, significant indications of undercutting is evident near structures built over the past 30 years (piers, bridges over the Mekong and its small
tributaries cutting through the levees, the “prek”) which are consistent with bed incision. Bed incision may locally reach 1 to 3 metres in this reach where the role of reservoir trapping is minimal or non-existent. Further incision, which may be expected giving on-going and planned extraction, may threaten infrastructure.

In some places, concave banks are present which show significant lateral erosion, for instance in Saman, downstream of Kratie. According to local residents, faster erosion, threatening villages on the levee, had been triggered by dredging and the village obtained a halt to extraction.

The investigations by Brunier, et al., (2014), summarised in Section 6.1 of this report show changes to channel morphology in the delta consistent with the extraction of material from the channel. The modification of the channel geometry (Brunier et al., 2014) indicates that the cumulative impact of extraction from the river for at least the past 20 years has exceeded and probably still exceeds the input of sediment from the river basin.

Climate change is also considered responsible for increased bank erosion. According to Darby et al. (2011), ENSO cold phases are associated with earlier onset and enhanced intensity of the monsoon, with increased numbers of intense tropical storm systems and higher rates of riverbank erosion. Without denying this possible cause, it is suggested that based on the quantities being extracted from the river, and the observed changes in channel morphology, the impact of dredging is underestimated and should be recognised separately from climate change.

The results require a re-assessment of the sediment budget of the river, to reflect the 34.5 million cubic metres, or 55.2 million tonnes of sand which are no longer transported through the delta to the sea.

The suspended-sediment discharge of the Mekong River has historically been estimated to be 145 to 160 million tonnes at Kratie (Milliman and Meade, 1983) and is thought to be (primarily) composed of “fines”, i.e. silt and clay. The share of suspended sand in this total is unknown, but thought to be limited. Moreover, bedload contribution estimates are unknown. The authors suggest that the sediment discharge of the Mekong is underestimated because sand transiting as bedload and as suspended load has not been assessed. That being said, recent evaluations of suspended-sediment discharge incorporate some sand in an unknown proportion, which may reduce the discrepancy (e.g. DSMP data indicates approximately 20% of suspended load at Kratie is sand-sized). A conservative estimate of sand in suspension and sand transiting as bedload could add 10 to 30 million tonnes to the common estimate of 145 to 160 million tons of suspended sediment. The quantities of extractions need to be considered within this context, and a more complete discussion is provided in Section 7.

The impact of Chinese dams has been seen as an important component in the altered sediment budget. Indeed, they may affect fine suspended load transiting from upstream without deposition before the low lands of Cambodia. However, they have not affected sand transport yet because it is still possible to remove considerable amounts of sand from in-channel landforms in the upper mountain reaches of Laos. The impact of the Lancang dams is probably delayed concerning medium and coarse sand and part of the fine sand.

5.1.5 Conclusions

This paper provides an initial quantitative evaluation of the volumes of sand and gravel extracted from the Lower Mekong mainstem in 2011-12 and of the trends associated with the industry. The information is relevant to scientists and decision-makers and highlights the importance of sand mining for the management of river-related natural resources and biodiversity conservation. The dissemination of scientific data concerning the impacts of
extraction worldwide and more specifically of preliminary results obtained in the Mekong basin should highlight the present status and issues to managers.

This first assessment calls for better monitoring not only of sand and gravel transport, but also of future extraction activities. Future monitoring should incorporate and be put in the context of social, economic and political issues, so a holistic understanding of the industry can be gained and appropriate regulation can be developed through regional cooperation.

Undeniable efforts have been made by the Lower Mekong countries during the past decade to improve transboundary management of river resources. But the lack of quantitative assessments and the fact that governance institutions in place still have their limitations has been a barrier to the establishment of an effective regulatory framework. Lessons from other countries, including institutional and legal tools, self-imposed corporate regulation, industry codes of conduct can be called upon to guide trans-boundary management of sediments resources.

The concept of integrated river-basin management is now widely acknowledged and it is recognised that hydropower development and sand mining cannot be managed independently. In the case of the Mekong basin, these two aspects are probably among the most important in a basin-wide development plan.

6 Delta & coastal water investigations

6.1 Morphodynamics of Mekong delta channels

Brunier et al., (2014) investigated the morphological changes associated with anthropogenic activities in the two main deltaic channels in Vietnam (Figure 6.1). The research hypothesis was based on the recognised relationship between sediment dynamics and the reduction in flood frequency related to flow regulation by upstream dams (Wolanski et al., 1996; Gupta & Liew, 2007; Kummu & Varis, 2007; Le Hir et al., 2007; Kummu et al., 2008 and 2010) and the resulting impacts on channel morphology in delta environments. Furthermore, the urban and economic development of Vietnam and, more generally, South-East Asia, involves considerable extraction of aggregate (sand, gravel) within channels and is likely to exert a strong impact on the bed morphologies. In order to study these aspects, the investigation focussed on river bed changes based on the comparative analysis of bathymetric datasets from the Vietnamese reaches of the Mekong and Bassac Rivers. The observed river bed changes were then analysed with respect to river hydraulic parameters.
6.1.1 Methods

River bed changes were determined based on the comparison of digitized bathymetric data stemming from two Vietnamese delta hydrographic atlases, one from 1998 and the other from 2008. The spatial coverage of these data is approximately 400 km along the main navigable waterways of the delta (Figure 6.1), namely the main reach of the Mekong River (Tien Giang, Vam Nao and My Tho channels) and the Bassac River, from Vam Nao and the connection with the Mekong River.

Bathymetric data sets are available for the channels as shown in Figure 6.2, with coordinates projected in Universal Transverse Mercator (UTM) Indian Datum 1954, 48 North (conformal and metric projections). Elevation values are in metres relative to the “Low Lowest Water” (LLW), and are converted in metres relative to the Mean Sea Level (MSL) at Hà Tiên (Vietnam, Gulf of Thailand coast).

Sampling densities varied between the two bathymetric surveys, with the 2008 data set containing 14,000 points, whereas the 1998 dataset was limited to 10,000 points over the same area. To establish a reliable comparison between the data sets require the two data sets to have a similar data density. This was accomplished by reprojecting the initial profiles onto Cartesian coordinates of distance and depth. These new coordinates enabled a linear depiction of the initial profiles. A polyline was generated using the ArcGIS® module ETgeowizard® from the profile points, and new points were extracted from this line every...
100 m with X (distance to mouth) and Y (depth) coordinates (Figure 6.2 A,B). The new generated profiles had similar reference frames and number of individual points, making them suitable for comparison.

The thalweg was identified in the data sets by identifying the lowest point in each cross-section (taking general channel bottom morphology into account), and aligning these values on a longitudinal axis down the river (Figure 6.2 C) providing a reference point for each location in terms of its distance from the channel mouth to the Vietnam-Cambodia border.

Mapping of channel bottom morphology was conducted through polygon digitization of riverbed forms (thresholds, pools and bars) via the generation of isobath polylines at every 5 m depth. Volume gains and losses were calculated from the raster of depth differences between 1998 and 2008 (Figure 6.2 D) using tool boxes in the ArcGIS* 10 modules SpatialAnalyst and 3D Analyst. Channel banks and bars and islets affected by depth changes between 1998 and 2008 were further mapped using satellite imagery converted to the same projection as that of the channel depth data. Changes to these features between the two data periods were also mapped quantified.

Stream energy for various reaches was calculated using the same approach and data as adopted by Bravard, et al., 2013 (Section 4.1.2).

Historical records (1960 to 2011) of water level and discharge at the Vietnamese stations of Tên Châu (Mekong River) and Châu Doc (Bassac River) were used as a complement in this study. They have data gaps due to the political instability for the period from 1969 to 1974 (Kummu & Varis, 2007). Water levels are measured at bank-level and referenced to Hà Tiên MSL.

The full report should be consulted for more details of the methodology employed.

Figure 6.2. Channel depth data and processing. A: an example of data sampling (numbers of cross section profile varies according to dates and sectors). B: construction of the thalweg line from the deepest point of each profile. C: an example of depth raster processing (cell 50 m) and 5 m depth contour. D: the depth-change images are subtracted to build a depth- difference image enabling the extraction of bed material volume differences, as seen in D.
6.1.2 Results

6.1.2.1 Channel morphology
The general morphology of the Mekong thalweg profile presents a very irregular system of pools and riffles in the central part of the delta (Figure 6.3, top left graph), with the deepest pools having depths of -30 m to -45 m. The pools are located in meandering reaches such as Sà Dec (km 135-140) or in narrower sections such as upstream of Ham Luong (km 125) and Co Chien (km 100) bifurcations. Riffle areas correspond to depths from -15 to -5 m. In the My Tho channel (Figure 6.3, top graphs), the thalweg profile shows a bed bottom rise with pools around -15 and -10 m and riffles around -10 and -5 m. Morphological irregularities are less pronounced downstream of the Co Chien bifurcation as compared to upstream, probably due to the decrease in stream energy associated with the upstream bifurcations and by estuarine dynamics (Wolanski et al., 1996).

Figure 6.3. Morphology (top panels) and depth changes (bottom panels) of the thalwegs of the Mekong (A) and Bassac (B) channels in 1998 and 2008.

The general morphology of the Bassac thalweg is less irregular than those of the Mekong and My Tho channels (Figure 6.3, top right), probably because of its lower discharge (about 1,300 m³/s annual average). The deepest pools lie between -30 m and -25 m (near Can Tho, km 90-130) with the exception of one that descends up to -40 m (km 190) corresponding to a narrow channel sector at the bifurcation of the Bassac and Vam Nao, the latter accounting for part of the Mekong water discharge. As in My Tho, the bed becomes elevated and more regular near the mouth (from km 50).

A more in-depth discussion of specific examples from within these reaches is presented in Brunier et al., (2014) and should be consulted for additional detail.

6.1.2.2 Changes to the thalweg between 1998 and 2008
The comparison of thalweg profiles clearly shows bed lowering over most of the study areas (Figure 6.3, bottom graphs). On the Mekong River, 59% of the investigated channel showed erosion, as compared to 16% experienced accretion and 25% showed no significant change (between -0.6 m and 0.6 m). The average elevation change was -1.40 m. The spatial
variability of incision is very irregular, especially upstream of the Co Chien bifurcation (km 95), where the average elevation change of the channel was -1.8 m, compared to -1 m downstream of the bifurcation in the My Tho reach.

In the Mekong, most of the scour areas are located on riffle sectors (km 46 - 58 on the My Tho channel; km 89-97, km 106-111, km 114-122 and km 195-209 on the Mekong). Noteworthy incision sites are present downstream of the Ham Luong bifurcation (km 106-125) with deepening ranging from -5 to -15 m in riffle sectors, but also on the east branch of Cu Lao Tay Island (km 190-213) with a deepening from -5 to -7 m. Existing pools tended to widen rather than deepen (km 145-155 or 175-185 on the Mekong). Changes in the thalweg profile of the Mekong are more irregular and larger in amplitude (by a factor of 1.5 to 10) as compare to the My Tho channel. The My Tho channel is one of the three outlets of the Mekong; it receives only a part of the hydraulic power and is a net depositional area, due to tidal influence (Wolanski et al., 1996).

On the Bassac, the comparison between the 1998 and the 2008 profiles shows deepening of the thalweg is more pronounced than on the Mekong with 70% recording erosion as compared to 12% accretion and 18% without significant changes. These important changes are concentrated mainly on the riffles sectors and close to the mouth. Pools were found to have both deepened and widened. The average elevation change, -1.34 m for the channel is practically identical to that found on the Mekong channel, despite the differences in water discharge. The average depth change from km 50 to the estuary is higher with a reduction of 1.46 m recorded as compared with, -1.33 m, upstream. The results suggest an abnormal and probably unnatural estuarine dynamic.

The pattern of bed changes between 1998 to 2008 on the Mekong and Bassac includes the extension and deepening of pools (<-10 m) over riffle areas (between -10 and -5 m), with pits located on riffles and benches (> -5 m). The form and locations of these features are incompatible with the general morphology of the bed, and are interpreted as artificial, and presumably associated with sand mining. Examples of these changes are evident at (1) Cu Lao Tay on the Mekong River main stream, (2) downstream of the Co Chien/Mekong bifurcation on the My Tho River, and (3) near Can Tho city on the Bassac River, which are shown in Figure 6.4.

![Diagram showing depth changes and bed morphology](image-url)
6.1.2.3 Bed material gains and losses
The change in bed volume was determined for the reaches 205 km upstream of km 30 on the Mekong and 143 km upstream of km 45 on the Bassac. Some meandering sectors such as Sà Dec (Km 130) are excluded, due to significant lateral mobility. Also near the river mouths, the spatial coverage of channel depth does not include the entire channel.

The Mekong and Bassac rivers show large-scale bed material losses with 90 million m³ and 110 million m³, respectively, over the 10-year comparison period (Figure 6.5). These losses cover almost all of the channels and are concentrated in riffle sectors. These losses are greater in the Bassac despite the much lower water discharge of this channel compared to the Mekong. This is another line of evidence supporting human impact as the source of the channel bed changes in the delta. In the Mekong channel, the volume changes are largest upstream of the Co Chi/en/My Tho bifurcation (km 100), with more moderate losses on the My Tho channel. In contrast, the losses in the Bassac channel tend to be more uniform between pools near Can Tho city and the riffle sector at km 80, before increasing sharply downstream (Figure 6.5 B).

Figure 6.4. Bed morphology evolution in the Mekong Bassac channel near: Top left: Cu Lao Tay Island sector (kp 195 to 220); Top right: Ham Luong/My Tho bifurcation sector (km 84 to 98); and Bottom left: Can Tho city (Km 110 to 125) showing dredging impacts on a riffle, bench and bar sector. A: the situation in 1998; B: the situation in 2008; C: depth changes between the two surveys.

Figure 6.5. Changes in depths of channel thalwegs and net bed budgets of the Mekong (a) and Bassac (b) Bed material gains and losses in the Mekong (A) and Bassac (B), over the 1998 -2008 period. The figures illustrate the magnitude of total sediment losses. Moderate accumulation occurred in the most upstream sector of the Mekong just downstream of the Viet Nam Cambodia border.
6.1.2.4 Bed elevation changes and hydrological parameters

The hydraulic parameters boundary shear stress \( (T', \text{N/m}^2) \) and unit stream power \( (\omega, \text{W/m}^2) \) were derived using the average water level depth and discharge for four reaches on the Mekong and Bassac distributaries (Figure 6.6). The results showed weak to moderate correlations, suggesting that channel depth changes are not related to the hydraulics of the river.

![Figure 6.6](image)

Figure 6.6. Hydraulic parameters for 1998 and 2008 regressed against depth data for the same years, and map showing sectors for which the regressions were run: (a) unit stream power regressed against depth; (b) boundary shear stress regressed against depth; (c) sites: (1) Cu Lâu Tay island (km 188-216); (2) the Mekong upstream of Sa Đéc (km 148-163); (3) the Bassac downstream of Vam Nao (km 173-185); (4) the Bassac upstream of Cần Thơ (km 150-161). The coefficients indicate weak to moderate relationships that suggest that channel depth changes are not a response to changes in river discharge.

6.1.3 Discussion and findings

The observed changes to channel bed elevation between 1998 and 2008 combined with the lack of relationship between hydraulic parameters and channel incision strongly suggests that factors other than hydraulics are responsible for the wide-spread significant changes to channel depth in the delta. Over such a short time period the marked changes in thalweg morphology and channel bedload may be attributed to the two main human activities that are also regarded as the primary generators of sediment deficits in deltas, namely dams and mining of sand aggregates from the channel and tributaries. The volume losses in the Mekong may reflect a sediment deficit resulting from trapping by dams already in operation in China, however, the lack of reliable sediment flux results precludes quantification of the impact.

There is more information about sand and gravel extractions (see other reports in this volume). Large scale bedload extractions started in the 1990s and Bravard et al, (2013) estimates that nearly 35Mm³ of material was extracted from the Mekong in 2012, with 7.75 Mm³ extracted from the Mekong and Bassac in Vietnam, excluding the Ham Luông and My Tho distributaries. The estimated volume of mined sand in Vietnam accounts for about one-third of the 200 Mm³ bed loss over the 10-year comparison in the two channels.
The relatively random nature of the channel bed changes and the distribution of the loss areas are also consistent with river-bed mining, carried out by deep dredging on an industrial scale in the delta.

Aggregate removal results in the lowering of the bed elevation and of the water level, and in an increase in the bottom slope. Incoming sediment load from upstream becomes trapped gradually in the excavations and partially fills these pits. The inflowing sediment is insufficient to overcome the net deficit in material, leading to a net reduction in bed elevation. Overtime, the bed slope profile may return to its equilibrium value, but the channel would have deepened in the meantime. This process may also account for overall less marked deepening in the upstream reaches where sediment availability for infilling is greater.

Other impacts associated with bed lowering include bank instability, increased salt-water intrusion, and shore-line erosion, all of which have been observed in the Mekong Delta. In a context of exacerbated vulnerability to sea-level rise, the sediment balance and future stability of the Mekong delta, and the assurance of the continuity of its ecosystem services, are likely to be strongly impacted not only buy the effect of dams, but also by sand extraction if this activity is maintained at current rates.

Additional discussion and interpretation of the results are available in Brunier et al. (2014).

6.2 Delta stability investigations

Anthony et al. (2014 a&b) completed two investigations into the stability of the coastline of the Mekong delta. The first work focusses on approximately 400 km of the Mekong delta front, extending from the mouths of the rivers in the east to Ca Mau Point in the southwest. The second stage of the work examined approximately 200 km of the Gulf of Thailand shoreline on the western delta. The aims of the investigations were:

- Using satellite imagery between 2003 and 2011, map changes to the South Sea shoreline from the mouths in the east to Ca Mau Point in the southwest (ca. 405 km);
- Interpret the results with respect to sediment supply, distribution and storage;
- Discuss the implication of the results in the context of future hydropower developments and sea level rise.

6.2.1 Overview of Mekong Delta

The Mekong delta hosts a population of nearly 18 million people (MRC, 2010) and is crucial to the food security of the region with respect to both agriculture and animal husbandry. A high sediment supply and a suitable geological context favoured very rapid growth of the delta over the last 6 ka, with advancement rates of up to 16 m/yr between 5.3 to 3.5 ka. Rates decreased following this period due to increasing wave influence (Hanebuth, et al., 2012; Tamura et al., 2012; Xue et al., 2010). The present hydrodynamics of the shoreline favour essentially fine-grained sediment dispersal towards the western part of the delta, where shoreline accretion rates of up to 26 m/yr have been recorded over the last 3.5 ka (Xue, et al 2010).

The sedimentary and erosional process of the Mekong delta coast are complex, reflecting the combined influence of tides, tidal currents, waves and occasional cyclones, and to date there has been no systematic work on the coastal morpho-dynamics of the Mekong River delta. Like all deltas, the integrity and beneficial uses offered by the Mekong delta are linked to the sustained delivery of sediment from upstream.
6.2.2 Methods

High resolution SPOT and Landsat satellite images were analysed to determine retreat or advance between 2003 and 2011 over the 610 km of delta shoreline, from north of the mouth of the My Tho river, to the Rach Gia Bay on the Gulf of Thailand. Shoreline changes were documented by digitizing ortho-rectified colour satellite images from 2003, 2007 and 2011/early 2012 at a scale of 1:10,000. ArcMap extension module DSAS, coupled with ArcGIS 10 was used to complete the analysis. A similar methodology was used on lower resolution LANDSAT imagery of the Gulf of Thailand coast to extend the investigation to include the 1989 to 2004 period.

Three field visits provided ground-truthing for the images, and established that the vegetation limit, consisting of mangroves in the muddy western sector and of upland brush or plantations on beach ridges in the western river mouth sector, was the representative shoreline marker. The distance between the vegetation limit and a baseline was established at an interval of 500 m for the three sets of images (2003, 2007, 2011), providing measurements at approximately 1,200 transects upon which to base the analysis. The shoreline rate of change was calculated by dividing the change in shoreline location by the time period between successive satellite images to provide an End Point Rate (EPR).

A cumulative error, reflecting digitization errors and errors associated with the identification of vegetation limits was estimated to be in the range of 3.5 to 5 m/yr.

A complementary field experiment aimed at understanding the processes and morphodynamics of the delta shoreline was completed near Ba Dong, Tra Vinh province between January 2011 and February 2012. During this period a reconnaissance mission and two field experiments were completed. High resolution survey methods were used to map a 10,000 m² swath of the beach to capture cross-shore and longshore morphological variations induced by the multiple bar-trough and drainage channel system. Hydrodynamic measurements spanning a spring to neap tidal semi-cycle were collected in May / June 2011 using and ADCP current profiler deployed on a bar on the lower beach. This allowed the simultaneous measurement of the mean current and the longshore and cross-shore...
currents. The experiments were conducted during the rainy season/low wave energy period (May 2011) and dry season/high wave energy period (Jan/Feb 2012).

6.2.3 Results
The investigation found there was an average shoreline retreat rate of -4.4 m/yr along the East China Sea coast, with 48% of the coast experiencing retreat. Coastline advancement was recorded along 22% of coast, mainly in the eastern river mouth sector, where the average rate of change was +3.2 m/yr (Figure 6.9). Over 70% of the muddy western sector, where advance rates in the last three thousand years were highest (Xue, et al, 2010), has been retreating at a mean rate of -12.2 m/year.

Along the Gulf of Thailand coast, the average net change was -3.73 m/yr, with 36% of the coastline showing retreat over the 2003 to 2011 period. Retreat has been more pronounced in the southern half of the shoreline as compared to the north (Figure 6.10). This suggests the southern sector has a larger susceptibility to a sediment-source deficit from the mouths of the Mekong in the South Sea, and a more sheltered context for the northern half of the shoreline, which is farther from the mouths.

Figure 6.8. Main map: Summary of net shoreline change over the period 2003 – 2011 based on SPOT 5 high-resolution satellite imagery. Bar graphs on right show rates of change for the entire period, and the intermediate periods of 2003 to 2007, and 2007 to 2011.

Figure 6.9. Rates of change in the sand-rich eastern delta-mouth sector and in the muddy, mangrove-dominated western sector.
The analysis of the lower resolution LANDSAT imagery for the period 1989 to 2004 was also consistent with retreat being the predominant change along much of the Gulf of Thailand shoreline.

The results from the ground based survey and mapping investigations, which were completed in the eastern sandy river-mouth sector, showed substantial retreat of the dunefoot over the year of investigation, and are consistent with shoreline re-organisation (e.g. reworking of coastal sediments) under a regime of decreasing sediment supply. South of the mouth of the Bassac, this reworking involves discrete sand banks migrating to the southwest as mangroves and mud are lost through erosion.

The typical coastal morphology in the sand rich sector is that of a bar-trough (ridge-and-runnel) beach associated with three to four systems of alternating bars and troughs. Sand and mud discharged from distributaries are transported by longshore currents which cause downdrift fining of grain size as the coarser grains are selectively deposited up-drift.
6.2.3.1 Discussion and integration of results

The sedimentary and erosional processes of the Mekong delta coast line are complex, reflecting the combined influence of sediment supply, the hydrodynamic regime, and possibly large-scale delta self-organisation. The erosion trend indicates either a net reduction in sediment supply to the delta and/or changes in patterns of deltaic sediment storage. Regarding sediment supply, the precipitation in the catchment, which determines river water discharge, is closely related to the strength of the south-westerly summer monsoon, and may be controlled by global warming and decadal-scale climate change, but there is no certainty of this (Wang, et al., 2011).
With respect to the second hypothesis, the rapid erosion of the western muddy part of the shoreline may suggest that mud is trapped in the river-mouth sector, rather than being transported towards the west. Erosion of the Gulf of Thailand shoreline has been reported as early as the 1870s, so the erosional pattern may not be wholly attributable to human-induced activities. There is evidence for changes in patterns of delta sediment redistribution from modelling of the coastal plume in which mud exiting from the river mouths is dispersed offshore and along the coast. Xue et al., (2012) have found that the strongly eroding western part of the delta presently receives less than 2% of the terrestrial mud supply stored in the mouth sector, even though this area previously exhibited the highest advance rates due to mud deposition derived from the rivers and transported by longshore currents (Xue et al., 2010).

Modifications to the channels of the Mekong may also be related to the observed changes in sediment transport:

- Deepening of river channels through sand mining may be increasing the trapping of fine-grained sediments within the river and delta, especially in channel-bifurcation zones;
- Salt wedge intrusion during the low discharge season may have increased, reintroducing back into the channels some of the fine-grained river sediment deposited in shallow coastal waters;
- Numerical modelling of flood levels suggests that the numerous dykes and embankments constructed in the delta increase the flow velocities in the river channels and canals, resulting in deepening (Hoa et al., 2007). This in turn could exacerbate salt-wedge intrusion and sediment trapping;

The sediment budget of the delta will be affected by future catchment developments, especially the construction of hydropower schemes and the continued extraction of aggregate for construction. Should all of the proposed hydropower projects be realized, the sediment trapping efficiency of reservoirs in the Mekong Basin would increase from about 11-12 Mt/year to 70-73 Mt/yr, which is a very substantial portion of the present estimates of sediment flux in the river.

In addition to the development activities decreasing sediment supply to the delta, the high vulnerability of the delta to sea-level rise and to extreme weather events such as cyclones, must also be taken into account. Future decreases in the sediment budget of the delta will lead to increased erosion rates, and large scale geomorphic re-organisation of the delta shoreline. The highly populated, ecologically rich and extremely productive Mekong delta is a mega-delta at risk.

### 6.3 Analysis and variability of transfer of nutrient in the Mekong delta

Loisel et al., (2014) used satellite images to investigate nutrient fluxes and the distribution of nutrients in the delta over different seasons. Coastal river plumes represent one of the final stages of material transport across the land-sea interface. The nutrient fluxes discharged from rivers directly impacts the concentration of phytoplankton in coastal areas. Chlorophyll-a concentration, (Chl-a), is a common pigment to all phytoplankton species, and can be used as a trace of nutrient enrichment and related processes.

Satellite remote sensing of ocean colour can be used to estimate Chl-a and other biogeochemical compounds, and is a powerful tool owing to the spatial and temporal coverage offered by the satellite observations. The satellite data are limited to the surface layer, and are not as accurate as in situ measurements. In situ measurements are required
to validate the satellite results in terms of absolute values, and in terms of temporal variability where long-time series are available.

The aims of this investigation are:

- To provide biogeochemical information on the surface waters of the Mekong estuary and surrounding coastal areas from satellite observation so of ocean colour;
- To analyse the derived bio-geochemical variables in order to detect seasonal and inter-annual trends.

This information is relevant to

- Understanding the nutrient contribution of the Mekong to the delta region and neighbouring coastal areas;
- Identifying high density zones potentially pointing towards high biodiversity and high fish resource areas;
- Understanding the evolution of nutrient discharge and distribution over the past decade.

### 6.3.1 Methods

Approximately 2,000 ocean colour satellite images were analysed for the period 1 January 2003 to 31 October 2011 covering the area shown in Figure 6.14. The images included MERIS Full Resolution (300 m), MERIS Reduced Resolution (1 km), MODIS (1 km) and SeaWiFs (1 km).

The number of images available for each year is summarised in Figure 6.15. The fewer number of images available for 2003 was taken into account when analysing the results.

![Google Earth image of the study area.](image1)

![Number of ocean colour satellite images available for each year for the study area.](image2)
The interpretation of ocean colour images from the Mekong delta region is challenging owing to the present of cloud cover associated with the two annual monsoons (May to October, November to April) and high turbidity of the water. Cloud cover and turbidity are both expressed as bright elements in Ocean Colour images, and need to be recognised and corrected. To alleviate these issues, an atmospheric correction was developed specifically for this project, and applied to all images. Following this, several algorithms which correct for high-turbidity were applied.

The following parameters were included in the analysis:

- Particulate backscattering coefficient (b<sub>bp</sub>) which is a good proxy for Suspended Particulate Matter (SPM);
- Spectral shape of b<sub>bp</sub> which is sensitive to particle size distribution and was used as an indicator of the relative proportion between small and large particles in the surface water (based on Loisel et al., 2006);
- Absorption coefficients of phytoplankton (a<sub>phy</sub>) as a proxy of nutrient concentration;
- Absorption coefficient of coloured detrital matter (a<sub>cdm</sub>) as an indicator of the level of organic compounds in the water either due to anthropogenic activities or decomposition of terrestrial vegetation;
- Vertical attenuation coefficient for the down-welling irradiance (K<sub>d</sub>) as an indicator of the quantity of light available in the water column.

The 2000 images were analysed using 12 algorithms to derive the previously listed parameters, with the results statistically analysed (median, std dev, number of results) on a monthly and annual basis. The statistical parameters were used to produce monthly and annual maps. In addition to the parameters, a bio-optical threshold was evaluated based on chl-a levels which provided an indication of what percentage of time a suspended sediment concentrations exceeded a specified threshold (e.g. 3 g/m²). The persistence values provide information about areas where light availability is limited, which can directly impact marine life.

Validation of the results was completed via two oceanographic cruises which collected optical and biogeochemical data at 12 stations. Parameters included dissolved organic carbon, coloured dissolved organic matter, chlorophyll concentration and total, organic and inorganic suspended particulate matter.

A trend analysis of the results was completed using the X11 method, adapted in Vantrepotte et al., (2011). The X11 technique is based on the ‘ratio to moving average’ described in 1931 by Macaulay and modified by Pezzuli et al., (2005). The approach is based on the assumption of statistical stationarity of the time series and the consideration of a linear trend, both of which are reasonable assumptions for a time series of relatively short duration. The X11 method involves three steps:

- Estimation of the (linear) trend over the whole time window by a moving average;
- Removal of the trend from the initial signal, thus leaving the seasonal and irregular components;
- Estimation of the seasonal component using moving averages to smooth out irregularities.

For this study, the X11 method was used at two levels:

- At a pixel level, thus providing maps of seasonality;
- For each biogeochemical parameter averaged as a single value at the Mekong delta mouths.

Within the trend analysis, a variety of algorithms were used to cross-check and compare results. The full report should be consulted for a more completed description of the analysis under taken.

![Image](image.jpg)

**Figure 6.16. Area from which biogeochemical parameters are averaged to conduct the trend analysis**

### 6.3.2 Results

Median monthly Chl-a results for 2005 are presented in Figure 6.17 to provide an example of monthly patterns during a representative flow year (Xue et al., 2012). The highest Chlorophyll production occurs in December and January, which is two months after peak river flow. During this period, the Mekong plume is oriented south-westwards due to the general direction of the winter monsoon. The variability of results during January was found to be higher than during June, although median values were similar (although spatially more limited), with the difference most likely attributable to increased wave action during this period.
Summary of IKMP & WWF Sediment Investigations
The stability of chlorophyll distribution in the delta area is demonstrated in Figure 6.18 where the number of months in each year that median chlorophyll values exceed 2 g/m³ is shown. Except for 2003, for which a limited number of images are available, there is a high level of consistency between the years, with elevated chlorophyll levels occurring 8 months in the near delta region.
Summary of IKMP & WWF Sediment Investigations
Figure 6.18. Level of persistence of high chlorophyll concentrations. Maps show number of months in the year when median chlorophyll value exceeded 2 g/m³.

The particle backscatter results, as an indicator for Suspended Particulate Matter, (Figure 6.19) shows that the distribution of turbidity varies extensively during the year, which is attributable to several factors:

- Wind effects superimposed on the plume drift affects the distribution and strength of upwelling;
- The water discharge from the Mekong River;
- Wave action

The maps show elevated turbidity in August to October, coinciding with flood flows in the Mekong, however, turbidity remains elevated through November and December. This is due to increased wave energy associated with the onset of the November to April monsoon.
Summary of IKMP & WWF Sediment Investigations

January

February

March

April

May

June
Figure 6.19. SPM distribution maps as shown by the monthly median value of backscattering coefficient for 2005.
6.3.3 Results of field investigations
The results from the two oceanographic cruises completed in December 2011 and March 2012 show that whilst the surface concentration of Chlorophyll spans about the same range for the two periods (0.65 – 9.34 mg/m³ in December, 0.23-10.38 mg/m³ in March), the composition of the particulate matter is very different, with the organic fraction of the particulate fraction averaging about 20% in December and 40% in March. This observed increase occurred for both the near shore and off-shore monitoring sites.

6.3.4 Trend analysis
Trend analysis results for the biogeochemical parameters showed similarities. An example of the results for Kd 490, which integrates Chlorophyll, SPM and CDM is presented in Figure 6.21, and a summary figure for three parameters being representative of the results overall is contained in Figure 6.22. Results for Chlorophyll-a (indicator of nutrients and phytoplankton), Kd 490 (indicator of turbidity), and bbp (indicator of SPM) all have decreasing trends over the study period. The results also suggest that the seasonal amplitude is decreasing which is probably a major factor in explaining the overall reduction.

The decreases in SPM are mainly observed during the high flow season. The distribution of SPM in the coastal waters near the delta reflect the integrated and combined effects of natural and anthropogenic forcings affecting the delta. While further examinations, based on longer data records are needed for understanding the observed decreaseing trend in suspended fine sediment, the impact of different natural and anthropogenic forcings such as hydropower dam impact, river bed aggregate extraction and meteorological extreme events should be examined. Whatever the mechanism, the trend analysis suggests a decrease in Chlorophyll and sediment loads of up to 5% per year in the SW axis of the Mekong plume as well as in the south of the delta.
Figure 6.21. Example of trend analysis results for Kd 490. This parameter is presented as it integrates Chlorophyll, SPM, CDM and as it

Figure 6.22. Summary of averaged evolution of biogeochemical parameters in the Mekong delta. Chl-a is indicator of phytoplankton and nutrients, Kd 490 is Coefficient for down-welling irradiance and a measure of turbidity, and bbp is indicator of particle size distribution

Care needs to be taken when interpreting these results. Although several different methods have been used which show consistent results with the trends presented here, the Mekong delta waters are very turbid and application of optical image information in the visible part of the spectrum is still subject to research. There remain uncertainties with some of the parameters, and the study is limited to a ten-year period which may not be indicative of longer trends.
However, there is a common indication that biogeochemical compounds being delivered to the sea from the Mekong are declining. The level of decrease may be refined through future investigations but the direction of the trend is similar across the various methods used.

7 Synthesis of results

The sediment and geomorphology investigations completed by IKMP and the WWF have greatly increased the available information and knowledge about sediment transport and geomorphic processes in the Mekong River, and the delivery and movement of sediment and associated nutrients in coastal waters near the delta. The investigations have highlighted changes which have occurred over time-scales of years to decades, and can be used to understand potential future changes associated with development scenarios, such as hydropower development.

This section synthesises the results of the investigations, and highlights the advancements which have been achieved through the co-operative MRC – WWF approach. The synthesis is also used to identify areas where additional information is needed to understand the processes operating in the LMB and can be used to guide future research directions.

This synthesis is brief, and limited to provide a technical discussion of the results in the context of sediment transport and geomorphology. Additional discussions regarding potential impacts and linkages with ecosystem or social issues can be found in the original reports and published papers, and should be consulted for more detail.

The areas where the investigations have greatly increased the understanding of sediment and geomorphology in the LMB can broadly be categorised as follows:

- The magnitude, pattern and modes of sediment delivery;
- The processes controlling and activities affecting sand and silt in the river, delta and coastal waters;
- The overall sediment budget of the Mekong taking into account existing catchment development.

7.1 Magnitude, pattern and timing of sediment delivery

7.1.1 Suspended sediment

As discussed in Section 2, prior to these investigations, the suspended sediment load of the Mekong River was cited as being ~160 Mt/yr, with ~50% derived from the catchment upstream of the border with China based on sediment monitoring results from the 1960s to mid-2000s (Walling, 2005). The concentrations of suspended sediment increased at the initiation of the wet season, and remained elevated throughout the high flow season. The nature of the suspended sediment was widely regarded as being dominated by silt, and there was virtually no information about the nature or volumes of material being transported as bedload.

The sediment monitoring completed under the DSMP, has demonstrated that the magnitude of sediment transport in the river is substantially less than 160 Mt/yr, with an average value of 77 and 73 Mt/yr measured at Stung Treng and Kratie, respectively for the period 2009 to 2013. The sediment load entering from China is now estimated to be approximately 10 Mt/yr, as compared to ~70 to 80 Mt/yr historically. This reduction is consistent with the
trapping of sediment in the upstream Lancang hydropower cascade, with the magnitude of reduction consistent with the model prediction derived by Kummu (2010). In the 3S River system there are no historic monitoring results, but the 8.5 Mt/yr sediment load recorded by the DSMP is consistent with post-dam sediment loads modelled by Carling (2009) which suggest that sediment discharge from the tributary has undergone a reduction from 17 Mt/yr to 10 Mt/yr.

In the 2009 to 2013 period, suspended sediment concentrations tended to peak at the onset of the wet season, and then declined over the high flow period, which is a substantial difference from historic measurements, and suggests that there is a lack of sediment available for transport. The field observations collected by Bravard et al., (2013) did not include any clear evidence of sand erosion to the river banks between Chiang Saen and Luang Prabang or even farther downstream, although it is acknowledged that no inter-annual comparisons were included. The authors suggest that the area prone to bank erosion at present is likely limited to the reach between the lowest Lancang dam and Chiang Sean, which was not included in the investigations.

The magnitude of the suspended sediment loads has been found to vary considerably between years, but the pattern of sediment delivery is uniform in the Mekong, with approximately 60% of the sediment load transported in August and September, and 80% of the load transported between July and October.

The DSMP investigations have provided insight into the elevated suspended sediment concentrations and fluxes frequently reported in the central LMB, particularly at the sites of Mukdahan, Kong Chiam. It is likely these results are reflecting the increased suspension of sand in the water column due to the channel hydraulics, combined with the use of undersized suspended sediment monitoring equipment, resulting in the over-sampling of the suspended sediment in the water column. The existing results are likely to over-estimate suspended sediment transport through this reach and future investigations are required to better define sediment transport in this important zone of the river. Upgrading the monitoring equipment used in these river reaches is critical to advancing the understanding of sediment movement in the Mekong.

The investigations by Bravard et al 2013, and Dramais et al., (2013) have advanced the understanding of sand movement in the river. The authors present clear evidence that sand is transported as bedload, and as graded and uniform suspension in the river. The spatial distribution of results is consistent with sand being transported in suspension in steeper reaches, and during periods of higher flow, as demonstrated by the strong link between the hydraulic energy of river reaches and the elevation of sand deposition above low water level. The work has highlighted that the mode of sand transport varies over time and distance in the river, which, in conjunction with the over-sampling of suspended material due to equipment limitation, may account for some of the ambiguities in previously reported sediment balances (e.g. higher suspended loads at Mukdahan and Kong Chiam as compared to upstream or downstream).

The monitoring results from the DSMP are consistent with these findings, with sand being present in suspended sediment samples throughout the catchment during periods of higher flow. Contrary to the view that the suspended sediment load of the river is restricted to silt, the monitoring results shows that approximately 20% of the suspended load at Kratie consists of sand sized material on an annual basis. Further upstream in the catchment the percentage of sand increases in the suspended load, accounting for 85% and 75% of the suspended load at Chiang Saen and Luang Prabang, respectively.

Bravard et al. (2013) and the DSMP results highlight the importance of sediment inputs from tributaries downstream of the Lancang cascade, with the Nam Ou identified as an
importance source of courser grained material. The DSMP results suggest that a similar quantity of suspended sediment is entering the Mekong between Chiang Saen and Luang Prabang (~11.5 Mt/yr) as is presently entering the Mekong from China (~10.8 Mt/yr).

7.1.2 Bedload transport
Bedload is extremely difficult to monitor and results for the Mekong are limited but the DSMP monitoring results and modelling provide order of magnitude estimates of bedload movement in the catchment. The quantity of material moving as bedload is low compared to the suspended load of the river, with estimates in the range of 1 to 5 Mt/yr based on the physical collection of samples, and 1 to 10 Mt/yr at the monitoring sites based on modelling. An ex exception is Mukdahan, where modelling suggests potential bedload transport rates of up to 20 Mt/yr during a wet year (2011). The results are equivalent to ~3% to 6% of the suspended sediment load at Kratie, but up to ~20% at Nong Khai, where current suspended sediment loads are considerably lower as compared to historic monitoring results. The grain-size of bedload material fines downstream, with gravels and sands predominating at Chiang Saen, and sands and silts at Kratie.

The physical sampling of bedload is extremely difficult under conditions of high flow, and future monitoring should include the use of ADCP ‘moving bed results’ to better understand bedload transport. Estimates of bedload using this approach at Nong Khai (1.3 – 4.1 Mt/yr) produced results of similar magnitude to physical sampling results or sediment transport modelling results. The ease of implementation warrants extension of these measurements to all sites where ADCP measurements are collected.

7.2 Processes controlling and activities affecting sand and silt
The WWF investigations have highlighted the differences between the processes controlling and activities affecting sand-sized and silt-sized sediment in the Mekong River.

Sand sized material is transported as bedload and suspended load in the river, and is highly visible within the river channel during low flow periods. The mapping and CM analyses completed by Bravard et al, (2013), demonstrate that sand can be carried throughout the water column (uniform suspension) during high flow periods or as graded suspension during lower flow. The temporary storage of sand within the channel is evidence of the episodic nature of sand transport, and the inter-annual storage of sand sized material which occurs in the LMB.

In contrast, once suspended in the river, silt and finer material is typically transported as wash-load, with limited inter-annual storage. Fine material is trapped in some quiescent environments, but the abundance of sand as compared to silt in the mapped features of Bravard et al, (2013) combined with the high percentage of silt and finer sized material in the suspended load at the river upstream of Phnom Penh (>80%) underscores the tendency for these finer grain-sizes to remain in suspension and be transported downstream without interruption.

In addition to difference in transport processes, the fate of the material and the activities which affect the delivery of sediment to the sea are different for the grain-size classes.

7.2.1 Sand sized sediment
The transport of sand has been demonstrated to be linked to the hydraulics of the river channel and vary over time and space within the Mekong. The intermittent or episodic nature of sand suspension contributes to ambiguities in the sediment budget of the river, with proportionately more sand being carried in suspension in some reaches as compared to
others. The work of Bravard et al., (2013) suggest that conveyance losses to the floodplain are not required to understand the observed discrepancies in the sediment budget.

The WWF survey of sand and gravel mining activities in the LMB has enhanced the understanding of the sand-budget of the river by providing the first quantitative estimate of the magnitude of material being extracted from the river, and the spatial and temporal distribution of sand mining activities.

The survey results, which should be considered as minimum values, conservatively estimate extractions from the river at ~34.5 Mm$^3$/yr (equivalent to ~55 Mt/yr), with 90% of the extractions comprising sand and 60% attributable to activities in southern Cambodia, indicate this is a major activity, which must be considered in the context of the sediment budget and geomorphic functioning of the Mekong River. The estimated extracted quantities of sand and gravel are an order of magnitude greater than the recent estimates of bedload transport in the river at Kratie. Even taking into account the ~20% of the suspended load at Kratie which is sand-sized (~14 Mt/yr), the magnitude of sand being extracted from the river greatly exceeds the quantity of sand being transported by the river under present conditions.

The imbalance between the volumes of material being extracted from the river compared to the sand load being transported by the river accounts for the transient nature of most extractive operations, with operators needing to continually identify ‘new’ deposits as existing ones are depleted and not replenished.

Geomorphologically, the extractive activities result in ‘borrow’ pits on the bed of the river, which are evident in echo soundings of the river. The persistence of these features demonstrates that sediment deposition is insufficient to re-fill these features over short time frames.

The investigations of Brunier et al., (2014), which documented widespread channel deepening and to a lesser extent channel widening in the Mekong and Bassac in the delta region are consistent with the sand extraction survey results. The evidence is even more compelling when the lack of correlation between stream hydraulics and channel deepening is considered, indicating there is a very low probability that the channel changes are attributable to river flow alone. The comparative survey results show channel losses equivalent to 90 Mm$^3$ and 110 Mm$^3$ in the Mekong and Bassac channels, respectively, with the majority of this attributed to impacts from extractive activities.

Channel deepening in the delta (and river) is not limited to the extent of the extractions, as following sand mining, bed slopes will tend to steepen, leading to increased river energy and additional channel deepening through scour. Over time, the channel bed may regain the pre-mining slope, but at a reduced bed elevation. The flow-on effects from channel deepening include bank instability, increased salt-water intrusion rates, and increased sediment trapping.

Sand mining has increased over the same period that sediment input from China has decreased suggesting cumulative impacts are likely to be affecting the delta. Within the context of the LMB sediment budget, the loss of ~200Mm$^3$ from the channels of the Mekong and Bassac over a 10-year period is consistent with extractive activities removing ~8 Mm$^3$/yr locally, and 35 Mm$^3$/yr on a catchment basis over a 20-year period, during a time when sediment inputs decreased substantially.

Anthony et al., (2013a & b) have documented changes to the delta near the sandy eastern river mouths of the Vietnam delta, and has interpreted these changes as evidence of delta ‘reorganisation’. These changes are likely being driven by the alterations in sand delivery to the delta front, owing to upstream reductions in sand inputs, extractive industries, and
changes in the timing of sand delivery (higher concentrations limited to the onset of the wet season).

The satellite and ground-based investigations of Loisel et al., (2014) indicate that under the monsoonal climate patterns which characterise the delta, sand and mud discharged from distributaries are transported via longshore currents which cause down-drift fining of grain sizes as the coarser grains are selectively deposited up-drift. Shoreline re-organisation is occurring due to an increase in the reworking of coastal sediments under a regime of reduced sediment supply. South of the Bassac mouth, this reworking involves discrete sand banks migrating to the southwest as mangroves and mud are lost through erosion.

In summary, the sand balance / budget of the Mekong is in a state of change, owing to the reduction in sediment input from upstream, the large quantity of material being extracted from the river, and the flow-on effects of these changes on the geomorphic processes operating in the Mekong (bank instability, channel deepening, changes to sediment delivery patterns, changes to water levels associated with channel changes, etc.). Bravard et al. (2013) noted that there was no evidence of bank erosion associated with a reduced sediment supply following development of the Lancang cascade, which suggests there is a high risk of additional reductions in sand transport through the river as impacts associated with the development of the cascade propagate downstream, or future tributary dams further decrease sand supply to the mainstream Mekong.

7.2.2 Silt sized sediment
The transport mode of silt-sized and finer material in the Mekong is generally as wash-load. There is little inter-annual storage of this material however bed samples collected during the low flow periods have had finer-grain sizes as compared with samples collected during high flow, suggesting some inter-annual storage of fines does occur.

The recent sediment investigations have shown a large reduction in the suspended sediment load of the Mekong relative to historic monitoring results. Silt is the predominant size fraction present in the suspended sediment load, as observed historically and quantified through the DSMP, and it is highly likely that there has been a large reduction in the quantity of silt entering from upstream of the LMB, although there are no grain-size results from historical monitoring to quantify grain-size changes.

Because silt sized material tends to remain in suspension in the river, the reduction in sediment load is unlikely to have resulted in large scale geomorphic changes to the river to date (impacts on delta are discussed below), which is consistent with the observations of Bravard et al. (2013). A reduction in wash load transport is likely to lead to geomorphic changes over longer-time periods, with lower sediment transport rates promoting channel incision. Deeper channels may reduce flooding and reduce sediment deposition on flood plains, leading to a loss of fertility. The floodplains of Cambodia and Vietnam would be at most risk from these changes.

There is a high likelihood that the reduction in silt-sized material is contributing to some of the documented changes presently occurring at the delta front and in the coastal sediment plume.

The extensive shoreline retreat of the muddy western delta and coast of the Gulf of Thailand as observed by Anthony et al., (2013 a&b) is consistent with a reduction in fine-grained sediment supply to the sea. Retreat rates of -12 m/yr have been recorded along the western part of the delta, which in the past was accreting at rates of >20 m/yr (Xue et al., 2010).

A reduction in SPM, Chl-a and other indicators in the coastal plume are also consistent with a reduction in sediment inputs from the river. The largest reductions in coastal SPM have
been documented during high flow periods, which parallel the reduction in suspended load of the river during the wet season.

It is not possible to directly link the reduction in sediment loads entering the LMB from China to the observed changes in the delta, because there are other processes which can also be contributing to the decline in sediment delivery, such as increased deposition of fines in ‘borrow’ pits created by aggregate extraction, increased deposition in the upper delta due to flow changes, increased remobilisation of material from the coastal area back into the delta due to increased salt-wedge intrusion, and decreased delivery of sediment to the sea due to changes in the flow regime, monsoon patterns or climate change related phenomena. However, the observed retreat of muddy coasts along the southwestern delta front and the Gulf of Thailand, and the observed suspended particulate matter, nutrients and turbidity in satellite images are all consistent with a decrease in sediment delivery to the sea.

### 7.3 Revised sediment budget for the Mekong River

The IKMP and WWF investigations have refined the understanding of sediment transport in the Mekong and can be used to construct a sediment budget for the river, as shown in the Tables below.

#### Table 14. Summary of sediment transport estimates in the Mekong

<table>
<thead>
<tr>
<th>2009-2013 Monitoring Results</th>
<th>Chiang Saen</th>
<th>Kratie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average suspended sediment (Mt/yr)</td>
<td>10.8 Mt/yr</td>
<td>72.5 Mt/yr</td>
</tr>
<tr>
<td>% Sand</td>
<td>85% (9.2 Mt/yr)</td>
<td>20% (14.5 Mt/yr)</td>
</tr>
<tr>
<td>% Silt</td>
<td>15% (1.6 Mt/yr)</td>
<td>60% (43.5 Mt/yr)</td>
</tr>
<tr>
<td>Bedload estimate range (sand &amp; larger)</td>
<td>1.6 Mt/yr (measured)</td>
<td>1 – 16 Mt/yr (measured, modelled)</td>
</tr>
</tbody>
</table>

#### Table 15. Summary of sediment extractions from the Mekong in 2011-2012. Values should be considered as minima.

<table>
<thead>
<tr>
<th>2011-2012 Extractions</th>
<th>Percent</th>
<th>Mass (Mt)</th>
<th>Volume (Mm³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total based on survey</td>
<td>100</td>
<td>55.2</td>
<td>34.5</td>
</tr>
<tr>
<td>% Sand</td>
<td>90</td>
<td>49.7</td>
<td>31.1</td>
</tr>
<tr>
<td>Lao PDR</td>
<td>3.9</td>
<td>2.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Thailand</td>
<td>13.1</td>
<td>7.2</td>
<td>4.5</td>
</tr>
<tr>
<td>Cambodia</td>
<td>60.3</td>
<td>33.3</td>
<td>20.8</td>
</tr>
<tr>
<td>Vietnam</td>
<td>22.5</td>
<td>12.4</td>
<td>7.8</td>
</tr>
</tbody>
</table>

The average sediment transport in 2009 – 2013 is substantially less than recorded in previous years (see Figure 3.7), reflecting the reduction due to the construction of the Lancang Cascade in China and other land use changes. The percentage of suspended sediment entering from China now equates to ~15% of the suspended load at Kratie, rather than 60% as shown by historical results.

The scale of extractions from the Mekong is equivalent to 62% to 75% of the total sediment load (based on average value at Kratie and range of bedload estimates). However, the extractions are limited to sand-sized and larger material. The monitoring results suggest a maximum of 30 Mt/yr of sand is being transported in the suspended and bedload fractions in the lower river. Even if all of the sand were deposited in the river and available for mining, there would be a deficit of ~ 25 Mt/yr (15.6 Mm³) of sand in the river.
With the large reduction in sediment input from China, tributary inputs have increased in relative importance to the sediment budget. The 3S River system is estimated to contribute 8.5 Mt/yr or ~12% of the suspended sediment load. Additional information about the sediment contribution from other tributaries is required to better understand the distribution of sediment inputs in the LMB.

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