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Case study on sediment in the Mekong River Basin: Current state and future trends

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List of abbreviations

DSMP	Discharge and Sediment Monitoring Programme
IHP	International Hydrology Programme
IKMP	Information and Knowledge Management Program
ISI	International Sediment Initiative
IWRM	Integrated Water Resources Management
LMB	Lower Mekong Basin
LMC	Lancang Mekong Cooperation
MRC	Mekong River Commission
Mt/year	Million tonnes/year
PDG	Preliminary Design Guidance
PRECIS	Providing Regional Climates for Impacts Studies
RBO	River Basin Organization
SEI	Stockholm Environment Institute
SSL	Suspended Sediment Load
SWAT	Soil and Water Assessment Tool
UMB	Upper Mekong Basin
UNESCO	United Nations Education Scientific and Cultural Organization

EXECUTIVE SUMMARY

The Mekong River flows through six countries: China, Myanmar, Lao People's Democratic Republic (PDR), Thailand, Cambodia and Viet Nam. Approximately 70 million people live in the basin and about 60 million in the Lower Mekong Basin (LMB). The Mekong is a nutrient-rich sediment river. Sediment and nutrient transport are critical to ecological health and the distribution of aquatic habitats, and also important for water quality, floodplain processes and overall basin productivity, particularly in fisheries and agriculture. Sediment transport in the Mekong will be affected by existing and planned large-scale hydropower projects in the mainstream and its tributaries, as well as other activities such as riverbed mining, deforestation and development in both the floodplains and the Mekong Delta. Land use change and extreme events linked to climate change are expected to exacerbate the current situation. To ensure sustainable development, sediment management needs to become a key consideration in land and water resource planning and implementation,.

This report identifies the key issues around sustainable sediment management in the Mekong River Basin based on a desk study review. The study seeks to contribute to the implementation of the International Sediment Initiative (ISI) of UNESCO's International Hydrological Programme (IHP). It is also expected that this information will be useful for policymakers in the region and beyond, as well as for external donors to improve the targeting of support for sediment management efforts in the Mekong Basin. The study identifies a number of the key messages on and challenges facing sediment management in the Mekong Basin.

- It has identified in previous studies that large hydropower developments in the Upper Mekong/Lancang River, the Mekong River and its tributaries, as well as riverbed mining particularly in the Mekong Delta, would lead to substantial reductions in the amount of sediment entering the Mekong mainstream system. However, the degree of sediment load reduction has been greater than estimated in previous studies.

- Evidence from monitoring results published by the Mekong River Commission (MRC) in 2013 on the situation before 2003 and after 2009 shows that average suspended loads reduced at Chiang Saen station from 60 to 10 Mt (an 83 per cent reduction), at Pakse from 120 to 60 million tonnes/year (a 50 per cent reduction) and at Kratie from 160 to 90 million tonnes per year (Mt/yr), a 43 per cent reduction.

- If all the dams proposed for the LMB are developed, including mainstream dams (the full hydropower development scenario), it is estimated that about 96 per cent of the sediment load will be trapped. This would mean that the sediment load reaching the delta region would drop to just 4 per cent of current levels.

- Land use change and extreme events linked to climate change will exacerbate the current situation and increase uncertainty over sediment transport from the catchments. These two factors have not been considered in the design phases of water resources infrastructure development, such as for hydropower dams and flood protection dykes.

- The decline in sediment transport linked to the development of large hydropower projects in the mainstream is expected to have a heavy impact on nutrient transport. Under the full hydropower development scenario, the total transport of phosphorus in the mainstream at Kratie is projected to reduce from 47 to 53 per cent, and of nitrogen from 57 to 62 per cent.

- In Viet Nam in the Mekong Delta, there has already been a significant change in the colour of the river from a reddish-brown to an ocean-like blue. Mainstream dams cutting the transport of sediment and nutrients, as well as loss of habitat, will induce a 12-27 per cent reduction in the primary productivity of the aquatic systems, that is, the vegetal productivity of the delta region.

- Fish reproduction, in particular of some river fish species such as Lithophils, Psammophils and Pelagophils, is dependent on bedload and wash load. These fish may not be able to adjust to changes in their feeding and spawning grounds. Many studies indicate that a reduction in sediment and nutrient loads could lead to river and coastal fisheries yield depletion. However, fish production in the Mekong is a multi-factor phenomenon and is not dependent on sediment alone. Lack of knowledge about fish replacement, growth and mortality weakens the assessment of the relationship between sediment load and fish production.

- The Mekong Delta is one of the most productive regions for fisheries and agriculture in the world. The projected sediment reduction linked to the 11 existing and proposed mainstream dams in the LMB could potentially result in a decline in total rice production in Viet Nam and Cambodia of approximately 552,500 tonnes and 203,300 tonnes respectively in the next 10 years.

- Sediment monitoring data for both suspended and bed loads in the Lancang and Mekong rivers and their tributaries, however, are still too limited in terms of spatial and temporal resolution to accurately determine how much of the sediment load from tributaries enters the Mekong mainstream, floodplains and delta. As a result, there is no consensus on sediment baselines among the countries in the Mekong Basin.

- Best practices in sediment management and mitigation measures to address sediment transport and geomorphic aspects, for both upstream and downstream hydropower developments, have not yet been considered at every stage of the hydropower lifecycle in many projects.

- Coordination among different agencies is always a key challenge to the effectiveness of sediment management and control. On the sediment issue at the regional level there are policy gaps as well as barriers to integrating regional sediment management strategies/guidelines into national policies, and developing national action plans to reduce the risks from the reduction of sediment and nutrient loads in the Mekong mainstream due to the accumulated impacts of sediment trapping by reservoirs, riverbed mining, land use change, climate change, etc.

The study makes the following policy recommendations to guide river basin managers and operators in addressing the key challenges and knowledge gaps.

- Continue to improve and enhance sediment monitoring systems at the national and regional levels, covering major tributaries of the Mekong River and at strategic locations such as Tonle Sap, as well as key environmental hotspots, especially in the floodplains and delta areas.

- Enhance data sharing on sediment monitoring between China and the Lower Mekong Countries through existing mechanisms such as the MRC and Lancang-Mekong Cooperation (LMC), and develop joint projects to observe changes in sediment transport and assess the consequences and impacts downstream, particularly in the short term between the border with China and upstream to Vientiane.

- Establish sediment baseline conditions to assess the relative changes to and actual impacts on sediment due to development, land-use change and climate change, and define targets for sediment management and mitigation measures, particularly for large hydropower projects on the Mekong mainstream and its tributaries.

- Implement best practices on sediment management and mitigation measures so that sediment issues at the national and regional levels are integrated at every stage of the hydropower lifecycle from planning to development and operation.

- Develop regional standards and safeguards on transboundary sediment issues and institutional arrangements for their enforcement, and ensure that they are integrated into national policies, strategies and implementation plans. The MRC Preliminary Design Guidance for Mainstream Dams should be reviewed periodically to ensure that it reflects the current situation and issues on sediment transport.

- Improve coordination and collaboration on sustainable sediment management among different agencies at the national and regional levels through regular dialogue and enabling legal and institutional frameworks; establish working groups and engage with development partners.

- Increase the involvement of relevant stakeholders and communities in sediment management and developing mitigation measures to provide sufficient information on how they can improve river health and contribute to sediment management, and how they should adapt to adverse impacts.

- Enhance collaboration with international agencies and research communities such as the ISI to exchange experience on sediment problems, sediment management issues and techniques, and practical solutions among the various river basins.

1 INTRODUCTION

Geomorphology and sediment transport are the fundamental characteristics of a river ecosystem and play an important role in water quality, navigation and riverbank stability. Sediment transport and sediment characteristics are critical to the condition and distribution of aquatic habitats. Sediment is also important for water quality, floodplain processes and overall basin productivity.

The Mekong River flows through six countries: China, Myanmar, Lao PDR, Thailand, Cambodia and Viet Nam. Approximately 70 million people live in the basin: about 60 million in the Lower Mekong Basin (LMB) and remaining 10 million in the Upper Mekong Basin (UMB) (FAO 2011). While the region is undergoing rapid economic growth, many among the Mekong River Basin's population still live in poverty. The livelihood and food security of most of the people are directly linked to the Mekong River and the resources it provides. The Mekong is a nutrient-rich sediment river. This is in part a consequence of the river's flood pulse character, whereby at any given period large volumes of water are moving through the system along with associated sediments. The fine materials are rarely deposited but suspended in water and generally carried through the system to the sea. Slightly coarser material may end up on flood plains and riverbanks, where it helps floodplain farms with fertilizer and food for fisheries. Larger particles such as sands and gravels may take decades or longer to be transported and so are temporarily stored in the channel or on riverbanks where they create stable and resilient channels, providing important ecological habitats and navigation.

The health of rivers and the natural services they provide deteriorate when natural flows of water, sediments and organic materials are disrupted. The amount of sediment delivered to the Mekong is controlled by tributary flows and catchment characteristics and activities. The Mekong River provides drinking water, irrigation supply, groundwater recharge, navigation and fisheries. A number of hydropower dams are planned and are being developed along the mainstream and tributaries of the Mekong River. The sediment trapped by existing and proposed dams will significantly reduce the sediment loads entering the Mekong River (Kummu et al. 2010; Pukinskis 2013; Kondolf et al. 2014). Other activities affecting sediment transport are riverbed mining, deforestation and development of the floodplains and the Mekong Delta (MRC 2016b). To ensure sustainable development, sediment management needs to be a key consideration in land and water resources planning and operations.

UNESCO's International Hydrological Programme (IHP) launched the International Sediment Initiative (ISI) in 2003. The ISI aims to develop a decision support framework for sediment management, to provide guidance on legislative and institutional solutions applicable to various socio-economic and physiographic settings, and to further advance sustainable sediment management in the context of global change. In 2012-13, the ISI carried out a comparative study of sediment issues in major river basins in Asia and the Pacific. The study will contribute to the implementation of the eighth phase of the IHP (IHP VIII 2014-2021), 'Water Security: Responses to Local Regional and Global Challenges'. To continue this initiative, the UNESCO-IHP intends to carry out a case study in the Mekong Basin.

The aim of this report is therefore to identify the key issues on sustainable sediment management in the Mekong Basin, which faces vulnerabilities linked to rapid development and climate change. It was undertaken based on a literature review. It is intended that this information will be useful for policymakers in the region and beyond, as well as external donors to help them better target their support for sediment management efforts. This report summarizes the current state of knowledge on sediment in the Mekong Basin, as well as the current situation and future trends, the impacts of development and climate change on sediment transport, and the environmental, social and economic implications and key challenges. It also makes policy recommendations on sustainable sediment management.

2 STUDY AREA

2.1 Physiography and Geomorphology

The Mekong River is the tenth longest river in the world. It originates on the Tibetan plateau and flows through a narrow, deep gorge along with the Salween and Yangtze Rivers, which together is known as the 'Three Rivers Area'. The Mekong River then flows through Myanmar, Lao PDR, Thailand and Cambodia before finally draining into the sea creating a large delta in Viet Nam covering an area of 795,000 km^2 (see Figure 1). The basin is divided into two parts: the Upper Mekong Basin (UMB), consisting of the Tibetan plateau, the Three Rivers Area and the Lancang Basin; and the Lower Mekong Basin (LMB), consisting of the Northern Highlands, the Khorat Plateau, the Tonle Sap Basin and the Mekong Delta.

Figure 1: The Mekong River Basin (FAO 2011)

The geomorphology of the Mekong River is divided into six zones, based on the general geomorphic characteristics of the mainstream as shown in Figure 2. The Mekong River in the UMB is confined to a narrow, steep bedrock valley for the first 1800 km of its course. Gradients reduce substantially in the LMB. In the LMB, the course of the river is mainly over strong bedrock in northern Lao PDR, before it enters a predominantly alluvial zone in the upstream area of Vientiane, which extends downstream to Savannakhet in Lao PDR and Mukdahan in Thailand. Downstream of this point, the river is structurally controlled to varying degrees until it enters the alluvial reaches of the floodplains near Kratie in Cambodia. The floodplain reaches, which include the Tonle Sap River, Tonle Sap Great Lake and the Mekong Delta, are considered sediment sinks in the context of the Mekong, although sediment is also derived from the tributaries that feed the Tonle Sap Great Lake (see Table 1).

Table 1: Geomorphic characteristics of the six zones in the Mekong River (modified from MRC 2016b)

Zone	Reach Description	Approximate Length (km)	Geomorphology
1	Lancang River in China	1800	Bedrock valley and narrow steep sloped channel
2	China border to upstream Vientiane	750	Single bedrock channel
3	Upstream Vientiane to Kong Chiam	800	Alluvial-braided with bars; sediment storage and reworking with high sediment input from tributaries
4	Kong Chiam to Kratie	350	Anastomosed bedrock channels, storage and reworking
5	Kratie to Chaktoumuk, Tonle Sap River and Great Lake	230	Meandering alluvial channels, floodplain and Tonle Sap system
6	Phnom Penh to Mekong delta in Viet Nam	350	Deltaic alluvial channels and distributaries

The major tributaries of the Mekong River are: Nam Ta, Nam Ou, Nam Soung, Nam Ngum, Nam Khan, Nam Mae Kok and Nam Mae Ing, in the Northern Highlands in zone 2; and the Songkhram and Mun rivers and the steep Nam Ca Dinh, Se Bang Fai and Se Bang Hiang rivers on the Khorat Plateau in zone 3. Further downstream, Se Kong, Se San and Sre Pok (the 3S Basin) enter from the left bank in zone 4 and the Tonle Sap Lake enters from the right bank during the dry season, while the flow reverses during the wet season, in zone 5. The Mekong Delta begins at Phnom Penh and the river splits into a number of smaller distribution channels to form an area known as the Nine Dragons in Viet Nam (zone 6).

2.2 Climate and hydrology

The upper part of the basin has a temperate climate. The taller peaks of the Tibetan Plateau are covered by snow in the winter months. These snows slowly melt during the dry season, feeding into the Mekong River. The Lower Mekong is usually hot and humid and has a tropical monsoon season. The south-west monsoon season runs from mid-May to mid-October. The highest annual rainfall (2500 mm) occurs in the western region of Lao PDR and the lowest (1000 mm) in the central region of Thailand. The hottest months are March and April, when the average temperature is 35^0C, while the temperature drops to 15^0C at higher elevations in the winter of November to February. Evaporation rates vary between 1000 and 2000 mm, with little variation from year to year due to the high relative humidity.

The upper Mekong tributaries contribute around 16 per cent of the total flow; 55 per cent comes from the larger left bank tributaries in Lao PDR and the 3S River system; and around 20 per cent is contributed by the Mun/Chi tributaries. The total annual discharge of the Mekong is 14,500 m^3/s, of which 75 per cent of the total volume flows (or or 460 km^3) is in the four-month period between July and October (MRC 2005). The annual hydrological regime of the Mekong is clearly defined by its seasonal monsoonal flood, which occurs between late June and late October. Flood pulse is the dominant trigger in the Mekong of the annual cycle of sediment flows and ecological processes within the fluvial system, which cause a distinct seasonality in the annual hydrobiological cycle between an aquatic phase and a terrestrial phase. As a consequence, there are highly seasonal biogeochemical cycles, growth rhythms and lifecycles among the many species of ecosystem system biota, such as algae, macrophytes, trees, fish and invertebrates, along the river (Piman et al. 2013b).

The major regional hazards in the Mekong Region are floods and drought. Annual floods have the potential to cause fatalities as well as damage to infrastructure, property, crops and productivity. Annual flood pulses also sustain the productivity of the Mekong freshwater fisheries. The average annual cost of the floods in the LMB is US$ 60-70 million but the average annual value of flood benefits is approximately US$ 8-10 billion (MRC 2017). Sediments and associated nutrients are the major factor supporting fisheries production in the basin (Baran et al. 2015). Unlike floods, droughts have fewer apparent benefits. Drought can result in food and water shortages, loss of income and higher levels of disease. Droughts are damaging to agriculture, especially rice, and can result in a total loss of crops, livestock and fisheries. During drought periods, the river will have less flow to transport sediment to the Mekong delta. Sediment deposition usually occurs in the middle reach of the river.

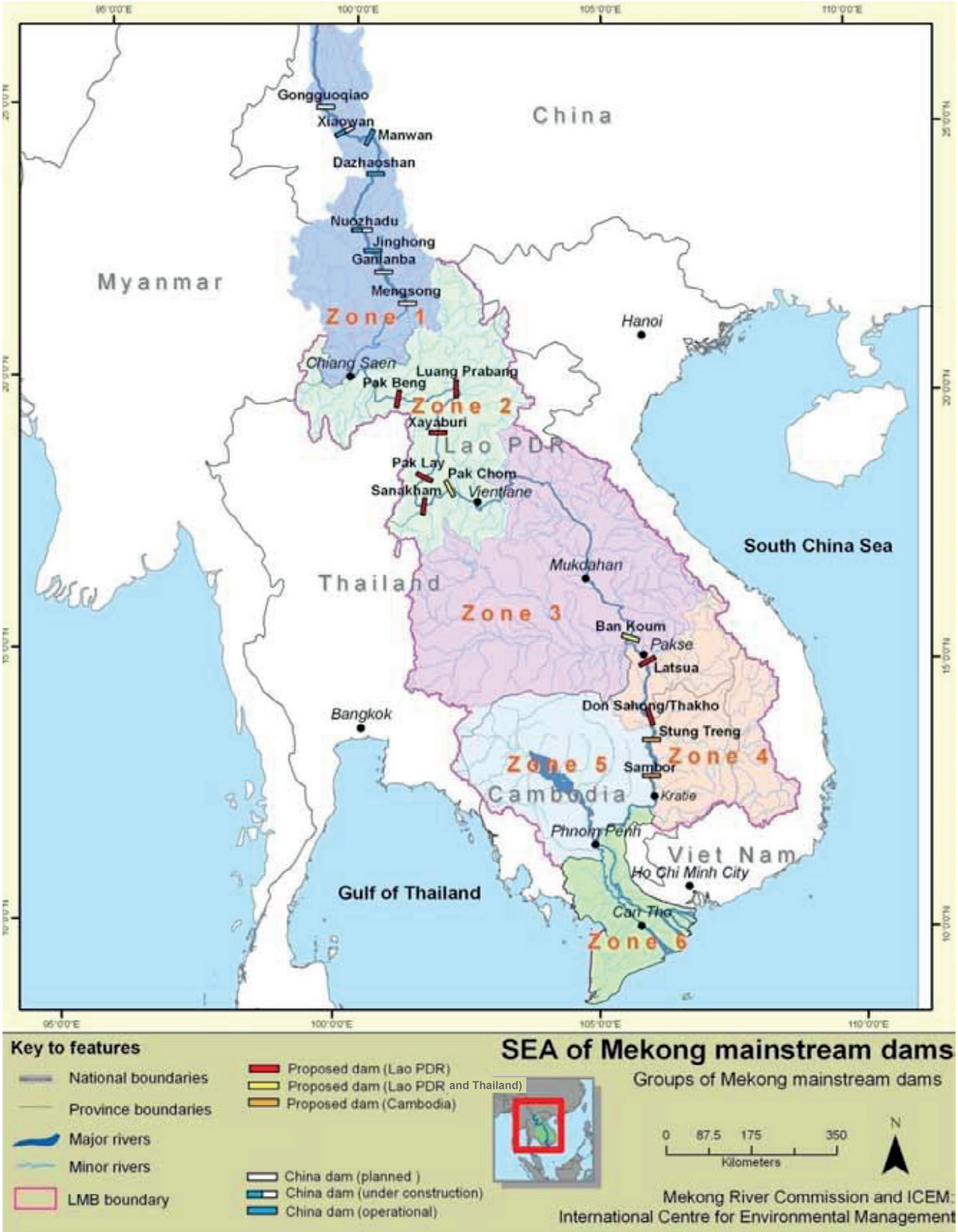

Figure 2: General geomorphic zones in the Mekong River and Mekong mainstream dams (ICEM 2010)

3 KEY WATER-RELATED DEVELOPMENTS IN THE BASIN

This section outlines the current status of the key water-related development sectors that have the potential to have a high impact on sediment transportation in the mainstream of the Mekong River.

3.1 Hydropower

Hydropower is a key active sector in the basin, particularly in China, Lao PDR and Viet Nam. Hydropower has led to several socio-economic benefits including bringing electricity to rural and urban areas. Total potential for hydropower development in the UMB is estimated to be 23,000 MW and total hydropower potential in the LMB is estimated to be 30,000 MW (MRC 2010). Of the latter figure, 13,000 MW is generated from 11 projects on the Mekong's mainstream. The remaining is from projects on its tributaries. About 13 projects are operational, under construction or planned in the UMB in China. Two large storage dams on the Lancang cascade – the 4200 MW Xiaowan and the 5850 MW Nuozhadu hydropower projects, with 9800 and 12,400 million m^3 of active storage respectively – recently became fully operational (see Figure 2). About 73 projects in the LMB are currently operational and a further 29 are under construction. These include the Xayaburi (1,260 MW) and Donsahong (260 MW) mainstream projects (WLE 2016). Only 16 of these were operating in 2000. The amount of live storage in hydropower dams in the LMB is shown in Figure 3, demonstrating how dams are regulating flows and trapping sediment. An additional 30 dams are planned in the next 20 years. It is predicted that sediment trapping by large dams in the mainstream and the cumulative impacts of tributary dams will drastically reduce sediment and nutrient loads in the Mekong River (ICEM 2010; DHI 2015).

3.2 Riverbed mining

Since at least the mid-1900s, sand and gravel mining on the Mekong River and its tributaries for construction and landfill have increased as the countries developed . The majority of sand extracted from the riverbed is for the construction of roads in the delta. These have been significantly extended and flood proofed over the past decade. There is also demand for sand and gravel in Malaysia and Singapore. This has triggered a large sand export business and led to larger-scale extraction. The locations of riverbed mining and estimated amounts of extraction are illustrated in Figure 4. The quantities of sand extracted are conservatively estimated at 50 Mt/yr (Bravard et al. 2014). This huge loss of sand caused water levels on the main channels to drop by more than a metre between 1998 and 2008, allowing salt seawater to flood rice paddies. Sand is also an important component of sediment and contributes to the creation of specific habitats for fish. This loss is a new issue for sediment management in the Mekong Basin, for maintaining sediment loads to the delta and riverbank stability.

3.3 Agriculture

About 70 per cent of the basin's population relies on agriculture for its livelihood. The total irrigation area of the basin is estimated to be around 4.3 million ha, of which 42 per cent is in Viet Nam, 30 per cent in Thailand, 12 per cent in China, 8 per cent in Cambodia, 7 per cent in Lao PDR and 2 per cent in Myanmar. Ninety-eight per cent of the cultivated area is irrigated by surface water. Groundwater accounts for the remaining 2 per cent (FAO 2011). In the Lower Basin, the dry-season irrigated area of about 1.2 million ha is less than 10 per cent of the total agricultural area. The Mekong Delta is one of the most productive regions in the world. It is often referred to as Viet Nam's 'rice bowl' as it produces more than 16 million tonnes of rice annually for domestic consumption and export (MRC 2010). The value of Thailand's agricultural exports in 2011 was US$ 37 billion and it had an agricultural trade surplus of US$ 27 billion. Viet Nam exported agricultural products worth US$ 14 billion in 2011, and its agricultural surplus was US$ 2 billion (MRC 2016a). Most of the LMB countries have ambitious plans to develop irrigation. Thailand has long considered water transfers from the Mekong mainstream to be a complement to national approaches to alleviating drought. Fertilization from sedimentation is important for agriculture production, particularly in floodplains such as Tonle Sap in Cambodia and the Mekong Delta in Viet Nam. Increasing the area devoted to agriculture will mean clearing land, and probably forest, which can increase soil erosion and the amount of sediment in the system.

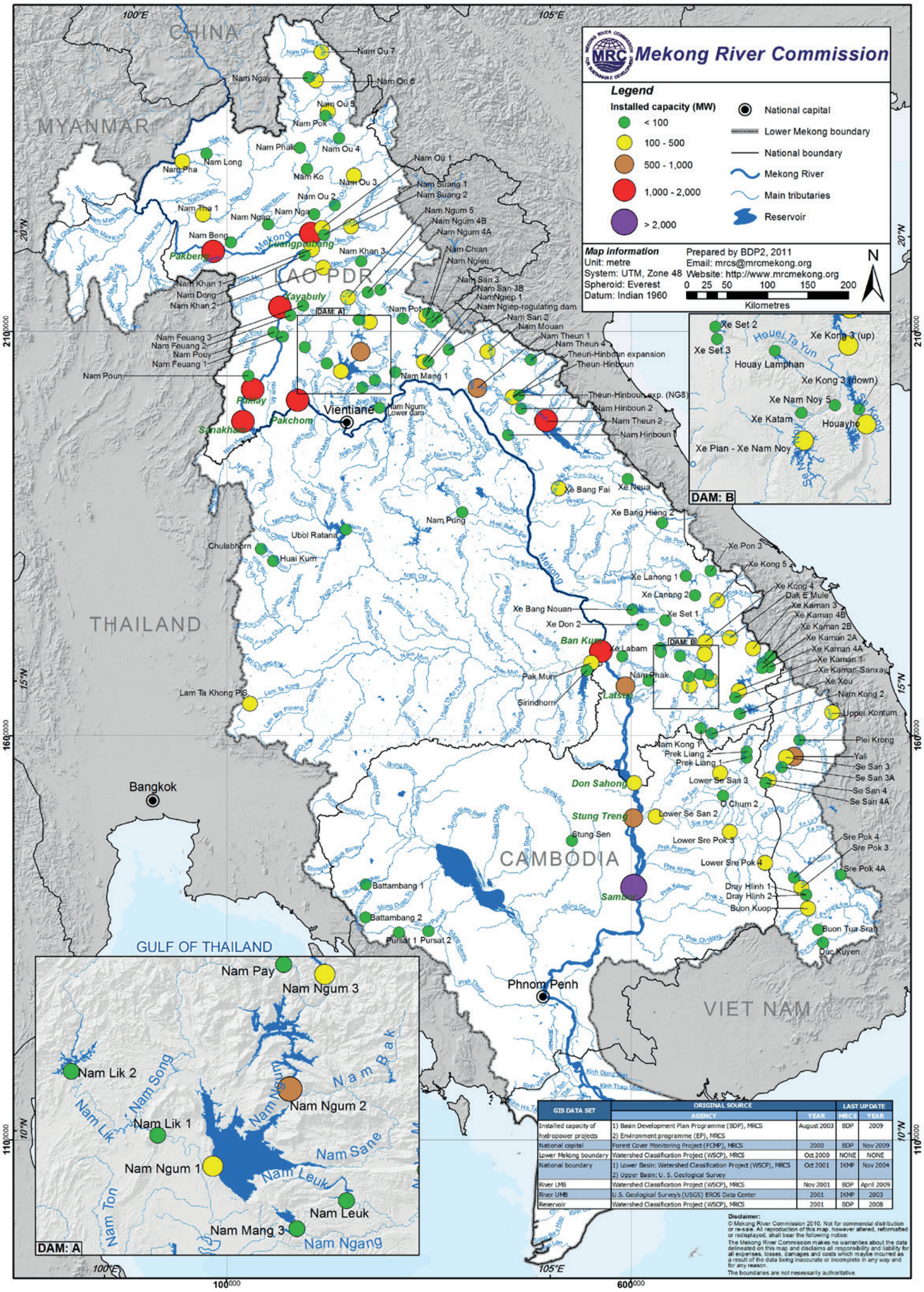

Figure 3: Live storage of hydropower dams in the LMB (MRC 2011b)

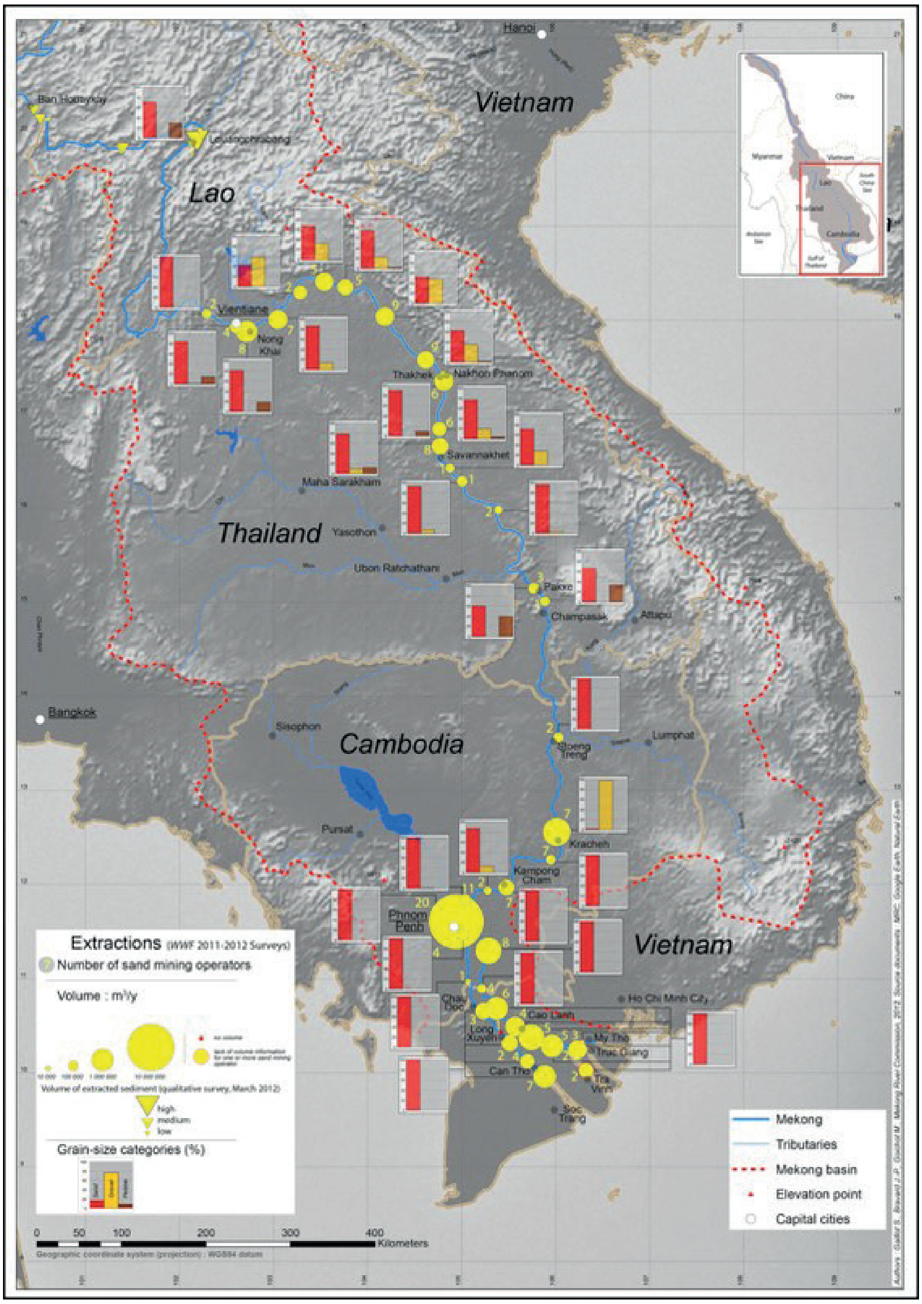

Figure 4: Locations of riverbed mining and estimated amount of extraction (Bravard et al. 2014)

4 CURRENT STATE OF SEDIMENT

4.1 Sediment characteristics

Sediment transportation occurs in the system when air, water or ice move particles along a sloping surface under the force of gravity. The particles are usually sand, gravel boulders (clastic rocks), mud or clay. Sediment transportation by flowing water in natural systems, such as rivers, stream flash floods and outburst floods form glacial lakes, is called a fluvial process. The types of sediment in the LMB are gravels, sands, silts and clays. Koehnken (2014) classifies grain size distribution:

- Gravel > 2.0 mm
- Coarse sand 0.5-2.0 mm
- Medium sand 0.25-0.5 mm
- Fine sand 0.063-0.25 mm
- Silt and clay < 0.063 mm

A major property of sediments is their ability to adsorb and transport small organic or inorganic compounds that stick to the sediment particles. This means that sediments are actually a combination of mineral, inorganic and organic compounds, all of which have different properties. It also means that sediments largely facilitate the transportation of organic or inorganic matter in the hydro-system (Baran et al. 2015).

Importance of sediment in the Mekong

Sediment concentration and grain size determine light penetration, which controls algal or other plant growth

The composition of sediments determines the availability of naturally occurring nutrients and affects the availability of oxygen.

Geochemical reactions between sediments and river water control fundamental water quality parameters such as pH, alkalinity and acidity.

The grain size and surface area of sediments are critical for the transportation of nutrients and other materials, which are transported on the sediments through adsorption.

Fine-grained sediment serves as the link between the solid and the dissolved in the aquatic environment.

Sediments in the Mekong River are found in two main forms: suspended and bedded.

a. Suspended sediment load

These loads are particles that move along the channel in the water column, mainly made up of silt and sand kept in suspension by the upward flux of turbulence generated on the bed of the channel. To be sustained, the upward currents must equal or exceed the particle fall-velocity of the suspended sediment load. The size and concentration of the suspended sediment typically vary logarithmically with the height above the bed. Coarse sand is highly concentrated near the bed and declines with height at a faster rate than fine sand. Fine silt is so easily suspended that it is far more uniformly distributed in a vertical section than coarser material. The suspended solids in the Mekong were found to be dominated by sands and silts at monitoring sites upstream of Kratie, and silts at downstream monitoring sites (Koehnken 2014). Suspended sediment concentration is conventionally measured as milligrams per litre (mg/L), which is the same as gram/m^3

b. Bed load

The larger particles (generally >0.062mm) that move through the channel fully supported by the channel bed itself are called the bed load sediment. These materials are made up of sand and gravel, and move by rolling and sliding through stress at the outer edges of the channel. According to Gupta and Liew (2007), most of the sediment in the Mekong River upstream of Cambodia appears to be stored inside the channel, either on the bed or against the banks. Bedload at Kratie was dominated by sand-sized material, which has transport rates of generally 1-3 per cent of the total suspended solid transport rate. Bedload transport became active at flow rates of more than 3000 m^3/s (Koehnken 2014).

4.2 Sediment monitoring

Sediment measurement in the Mekong River has been limited to suspended sediment samples, which were taken intermittently between 1960 and the mid-2000s. Walling (2005) evaluated the monitoring stations and identified five sites that were thought to have reliable results based on the amount of data available for each monitoring year. These sites are Chiang Saen, Luang Prabang, Nong Khai, Mukdahan and Pakse (see Figure 5). The lack of reliable sediment transport measurement has led to indirect methods of assessment of sediment transport being used to estimate loads and evaluate the impact of dams in the mainstream of the UMB on sediment supply between 1962 and 2003 (Wang et al. 2009).

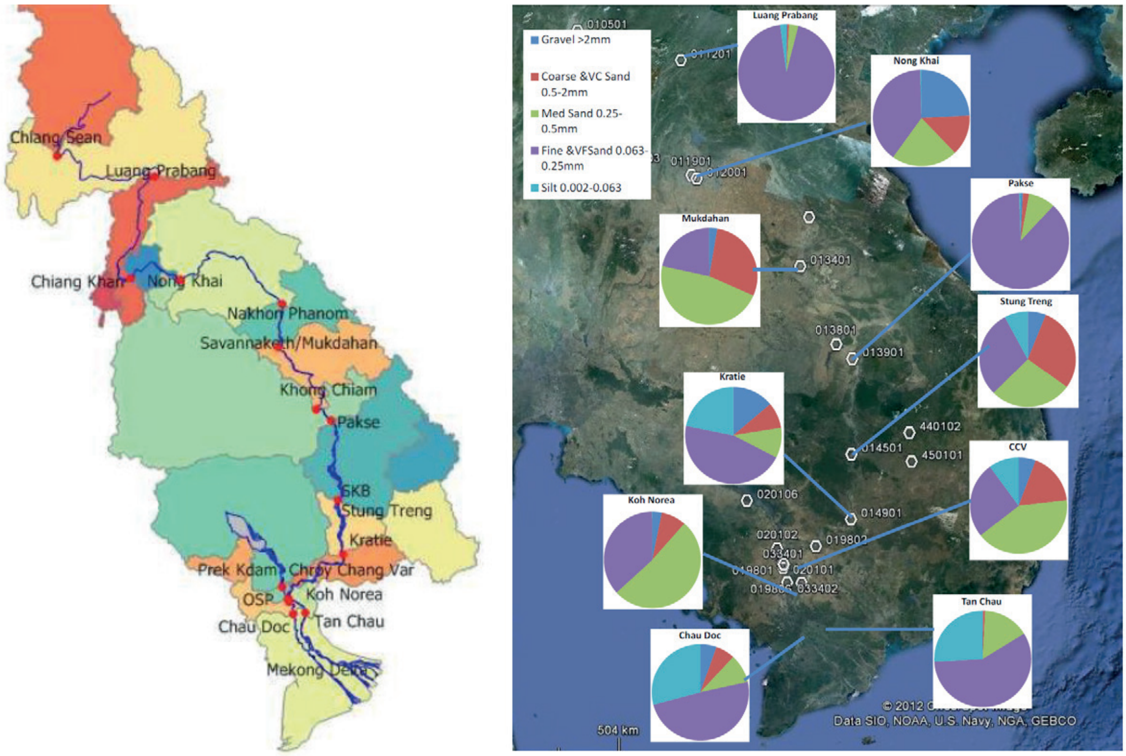

Figure 5: Locations of sediment monitoring in the Mekong River (left) and sediment grain size distributions (right) (Koehnken 2014)

In 2009-13 the Information and Knowledge Management Programme (IKMP) of the MRC used the Discharge and Sediment Monitoring Programme (DSMP) to conduct a review of discharge and sediment monitoring capacity in the region and develop a project for implementing regular discharge and sediment monitoring in the LMB mainstream (Koehnken 2014). Implementation of the DSMP involved flow and suspended sediment monitoring at 17 sites, taking 28-34 samples/yr (see Figure 5 left). The programme measured suspended sediment using a depth integration suspended sediment sampler, bed load using a BL-84 bed load sampler and bed material using a spring-loaded bucket sampler. Monitoring frequency under the DSMP was variable through the year: four samples per month were collected during the peak wet season of July to October and two samples per month for the remainder of the year. Similarly, the sediment grain-size analyses and bed load samples were also collected more frequently during the wet season – twice during July-October and once during the rest of the year. It was found that 60 per cent of the sediment was transported in the two months of August and September and 80 per cent in the four months of July to Oct, which coincides with the major 'flush' of river flows from the upper catchment. The grain size distributions of sediment at monitoring stations are presented in Figure 5 (right).

4.3 Estimation of sediment load in the Mekong River Basin

Studies of the origin of sediments in the Mekong Delta reveal a major switch in the source of sediments about eight million years ago (Clift et al. 2004; Clift et al. 2006). Between 36 and 8 million years ago, the bulk (76 per cent) of the sediments deposited in the delta came from erosion of the bedrock in the Three Rivers Area. However, in the period since the contribution from the Three Rivers Area has fallen to 40 per cent, while that from the Central Highlands rose from 11 to 51 per cent. One of the most striking conclusions of these origin studies is the small contribution of sediment from the other parts of the Mekong Basin, notably the Khorat Plateau, the uplands of northern Lao PDR and northern Thailand, and the mountain ranges south of the Three Rivers Area.

Based on historical data from the 1980s and 1990s, the mean annual total suspended sediment load of the Mekong Basin has been calculated at 160 Mt/year, of which 80-100 Mt/year has been attributed to the Upper Mekong Basin – less than 20 per cent of the natural flow inputs (Walling 2005, 2008). A sediment study by Walling (2005) found no clear evidence of a reduction in sediment load in the LMB after the construction of dams in China. However, the analysis and results have been questioned as they were based solely on grab samples collected at a low sampling frequency. In contrast, Lu and Siew (2005) found a significant decrease in sediment load at the most upstream LMB monitoring site, Chiang Sean, in 1992 following the construction of the Manwan Dam, but no statistical decline at sites located further downstream.

Kondolf et al. (2014) estimated sediment yield contributions in the Mekong based on geological history and geomorphic characteristics (see Table 2). They found that sediment yields are fundamentally controlled by tectonic uplift, climate, lithology and land use.

Table 2: LMB sediment yields by geomorphic province (Kondolf et al. 2014)

Geomorphic Province	Description	Estimated Sediment Yield (t km^{-2} y^{-1})
Lancang	Active tectonic and complex geology. Mekong River follows the fault between Sibumasu block and older block from South China-Indochina merge. High altitude, steep topography	450
Northern Highlands	Hard sandstones and limestones (Paleozoic), granite and metamorphic rocks. Late Miocene uplift	250
Loei-Fold Belt	Hard sandstones and limestones (Paleozoic), granite and metamorphic rocks. Late Miocene uplift	160
Mun-Chi Basin	Sandstones of early Cretaceous Khorat Group: almost exclusively quartz sandstones. This has the lowest relief and appears to be the oldest landscape, may be a relic of older, ore-Miocene drainage system, with little recent uplift. The area has been extensively modified for agriculture and other development, so erosion and sediment yields may have been anthropically increased in recent years, but these sediments would probably be dominantly grained.	40
Anamite Mountains	Hard sandstones and limestones (Palezoic), granites and metamorphic rocks. Late Miocene uplift	200
Kon Tum Massif	Heterogeneous geology of Paleozoic sedimentary rocks and igneous intrusive rocks, along with Khorat Group and younger Cenozoic basalts. Significant late Miocene uplift as reflected in deeply incised channels	280
Tertiary Volcanic Plateau	Heterogeneous geology of igneous intrusive rocks, younger Cenozoic basalts and underlying Paleozic sedimentary rocks. Significant late Miocene uplift as reflected in deeply incised channels.	290
Tonle Sap	The Tonles Sap basin consists mostly of lowland floodplain and small, short tributary drainage basins in the surrounding mountains. Net deposition from Mekong River backwater exceeds net sediment export	0
Delta	Net deposit	0

Figure 6 presents estimated sediment loads based on monitoring data in 2011 and observed flow data (in an extreme wet year) by Koehnken (2014). The analysis found that sediment transport and flow at the three upstream sites – Chiang Sean, Luang Prabang and Chiang Khan – were relatively uniform (13-26 Mt/yr) and showed low variability compared to both downstream sites and historical results (60-120 Mt/yr). Much higher sediment fluxes were documented at Mukdahan (107 Mt/yr) and Khong Chiam (166 Mt/yr), but these loads were not recorded at Pakse (73 Mt/yr) raising questions about the upstream results. Loads increased at Stung Treng (106 Mt/yr) and Kratie (116 Mt/yr) consistent with the inflow of sediment bearing rivers. The sediment transport calculated at Kratie in 2011 was considerably lower than the 1990-2000 average estimate of 166 Mt/yr, even though 2011 was a wet year.

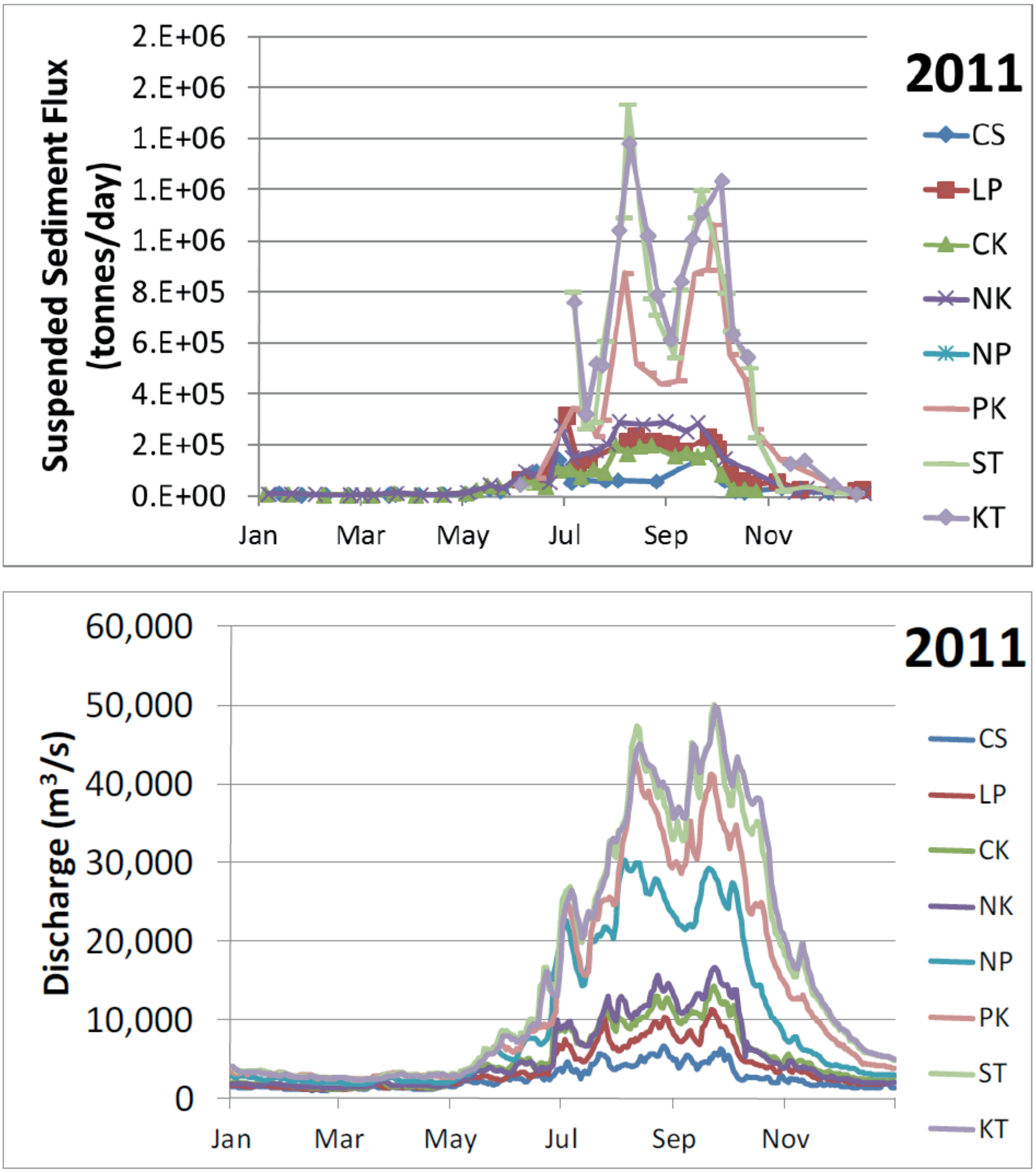

Figure 6: Estimated sediment loads and observed flows, 2011 (Koehnken 2014)

5 IMPACTS OF DEVELOPMENT, CLIMATE CHANGE AND LAND USE CHANGE ON SEDIMENT TRANSPORT

5.1 Impact of hydropower development

The MRC study indicates that half of the sediment in the Mekong originated in the UMB (MRC 2010). China's plans to build seven hydropower dams on the upper Mekong have become a matter of serious concern for the countries of the lower Mekong. Upstream Mekong development such as the construction of dams has led to significant trapping of sediment and nutrients, and could reduce the fertility of the Tonle Sap system (Kummu and Varis 2007). Although many have suggested that changes in water discharge and sediment flux have occurred since the dams in the upper Mekong River became operational (Chapman and He, 1996; He and Chen 2002; Oxfam Hong Kong 2002; Osbourne 2004), systematic analyses of water discharge and estimates of sediment flux at multiple gauging stations along the Lower Mekong River have not been conducted (Lu and Siew 2005). This lack of reliable sediment transport measurement has led to the use of indirect methods of sediment transport assessment to estimate loads and evaluate the impact of dams on the mainstream of the UMB on sediment supply between 1962 and 2003 (Wang et al. 2009). The investigators found that at Chiang Saen in northern Thailand, mean annual sediment load in the Mekong probably increased during the period of dam construction (1986-1992) and decreased after the dam commenced operation (1993-2003), although other catchment activities cannot be ruled out as having contributed to these changes.

The Manwan reservoir in China trapped around 60.5 per cent of the total sediment load transported between 1993 and 2003, causing significant effects on sediment variation downstream (Fu and He 2008). Lu and Siew (2005) reports that the sedimentation impact of the Manwan Dam extends as far as Vientiane in Lao PDR. A study conducted by the International River Network on the sediment impact of dam construction in China estimates that 35 per cent of the Suspended Sediment Load (SSL) needed to nourish the flood plains will be trapped by the Xiaowan Dam in future. That study is consistent with research by Kummu and Varis (2007), which also found decreases in sediment loads below the Upper Mekong River cascades. It estimated that the cascades would significantly change the hydrological regime and trap 94 per cent of the SSL drained from China to the LMB, with serious consequences further down river in Pakse, Lao PDR (Fu and He 2007). According to Gupta and Liew (2007) the trapping of sediments by dams in China could eventually turn the Mekong into a rock-cut canyon as very little exchange of sediment occurs between the main channel and the flood plain upstream of the Cambodian lowlands.

Kummu et. al. (2010) developed a method, based on Brune's method, to calculate the basin-wide trapping efficiency of the reservoirs along the mainstream. This was used to estimate the basin-wide trapping efficiency of existing and planned reservoirs. The existing dams in the basin have the potential to trap 34-43 million tonnes (i.e. 15-18%) of sediment annually. If all the planned dams are built in the sub-basins, the amount of trapped sediment would reach 95-100 Mt. This will decrease sediment input to the Cambodian and Mekong Delta by about half, and possibly up to 90 per cent if all the mainstream dams are implemented. More recently, Kondolf et al. (2014) modelled the cascade of dams in the UMB (Lancang). They found that the trapping efficiency of the cascade of dams in China is 83 per cent of the upper Mekong's sediment load (80 Mt/yr); and that with the 38 dams in the 'definite future' scenario, 51 per cent of the total sediment load of the river would be trapped before reaching the delta (see Figure 7 left). Full dam development in the LMB, including all the mainstream dams, would mean that about 96 per cent of the sediment load will be trapped, and that the sediment load reaching the delta would fall to just 4 per cent (see Figure 7 right).

Of particular concern is the ongoing and future development of 42 dams in the Srepok, Sesan and Sekong (3S) basin, which is the largest tributary to the Mekong Basin. Piman et al. (2013a) shows that the full hydropower development would result in a 63 per cent increase in dry season flows and a 22 per cent decrease in wet season flows at the outlet of the 3S basin. Wild and Loucks (2014) studied the potential for managing sediment and the impact on energy production in the 3S basin. The results of their simulations suggest that 40-80 per cent of the suspended sediment load could be trapped in 3S basin reservoirs, depending in particular on the number location, design and operation of the reservoirs, and to a lesser extent on the type and size of the sediment produced. Another proposed hydroelectric dam on the Mekong River located at Kratie Province, Cambodia might prevent significant quantities of sediment from reaching the Tonle Sap Lake and the Mekong Delta, two critically important features of the river basin (Wild and Loucks 2015). Analysis of the Lower Se San 2 Dam and the Sambor Dam suggests that large quantities of sediment are being trapped, starving downstream ecosystems of a resource that transports nutrients and maintains the geomorphic make-up of the system, among other functions (Mohanasundari and Balasubramanian 2015).

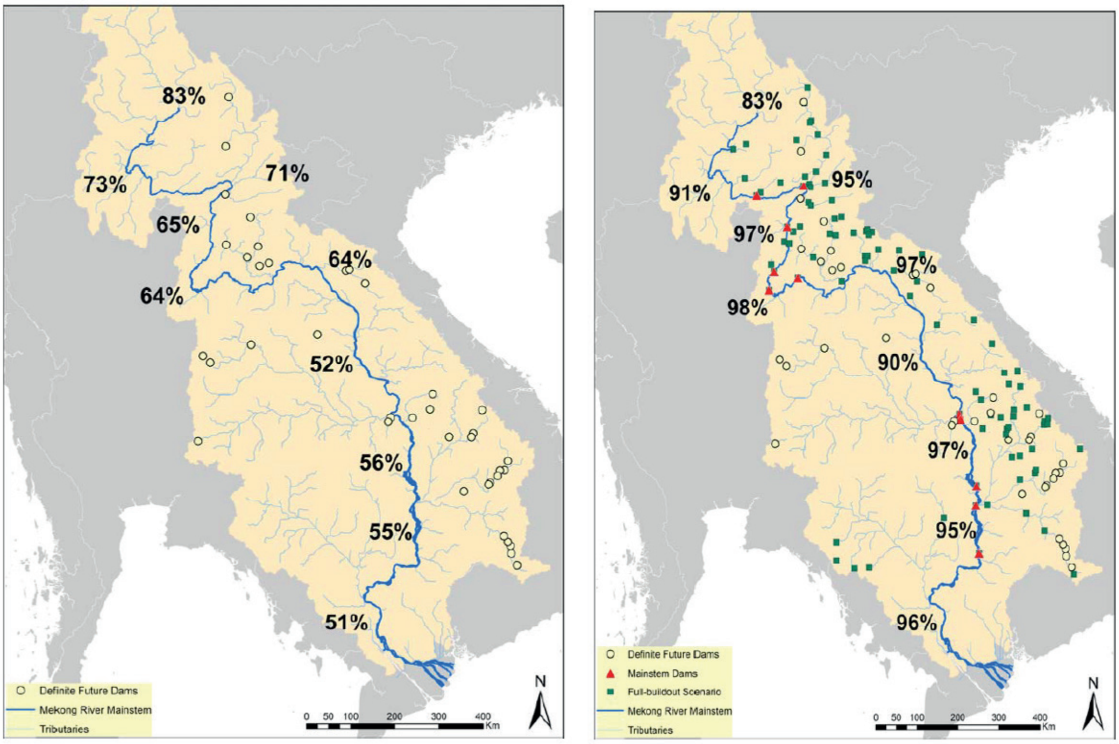

Figure 7: Dam trapping efficiency under the 'definite future scenario' (left) and the 'full dam Development scenario' (right) (Kondolf et al. 2014)

According to the MRC monitoring network, the suspended load from China is currently low and the main sources of silt and clay downstream are the tributaries, primarily in the Golden Triangle area of Myanmar, Lao PDR and Thailand. Suspended loads were reduced from 60 Mt to 10 Mt at Chiang Saen station, and from 120 Mt to 60 Mt at Pakse (see Figure 8) (Koehnken 2014). Furthermore, the Xayaburi reservoir, which is scheduled to open in 2020, will decrease the transport of sand from the upstream region of Luang Prabang, Lao PDR. Part of the sand will settle in the Xayaburi reservoir, although in the upper reach flow turbulence will not differ much from natural conditions (Bravard et al. 2014).

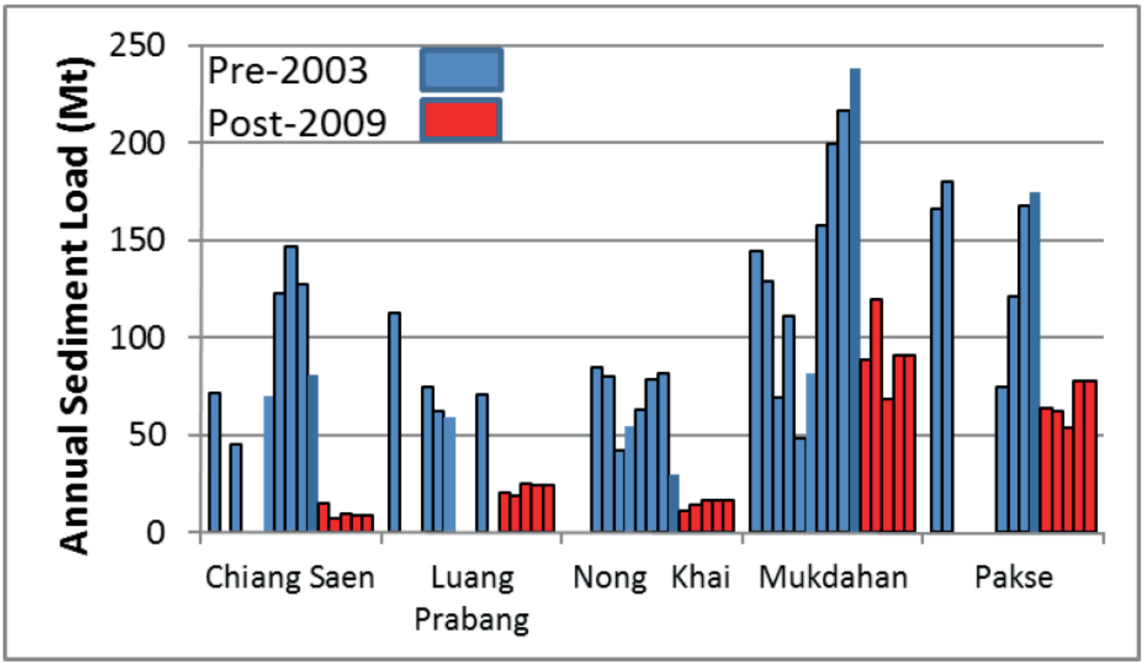

Figure 8: Comparison of annual sediment load at mainstream monitoring stations before 2003 and after 2009 (Koehnken 2014)

5.2 Impact of agriculture development

A comparison of landcover maps of the Mekong Basin for 1992-93 and 1997 shows that the area has a mosaic of different types of vegetation and land has been cleared in several places for different types of agriculture (Gupta et al. 2002). In the later map 13,969 km^2 of the upland part of the Mekong Basin had been cleared to form hill paddy to grow vegetables such as cucumber and long beans. These fields are abandoned after a couple of years and new areas cleared within a short distance of the village, again to grow crops. The mixed patches of cleared and vegetated land on the slopes are sites with a high potential for sheet and gully erosion and sediment transfer during the intense rains of the early monsoon season. The areas of high sediment production will change over time, as old fields are abandoned and new ones prepared (Gupta et al. 2002). In Cambodia, the proposed extensive forest clearance of the entire Angkor plain to form a vast expanse of rice fields could also have an impact on the sediments transported into the channels as well as the hydrology of the area (Evans et al. 2007). However, no comprehensive conclusions on these issues can be drawn from the limited information available.

5.3 Impact of riverbed mining

According to Sarkkula et al. (2010) the total amount of sediment flux from Chinese rivers upstream has decreased from about 2000 million tonnes per year in the 1960s to the current 400 million tonnes per year, based on data from 2000-2007. This massive reduction has taken place at a time when total water discharge has stayed relatively stable. The main reason has been the trapping of sediments by dams and reservoirs, which accounts for 56 per cent of the total sediment load reduction. Other reasons are soil and water conservation (23 per cent), water consumption (15 per cent) and in-channel sand mining (3 per cent).

Rapid development means that the demand for resources in South East Asia has increased. In lowland areas of Cambodia and Viet Nam, landfill is widely used to reclaim land and elevate roads and levees above flood level. This consumes a large volume of sand, which is drawn directly from the riverbed. The road network in the delta, which has been significantly extended and flood proofed over the past decade, is a major consumer of sand extracted from the riverbed.

The demand for sand and gravel from foreign countries has triggered a large sand export business in the Mekong region. Singapore's landmass has increased by 22 per cent since the 1960s, and it is the largest importer of sand in the world (Global Witness 2009). Since 2000, countries such as Viet Nam, Indonesia and Malaysia have banned the export of river and offshore sand, and the industry is shifting to countries with weaker institutional frameworks such as Cambodia. In 2012 the Cambodian government initiated dredging of the Bassac River and shallow areas near the Mekong waterways to improve navigation and protect bank collapses, but also to sell sand to Singapore and China.

The surveys conducted by Bravard et al. (2013) indicate that 34.48 million m^3 or 55.2 million tonnes (at a density of 1.6 tonnes per m^3 of dry sand) of sediment was extracted from the Mekong mainstream in Lao PDR, Thailand, Cambodia and Viet Nam in 2011. On average, sand represents 90 per cent of the total bulk, and the quantity of sand mined amounted to 31 million m^3, or 49.6 million tonnes, in 2011. The geography of sediment categories reveals that Cambodia was the largest extractor in 2011-12 (60 per cent) followed by Viet Nam (22 per cent) and Thailand (13 per cent). Lao PDR produced only 4 per cent of the total amount of sediment (see Table 3). There were 118 sites active at the time of the study. It was found that the location of the best extraction sites shifts along the river, and operators follow them to mine the best sites – particularly the most recent flood deposits.

Upstream of Phnom Penh, gravel and sand are mined during the low flow season, usually from December/January to May. Small extraction sites use mechanical shovels, tractors and light trucks, while bigger sites use pumping dredgers and conveyor belts for extraction and several large trucks. The level of activity depends on the accessibility of the site for trucks and mechanical shovels. Downstream of Phnom Penh, mechanical shovels operate from artificial levees in shallow areas. In deep areas pumping dredgers are the only way to mine sand, and their use makes extraction possible throughout the year except during peak flooding.

Table 3: Volumes and percentage of grain-size categories per country

Country	Extraction (cubic meter per year)			
	Sand	Gravel	Pebbles	Total
Lao PDR	904100	10000	454500	1368600
Thailand	3677200	857740	0	4534940
Cambodia	18748503	2044940	0	20793443
Viet Nam	7750000	0	0	7750000
Total	31079803	2912680	454500	34446983
Percentage	**90%**	**8%**	**1%**	**100%**

5.4 Impact of climate change

It is widely acknowledged that climate change is having a significant effect on stream flow and sediment flux (Shrestha et al. 2016b). Changes in temperature and rainfall can affect the rate of soil erosion and the sediment transport capacity of a river, which influences the sediment flux in that river. Based on a downscaled regional circulation model (PRECIS) and the Soil and Water Assessment Tool (SWAT), the change in future sediment flux attributed to climate change was assessed by Shrestha et al. (2016a). The simulation results show that future changes in annual stream discharge are likely to range from a 17 per cent decrease to a 66 per cent increase, which will lead to predicted changes in annual sediment yield ranging from a 27 per cent decrease to a 160 per cent increase. Changes in intra-annual (monthly) discharge as well as sediment yield are even greater: -62 to +105 per cent in discharge and −88 to 243 per cent in sediment yield. A higher discharge and sediment flux are expected during the wet seasons, although the highest relative changes are observed during the dry months. However, the intra-annual changes in sediment yields were higher than the corresponding changes in discharge. This implies that the potential impact of climate change on sediment yield is greater than on streamflow, because sediment yield increases more linearly with an increase in flow.

Shrestha (2016) also concluded that under climate change scenarios, the storage volume of the reservoir reduces faster than in a scenario without climate change, due to the increase in sediment flux in the Nam Ou Basin. Similarly, increased runoff from the Tonle Sap catchment and upstream catchments of the Mekong is likely to increase the input of sediments, influencing nutrient cycling in the Tonle Sap Lake and the fertility of cropping enterprises on the floodplain (Eastham et al. 2008).

In the downstream Mekong, in the 3S River Basin, it is predicted that the peak sediment load is likely to increase in the future, and that this increase will lie in the range of 63.5-94% for the whole basin (Shrestha et al. 2016a). Basin wide analysis shows that the annual sediment load is likely to increase in the future, despite differences in the direction of change among sub basin loads. The changes in sediment yield and discharge in response to climate change do not always happen in the same direction. This also suggests that the sediment yield projection is more sensitive to temperature and rainfall changes than flow. Decreases in rainfall and increases in temperature can lead to water stress, which reduces the growth of plants and hence increases the erosion rate. This change in erosion rate causes change in the sediment flux in a river (Shrestha et al. 2016a).

A recent study has demonstrated that spatial variations in the Mekong's suspended sediment load are correlated with observed variations in tropical cyclone climatology. Darby et al. (2016) estimated that between 1981 and 2005 the suspended load of the Mekong Delta declined by 52.6 ± 10.2 Mt, of which 33.0 ± 7.1 Mt was due to a shift in tropical cyclone climatology. The study also indicated that although the number and intensity of tropical cyclones tracking across the South China Sea were projected to increase under future anthropogenic climate change, their track locations will shift eastwards and away from the Indochina peninsula, leading to net reductions in accumulated cyclone energy across the Mekong Basin. If these projected reductions are correct, tropical cyclone-driven suspended sediment delivery to the Mekong Delta will decline further, exacerbating projected declines in sediment loads due to damming and sand mining.

5.5 Impact of land use change

Ongoing land-cover changes, particularly reservoir construction, will lead to flow alterations in the Mekong Basin. The rapidly growing area of cleared ground early in the wet season and the changing mosaic of cleared tracts over time (Chen et al. 2000) together indicate that the pattern of erosion and sediment transfer may be more complicated than normally assumed. Satellite images and field visits to the Mekong Region have identified large areas of deforestation for timber. Such areas are expected to release large volumes of sediment sand into the main river over a longer period of time than the load originating from small fields of shifting agriculture. Gupta et al. (2002) observed that in 1996-99 more slopes were cleared of vegetation in the north, and that the channel of the Mekong appeared to be progressively filling with sediment during that time. Bonheur and Lane (2002) also claim that siltation and sediment are increasing due to the degradation of upland forests.

This possible flow alteration linked to the changing climate and the construction of dams would affect the water level of the Tonle Sap Lake, increasing the dry-season water level by 0.15-0.60m and threatening the forest areas along the shore of the permanent lake. The partial or total destruction of this 'gallery forest' could affect the hydrodynamics of the floodplain, and consequently have an impact on the sediment dynamics of the system (Kummu et al. 2008). Kummu et al. (2006) calculate sedimentation loads for different land use classes around the Tonle Sap Lake (see Figure 9). Evans et al. (2007) show that the extensive water diversion from the natural rivers to the channels in the collector zone has had a major impact on the catchments, breaking the original Puok catchment into two: the Siem Reap and the new Puok catchments. This significantly changed the natural hydrology and led to problems with erosion and sedimentation in the channels. Moreover, extensive forest clearance over the entire Angkor plain, which stands in a vast expanse of rice fields, would have had an impact on the sediments transported into the channels and the hydrology of the area.

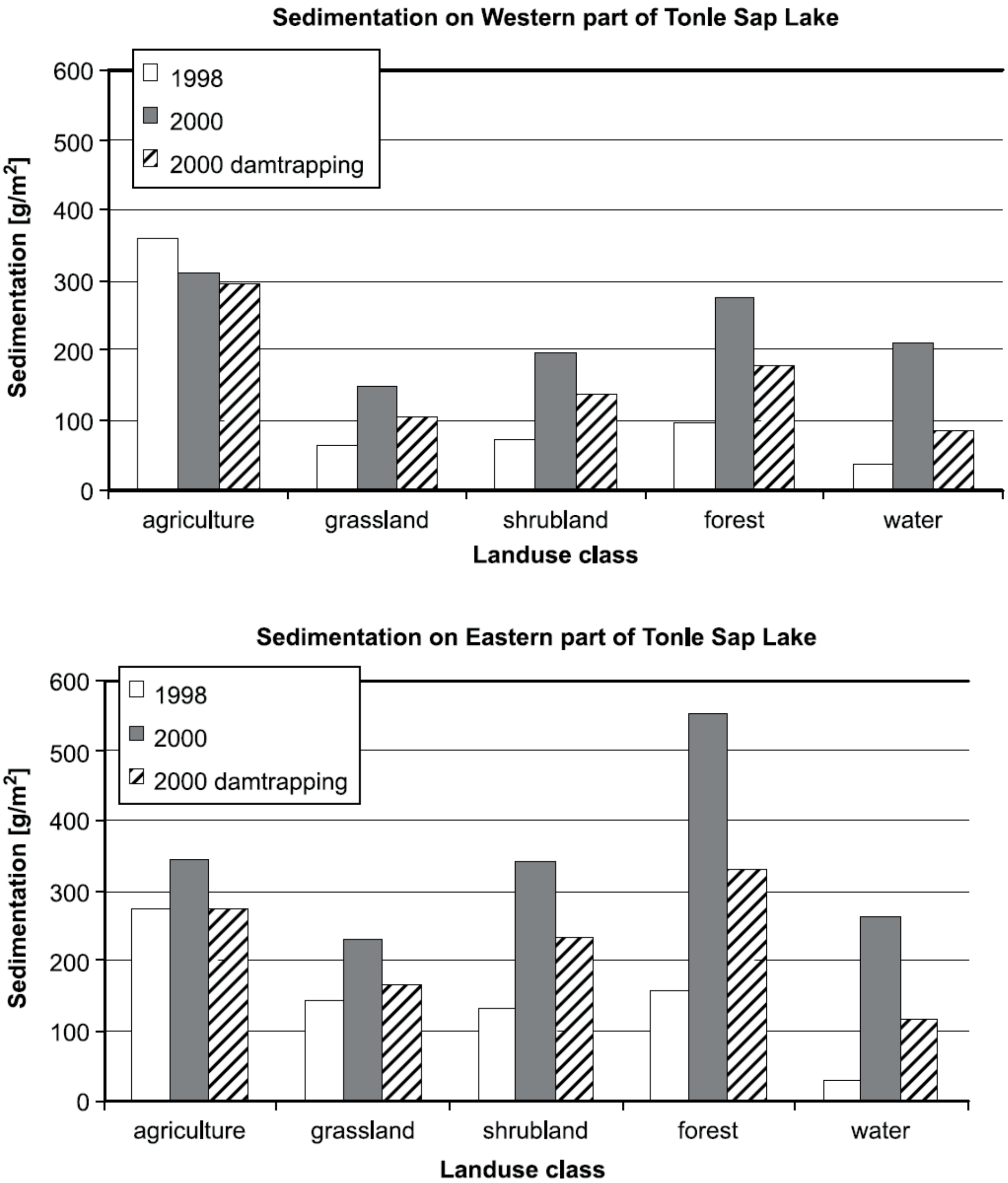

Figure 9: Calculated sedimentation loads for different land use classes in western (top) and eastern (down) parts of the Tonle Sap Lake (Kummu et al. 2006)

Following the introduction of rubber plantations and their subsequent rapid expansion in the mountainous areas across the entire Mekong region, the area devoted to rubber plantations is forecast to quadruple by 2050. It is predicted that this will lead to drier conditions at the local level as well as surface erosion, loss of soil quality, sedimentation and the disruption of streams, as well as an increased risk of landslides (Costenbader et al. 2015). More recently, a study by Rodriguez-Lloveras et al. (2016) on the sediment-related impacts of climate change and reservoir development in the LMB has concluded that land use changes are the most critical factor in erosion and sediment production. Hence, it is essential to examine the combined effects of climate change and land use change on the reservoir sedimentation and sediment outflow of the catchment.

6 ENVIRONMENTAL, SOCIAL AND ECONOMIC IMPLICATIONS OF CHANGES IN SEDIMENT

Sedimentation in the Mekong Basin is changing. Large hydropower development in upstream Mekong and its tributaries as well as riverbed mining, particularly in the Mekong Delta, will lead to substantial reductions in sediments entering the Mekong mainstream system at the regional scale. Additional alterations might be caused by land use change and climate change, where local effects can be expected. Changing and declining sediment loads from the catchment raise major concerns over a number of consequences.

6.1 Impact on river morphology, erosion and delta-shaping processes

Existing and ongoing development of hydropower dams and land use change in the Upper Mekong Basin are leading to serious reductions in sediment transport downstream of the cascade and further down the river. Therefore, the full development of Chinese dams is likely to have serious impacts on sediment transport in the upper reaches of the Lower Mekong Basin (Lao PDR and Thailand) in the near future. Ongoing development of the Xayaburi and Pakbeng hydropower projects in the Mekong mainstream in Lao PDR will further reduce bed material load downstream. The estimated deposition rates at Pakben and Xayaburi reservoirs are 18 and 5 Mt/yr, respectively (DHI 2015).

There is the potential for major changes to the morphology of the mainstream to be induced by current developments. The effects on river morphology will be noticed in the upstream reaches first, between Chiang Saen and Nong Khai, and in downstream reaches at a later date. The trapping of sediments in the upstream dams coupled with fluctuations in flows will cause scouring of the riverbed, and bank erosion downstream of the dam sites and along the mainstream.

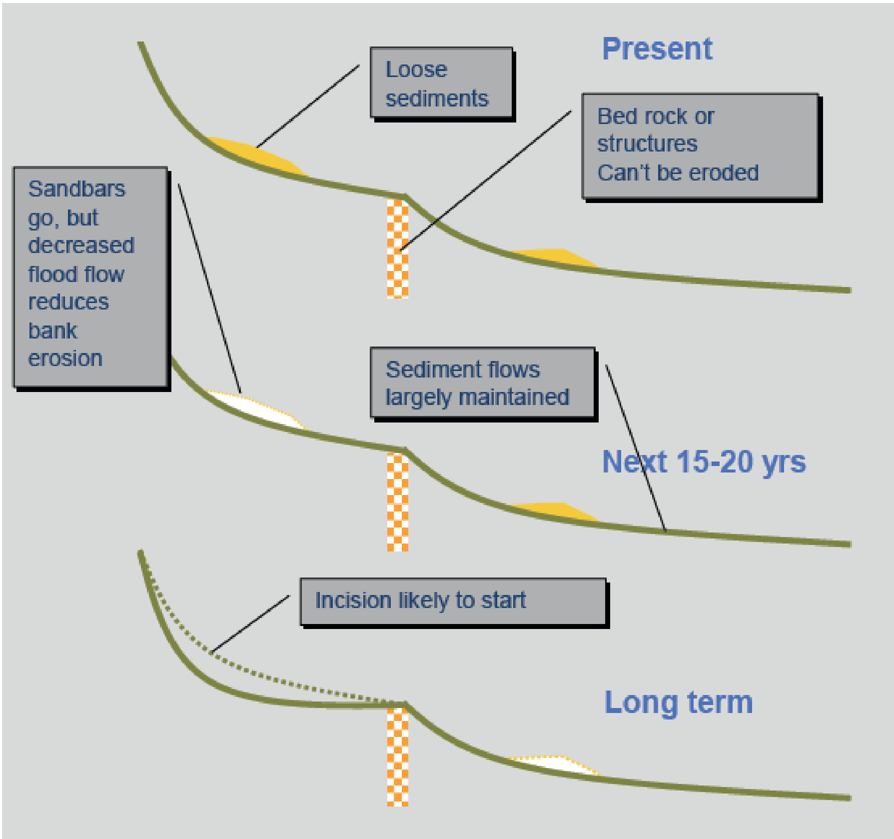

Figure 10: Illustration of geomorphological change process (MRC 2011)

The loss of impounded sediments in the upper reaches is being compensated for by the take-up of existing deposits in the system. Upstream effects may become evident in the next 15-20 years. In the longer term (> 20 years), the river's shape will start to adjust more rapidly (MRC 2011a).

Rapid coastal erosion rates in deltas worldwide provide the most dramatic evidence of declining sediment inputs from their catchments (Coleman et al. 2008; Syvitski et al. 2009). A reduction in sediment loads in the Mekong mainstream would consequently result in a reduction of sediment on to floodplains such as the Tonle Sap Lake in Cambodia and reduce the Viet Nam delta's capacity to replenish itself, making it more vulnerable to erosion at and near the river mouths. This will lead to erosion and the slow sinking of the delta. However, urbanization, sand mining and a reduction in mangroves in the delta have in the past induced – and are more likely than the operation of the existing dams to induce future – effects on channel morphology and coastal change (Allison et al. 2017).

Erosion problems linked to declines in sediment delivery from dam trapping and the increase in the rate of sea level rise will become increasingly visible in the medium (next 10-15 years) and long term (next 20-30 years). DHI (2015) estimated an increase of 4-12 metres/year in erosion at river mouths compared with current conditions, due to sediment trapping by currently operational and proposed mainstream dams. In recent years local people in Viet Nam's Mekong Delta have noticed a significant change in the river: it keeps changing colour from a reddish brown to an ocean-like blue (Tuyen 2016). This is further evidence that the Mekong River is becoming sediment and nutrient deficient and therefore less productive (Figure 11).

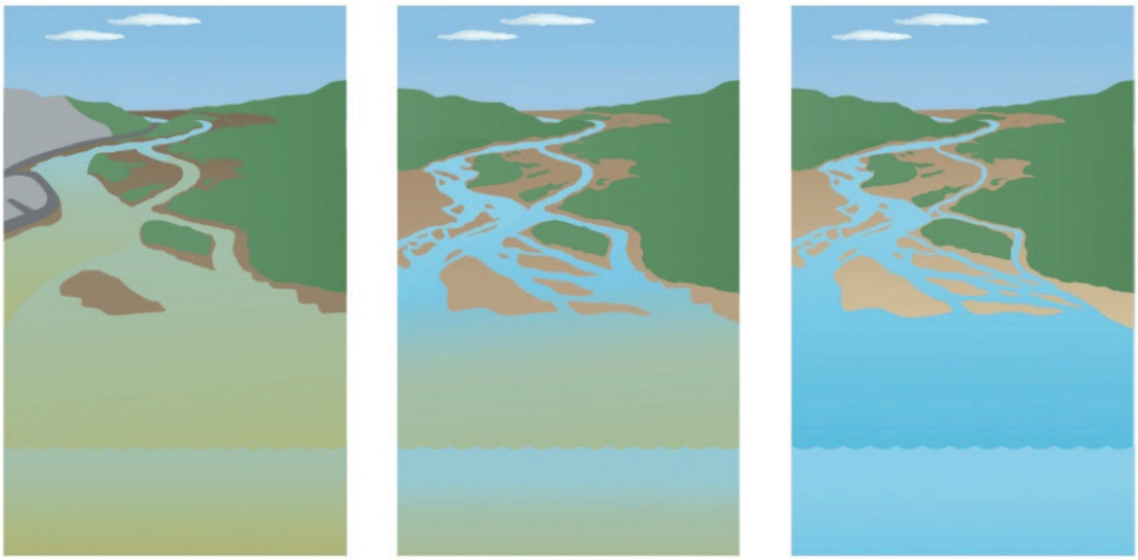

Figure 11: The process of reduction of the sediment and nutrient load in a river (Baran et al. 2015)

6.2 Nutrients and primary productivity loss

Sediment in the Mekong River serves as a major carrier and storage agent for nutrients such as phosphorus, nitrogen and potassium. The dominant sediment categories in the Lower Mekong Basin are fine sands, silts and clays; and the proportion of organic particles represents 2-8 per cent of the total sediment load, which is considered high by global standards (Baran et al. 2015). The high level of biological productivity in the Mekong floodplains is a result of a combination of the flood pulse, the high proportion of primary production (69%) entering the food web and the high concentration of sediment and nutrient loads in the water. Phosphorus is the nutrient that generally controls primary production in freshwater ecosystems. The 67-145 million tonnes of sediment reaching the delta each year also contributes to the biological productivity of the coastal zone (Baran et al. 2015).

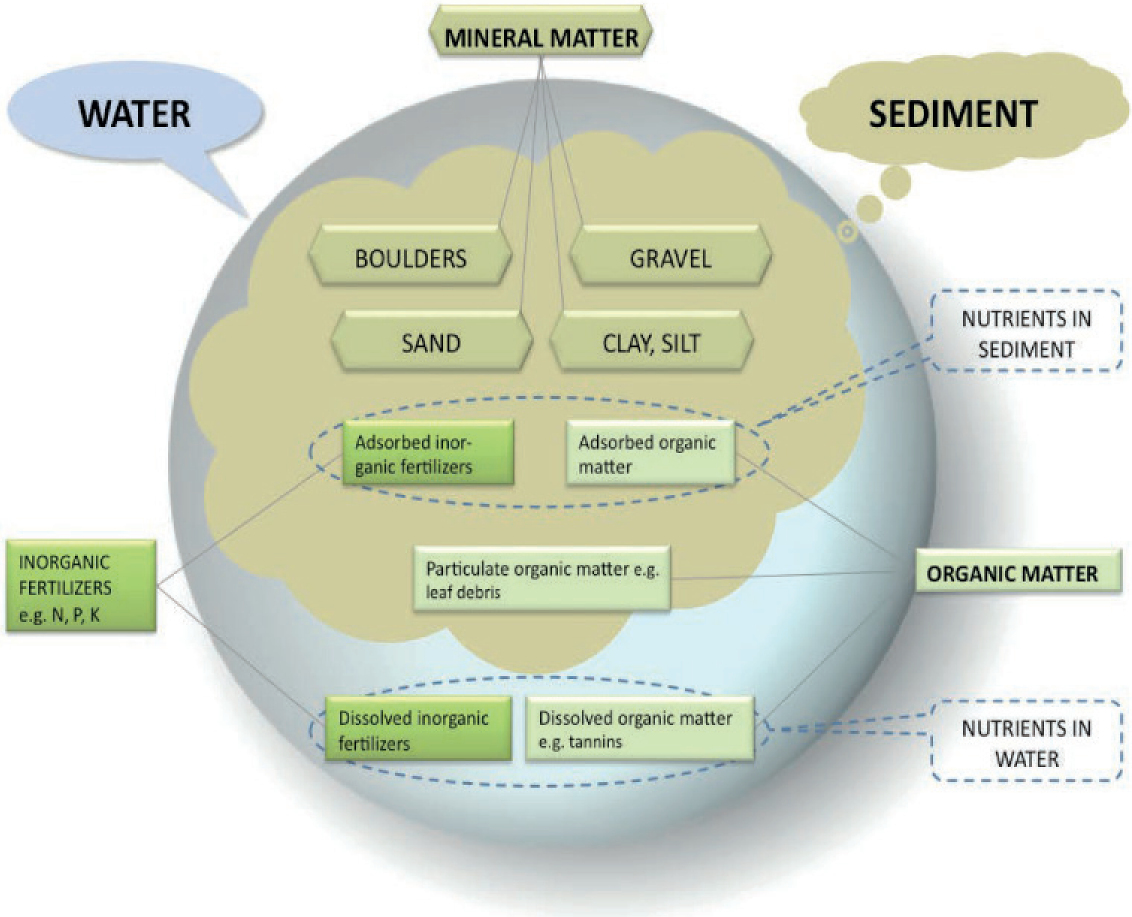

Figure 12: Main components of river sediment (Baran et al. 2015)

As a result of the decline in sediment transport and deposition, nutrient transport is also projected to be heavily affected by large-scale hydropower development on the mainstream. Under conditions of full hydropower development in the Lower Mekong mainstream at Kratie, total transport of phosphorus is projected to reduce from 47 to 53 per cent; and of nitrogen from 57 to 62 per cent, respectively (DHI 2015). Cutting the transport of sediment and nutrients in the mainstream through damming and loss of habitat would lead to a 12-27 per cent reduction in the primary productivity of the aquatic systems, or vegetal productivity (ICEM 2010).

The Tonle Sap is a 2600 km^2 permanent shallow lake with a 12,876 km^2 floodplain during the wet season. It is the single most productive floodplain wetland in the Mekong Basin, which provides a critical spawning and rearing habitat for one of the largest freshwater capture fisheries on the planet (Arias et al. 2014; Cooperman et al. 2012). Kummu et al. (2008) found that 72 per cent of the suspended sediments with associated nutrients entering the Tonle Sap are from the Mekong mainstream.

Decreases in suspended sediment concentrations pose a serious risk to nutrient balance in the lake, and therefore to the system's productivity. A decrease in the fertility of the flooded forests that serve as important habitats and breeding grounds for fish will reduce the size of fish landings (Kummu et al. 2008). If all the planned mainstream and tributary dams are built, it is estimated that productivity in large areas of the Cambodian floodplains will be halved (Koponen et al. 2010). By 2030, it is projected that total annual primary production in the Tonle Sap will be reduced by 31 per cent as a result of hydropower trapping sediment and nutrient loads, by 9-15 per cent as a result of climate change and by 33-39 per cent as a result of the combined effects of climate change and hydropower (Arias et al. 2014).

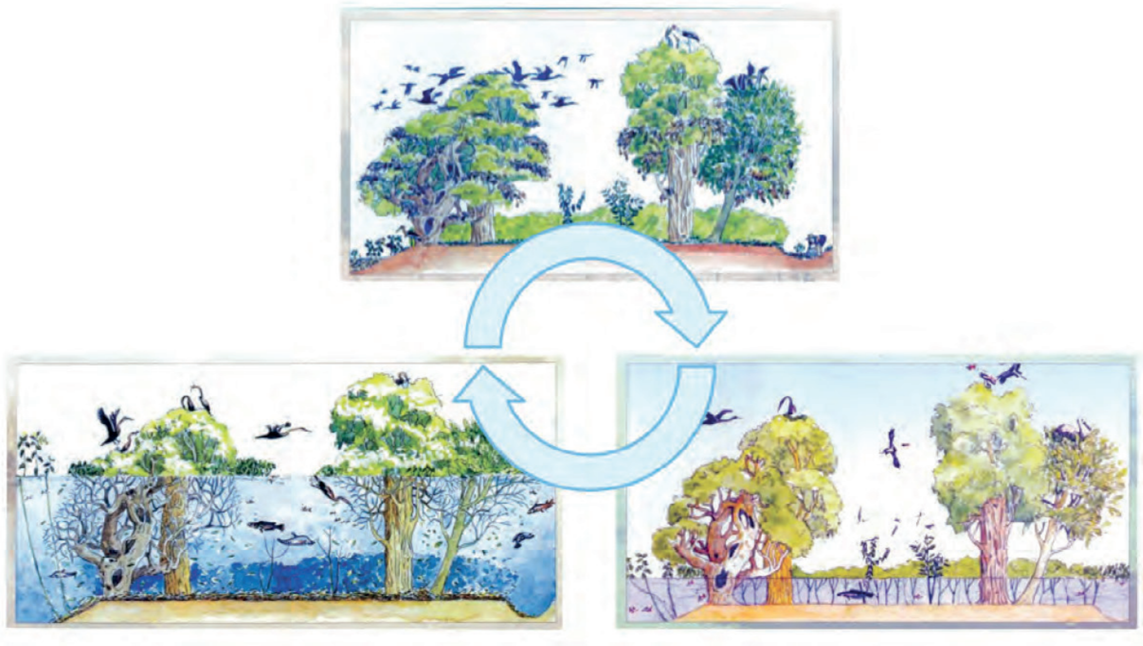

Figure 13: Flood pulse in Tonle Sap Lake (Baran et al. 2015)

6.3 Impact on fisheries species and production

Sediments play an important environmental role in fish bio-ecology. The fish species that inhabit a river body adapt to specific sediment characteristics, such as seasonal and inter-annual variations, which are not constant. Fish nutrition and growth depend on the concentration and composition of sediments in the river. Some fish, such as mullet, feed directly on sediment. Together with the nutrients released from floodplain soils, the nutrients dissolved in or adsorbed by sediments are the main input for vegetation growth (i.e. phytoplankton, algae and macrophytes). Substantial reductions in sediment and nutrient loads modify food webs and result in changes to fish communities and the dominant species. Reproduction of some river fish species, such as Lithophils, Psammophils and Pelagophils, is dependent on bedload and wash load, which means that they may not be able to adjust to changes to their feeding and spawning grounds (Kummu and Varis 2007; Ospina-Álvarez et al. 2012 Baran et al. 2015)

According to the most reliable estimate, the Mekong produces 2.1 million tonnes of fish each year. When coastal fisheries are included, the Mekong fisheries yield between 2.6 and 3.3 million tonnes of fish per year (ICEM 2010). Three main fish production zones can be identified (Baran et al. 2015).

- The near-shore zone, corresponding to the coastal area of the South China Sea, influenced by the Mekong discharge, or the Mekong plume;
- The downstream zone, which includes all the floodplains (the Mekong Delta, the Cambodian lowlands and the Tonle Sap) and ends upstream at the Khone Falls on the border between Cambodia and Lao PDR; and
- The upstream zone, which corresponds to the Mekong River section between the Khone Falls and upstream reach.

In the downstream zone of the Mekong Basin and the near-shore zone, fish resources depend mainly on sediment loads, the flood pulse, migrations and water quality. For upstream parts of the Mekong Basin, fish resources depend mainly on sediment loads and migrations, while the influence of the riverine flood pulse is less pronounced than in the floodplains and coastal areas.

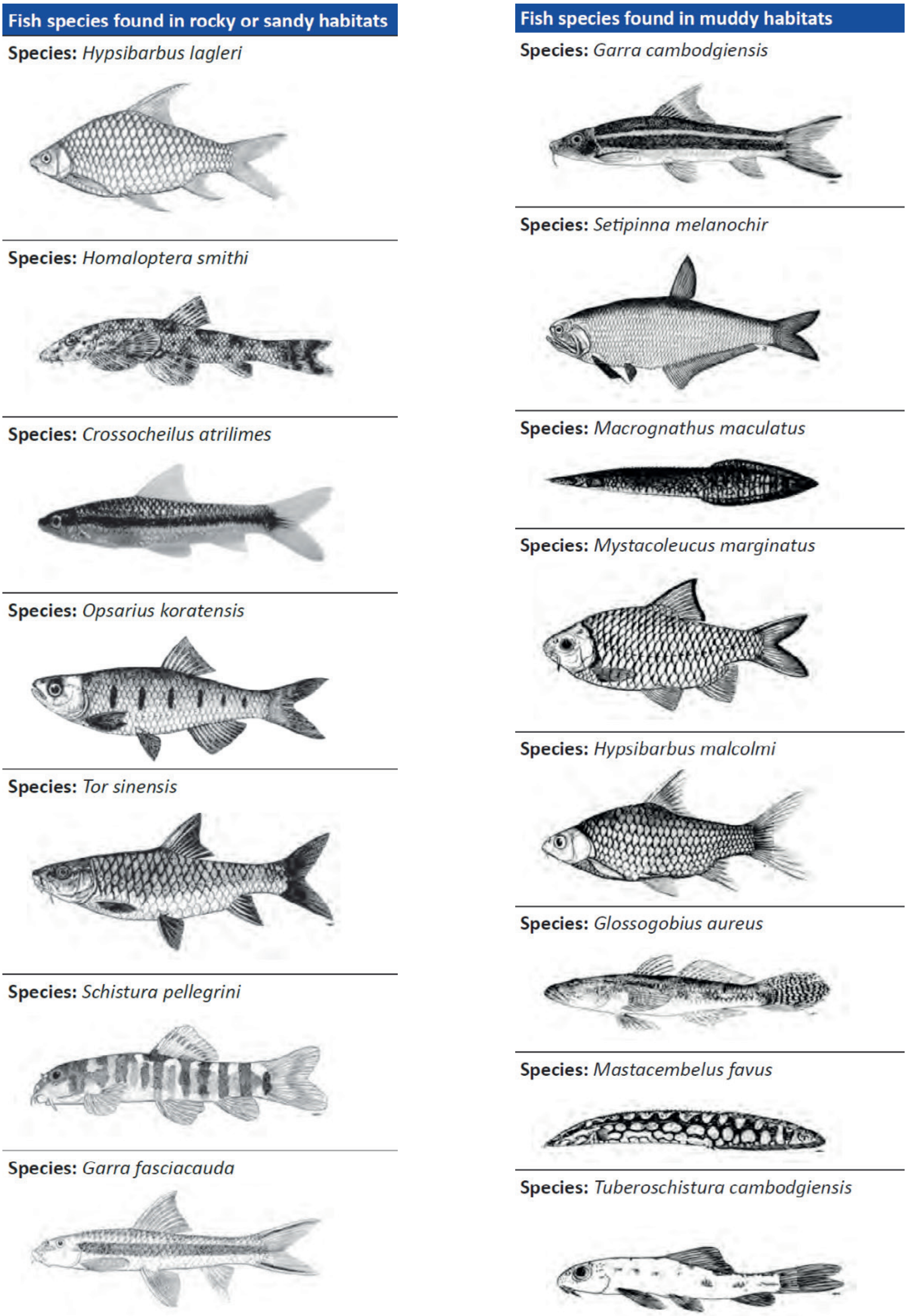

Figure 14: Examples of fish species whose ecology is dependent on sediments (Baran et al. 2015)

Cambodian communities downstream of Viet Nam's Yali Falls dam have reported a dramatic decline in fish catches since the construction of the dam. The decline has been linked to increased turbidity and sediment loads as a result of sediment hungry waters eroding riverbanks, which have smothered algal growth. High sediment loads have resulted in sediment deposition and in-filling of important fish habitats. There has also been a negative impact on fish species that cannot tolerate high sediment loads (Wyatt and Baird 2007).

Many studies have predicted that a reduction in sediment and nutrient loads following sediment trapping behind dams and sand mining will lead to river and coastal fisheries yield depletion and subsequently affect the fishing sectors and fish trade in Cambodia and Viet Nam – sectors that have shown strong growth in the past 10 years (Koponen et al. 2010; ICEM 2010; MRC 2011a, Bravard and Goichot 2012; Arias et al. 2014; DHI 2015). However, fish production in the Mekong is a multi-factor phenomenon and is not related to sediments alone. Lack of knowledge about fish replacement, growth and mortality weakens any assessment of the relationship between sediment load and fish production. Very little is currently known about the possible impact of reduced sediment and nutrient loads on river and coastal fish resources in Viet Nam and Cambodia (Baran et al. 2015).

6.4 Impact on agriculture production

When rivers flood, they deposit sediments on floodplains. Floodplains are highly fertile and play an important role in agricultural productivity. The Mekong delta is one of the most productive regions in the world. Often referred to as Viet Nam's 'rice bowl', the delta produces more than 16 million tonnes of rice annually for domestic consumption and export. Sediments carried from far upstream replace the land lost through natural erosion (MRC 2010). ICEM (2010) and the MRC (2011a) predicted that floodplain sedimentation would decrease within a decade, with a consequent reduction in agricultural productivity. While the immediate impacts on regional rice production were expected to be modest, the long-term impacts could be more serious.

DHI (2015) indicates that, rather than inundation, sediment reduction due to trapping by 11 mainstream dams in the Lower Mekong Basin is the key factor affecting rice and maize production in the Mekong Delta. Rice production in Viet Nam and Cambodia is predicted to decline by 552,500 tonnes and 203,300 tonnes, respectively, in a scenario of 10 consecutive years of impact. However, if sediment reduction lasts longer (up to 50 years), falls in rice production could reach in excess of 2.4 million tonnes, and up to 430,100 tonnes in Cambodia's floodplains alone. Maize production would decline by 21,700 tonnes (approximately 10%) in Viet Nam and 41,000 tonnes (approximately 21%) in Cambodia.

6.5 Impact on livelihood and economy

Reduced sediment loads will also result in the loss of agricultural land in inundated areas, riverbank gardens and floodplains. The poor will be most affected by these losses of agricultural land (Hai et al. 2009). ICEM (2010) showed how reduced nutrient loading will require an estimated USD 24 million/year to maintain the productivity of floodplain agriculture; and that one-third of the reduction is due to LMB mainstream hydropower. The abuse of fertilizer application will also increase the cost of production, which in turn will reduce farmers' earnings. Losses of farm income could exceed 20 per cent in many of the riparian areas of Dong Thap, An Giang in Viet Nam, and Kandal and Kampong Cham in Cambodia (DHI 2015).

A reduction in the production of primary products and fisheries production linked to decreased sedimentation could also have negative consequences for people living downstream who are dependent on fisheries, particularly in the wetlands, floodplains and delta areas (Dugan et al. 2004; Arias et al. 2014). The potential impacts on capture fisheries would indirectly affect the food security, social well-being and economic status of a large segment of local livelihoods that rely either part- or full-time on fishing and associated occupations. After the fish are caught, they are passed on to collectors, transporters, wholesalers, processors, market sellers and restaurant owners, and monetary value is added at each step. This monetary value directly increases purchasing power, allowing more to be spent on food, which in turn increases food security. Adverse impacts on capture fisheries would therefore translate into substantial economic hardships for many individuals and families, and at worst could lead to people migrating from rural to urban areas in search of new or different sources of employment (DHI 2015).

7 RELEVANT POLICIES AND STRATEGIES ON SEDIMENT MANAGEMENT

The countries in the Mekong Basin recognize the importance of water resource development and management, and the importance of healthy rivers. This has led to the development and implementation of laws and regulations, policies and strategies governing land and water use and environmental management in the basin at both the national and the regional levels. Developing and regulating policies and strategies on sediment management to sustain socio-economic development and protect the environment of the basin at the regional scale, however, is a relatively new concept among the countries on the Mekong region.

The rapid development of hydropower in the past 10 years has made the accumulated impacts of sediment trapping by reservoirs a critical concern for many groups in the basin (MRC 2011a). It is evident that there has been a substantial reduction in sediment loads in the LMB due to the existence of large hydropower dams in the UMB and LMB tributaries. Recent monitoring results by the Mekong River Commission (MRC) suggest that suspended sediment loads in the LMB are now in the range of ~70 Mt/yr, compared with historic values of ~160 Mt/yr (Koehnken 2014). The resulting loss of sediment becomes a regional and transboundary problem. This section therefore focuses on the policies and strategies related to reservoir sediment management at the global, regional and national levels.

7.1 Global level

UNESCO launched the ISI in 2003 to develop a decision support framework for sediment management in order to provide guidance on the legislative and institutional solutions applicable to various socio-economic and physiographic settings in the context of global change. The ISI aims to further advance sustainable sediment management on a global scale by drawing on international experience of sediment measurement and management to provide guidance for policymakers dealing with water and river basin management (UNESCO& IRTCES 2011). The key strategic activities of the ISI are to:

- Continue the development of a global repository for sediment-related data, including information and documentation on soil erosion, sediment transport and sediment-related issues, to serve as the basis for a global assessment of erosion and sedimentation problems and their social, economic and environmental implications.
- Update existing ISI river basin case studies and initiate new studies to provide representational examples of sediment processes, problems and management in different physiographic and institutional settings.
- Develop activities and joint programmes to promote the improved understanding of sediment processes and methods for investigation and monitoring.
- Support scientific exchange, education and capacity building for sustainable sediment management at all levels through the organization with partners of conferences, training events and other capacity-building initiatives.
- Develop information materials, policy briefs and procedures relating to sediment problems and their management for local and national authorities, river basin commissions, relevant technical agencies, local communities and other stakeholders.

The ISI has shared possible practical measures for dealing with sediment management in reservoirs through its case study on the Rhine River (see Figure 15). Although there are new technologies available to manage sediment in reservoirs, sediment still poses a huge technical challenge to engineers around the world. Adapting methods to suit the conditions of the area is a key component of sediment control and management.

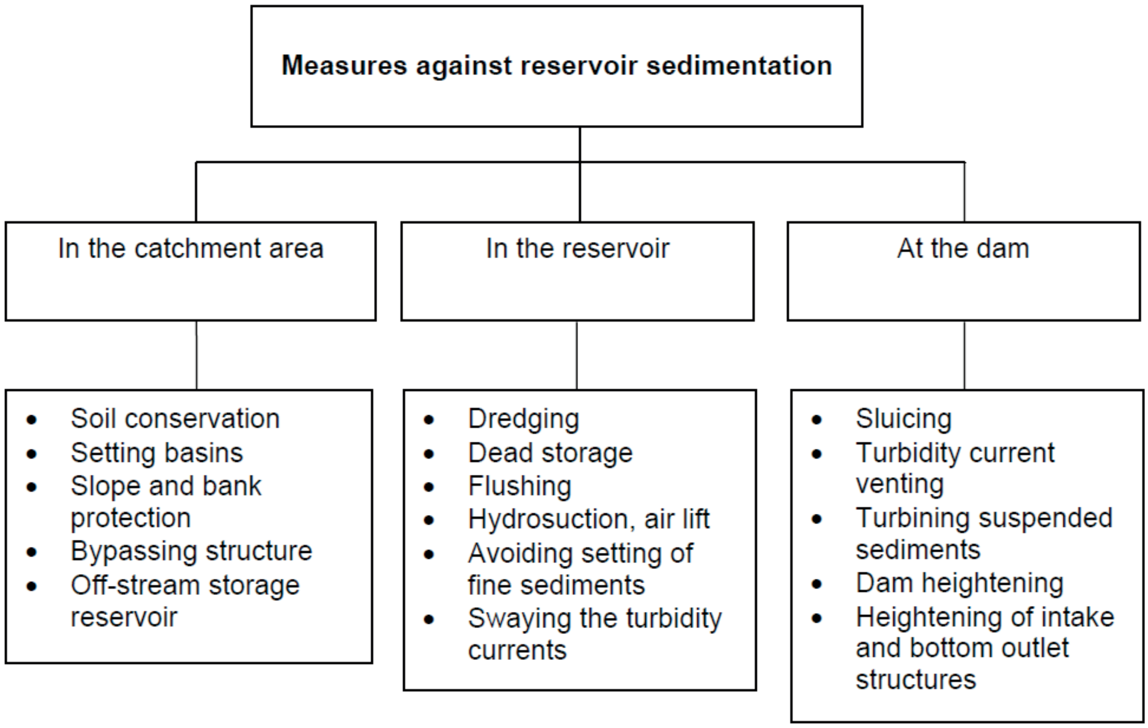

Figure 15: Measures to counter reservoir sedimentation (UNESCO& IRTCES 2011)

7.2 Regional level

At the basin level, the MRC is a key body for transboundary governance of the Mekong River Basin. The MRC was formed in 1995 by the Mekong Agreement between the governments of Cambodia, Lao PDR, Thailand and Viet Nam to ensure 'reasonable and equitable use' of the Mekong River system through a participatory process of consultation and discussions. The People's Republic of China and the Union of Myanmar engage as dialogue partners.

In 2009 the MRC Preliminary Design Guidance (PDG) for Mainstream Dams (MRC 2009) provided an overview of the potential sediment-related impacts associated with the development of hydropower projects and approaches to mitigation and management. The main impacts are: reservoir deposition; changes to sediment transport from inflowing tributaries, both in the reservoir and downstream; downstream channel adjustments related to changes in hydrology and sediment loads; and associated impacts on habitat distribution and quality. A summary of guiding principles on the consideration of sediment-related issues during the planning phase was provided for developers. These highlight the importance of:

- Understanding the relationships between hydraulics, river morphology and ecology;
- Assessing whether dam developments should be avoided in reaches susceptible to severe morphological change;
- Making dams transparent to sediment transport as much as possible;
- Considering the sediment transport issues associated with tributary inputs.

The PDG discusses a range of sediment management options, such as sediment routing, sediment bypass, sediment flushing, mechanical removal, sediment traps and sediment augmentation downstream of reservoirs. General guidance is provided with respect to site selection, the modelling and monitoring of sediments into, within and downstream of the impoundment, and the inclusion of gates to enable sediment management options. The operational and ecological issues associated with the timing of sediment management are also highlighted, with an emphasis on continued monitoring over the lifecycle of the project to guide management strategies. Reactive measures, such as physical bank protection, are indicated as a means of mitigating impacts that cannot be avoided through management of the project.

The MRC Integrated Water Resources Management (IWRM)-based Basin Development Strategy (BDS) for 2011-15 (MRC 2011b) recognized the knowledge gap on sediment monitoring and the urgent need for collaboration to capture the opportunities and address the impacts of ongoing development. The BDS placed immediate priority on the detailed identification of impacts, and mitigation and benefit-sharing measures, as well as coordination between the countries of the LMB on tributary dam operation, and with China on its Lancang dam operation. This would ensure the certainty and security of LMB dry season flows, reduce flood peaks and minimize the loss of wetland, sediment and nutrient supply. The key strategic actions on basin development and management related to sediment management were to:

- Strengthen cooperation with China on coordinated operation of the Lancang hydropower dams to secure the benefits of increased dry season flow, address the issue of sediment transport and provide early warning of dam water releases.
- Help national agencies, River Basin Organizations (RBOs), communities and project developers to work together on the design and operation of tributary dams, minimizing sediment and nutrient trapping and the blocking of fish migration, and reaching agreement on management measures for valuable wetlands from ecosystem and livelihood perspectives.
- Conduct detailed studies on the changes in sediment transportation from both ongoing and planned water resources developments and analyse the impacts of these changes on river incision; bank erosion; water quality; floodplain sedimentation; the productivity of fisheries, agricultural land and wetlands; and sediment movement to marine water in order to fill knowledge gaps and develop risk mitigation measures.
- Continue to improve sediment monitoring systems and analyses.

The current MRC IWRM-based BDS for 2016-20 (MRC 2016a) recognizes that without coordinated development and effective management, the risks from economic development, not least reductions in sediment loads and a deterioration in ecosystem services and biodiversity, will continue to threaten the Mekong River's ecosystems. The strategy highlights that implementation of the BDS 2011-15 reduced knowledge gaps in a number of areas of sediment transport through studies such as the Council study, the Delta study and the impact monitoring study by the Thai National Mekong Committee. The BDS continues to promote development opportunities and minimize adverse transboundary impacts through regional cooperation. The key strategic actions relevant to sediment management are updating the PDG on mainstream dams, strengthening the protection of mutually agreed environmental assets, optimizing basin-wide sustainable development, and cost and benefit sharing. Moreover, the MRC will continue the maintenance and improvement and, where necessary, expansion of monitoring systems on sediment transport (MRC 2016c).

7.3 National level

In the Mekong region, sediment management policies and strategies at the national level are normally integrated into policies and plans on land management, water resource management, watershed management and environmental management, under the different implementing agencies of the various ministries, to address national and local sediment issues such as land and riverbank erosion, loss of reservoir storage capacity, downstream degradation of sediment loads, and damage to wetland, floodplain and estuary ecosystems reliant on sediment. Table 4 provides an overview of the legal and relevant government agencies governing sediment management in each country. Coordination among the different agencies is a key challenge to the effectiveness of sediment management and control. Despite the sediment issues at the regional level, there are policy gaps and barriers to integrating regional sediment management strategies and guidelines into national policies and developing national action plans to reduce the risks arising from the reduction of sediment and nutrient loads in the Mekong mainstream due to the accumulated impacts of sediment trapping by reservoirs.

Table 4: Overview of legal and administrative structures in each country in the Mekong Basin

Counties	Laws/policies/strategies	Relevant government agencies
Cambodia	Law on Environmental Protection and Natural Resource Management (1996) National Forest Policy (2002) and Forest Law (2002) National Policy on Water Resources (2004) Law on Water Resources Management (2007) Strategy for Agriculture and Water, 2006-2010 National Environmental Action Plan, 1998-2002 National Strategic Development Plan, for 2014-2018 National Forest Programme, 2010-2029	Department of Water Resources Management and Conservation Department of Hydrology and River Works Department of Irrigated Agriculture Department of Hydropower The state power company, Electricity du Cambodge Department of Environmental Impact Assessment Review Department of Forest and Wildlife Department of Fisheries
People's Republic of China	Water Law of the People's Republic of China (2002) Flood Control Law of The People's Republic of China (1997) Law of the People's Republic of China on the Prevention and Control of Water Pollution (1996) Law of the People's Republic of China on the Conservation of Soil and Water (1991) Hydrology Regulation of the People's Republic of China (2007) The Prevention and Control of Water Pollution (1989)	Ministry of Water Resources Department of Planning and Programming Department of Policy, Law and Regulations Department of Construction and Management Department of Water and Soil Conservation Ministry of Environmental Protection Department of Environmental Impact Assessment Department of Water Environment Management Department of Soil Environment Management
Lao PDR	Law on Water and Water Resources (1996) National Water Resources Policy and Strategy Development (2010) Sustainability of Hydropower Sector in Lao PDR, 2006 Electricity Law, 2012 Law on Investment, 2009 National Environment and Social Policy Strategy for Agricultural Development, 2011-2020 Forest Strategy, 2005-2020	Department of Water Resources Department of Environmental and Social Impact Assessment Land Policy and Land Use Inspectorate Land Use Planning and Development Department Department of Agriculture Department of Irrigation Department of Energy Policy and Planning, Department of Energy Business
Myanmar	Conservation of Water Resources and River Law (2006) Forestry Law, 1992 Forest Policy, 1995 National Water Vision, 2004 National Water Policy, 2014 Water Law/Water Act, 2015 Environmental Conservation Law, 2012 National Environmental Policy, 2016	Directorate of Water Resources and Improvement of River Systems Department of Hydroelectric Power Irrigation Department Environment Conservation Department Forestry Department
Thailand	Royal Irrigation Act, 1942 Promotion and Protection of National Environment Act, 1992 Enhancement and Conservation of Environmental Quality Act, 1992 National Strategic Plan on Water Resources Management, 2015-2026 Policy and Plan for Enhancement and Conservation of National Environmental Quality, 2017-2036 Environmental Quality Management Plan, 2017-2021	Office of Natural Resources and Environmental Policy and Planning Department of Water Resources Royal Irrigation Development Electricity Generating Authority of Thailand Forest Department Department of Environmental Quality Promotion

Counties	Laws/policies/strategies	Relevant government agencies
Viet Nam	Law on Water Resource, 2012 Law on Environmental Protection, 2014 Decree stipulating the implementation of the law on water resources, 1999 Decree on Water resource information management, 2003 Decree on Licensing for the exploitation, utilization, use and discharge of waste water, 2004 Decree on sanctions against administrative violations of water resources management regulations, 2005 Decree on reforestation investment as alternative to forest used for hydropower purposes, 2006 Decree on policies for forest environmental services, 2010 National strategy on water resources to 2020 National Strategy on environmental protection to 2020	Department of Water Resources Management Department of Hydrometeorology Department of the Environment Department of Environmental Impact Assessment and Appraisal Department of Land Hydropower Department

8 KEY CHALLENGES AND POLICY RECOMMENDATIONS

8.1 Knowledge gaps

The following key challenges and knowledge gaps in sediment management were identified by this study.

1. The amount of research and the number of studies on sediment issues along the Mekong River have grown in the past decade. Sediment monitoring data on suspended and bed loads in the Mekong River and its tributaries, however, are still too limited at the spatial and temporal resolution to accurately determine how much of the sediment loads from tributaries enter to the Mekong mainstream, floodplains and delta. There is therefore no consensus on sediment baselines among the countries in the Mekong Basin.
2. The sharing of information on sediment monitoring in the Upper Mekong Basin between China and countries lower down remains limited to monitoring changes in sediment loads due to the operation of the large hydropower dams in China, as well as quantifying the consequences for and impacts on nutrients, river morphology and fisheries.
3. There are no integrated monitoring systems at either the national or the regional levels to monitor extraction loads of riverbed mining and other activities that affect sediment transport, such as developments in floodplains. Large volume extractions can lead to bed incision and channel instability due to the over-steepening of banks.
4. The actual impacts of the reduction of sediment loads in the Mekong mainstream on nutrients, riverbank erosion, the dynamics of floodplains and deltas, fisheries and agricultural production, and local livelihoods remain key knowledge gaps. Their problems are not linked to sediments alone as these systems are complex. Quantification of the impacts of other major factors will be required before an assessment of the relative role of sediments can be made.
5. Sustainable sediment management practices to reduce sediment trapping by reservoirs, such as sediment bypassing around dams, sluicing sediment through large low-level outlets in dams during floods, draw down flushing through dams, and so on, cannot be implemented at existing dams because they currently lack the facilities to bypass sediment.
6. Best practices on sediment management and mitigation measures to address the sediment transport and geomorphic aspects of hydropower developments, both upstream and downstream, must be considered at every stage of the hydropower lifecycle. Best practices and mitigation must be an integral part of the planning, development, construction and operational periods of a project – not something that is considered reactively in response to a problem.
7. The construction and operation of large hydropower dams on the mainstream river and the cumulative impacts of large dams in tributaries have the potential to create transboundary impacts and international tensions in the Mekong Basin due to: (i) reduced ecosystem integrity; (ii) reductions in sediment and nutrient loads; (iii) disruption to other users of the Mekong; (iv) reductions in productivity in fisheries and agriculture; and (v) increased food insecurity in affected sub-basins and the delta. The framework of regional standards and safeguards on transboundary and downstream effects and the institutional arrangements for their enforcement, however, are not fully developed and are not adequate for the requirements of project risk management.
8. A number of barriers – such as legal and institutional frameworks, and limitations of capacity, funding and tools – hinder the effectiveness of coordination and collaboration on sustainable sediment management among different agencies at the national level and among countries at regional level.

8.2 Policy recommendations

The following policy recommendations are intended as a guide for river basin managers and operators, and other concerned agencies, to address the key challenges identified above:

Recommendation 1: Continue to improve and enhance sediment monitoring systems at the national and regional levels, to cover major tributaries of the Mekong River and at strategic locations such as Tonle Sap, as well as key environmental hotspots – especially in the floodplains and delta areas.

Recommendation 2: Enhance collaboration with international agencies such as the ISI on developing a commonly accepted international protocol for monitoring sediment transport and sedimentation in river systems, as well as exchanging experience on sediment problems, and sediment management issues, techniques and practical solutions among other river basins.

Recommendation 3: Establish a monitoring and database system to monitor extraction through riverbed mining on the Mekong mainstream, improve accounting for sediment budgets in the system and assess the causes of sediment transport.

Recommendation 4: Establish sediment baseline conditions to assess relative changes in sediment linked to development, land use change and climate change, and define targets for sediment management and mitigation measures, particularly for large hydropower projects on the Mekong mainstream and tributaries.

Recommendation 5: Enhance data sharing on sediment monitoring between China and the MRC, and develop joint projects to observe changes in sediment transport and assess the actual consequences of impacts downstream, particularly between the border with China and upstream Vientiane, Lao PDR.

Recommendation 6: More studies on actual impacts are needed to better understand the complex interactions of sediments and the wider implications for nutrients, riverbank erosion, the dynamics of floodplains and deltas, fisheries and agricultural production, and local livelihoods.

Recommendation 7: Ensure that best practices on sediment management and mitigation measures, which address sediment issues at the national and regional levels, are integrated into every stage of the hydropower lifecycle, from planning to development and operation, in order to sustain hydropower development. Hydropower developers should proceed with caution and take responsibility for any adverse impacts at both the national level and the regional level. A sediment management strategy and mitigation measures should also be developed, taking account of existing best practices and technologies for minimizing negative impacts.

Recommendation 8: Develop regional standards and safeguards on transboundary sediment issues and institutional arrangements for their enforcement, and ensure that they are integrated into national policies, strategies and implementation plans. The MRC Preliminary Design Guidance for Mainstream Dams should be reviewed periodically to ensure that it reflects the current situation and current issues on sediment transport.

Recommendation 9: Increase the involvement of relevant stakeholders and communities in sediment management and developing mitigation measures to provide sufficient information on how they can improve river health and contribute to sediment management, and how they should adapt to change and adverse impacts.

Recommendation 10: Improve coordination and collaboration on sustainable sediment management among different agencies at the national and regional levels through regular dialogue, enabling legal and institutional frameworks, establishing working groups and engaging development partners especially through mechanisms and institutions such as the MRC and LMC.

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