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MRC SEA FOR HYDROPOWER ON THE MEKONG MAINSTREAM

HYDROLOGY & SEDIMENT BASELINE ASSESSMENT WORKING PAPER

8 March 2010

The MRC SEA of Hydropower on the Mekong mainstream comprises 4 main phases: (i) scoping, (ii) baseline assessment, (iii) opportunities & risks assessment, and (iv) avoidance, enhancement and mitigation assessment.

The Baseline Assessment Report has two volumes:

VOLUME I: Summary Baseline Assessment Report

VOLUME II: Baseline Assessment Working Papers

This working paper is one of eight in Volume II of the baseline assessment report. The two volumes formally conclude the baseline assessment phase of the SEA and documents the outcomes of the baseline consultations and SEA team analysis.

Disclaimer

This document was prepared for the Mekong River Commission Secretariat (MRCS) by a consultant team engaged to facilitate preparation of a Strategic Environment Assessment (SEA) of proposals for mainstream dams in the Lower Mekong Basin.

While the SEA is undertaken in a collaborative process involving the MRC Secretariat, National Mekong Committees of the four countries as well as civil society, private sector and other stakeholders, this document was prepared by the SEA Consultant team to assist the Secretariat as part of the information gathering activity. The views, conclusions, and recommendations contained in the document are not to be taken to represent the views of the MRC. Any and all of the MRC views, conclusions, and recommendations will be set forth solely in the MRC reports.

This document incorporates a record of stakeholder consultations and subsequent analysis. Whether they attended meetings or not all stakeholders have been invited to submit written contributions to the SEA exercise via the MRC website.

For further information on the MRC initiative on Sustainable Hydropower (ISH) and the implementation of the SEA of proposed mainstream developments can be found on the MRC website: http://www.mrcmekong.org/ish/ish.htm and http://www.mrcmekong.org/ish/SEA.htm

The following position on mainstream dams is provided on the MRC website in 2009.

MRC position on the proposed mainstream hydropower dams in the Lower Mekong Basin

More than eleven hydropower dams are currently being studied by private sector developers for the mainstream of the Mekong. The 1995 Mekong Agreement requires that such projects are discussed extensively among all four countries prior to any decision being taken. That discussion, facilitated by MRC, will consider the full range of social, environmental and cross-sector development impacts within the Lower Mekong Basin. So far, none of the prospective developers have reached the stage of notification and prior consultation required under the Mekong Agreement. MRC has already carried out extensive studies on the consequences for fisheries and peoples livelihoods and this information is widely available, see for example report of an expert group meeting on dams and fisheries. MRC is undertaking a Strategic Environmental Assessment (SEA) of the proposed mainstream dams to provide a broader understanding of the opportunities and risks of such development. Dialogue on these planned projects with governments, civil society and the private sector is being facilitated by MRC and all comments received will be considered.

CONTENTS

1.0 INTRODUCTION

The SEA hydrology and sediment baseline divides the Mekong Basin into six hydro-ecological zones and uses these to organize spatial analysis (see figure 1). The baseline also uses the scenarios developed by the MRC Basin Development Programme (BDP) to characterize development. Given that the earliest time a mainstream project could come online is post-2015, the SEA 'baseline' projects into the future including the BDP Definite Future Scenario (see figure 2). Annex 1 gives full details. All figures to this report appear as Annex 3.

PHASING OF THE SEA HYDROLOGY AND SEDIMENT ASSESSMENT

In the SEA impact assessment, the mainstream projects are assessed against a baseline of economic, social and environmental conditions. The baseline "without" the mainstream dams should represent an accurate description of the past and current situation and present a realistic projection of future conditions for a period when the mainstream dams might be constructed and operational. For the Mekong hydrological regime, the BDP Baseline has been taken as an accurate description of the past and current situation. For the projected baseline, the hydrological assessment selected two BDP scenarios – the Definite Future to 2015 and the LMB 20 Year Scenario to 2030. In this paper only the Definite Future is analysed. The LMB 20 Year baseline will be analysed during the impact assessment phase so that the mainstream project can be assessed for their effects against two sets of baseline conditions. The SEA team considers the Definite Future development scenario to be the most likely baseline conditions for the mainstream project, which if they were to proceed, would only be a reality in a post-2016-2020 Mekong basin. The LMB 20 Year scenario enables the mainstream projects to be assessed against a more extreme projected development baseline.

1.1 THE MEKONG FLOOD PULSE

The Mekong River is 4,880km long with a total fall of 4,583m, area of 795,000km² and average annual flow of 505km³ (MRC, 2005; Kummu et al, in publication). Originating in the Tibetan plateau the river spans a wide range of geologic, climate, drainage and ecological zones. The unifying hydrological feature of the system is the river's flood pulse, which sees the individual rainfall-runoff events throughout the catchment coalesce into a stable and predictable hydrograph with distinct hydrological seasons (figure 3). For the Lower Mekong Basin (LMB) it is the Mekong flood pulse which drives the river's high levels of aquatic and terrestrial biodiversity and system productivity (Kummu et al, 2007). The annual mainstream hydrograph for the Mekong River has three important features which are critical in establishing the current hydrological regime. First, the response of the hydrograph to the SW monsoon exhibits a single amplitude peak complemented by a highly predictable phase (MRC, 2006). Second, the onset of the flood season occurs within a consistent and small time window with a standard deviation of approximately two weeks (MRC, 2006). Third, there is a long period of low flows which facilitate the seasonal transition from aquatic to terrestrial environments. This predictability of the river hydrology has resulted in a good understanding of the natural equilibrium that is manifest throughout the 90years of sampling data. The baseline assessment uses this understanding of the Mekong hydrological regime and key aspects of the hydrograph as the platform against which future developments are assessed.

1.2 TRENDS IN THE DRIVERS OF CHANGE

Given the stability of the natural hydrological regime, change over short (human) time scales will arise from human activity in the basin. Therefore the proposed LMB mainstream hydropower projects must be considered in the development context into which they may enter. From a surface water point of view, development in the basin can affect the availability of water, the consumption of water, and the storage of water at seasonal and inter-annual time-scales. These three areas are briefly summarized below:

1. **Water Availability:** human activity can affect the availability of water by: (i) altering the rainfall-run off relationship – most commonly through land clearing or deforestation, or (ii) by changing the timing and duration of precipitation events through long-term climate change.

   i. *Rainfall-runoff relationship:* There has been an average 15-20% reduction in forest cover in all Mekong countries (Table 1), and currently approximately 40% of the LMB is devoted to agriculture (Hall et al, 2005). Some areas of the basin, in particular Thailand and Yunnan province have seen greater rates of land clearing.[1] From an hydrological point of view, these land use changes have local level impacts but have not yet significantly affected the regional hydrological regime of the Mekong to date.

   ii. *Climate Change:* will be dealt with under a separate theme paper. The general trend will be an increase in annual run-off for most zones of the Mekong Basin, and a decrease in dry season run-off for southerly zones of the LMB (see climate change paper).

Table 1: Trends in percentage forest cover for Mekong Basin countries (source: MRC, 2007)

COUNTRY	1960s-1970s	~1980	~1990	~2000	*% Change*
Cambodia	0.70	0.70	0.67	0.53	0.17
Lao PDR	0.60		0.47	0.41	0.19
Thailand	0.53	0.34	0.28	0.29	0.24
Vietnam	0.42		0.28	0.30	0.12
Burma	0.58			0.52	0.06
Yunnan	0.55			0.33	0.22
AVERAGE	*0.56*	*0.52*	*0.43*	*0.40*	*0.17*

2. **Water consumption:** water consumption can be increased by: (i) increased irrigation and mainstream off-takes, for example, there have been previous plans for large-scale inter-basin transfer from the Lancang River and 'mega-irrigation' projects in Northeast Thailand, (ii) domestic consumption, and (iii) increased evaporation from agricultural or hydropower storage.

   i. *Mainstream irrigation:* under the BDP Definite Future (DF) scenario the area irrigated by the Mekong will reach 6.8 million hectares, which represents a marginal 3% increase from the baseline.

   ii. *Domestic water supply:* under the BDP DF the volume of water abstracted for domestic and industrial supply will increase from 1.78km³ to 2.83 km³ (59% increase), or 0.6% of the mean annual flow in the Mekong River.

   iii. *Increased evaporation:* under the DF the total mean surface area of the proposed hydropower projects will increase from 928km² to 1,688km², while the Tonle Sap Lake surface area will

[1] *This issue is addressed in more detail in subsequent sections – especially for Zone 1 (Yunnan Province)*

decrease in the order of 500k m² (see discussion below) which represents a nett 30-40% increase in evaporation volumes. Current basin-wide evaporation rates range from 1-2m/yr depending on the region with little inter-annual variability (MRC, 2005).

3. ***Water storage:*** Water storage can be natural or human induced. Surface storage is typically seasonal receiving water in the wet season and releasing back into the Mekong during the dry season. Subsurface storage can be both seasonal and nett. An overview of the types of storage in the LMB is presented below.

   i. *Natural storage:* The majority of the natural storage results from infiltration of rainfall into the soil horizon and groundwater aquifers. Using a basin-wide mean precipitation of 1.5m/yr, a basin area of 795,000km² and a historic mean annual runoff of 512km³ (MRC, 2005; Eastham et al, 2006), subsurface infiltration in the order of 1million km³ of water infiltrates the ground surface. Looking specifically at the LMB the major groundwater aquifers are:

   Lao PDR has three main aquifer systems, Annamian (northern and eastern Lao PDR), Indosinian (central) and Mekong alluvial with both superficial and deep lenses (Eastham et al, 2006). The limestone aquifers of the Indosinian group currently hold the greatest groundwater reserves (Eastham et al, 2006). Some of the aquifers, in particular the alluvial, are hydrologically connected with surface waters and provide seasonal storage discharging back into the Mekong and its tributaries during the dry season.

   Northeast Thailand has shallow (1-10m) alluvium aquifers in all Mekong provinces, but predominantly in the northern provinces of Vientiane, Nakhom Phanm and Mukdahan (Eastham et al, 2006). Hoanh et al (2003) estimate that 5-6% of rainfall recharges aquifers in these regions, with a maximum of 14-31% of rainfall in the western parts of Ubon Ratchathani province (Eastham et al, 2006).

   Cambodia's freshwater aquifers are typically shallow and hydrologically connected to the Mekong and Tonle Sap Lake system, with groundwater levels within a 30km band of the Mekong directly responding to water level fluctuations in the Mekong River (Eastham et al, 2006). This is because the floodplain consists of a thick lens of Quaternary sediments underlain by shale, slate and sandstone bedrock (ADB, 1999, Eastham et al, 2006). Recharge in the floodplains can occur through direct infiltration (as in Lao PDR and Thailand) or seepage during flooding. Table 2 highlights the connectivity between inundation area and groundwater recharge where yearly fluctuation in inundated area can affect total groundwater storage.

Table 2: Comparison of groundwater storage and flooded area in the Cambodian floodplain (adapted from: Eastham et al, 2006)

CAMBODIAN FLOODPLAIN	1993	1997	1998*
Inundation area (km2)	5,200	4,212 *(-19%)*	2,912 *(-44%)*
Groundwater storage (km3)	52	36 *(-31%)*	30 *(-42%)*

** 1998 represents a dry year*

   Vietnam has five main aquifers in the Mekong Delta which are estimated to extend in the order of hundreds of kilometers into the South China Sea and the Gulf of Thailand (Eastham et al, 2006). Interestingly, flooded water levels may induce submarine groundwater discharge into the Mekong marine environment (Eastham et al, 2006). A substantial proportion of shallow and medium aquifers have already been exhausted due to over-exploitation and improved surface drainage during the 1990s, consequently, only areas in the vicinity of the Mekong mainstream channels provide reliable groundwater supply (Eastham et al, 2006). In these areas the groundwater table can drop 2-3m during low flow years (Le Anh Tuan et al, 2007).

The Mekong River has a relatively low capacity for natural surface storage, with major storage components comprising the floodplains and Tonle Sap system (max 6-12million ha) (Hall et al, 2005). These areas provide seasonal storage holding wet season flows for release in the dry season.

ii. *Human induced storage:* Under the BDP DF the number of tributary dams will increase from 16 to 46 which correspond to a 450% increase in active storage capacity (9.9 – 44.4km³) or a capacity to store 10% of the Mekong's mean annual flow by 2015.[2] By number almost half (20) of these projects are in Lao PDR, with 13 in the Central highlands of Vietnam, however, the 6 projects in China (known as the Yunnan cascade) collectively account for 23.7km³ of this storage (53%). Further, the Xiowan (active storage 9.9km³) and Nuo Zhadu (active storage 12.3 km³) projects each represent ~22-28% of the total storage projected for 2015 (table 3). This represents the first time when a single human activity will have the capacity to alter the hydrological regime of the entire Mekong Basin.

Table 3: Salient features of the Yunnan cascade

Yunnan project	Dam water level (m)	Mean Annual Inflow (km3)	Active storage (km3)	Active storage/mean annual flow (%)	Trapping Efficiency 1 (%)	Trapping Efficiency 2 (%)
Gong guoqiao	1319	31	0.12	0.04	39	30
Xiao wan	1240	39	9.90	2.54	93	98
Man Wan	994	39	0.34	0.09	60	60
Da Chaoshan	899	42	0.47	0.11	64	66
Nuo Zhadu	812	55	12.30	2.24	92	98
Jing Hong	602	58	0.58	0.10	62	64
Gan Lanba	533					
Meng Song	519					
YUNNAN TOTALS			**23.71**		**71-81%**	

2.0 REGIONAL HYDROLOGY: PAST TRENDS AND CURRENT STATUS

The LMB hydrological regime is comparatively homogenous upstream of Kratie, with comparable timing and duration of seasons in most LMB mainstream stations (see figure 3) MRC (2006). This homogeneity is driven by two main components: (i) the Southwest Monsoon which dominates the rainfall-runoff relationship in the LMB and occurs with small temporal variability (see above), and (ii) the Yunnnan flow component which is an important contribution to maintaining dry season flows through snow and glacial melt in the upper catchment. The key features of the hydrograph are:

- **Large seasonal variation in the flow regime**: reflecting the dominance of the Monsoon and typhoon events in the wet season, flow volumes peak in September approximately 4-6weeks after the peak in run-off. This results in minimum dry season flows of on average 7% of the maximum wet season flows

[2] *There are in total 92 hydropower dams planned for the Mekong River, if all these went ahead basin storage could increase to a potential 91.4km³ representing ~20% of the mean annual flow in the Mekong River (Kummu et al, in publication).*

with the seasonal variation reducing with distance downstream (Chiang Saen sees an average maximum variation of 12% with 5-6% at both Pakse and Kratie).

- **Predictable flood peak:** A flood peak which occurs with predictable regularity and is often preceded by a smaller lead peak at the beginning of the flood season. On average, the flood season at all stations between Chiang Saen and Kratie begin on the 1st of July and lasting until 4-11th of November, with a standard deviation of 2weeks (Adamson, 2005)
- **High variability at the onset of the flood season:** Comparably high variability in flow during the transition season as the first rainfall events induce a series of *spates* into the hydrograph which play an import ecological role in triggering response in biota.

Downstream of Kratie the Mekong system shifts to a complex floodplain environment and there is significant variation in the hydrograph form compared to upstream. 83% of the Mekong flooded area is located in Cambodia and Vietnam, these areas are important for regional biodiversity, as well as national agriculture and fisheries production. While, approximately 750,000ha lie along the Mekong channel in Lao and Thailand, of which 64 – 69% flood to depths greater than 3.0m. Key features of the floodplain include:

- **Reduction in the flood peak discharge:** flows become less constrained to the Mekong channel and spreads out over the flood plain with a corresponding reduction in flow and water level in the channel.
- **Lag in flood recession:** Hydrology is driven by water levels in the flood plain rather than channel flow, with the recession of overbank floodwaters and storage of floodwaters in the Tonle Sap lake prolonging the flood season into January/February. Overland flow accounts for approximately 30% of the flood flow into the Mekong Delta (SIWRP, 2006).
- **Higher daily variation in flows:** the complex hydrodynamics of receding floodwaters, reverse flow in the Tonle Sap and overland flow can cause greater fluctuation in water levels at a daily and weekly time-step (see for example average daily water levels for Chau Doc).
- **Cyclical variation in flood volumes:** Flooding is a regular occurrence south of Kratie and shows some variation in annual peak levels. Taking Tan Chau as an example, high flood water levels (>4.2m) have been exceeded 24times between 1929 – 2005 which represents an average exceedance of once every three years. Therefore, high flood levels are a frequent occurrence of the natural system. Flood related disasters do occur in the delta but are aligned with extreme events such as typhoons, severe storms.
- **Flooded depth:** The majority of Cambodian flooded areas reach depths of more than 3m during the flood season and upwards of 7m in the Tonle Sap Lake and Kratie, while Vietnamese areas reach depths of 0.5 – 3.0m.

H1: Flow variation

PAST TRENDS & CURRENT SITUATION

There has been small inter-annual variation in the Mekong hydrograph over the past 90years of monitoring. The hydrograph can be characterized by four distinct hydro-biological seasons with large seasonal variation between flow and water levels – on average minimum dry season flows are 7% of the average maximum flow. This dynamic equilibrium is characteristic of large pulsing river systems and allows for the seasonal oscillation from terrestrial to aquatic habitat which is fundamental to the productivity of the Mekong River and its floodplains.

FUTURE TRENDS TO 2015

The best indication of the hydrological changes to be expected from the Yunnan cascade can be extrapolated by comparing the current and future mean daily and monthly hydrographs for the LMB (see figures 4-9 and table 4 below).

- **Average annual flow:** under the BDP DF there is no significant increase in average annual flow
- **Average seasonal flow:** Dry season flows will increase by ~690 m³/s, while wet season flows will be reduced by ~700m³/s. These results differ from the modeling results presented by ESCIR at the 2nd BDP Regional Stakeholder Consultation, in which the increase in dry season flow was almost double (1,200 m³/s) while the reduction in wet season flow was 1,200 - 1,400 m³/s (Pimpan, 2009). As mentioned above, this significant discrepancy is yet to be resolved but could be the result of differing reservoir operational strategies defined in the model and is a critical issue for the SEA (discussed further below). Figures 10 & 11 present the average, min and max flows and water levels for each station Chiang Saen to Kratie for both the BDP baseline and definite future.

Table 4: Changes to seasonal flow based on the MRC and ESCIR modelling

Seasonal flow	MRC	ESCIR
Increase flow in dry season (m^3/s)	690	1,200
Decrease flow in wet season (m^3/s)	700	1,400

- **Peak flood flow:** The peak flow is decreased reflecting lower annual flood volumes.
- **Seasonal flow:** The changes in seasonal flows broadly reflect the importance of the Yunnan flow contribution to the stations of the Mekong. There is a greater percentage increase in dry season flows for all stations because at this time the Yunnan component makes up 40% or more of the natural flows down to Kratie – this results in a 10-70% increase in dry season flow for the 6 LMB mainstream stations. While during the wet season, flows from the Lao tributaries dominant the seasonal flow, consequently, the changes to the wet season flow volume is of the order of -18% to -2% (See figure 12). In absolute terms the seasonal increases and decreases are of comparable magnitude.
- **Flood-related disaster:** The Yunnan cascade will not directly reduce flood risk because flood risk attributed to Lancang flows is not as significant as the flood risk from Lao tributaries. This is because flood risk is not driven by seasonal flow fluctuations but by the occurrence of extreme events. An historical assessment of storm and cyclone events indicates that major storm events track further south than the Yunnan cascade and so reduce their ability to directly mitigate storm consequences by buffering flows. Conceivably, dam releases could be altered to reduce the Yunnan flow contribution and provide additional downstream capacity to absorb extreme events, however, this would require intensive transboundary coordination with potential impacts on energy production.
- **Flooded area:** The Definite Future will see a typical reduction of ~250,000ha in flooded area, the majority of which will affect areas with flood depths greater than 3m. This will affect more than 15% of the flooded areas in Thailand and Lao PDR, and less than 5% of the area in Cambodia and Vietnam.

Table 5: Average, Max and Min Flows for the Mekong mainstream under existing and predicted 2015 scenarios

	CHIANG SAEN	VIENTIANE	PAKSE	KRATIE	TAN CHAU	CHAU DOC
BASELINE						
AVERAGE Flow (m3/s)	2,622	4,299	9,390	12,869	10,488	2,121

MAX Flow (m3/s)	6,476	12,121	27,333	36,297	20,764	5,605
MIN Flow (m3/s)	791	1,012	1,532	2,001	2,160	139
DEFINITE FUTURE						
AVERAGE Flow (m3/s)	2,615	4,282	9,319	12,798	10,633	2,126
MAX Flow (m3/s)	5,512	10,848	25,919	34,793	20,236	5,406
MIN Flow (m3/s)	1,557	1,786	2,407	2,953	2,972	248

H2: Timing and duration of the hydro-biological seasons

The historic consistency of the Mekong hydrograph allows for the definition of 4 clear hydro-biological seasons which are statistically discernible from one another. The seasons are as follows.

Table 6: Physical and statistical definitions of the Mekong hydro-biological seasons (adapted from: MRC, 2007)

No	MEKONG HYDRO-BIOLOGICAL SEASONS	STATISTICAL TEST FOR END OF SEASON
1	**DRY SEASON** • Flows below annual average • Constant hydrological recession • Minor intra-seasonal variability • Flows are maintained by natural storage in the Mekong system (in soil horizons, groundwater, riparian wetlands and Tonle Sap Lake)	• End of the dry season is the first time in the year when flows exceed twice the minimum dry season discharge of that year • This is usually associated with the first pulse of early rainfall or snowmelt
2	**TRANSITION A** • Transition from dry to flood season • Noticeable increase in flows • Increased variance in flow conditions • The rising limb of the flood peak	• First upcrossing of the long term mean annual discharge
3	**FLOOD SEASON** • Acceleration in flow rate • Period of the year when flows are above the long-term average discharge • Peak annual discharge (may include a leading and falling peak) •	• Last downcrossing of the mean annual discharge
4	**TRANSITION B** • Transition from flood to dry season • Faster rate of recession than the dry season •	• Mean daily flow decrease of 1% or less for 15 days

The onset of the four hydrobiological seasons occurs with a standard deviation of ~2weeks (Table 7). This remains consistent from Chiang Saen to Kratie.

Table 7: Changes to the timing and duration of the Mekong Hydro-biological seasons

		END OF DRY	END TRANS. A	END OF FLOOD
STATION	SCENARIO	2*Q(min)	Q>Q(ave)	Q<Q(ave)
CS	BS	20-May	24-Jul	11-Nov
	DF	17-Jul	28-Jul	13-Nov
VTE	BS	14-May	25-Jun	14-Nov
	DF	10-Jun	27-Jun	13-Nov

PK	BS	18-May	16-Jun	8-Nov
	DF	29-May	14-Jun	7-Nov
KT	BS	17-May	17-Jun	12-Nov
	DF	23-May	17-Jun	11-Nov
TC*	BS	*25-May*	*30-Jun*	*17-Dec*
	DF	*4-Jun*	*2-Jul*	*18-Dec*
CD*	BS	-	*15-Jul*	*11-Dec*
	DF	-	*16-Jul*	*11-Dec*

**timings for transitions have been calculated for Tan Chau and Chau Doc, however, it should be noted that for these stations these values are or*

PAST TRENDS AND CURRENT SITUATION

The LMB experiences four identifiable seasons which occur with regularity:

- The low flow season begins at the end of the calendar year and extends through to mid/late May. Flow is maintained by snow melt in the Mekong headwaters and the minimal natural storage of the basin in the soil horizon, groundwater and wetlands.
- The transition to flood season is characterized by the first *spates* of the Monsoon season with an increase in both flow rate and flow variability. The transition season ends in mid July
- The flood season begins when flows exceed the long term average and is characterized by the flood peak in September and sometimes a smaller leading peak. The season finishes in early to mid-November when flow drops below the long term annual average.

FUTURE TRENDS TO 2015

- ***Onset (figure 13):*** changes to the timing of the seasons is greatest in the upper reaches of the LMB where the Lancang flows contribute a greater proportion. The timing of Transition A from the dry to the flood season will be most affected, starting ~7- 8weeks earlier at Chiang Saen and ~1 week at Kratie. This season is important in triggering seasonal patterns in the river's ecology (for example fish migrations). Upstream of Vientiane will also see an earlier onset of the flood season, though tributary flows from the left bank will reduce this to negligible variation downstream of Vientiane.
- ***Duration (figures 14 & 15):*** Upstream of Pakse will experience a 2-4week reduction in the transition season from Dry to Flood, which will drop to ~1 week in the Mekong floodplain. The duration of the flood season is not expected to be significantly affected except at the uppermost reaches of the LMB where the UMB flows still dominate wet season volumes. These cumulative reductions will see an increase in the duration of the combined Transition + dry season.
- ***Magnitude (figure 12):*** dry seasonal flows will increase by 70% at upstream stations decreasing to a 10% at the Mekong Delta. Conversely, wet season flows will decrease by up to 18% at upstream stations decreasing to 2% change at the Mekong Delta.
- ***Cumulative:*** The cumulative effects of the changes to the hydro-biological seasons is a reduction in duration of the two transitions seasons combined with a reduced variability between the wet and dry seasons. These two factors serve to homogenize the Mekong hydrograph and subdue the prevalence

of the flood pulse. This is most pronounced in the upper reaches of the LMB reducing downstream as the left bank tributaries begin to influence the hydrograph.

H3: Flow provenance

The size and variation in altitude of the Mekong River results in some difference in the basin's climate, however, the dominant climate control is the SW Monsoon, which divides the calendar year into the wet (May – late September) and the dry (October – late April). The consistency of the onset of the monsoon is important for the basin's hydrology (See table below). August to October is the wettest time of the year as the SW monsoon is compounded by the advent of the tropical cyclone season. Interacting with the Central highlands, the NE monsoon begins in late October, while the climate of the Lancang basin displays greater variation due to the large changes in altitude throughout its catchment. The Khorat Plateau is classified as semi-arid and is one of the driest areas in the basin. Figure 16 below better clarifies the interaction of the SW and NE monsoon with the cyclone season. The Northern Region (represented by Chiang Rai station) displays the clearest single peak in August which expresses the dominance of the SW Monsoon in northern Lao PDR. In the Central Region (Pakse station) and the Central Highlands (Pleiku station) rainfall totals are greatest and the distribution passes through two rainfall peaks reflecting a greater level of interaction between the monsoons as well as the influence of the cyclone season. The Khorat Plateau (Khon Kaen), displays a similar distribution to the Central areas but at a much reduced amplitude. Lastly, the Cambodian Floodplain (Phnom Penh) and Vietnam Delta (Cha Doc) exhibit the greatest lag in peak intensity and reflects the importance of cyclones to rainfall intensity in these areas. A number of devastating cyclones have hit the Mekong Delta in recent times and are responsible for extreme flooding.

Figure 17 breaks down the contribution of individual tributaries. It is useful to consider the importance of a tributary to Mekong flows as a ratio of flow contribution divided by tributary catchment area. A ratio greater than 1 suggests the tributary has a high flow yield. The Sesan (including the Srepok and Sekong) represents the biggest contribution of ~20% of the annual flow from a catchment area equal to ~10% of the Mekong total (ratio of 2). In fact, all left-bank tributaries from the Nam Ngum to the Sesan contribute a greater proportion to the Mekong flow than they take up of catchment area (ratio greater than 1). In contrast all the right-bank tributaries have ratios less than 1, with the exception of the Nam Mae Kok.

PAST TRENDS AND CURRENT SITUATION

Approximately 59% of the average annual flow originates from the left bank tributaries in Lao PDR, Cambodia and Vietnam, with 24% of the total originating between Pakse and Kratie (Z4), and 22% entering between Nong Khai and Mukdahan (Z3). The UMB (Z1) contributes 16% to the average annual flow, while the combined contribution from the right-bank tributaries (North and Northeast Thailand and the Tonle Sap tributaries) accounts for ~25%. During the wet season flow provenance is dominated by northern Lao PDR, the central highlands and the central region of Lao PDR in direct response to the Southwest Monsoon. Precipitation peaks in august at ~500mm for the latter two areas. During the dry season there is minimal precipitation in the LMB, while snow and glacial melt in the Lancang River mean that this zone dominates the dry season flow contributing up to 40% of the seasonal total at Kratie. The LMB tributaries are the main drivers of the peak in the flood pulse, while the Lancang River supplemented by catchment storage is critical in maintaining dry season flows.

FUTURE TRENDS TO 2015

The dominant impact of the BDP DF is the changes to flows in the Lancang River. The mean annual flow contribution from Zone 1 is 56km^3, which means that the Yunnan cascade can retain in active storage approximately 42% of the mean annual flow. The operational strategy for the Yunnan cascade is not known, but if project owners intend to maximize power production it is likely that the majority of reservoir storage will be utilized during the wet season. BDP modeling suggests a 17% reduction in wet season flow or storage of ~11km^3/yr. While the modeling presented by ESCIR suggest approximately a 30% reduction in wet season flows which would approximate the maximum storage capacity of the Yunnan cascade (22-23km^3). This presents a reasonable range over which changes to the Yunnan component can be considered.

The total storage capacity of all tributary projects in the LMB DF is 20.3 km^3, with LMB tributaries contributing approximately 300 km^3 to average annual flows. Given that most tributary flow eventuates during the wet season and the assumption that tributary projects will seek to maximize power production, it is estimated that tributary projects have the capacity to store 5-7% of the tributary contribution.

Therefore, the reduction in wet season flow and increase in dry season flows evident in the modeling is driven by the Yunnan cascade. Variation in this driver (as witnessed in the two modeling results of table 4) reflects both the importance of the reservoir operational strategies to the downstream hydrograph, and the need for closer collaboration between the Mekong countries. The implications of the Yunnan cascade on the LMB hydrograph could be severely exacerbated if optimal power generation is adopted and full storage capcity is utilized.

The BDP Definite Future scenario is a lower range estimate as to what the variation in flow induced by the Yunnan cascade is likely to be. The ECSIR prediction represent close to the upper range of the change in flow would escalate the magnitude of change experienced by the hydrological regime.

H4 Tonle Sap flow reversal

Tonle Sap River is ~110km long, the low channel slope and the high variation of flow in the Mekong River induce a seasonal change in the direction of flow in the Tonle Sap River. The reversal of flow produces two distinct seasons based on the direction of flow in the Tonle Sap River. Water flows with the channel slope during the dry season and reverses direction during the wet.

- **Wet season (May – September):** water levels in the Mekong rise in response to the SW Monsoon reaching ~9m at PP and ~8m at PD, with Qin(max) ~10,000cumecs in late august = 25% of Mekong discharge at this time of the year (MRC, 2007). The elevated water levels reverses flow up the Tonle Sap River into the lake and peak inflows are reached typically three months after flow reversal. On average 45km3 flows into the Tonle Sap lake via the River and overland flow across the floodplain, representing 57% of the total lake inflows (tributaries contribute ~30% and direct precipitation the remainder) and 25% of the august flows in the Mekong(MRC, 2006).

- **Dry season (Oct/Nov – April/May):** water levels in the lake are at their highest (6-9m) and, as the Mekong floodwaters begins to recede, the hydraulic gradient reverses direction and flow resumes the natural direction reaching a flow of 10,000cumecs in just a few weeks (MRC, 2007). Peak inflow is reached 3months after the reversal in flow/start of the wet season, but return flow to the Mekong rises much faster taking just weeks to reach the same rates (i.e. four times faster). . Approximately 70km3 is conveyed back to the Mekong from the Tonle Sap Lake, which represents ~87% of the total lake outflow (the other major component is evaporation) (MRC, 2006).

The reversal of flow is driven by the hydraulic gradient between the Tonle Sap Lake (KPL) and the Mekong River (PD and PP). Figure 18 shows that the reversal in flow occurs at the two transitions between the wet and dry season (May and September).

- **Outflows Mekong – Tonle Sap:** The maximum outflow gradient KPL-PP is 2.11m (typically occurring in December) and it remains greater than 1m for at least 4 months of the year. The gradient KPL-PD peaks at 1.13m, remaining above 1m for 3months of the year. Outflows begin on the falling limb of the flood peak as flood waters recede. The difference between the outflow gradient at PP and PD is greatest at the onset of the outflow season (more than 50% difference October-January) and less pronounced February – May (20-30%) see figure 18 below.
- **Inflows Tonle Sap – Mekong:** The max inflow gradient PP-KPL is 1.09m in July with a gradient greater than 1m for 2months of the year, while the PD-KPL gradient peaks at ~0.85m. There is less seasonal variation between the PP-KPL and PD-KPL gradient. The time series data available suggest that there is seasonal consistency between the timing and magnitude of the flow reversal. However, the system is strongly dependent on the size of the yearly flood and dry years together with heavy flood years bear a significant effect on the Tonle Sap water balance and the reversal of flow capable of affecting flow volumes by 30-40%. (see table below).

Table 8 Inter-annual variation in Tonle Sap in and out flows (1997 -2003) (based on: MRC, 2006)

	Dry Year (1998)		Average (1997-2003)	Wet Year (2000)	
	[km3]	% decrease	[km3]	[km3]	% increase
Inflow*	44.1	- 44%	79	106.5	+35%
Outflow*	43.5	- 45%	78.6	104.8	+ 33%

*Note: inflows and outflows quoted in this table relate to the total water balance of Tonle Sap Lake, including: Mekong flows, evaporation, tributary flows, & direct precipitation

CURRENT & PAST TREND

Each year at the advent of the dry wet season (May) there is a reversal in the direction of flow of the Tonle Sap River for a period of 4-5months. This flow reversal is driven by a maximum hydraulic gradient of 1.0 – 1.25m and results in the storage of 45km3 of wet season flows which are then returned to the Mekong system during the dry season. There is evidence that this magnitude of hydraulic gradient has existed since records began, and the Tonle Sap dry season contribution accounts for significant portion of the combined dry season flow at Tan Chau and Chau Doc with the peak contribution arriving in the dry months of December/January.

TREND TO 2015

- ***No change to the timing/phasing of the hydrographs in the Tonle Sap system:*** The predicted 2015 flow regime will see lower variation between the wet and the dry season flows and water levels in Zone 5 due to regulatory effects of hydropower in China (see hydrographs for Kratie). Figure 19 compares the current and 2015 hydrograph for KPL and PP based on 13 years of monitoring and 13 years of simulated model results. The hydrographs demonstrate that there is not a significant change in the timing of water level maxima/minima, nor in the length of the transition phases, however, there is a reduction in the amplitude of the seasonal water level extrema.
- ***Decrease in amplitude of seasonal WL extrema:*** Figure 19 below indicates that during January – June water levels will increase by 0.1-0.25m at PD and 0.1m or less at KPL. The peak increase in PD water levels occurs in April, just before the end of the dry season and the traditional reversal of flow in the Tonle Sap. Water levels at KPL during this period are not as vulnerable to changes in the Mekong mainstream water levels because the lake surface is higher than the river level and so the incremental increase of 0.02-0.1m results in increased backwater effects delaying the return flow of water to the Mekong system.

From July – December, there is a larger decrease in water levels at both stations. PD levels are reduced by a maximum of 0.28m in August/September which corresponds to the flood peak and the beginning of flood water recession. KPL water levels are reduced by up to 0.26m in September. The biggest changes in water levels will occur at the time of the flow reversal in the Tonle Sap River.

Table 9: Change in Water Levels of the Tonle Sap system

	CHANGE IN WATER LEVELS BY 2015 (m)	
	JAN - JUNE	JULY - DEC
Prek K'dam (PD)	0.04 to 0.24m	-0.03 to -0.28m
Kampong Luong (KPL)	-0.03 to 0.1m	-0.02 to -0.26m

- ***Change in the timing and magnitude of the Tonle Sap hydraulic gradient:*** These changes in water levels will impact on the magnitude of the hydraulic gradient driving the reversal of flow. Figure 21 identifies that the timing of all major phases in the average hydrograph remain the same (peak inflow and outflow gradients, Sept/Oct reversal of flow), with the exception of the May reversal of flow. The start of Mekong inflows into the Tonle Sap Lake is likely to be delayed by up to 1 week on average.

  Figure 22 illustrates the computed decrease in hydraulic gradient PD-KPL., from which three main conclusions can be drawn:

  (i) during the infilling season (May – September) there is a 10-15% decrease in the hydraulic gradient driving flow into the Tonle Sap Lake

  (ii) The falling limb of the flood season (October to December) experiences the smallest change in hydraulic gradient with typically 5% or less reduction

  (iii) The biggest reduction in hydraulic gradient occurs during the heart of the dry season (January – May) with a 10-40% reduction in gradient.

  This suggests that the hydraulic gradient behind the reversal of flow in the Tonle Sap is more vulnerable to elevated dry season water levels rather than decreases in peak flood levels.

Conclusion: developments by 2015 will result in a maximum 0.28m reduction in wet season water levels in the Tonle Sap River with a 0.1-0.25m increase in dry season level. This correlates to a 5-40% reduction in the hydraulic gradient driving the reversal of flows. These changes will not stop the seasonal reversal of flows but they are likely to delay the onset of the reversal by the order of a week as well as reduce the amount of water transferred between the Mekong and Tonle Sap systems.

H5: Flooding of the Tonle Sap basin

Hydro-physical characteristics of the lake

The dry season Tonle Sap Lake (TSL) represents the permanent inundation of the Tone Sap River floodplain for an "S"-bend reach approximately 110km upstream of the confluence with the Mekong River. The TSL system includes the dry lake area, it's floodplain, a complex of braided channels at the lake's outlet to the Tonle Sap River and 13 tributaries flowing radially into the Lake. The wet season lake area typically sees a 6 fold increase in lake area bounded by: Kampong Thom and Siam Reap in the north; Sisophon in the west; Battambang, Moung Roessei and Pursat in the south and joing the Cambodian flooplain of the Mekong River in the east (see figure 23 above). The lake bed is 0.5-0.7m amsl (Hatien Datum Vietnam) (MRC, 2006), with deepest sections of the Lake approximately match the ancestral thalweg of the Tonle Sap River (see bathymetry map below).

Flooding of the Tonle Sap Lake:

- **Flow sources:** wet season flooding is driven by:
    1. reversal of flow in the Tonle Sap River (57% Qin),
    2. overland flow from the Cambodian Floodplain (5% Qin),
    3. Monsoonal discharge in the 13 tributaries of the Tonle Sap (30% Qin), and
    4. direct precipitation onto the lake surface (13 %Qin) (see water balance schematic below & map of Tonle Sap Tributaries) (see water balance schematic below)
- **Seasonal states:** The water levels (WLs), surface area (SA) and volume(V) of the lake varies with seasons. Based on the 1997-2004 average:
    - o At the end of the outflow season: SA(dry) = 2,500km2, min WL (dry) = 1m (late April), V(dry) = 1-2 km3
    - o At the end of the inflow season: SA(wet) = 14,500km2 (MRC, 2007) 5.8 almost a 6-fold increase in SA, max WL(wet) = 6-9m (late sept), V(wet) = 50-80km3
    - o There is some inter-annual variation for these parameters, particularly in dry years or peak flood years. The wet season flooded area of Tonle Sap lake can range between 7,500 – 14,500km2 (with an average of ~11,000km2) – this represents ~ 17% increase in flooded area during wet years and ~30%decrease during dry years, with more variability in dry years than in peak flood years. While increase in lake water levels can fluctuate between 5.5 - 9m (average ~7.7m) (See table below).
- Empirical observation of water levels, surface area and volume indicate that there is a strong quadratic relationship between WL and surface area and WL and lake volume with correlation coefficients for both greater than 0.99 (Figure 24) (MRC, 2006).

Table 10 Inter-annual variation in the hydro-physical dimensions of Tonle Sap Lake (MRC, 2006)

TIME SERIES 1997-2003	WL [m]			SA [km2]			V [km3]		
	max	min	diff	max	min	diff	max	min	diff
Max	10.36	1.48	8.88	15,278	2,402	12,876	76.05	1.83	74.22
Min	6.86	1.19	5.67	9,637	2,061	7,576	33	1.35	31.65
Average	9.11	1.34	7.77	13,218	2,237	10,981	59.56	1.59	57.97

CURRENT SITUATION AND PAST TRENDS

Flooding in the Mekong River and the Cambodian floodplain is the main driver behind the seasonal expansion of the Tonle Sap Lake, contributing almost 60% of the Lake's flooded volume. The total influx of floodwaters results in an average7.77m increase of lake water levels. During this time the area of the lake expands by 7,500 – 13,000km2 (average of ~11,000km2), flooding large areas of forest and expanding the highly productive littoral zone of the lake. This represents an ~ 10,000km2 fluctuation in lake surface area, with the biggest expanses of flooded area situated in the western shoreline of the dry lake bed and north of Kampong Chnhnang. Recession of the lake during the dry season also exposed a complex system of anabranching channels near Chnoc Trou and Lake Chma which currently make navigation difficult and also provide fertile seasonal habitats.

2015 TREND

- ***Changes to water levels at Kampong Luong:*** BDP modeling indicates WLs at Kampong Luong will (figure 20):
    1. increase by a max of 0.1m between March – June,

2. remain unchanged between January – February
3. decrease by a max of 0.28m between July - November

- ***changes to lake surface area:*** based on the empirical ratings curve, this will result in the following changes to the lake surface area (see figure 25 & 26):
  1. a decrease in SA between July – January, with a maximum 3-5% (~400km2) decrease during peak September flooding in the Tonle Sap Lake
  2. an increase in SA between February – June, with a maximum 5-8% (~120km2) during the dry season
  3. this represents a 500-600km2 reduction in the inundation areas as the combination of increased dry season and reduced wet season compound one another
- ***Implications of the changes to lake area:*** the change in lake area lies within the observed range between wet and dry years for the lake, however the consistent change in lake area over the years will have significant impacts, including: permanently flooding much of the gallery forest around the riparian zone of the dry lake area, isolating other flooded forest areas from inundation at the extent of the TSL floodplain, and reducing the lake littoral zone since the reduction in wet season area will be most pronounced for shallow flooded areas - the north western flood plain (near Battambeng) and the north east area (near Kampong Chnhnag) (see bathymetry map)
- This analysis is indicative of the scale of change to be expected in 2015. It is recommended that detailed 3D hydrodynamic modeling is required to provide further detail.

Conclusion: By 2015, upstream regulation will seasonally alter water levels in the Tonle Sap Lake by +0.1m/-0.3m, which will decrease the maximum extent of flooding in the Lake by 3-5%, and increase dry season lake area by 5-8%. The decrease in wet season lake area will reduce the area of fringing forest flooded and reduce the littoral zone of the lake both of which are critical aspects of the lake's high productivity. The increase in dry season lake area will further exacerbate the reduction in the Tonle Sap floodplain by permanently inundating some areas. Together these effects will induce a 500-600km2 reduction in floodplain subject to the seasonal flood pulse and oscillation between terrestrial and aquatic environments – which represents 5-10% reduction in the floodplain area. This will reduce the productivity of the Tonle Sap System, but further study is required to quantify the magnitude of this reduction.

3.0 REGIONAL SEDIMENT DYNAMICS: PAST TRENDS AND CURRENT STATUS

Data/information limitations

Considerable scepticism surrounds the existing sediment data, which has been collected with inconsistent methods, measuring different parameters (SSC, and TSS) and has often yielded widely divergent estimates (see for example, Walling, 2006; Adamson, 2009b; Carling, 2009; Wang et al, 2009; Walling, 2009). Of the two data sets Suspended Sediment Concentrations are the most useful for estimating sediment loads in the Mekong, but the timing of samples has been erratic and utilised different methods (Walling, 2006). The sampling strategy of Total Suspended Solids is more consistent but samples are only taken monthly, which is not sufficient to pick up the high variability of sediment loads in the Mekong. Also, TSS is an inappropriate indicator of sediment load especially when there is more than 25% of sand size materials (USGS, 2000). Given these issues, SSC concentrations should be interpreted as having large error bars – in the order of 20-30%.

Drivers of Sediment transport

The main drivers of sediment transport are the sediment supply to the river system (typically measured as the suspended sediment yield of the watershed), and the sediment transport capacity of the river, which is a function of: flow velocity, channel cross-sectional area, channel slope, sediment grain-size distribution, depth of the water column and the dispersive and shear forces of flow. These two issues are discussed below in their regional context.

S1: The Mekong Sediment Load (SL)

Geologic context

The underlying geology of the Mekong is heterogeneous and active, consequently different areas of the basin were formed by different tectonic shift millions of years apart (MRC, unpublished). This has resulted in differing sediment yields for different areas of the basin. There are five main geologic zones in the Mekong Basin: (i) Tibetan gorges, (ii) Ailao Shear Zones, (iii) Wang Chao fault zones, (iv) Khorat Plateau, (v) Central Highlands (figure 27). According to marine sedimentary deposits the Ailao Shear Zones and the Central Highlands have dominated sediment provenance in the Mekong Basin for the past 8,000years (Clift et al, 2004).

Drivers of sediment supply

Sediment data is available from the 1960s to the present. The temporal range over which data was analysed will impact the estimate for sediment load. The main drivers and timing of variability in sediment load are summarised below for the Lancang catchment:

- **1960 – 1990 (Land clearing):** Period of population growth, intensification of land clearing, deforestation and agricultural expansion (Wang et al, 2009; Walling, 2009; MRC, 2007)
- **1990 – 2000 (hydropower development):** introduction of mainstream hydropower on the Lancang River with the construction and operation of the Manwan dam.
- **2000 – present (hydropower escalation & soil conservation):** intensification of mainstream hydropower with the addition of a second project (Daoshachsan) and the introduction of soil conservation strategies for the Lancang Catchment under the Chinese governments "Green for Grain" program (Walling, 2009)

Land clearing increases sediment yields, while soil conservation programs have been effective in many large river basins for reducing erosion and sediment yields (Walling, 2008). Hydropower typically increases sediment yields during the construction phase but then become sites of storage over their operational life. Depending on dam dimensions, the effectiveness and coordination of sediment release strategies Yunnan dams could inject spikes in sediment load during maintenance of reservoir areas.

For the LMB, the historic drivers are land clearing – particularly in Thailand (see Table 1). However, the lower population levels and development in the basin has resulted in a lower level of impact from land clearing in the LMB compared to the UMB. From a strategic point of view – the past drivers of change are centered on the UMB. Looking forward to 2015 hydropower will become the dominant driver changing sediment supply throughout the basin.

The primary zones of sediment production in the Mekong are the high elevation headwaters of the basin, located in Zone 1(Lancang Catchment) and Zone 4 (Central Highlands), with a maximum Suspended Sediment Yield (SSY) in the Lancang catchment of 700 t/km2.yr (Walling, 2009). Currently Zone 3 is a mixed zone of sediment transport and production, while data indicates that Zone 2 is a zone of nett sediment deposition. Zone 5 and Zone 6 comprise the floodplain and delta of the Mekong Basin and are important sites of sediment deposition. With minimal sediment sampling near the delta mouth it is difficult to estimate the sediment load exported to the marine environment.[3] In terms of sediment storage, a substantial volume is stored in the alluvial reaches of Z3 and Z4 in the order of 14,000 - 14,500Mt, while approximately 10-30% (15-45Mt) of the sediment load at Kratie is stored in the Cambodian floodplain (Carling, 2009; Kummu et al, 2009).

The average suspended sediment yield (SSY) for the Mekong Basin is ~ 200t/km².yr but varies significantly (Walling, 2009). This range suggests that some zones are more important for sediment production and others contribute little to the sediment load. This is confirmed by Clift (2004) who uses marine sedimentary profiles from the Cuu Long and Nam Con Son sediment basins to estimate the total volumes of sedimentary rock from the 5 main geologic zones.[4]

The graph 28 and 29 below summarises some of the range of annual average load estimates at; the Yunnan border, the major mainstream stations and the total load. Estimates at Chiang Saen vary between 59-100 $x10^6$ m^3, while the total basin yield estimates vary between 140 – 180 $x10^6$ m^3, which represents a variation of +/- 20-25%. These wide ranges in SL estimates partly reflect the data quality issues discussed above, but they also reflect the time snapshot over which the averages are calculated. Sorting in terms of the drivers of sediment supply discussed above, the historic trends in Sediment Load at Chiang Saen are summarised below:

1960 – 1990 (Land clearing): Trend lines show a statistically significant increase in sediment load from the 1960s to the late 1980s, this corresponds to an increase in average annual sediment load from 60Mt to 115Mt, i.e. almost a doubling over 25 years (Walling, 2005). Over the same period of time there is no discernible increase in run off volumes (Walling, 2009). For the same catchment area and same flow volumes there is an increase in sediment, which implies that erosion rates increased due to changes in the stability of the land surface. During a similar time period, forest cover in Yunnan province dropped from 55% to 30% (MRC, 2007). Using all estimates, the average pre-Manwan sediment load at Chiang Saen is 85Mt/yr.

1990 – 2000 (hydropower development): Manwan is the first mainstream dam on the Lancang River and became fully operational in 1996 (filing began in 1993).

Manwan has reduced mainstream sediment concentrations (see figure 30) with reductions ranging from 25-65% (Adamson, 2009b). The large discrepancy in range is the result of poor sediment data records and selection of time-series of differing lengths. Estimates of sedimentation rates by Chinese authorities suggest that 490M m^3 has been trapped by the Manwan dam between 1993 – 2005 (Walling, 2009). Therefore, the reduction in sediment load would be of the order ~50Mt/yr between 1993-2001, which corresponds to a post-Manwan sediment load of ~70Mt/yr at Jinghong.[5]

2000 – 2005 (hydropower escalation & soil conservation): Dachaoshan began filling in ~ 2001 and operations in 2003. Together these projects represent less than 4% of the proposed active storage of the Yunnan cascade, they also have estimated trapping efficiencies 30% less than the two biggest reservoirs in the proposed cascade. However, they have had an observable effect on the Mekong Sediment Load. Over a period of ~18months (2001-2003) approximately 30Mt has been trapped in the Dachshaoshan reservoir (Walling, 2009). This has further reduced the post-Manwan sediment load further with 70-80Mt/yr being trapped from 2001 onwards and the estimated annual sediment load at Jinghong of approximately 60Mt/yr. Marine sedimentary

[3] TSS estimates are available for the Bassac River for a period of 10 years (1999 – 2008), however, as discussed in a later section, TSS are unreliable for estimated sediment loads of the Mekong system

[4] A description of the geologic zones is presented in Annex I

[5] *These reservoir sedimentation rates are higher than those predicted by Kummu et al (2009) who estimated ~ 32-41Mt/yr. However, the estimate by Kummu calculates the theoretical trapping efficiency of the reservoirs and then takes the corresponding percentage reduction from the long-term average SL (1963-2005), the discrepancy between the two trapped volumes would reduce if the trapping efficiency as used against the 1980-1990 average sediment load.*

profiles and the SSC analysis indicate that the lower half of the Lancang catchment (yields of 425-489 t/km2.yr) is a greater source of sediment than the upper portion (~281t/km2/yr) (Clift et al, 2004; Walling, 2009; Kummu et al, in publication).

Annex 2 presents a comprehensive table by Kummu (in publication) giving the flow, area, sediment load, TE, and reservoir sediment loading for 31 catchments of the Mekong Basin, representing 75% (385km³) of the total basin area. Table 11 below summarises this information for the Mekong hydro-ecological flow zones. Although the studied catchments only represent 70% of the basin area, they give an indication of where the dominant sources are. The majority of sediment is supplied from the Zone 1, with an order of magnitude less from Zones 2,3 and 4. The total sediment contribution from Zone 4 is estimated at 17% (Sarkkula et al, 2010). Zone 5 sediment supply is equivalent to the sediment supply from the 13 Cambodian tributaries of the Tonle Sap (Table 11 only accounts for 3), which is equivalent to 1.96Mt/yr (See Tonle Sap section below).

Table 11: Summary table of annual average sediment load, flow and area for 31 catchments in the Mekong Basin (adapted from: Kummu et al, in publication). The full table is presented in Annex 2.

Zone	Catchment Area (ha)	Average Annual Flow (km3/yr)	Catchment annual average sediment load (Mt/yr)
1	185,973	75	91
2	61,970	45	12
3	207,745	149	11
4	78,529	100	10
5	26,490	17	1
6	-	-	-
Totals	560,707	386	125

There are 15 existing tributary dams in the LMB, which are estimated to trap ~1-2% of the Mekong load (Kummu et al, in publication).

2005 - 2015: A total of 8 mainstream hydropower projects are planned for the Lancang River. The Mengsong project at the downstream end of the cascade has been postponed because of potential impacts on fish migrations (Sichuan, 2009). In terms of the Sediment Load arriving at the Mekong, Xiaowan and Nuo Zhadu have the largest storage and account for ~22km³ of the total 23.7km³ of storage available in the cascade, they also have the highest trapping efficiencies of between 92-98%. The cumulative trapping efficiency of all eight projects would be between 78 – 81% (Kummu et al, in publication).

The other dominant zone of sediment production is the Central Highlands, within which a number of hydropower projects have been proposed. Based on an ADB study (1999) of 11 projects in the Se San, Se Kong, Sre Pok and Nam Theun catchments, trapping efficiencies ranger from 56 – 98% for individual reservoirs with three-quarters of the projects trapping more than 95% of the sediment influx. The Lower Srepok 2reservoir is located upstream from the confluence between the Sesan and Srepok and will trap ~66% of the Srepok sediment load, while Lower Sesan 2 upstream of the same confluence on the Sesan River will trap ~98% of the Sesan sediment load (ADB, 1999). The proposed reservoirs in the Sekong River are located further up in the catchments head waters with TEs of greater than 95% (ADB, 1999). These values are broadly consistent with the basin-wide TE assessment undertaken by Kummu et al (in publication). When all proposed development was considered, the combined TE for the Sre Pok, Sesan and Sekong were: ~77%, 86% and 32% respectively. When all the catchments of the central highlands are considered, Carling (2009) reports a combined 37% TE. This estimate should be seen as a lower limit and further assessment is need provide a more accurate figure given that the majority of the Mekong sediment arises from this zone. The current Three S sediment load is not well understood but is estimated as ~17Mt/yr and representing ~10% of the total Mekong sediment load (Sarkkula et al, 2010).

CURRENT SITUATION AND PAST TRENDS

The total Mekong sediment load displays a wide range of inter-annual variability (Walling, 2009). During wet years the LMB tributaries contribute a greater proportion of the annual load, while in dry years the dominance of the Yunnan component is increased (Sarkkula et al, 2010). On average, the annual sediment load is approximately 160Mt/yr (140 -180 Mt/yr), with approximately 50-60% originating from China. Land clearing, hydropower and soil conservation strategies have influenced the annual average sediment loads – especially in the Lancang catchment where the average load has increased to ~120Mt/yr when land clearing peaked(mid to late 80s) and reduced to ~65Mt/yr after the two existing mainstream projects came on line. The increasing sediment load witnessed during the period of land clearing and agricultural intensification in the Lancang catchment has been offset by the reductions in the sediment load caused by the two existing Yunnan dams, such that the post-2000 average is comparable to the mid-1960s average. However, in order to align the SEA with the BDP Scenarios, which do not include Manwan and Dachshaoshan in the BDP Baseline, the current sediment load from UMB is taken as 85Mt/yr.

The 'Three S' catchments in Zone 4 contribute ~ 17Mt/yr equivalent to ~10% of the total load, while the remainder of the basin is estimated to contribute 30% (Sarkkula et al, 2010). The majority of the contribution from the rest of the basin originates in the left-bank tributaries of Lao PDR – in particular from those in the southern portion of Zone 3 which drains part of the central highlands geologic complex.

FUTURE TRENDS TO 2015

- ***Sediment trapping in the Yunnan Cascade:*** The eight mainstream hydropower projects which make up the Yunnan cascade will dominate change to the Mekong sediment load because: (i) the Lancang catchment supplies the majority of the load, and (ii) the reservoir has a large storage capacity capable of retaining 42% of the mean annual flow in the Lancang River. The individual reservoir trapping efficiencies reach 90-98% while the cumulative effect of the entire cascade will be to trap 71-81% of the Yunnan load (Kummu et al, in publication). This will result in ~70Mt/yr being trapped in the Yunnan cascade and an annual sediment load entering Chiang Saen of 15-17Mt/yr.
- **Sediment trapping in the Three S basins:** less sediment data is available for the Three S basin, though current best estimates suggest ~17Mt/yr. An estimated 16 dams will exist in the Three S basin by 2015, with cascades of 5 or more dams in the headwaters of the Sesan and Srepok. Some of these reservoirs have trapping efficiencies of up to 90%, however, substantial sub-areas of the catchment will remain free-flowing by 2015, such that the best current estimate if the Three S trapping efficiency is 37% (Carling, 2009). Based on this estimate the future Three S sediment contribution is likely to drop to 11Mt/yr with on average 6Mt/yr trapped behind the 15 reservoirs. Further work is needed in setting up a better sediment monitoring program in these basins, given their importance to the Mekong River and also the number of projects planned in the future.
- **Sediment trapping in the rest of the basin:** Most of the remaining tributaries have mean annual sediment loads in the order of 0.1 -1 Mt/yr, except for the Nam Ou (~6.2Mt/yr) and Se Bang Hieng (3.2Mt/yr), both of which are not expected to be dammed by 2015 (Kummu et al in publication). Based on an analysis of the sediment load and trapping efficiency the existing LMB tributary projects currently trap 1-2% of the sediment load and future sediment trapping in the remaining LMB tributaries is likely to be a smaller impact on the future sediment balance than projects on the Lancang and Three S rivers.

Indicative 2015 sediment budget: It is not possible to undertake a comprehensive sediment balance given the problems and gaps in the data record, however, a quick back-of-the-envelope calcultation suggests that the Yunnan contribution will be reduced to 17Mt/yr, the Three S to 11Mt/yr so that the total sediment load at Kratie will drop from ~165Mt/yr to ~ 25-30Mt/yr with the deficit supplied from existing in-channel storage.

S2: Sediment transport capacity

Sediment transport capacity is the ability of the river to move sediments from the zone of production to zone of deposition. There are two dynamic mechanisms driving sediment transport, depending on the grain size of the sediment load (Bagnold, 1979). Upward and turbulent dispersive forces are capable of keeping smaller particles in suspension allowing downstream transport in the water column, while heavier sediments rely on *saltation* to move in successive 'jumps' along the channel bed. Both transport mechanisms rely on the flow, channel slope, channel dimensions. The relevant drivers of change for transport capacity include:

- Channel discharge:
- water levels
- Channel dimensions (channel width, channel slope)
- Sediment size and load

Sediment grain size distribution

Little information is available on the grain size distribution of the Mekong, the best estimates are based on one distribution curve for Pakse (presented in Carling, 2009). The curve shows that 99% of the sediment has a grain size smaller than 4.75mm (fine gravel) and 41% of the distribution is finer than 0.45mm (coarse sand) (see figure 31). The clay and cohesive sediments are likely to remain in suspension until the Mekong enters the Cambodian floodplain and the Mekong Delta. The sand size particles are an important component of the Mekong sediment load, because their movement is likely to change based on seasons shifting from saltation to resuspension and to in-channel consolidation based on the seasonal hydrodynamic conditions.

Table 12: Conventional grain size ranges for different sediment types. The majority of Mekong sediments are likely to be sand size or smaller.

D grain size range	Type of sediment
> 256 mm	boulder
64–256 mm	cobble
32–64 mm	very coarse gravel
16–32 mm	coarse gravel
8–16 mm	medium gravel
4–8 mm	fine gravel
2–4 mm	very fine gravel
1–2 mm	very coarse sand
0.5–1 mm	coarse sand
0.25–0.5 mm	medium sand
125–250 µm	fine sand
62.5–125 µm	very fine sand

3.9–62.5 µm	silt
1-3.9 µm	clay
<1 µm	colloid

Sediment storage

The existing annual deposition-resuspension cycle is driven by the monsoon flood hydrograph and considered to be largely in balance. Important sites of natural storage are:

- **In-channel storage:** Significant proportion of LMB south of Vientiane is alluvial with a wide, near-straight channel, several hundred deep pools and extensive in-channel features interspersed with bedrock outcropping. Carling (2009) provides a very rough estimate of 14,200MCM for in-channel storage south of Vientiane, based on a lens of sediment 5-15m deep. This storage is predicted to have remained constant over the last hundred years.

  The largest reduction in channel gradient occurs in the transition from bedrock to alluvial channel ~ 40-60km north of Vientiane (see Figure 32). In this reach, the channel gradient drops by 67% and the river morphology transitions to alluvial with infrequent bed rock outcrops and large alluvial vegetated island as well as smaller sand bars and inchannel islands comprised mainly of sands and gravel (Conlan, 2008). Sediment data indicates that Chiang Saen to Nong Khai (particularly Luang Prabang to Nong Khai) has become an important zone of sediment deposition (Walling, 2009). Given that this reach has negligible floodplain area, deposition is likely to be predominantly in-channel.

  A GIS assessment of the Mekong River channel using the MRC hydrographic atlas estimated that the wet season channel in Z2 occupied ~ 460km2 dropping to 240km2 during the dry season representing a difference of 220km2 (see aquatics paper). Approximately 66km2 or 30% of this difference has been identified as sand bars or visible sediment deposits. Geomorphology work undertaken for the MRC IBFM work (2007) observed sand bars of 5-10m above bed level and siltation benches of up to 25m, assuming ~30% of Zone 2 exposed wet season channel is used for seasonal storage, then between 0.33 – 2km3 of sediment is currently stored in the Zone 2 river channel representing about 1-2% of the total sediment load for the Mekong Basin (160Mt/yr).

  Sediment data indicates that Chiang Saen to Nong Khai (particularly Luang Prabang to Nong Khai) has become an important zone of sediment deposition. Walling (2009) illustrates that since the 1980s there has been a lower sediment load at Nong Khai than at Jinghong (see Figure 33). This is confirmed by Wang (2009) for Chiang Saen to Nong Khai (Figure 34). Given that this reach has negligible floodplain area, deposition is likely to be predominantly in-channel. Before 1980 the sediment load at Jinghong was consistently higher than at Nong Khai, which would suggest that deposition in Zone 2 is a new phenomena perhaps caused by changes to the sediment load at Nong Khai.

- **Floodplain storage:** the floodplains of Cambodian floodplains are likely to store 15-25% of the sediment load at Kratie. Estimating the Kratie sediment load at 160Mt/yr, this could range between 12-40Mt/yr, of which approximately 30% enters the Tonle Sap system. Estimates of storage in the delta are difficult to predict because of the intensive control of the hydrological regime with irrigation canals and sluices. No sediment depth profiles are available to indicate the total volume of sediment stored within the floodplain.

- **Delta building:** Lastly a significant but unmeasured proportion of Mekong sediments discharge into the South China Sea, where tides migrate sediments south along the Ca Mau peninsula until competing tides in the Gulf of Thailand and the South China Sea induce deposition on the coast line of the peninsula particular on the western face (discussed in further detail below). No solid estimates are available but delta building is likely to have maximums in the order of meters for some areas. There are also sections of the delta's eastern coastline which are subject to erosion.

Sediment transport capacity

According to Carling (2009) the reduction in peak flows due to the Yunnan cascade will not significantly reduce the energy available for sediment transport in the Mekong River. Using the system's shields parameter as an indicator, 97% of the Mekong's transport capacity remains available at Vientiane under the Definite Future scenario and 99% at Pakse (Carling, 2009). If transport capacity doesn't change but sediment supply from zones of production is reduced due to the presence of reservoirs, then the sediment currently stored in-channel is likely to be resuspended to compensate.

A comparison of the average peak daily flows at Chiang Saen (CS), Vientiane (VT) and Pakse (PK) for the Baseline and Definite Future scenarios are presented in Figure 35. The changes in the peak flow are compared to: (i) an estimation of the peak flow required at the center of deep pools to mobilize the in-pool sediment wave for pools in the vicinity of station, and (ii) the flow required to mobilize 99% and 41% of the sediment distribution as measured at Pakse. The former is an indicative measure of transport along the channel bed, while the latter is indicative of entrainment and suspended transport. The required peak flow at the channel bed was estimated based on the maximum velocities experienced in Ang Ngay pool where the pool centre flow during wave translation was at least 60% of the average peak daily flow during the same time period. Based on this analysis, it is likely flow remains capable of transporting that most of the sediment profile under the Definite Future scenario. Only at Chiang Saen will the average peak daily flow drop below the flow required to entrain 99% of sediment distribution, affecting the suspension and transport of larger particles from coarse sand to fine gravel.

The large seasonal variation in flows result in the majority of sediment transport occurring during the transitional and monsoonal periods when: (i) sediment supply is increased during to runoff generation and (ii) river flow increases providing more energy for transport. Figure 36 illustrates that peak sediment transport occurs 1-2 weeks before the flood peak. Changes to the duration of the transition and flood season will reduce the window for sediment transport.

Analysis of the changes to the hydro-biological seasons of the Mekong (see previous section) predicts at least a 50% reduction in the duration of the transition to flood season between Chiang Saen and Pakse. Further, Chiang Saen will see a further ~25% reduction in the flood duration with corresponding increases in the dry and transition to dry season. This will increase the importance of dry season sediment dynamics and highlight the importance of further study.

PAST AND CURRENT TRENDS

The sediment transport capacity of the Mekong River has remained constant over the history of monitoring based on the stability of the annual hydrograph. The sediment load of the Mekong shows large inter-annual variability, but there is a long term trend of sediment deposition in the Cambodian floodplain and the Mekong Delta, and a more recent (post-1980) trend of sediment deposition between Jinghong and Nong Khai. Excluding the Mekong delta, because of insufficient information, annual sediment storage in the Mekong Basin is currently concentrated in Z5 with maximum total annual storage likely to be in the range of 25 -40Mt.

FUTURE TRENDS TO 2015

Under the Definite Future scenario the transport capacity will reduce marginally (<3%) due to a reduction in the peak flow, however this is not expected to affect the transport of 99% of the Mekong Sediment Load for almost all mainstream reaches in the LMB (Carling, 2009). The only exception is Chiang Saen, where Lancang flows still dominate the flood peak and the reduction in the flood peak may reduce the capacity for larger than sand-size materials to be suspended and transported downstream.

Based on estimates of sediment trapping in the Definite Future reservoirs, an 135Mt/yr deficit will arise in the sediment load of the Mekong River. Consequently, the constant transport capacity is likely to induce re-suspension of sediment currently stored in the Mekong channel. The largest deposits are in the wide alluvial reaches downstream of Vientiane, which are likely to contain ~14,200MCM, with smaller storage in Z2. Annually, in the order of 1% of the total stored channel sediment is likely to be entrained. The resuspension process is likely to be a complex combination of scour and deposition determined by the channel geology with impacts first noticed in the vicinity of Vientiane – Nong khai and at current bed erosion hot-spots. Over the long term, this will result in a reduction of in-channel features such as islands, sand bars and siltation benches and potential incision of the channel within alluvial reaches (Carling, 2009). Carling (2009) concludes that in terms of changes to channel morphology, this uptake will result in localised impacts within 10 years and regional impacts within 20years, based on a rapid order of magnitude assessment of the gross depletion of channel deposits.

The reduction in sediment load from China and the increased entrainment of channel deposits may also induce a shift in the grain size profile of the suspended sediments. Further information on the grain size distribution of both the current washload and the channel bed is required to draw concrete conclusions, however, the following points are raise as indicative of the types of changes which may occur:

- **Nutrient loading:** One of the main pathways nutrients (especially Phosphorus) are introduced to freshwater systems is via erosion of headwater geology and suspended transport downstream to zones of deposition. This transport relies on bonding between nutrient and cohesive sediments which represent the clay size or finer. A shift in grain size distribution of the Mekong sediments will reduce the ability for the sediment load to transport nutrients which cannot be supported by larger or non-cohesive sediments (see nutrients section below).
- **Transport mechanism:** Conlan's (2008) study on deep pools reveal that transport of sand sized materials is governed by the interaction of a several transport mechanisms. With little bed load and most bed material being gravel size or smaller there is likely to be a complex process of suspension, deposition, saltation and resuspension moving sand through the water column and along the channel bed. Given the presence of at least 335 deep pools, this is likely to slow the downstream migration of sand size sediments (see deep pools section) as the sediment wave through the deep pool moves in the order of 1 pool crossing (~10km) per monsoonal cycle (Conlan, 2008).Further coarse sand movement is often aided by the presence of finer materials in the water column which help to induce and maintain suspension.
- **Flood plain transport:** One of the key features of the Cambodian foodplain is sediment deposition. As floodwaters rise and overtop the river banks they begin to deposit sediment in a process known as overbank siltation. This elevates the channel bank and slows the return drainage of floodplain waters back into the channel. The floodwaters then deposit nutrient-rich fine sediments over wide a wide expanse of floodplain. If the system shifts to larger size sediments then deposition will occur closer to the river bank and potentially within the channel itself.

S4: Bedload dynamics

There is very limited information available on bed load and bed material, concentrations and transport in the Mekong River (Kummu, in publication; Carling, 2009). Typically bed load accounts for less than 10% of the sediment load in major rivers. Below is a summary of current estimates in the literature.

Adamson (2009b) estimates bed load to in the order of 3% of total sediment load in Zone 2, while based on the Pakse grain size distribution only 1% of the load is greater than fine gravel (4.75mm) (Carling, 2009). Conlan (2008) undertook detailed field work of two deep pools near Vientiane and Pakse. Bedload data collected is still being reviewed and not available at the time of writing. However, for Ang Ngay pool (north of Vientiane), bed loads of 1,000m3 per metre of channel length were observed to pass along the bed from the upstream sandbars into the pool centre and out into the downstream sandbars in one monsoonal cycle (Conlan, 2008). Based on these estimates at Ang Ngay in the order of 1 Mt/yr of material passed through the deep pool which corresponds to <1% of the total sediment load. Conlan (2008) also noticed the presence of sands and gravels passing along the pool bottom, this together with the Pakse grain distribution curve are the best available estimates of the Mekong sediment distribution and they suggest that a large proportion of the bed load (sands and fine gravels) can be temporarily suspended in the water column and are therefore likely to move not strictly as bed load but as a complex combination of both saltation and suspension.

Estimates of the bed load proportion of tributary sediment loads are available for 11 sites in the Sesan, Sekong and Srepok river basins, based on an ADB (1999) cumulative impact assessment in these catchments. In the Three S basins on average bed load comprised 11 -12% of the total load.

Table 13: Sediment load and storage capacity of 11 tributary dams in the Sesan, Srepok and Sekong rivers (adapted from: ADB, 1999)

RESERVOIR	RIVER	TOTAL SEDIMENT LOAD IN (MCM/yr)	BED LOAD (MCM/yr)	% BED LOAD	TE	SEDIMENT RETAINED (MCM/yr)	RESERVOIR CAPACITY (MCM)	ACCUMULATION (MCM/50yr)
Nam Theun 1	Nam Theun	0.679	0.062	9.13	0.95	0.645	6000	32.3
Se Kong 4	Se Kong	0.279	0.035	12.54	0.98	0.273	7750	13.7
Se Kong 5	Se Kong	0.374	0.049	13.10	0.98	0.367	4750	18.3
Xe Kaman 3	Sekong	0.184	0.024	13.04	0.04	0.007	1.6	0.4
Nam Kong 1	Sekong	0.097	0.009	9.28	0.96	0.093	600	4.7
Houay Lamphan Gnai	Sekong	0.046	0.006	13.04	0.96	0.044	85	2.2
Low. Srepok 2	Srepok	1.099	0.143	13.01	0.66	0.725	12200	36.3
Low Se San 2	Se San	1.12	0.144	12.86	0.98	1.098	1581	54.9
SE San 3	Se San	0.283	0.03	10.60	0.56	0.158	140	7.9
Se San 4	Se San	0.789	0.087	11.03	0.93	0.734	2250	36.7
Upper Kontum 2	Se San headwaters	0.291	0.038	13.06	0.96	0.279	357	14.0
total						**4.424**	**35,715**	**221.2**
average				**11.88**				

PAST AND CURRENT TRENDS

Bedload is an important but poorly understood component of the sediment dynamics of the LMB, in particular for the meandering bedrock reaches north of Nong Khai. This area is likely to be the main zone of bedload deposition, with sands and gravels accumulating in sand bars, in-channel islands, and siltation banks in the up and downstream vicinity of channel constrictions or at bends in the river planform. It is difficult to estimate the proportion of bed material in the sediment load. Most bedload in Zone 2 is likely to be stored in the river channel, with current sand bar storage approximated as ~30% of the exposed wet season channel area with a further component of bedload likely to be stored in the channel bed, especially at tributary confluences. The movement of bed load is likely to be in the order of ~10km per year (or one pool crossing) hampered by the presence of deep pools which accumulate material during the onset of the flood season before the high flows of the flood peak pass the material into the downstream storage areas.

FUTURE TRENDS TO 2015

The Yunnan hydropower cascade will trap up to 80-90% of the sediment entering Zone 2 (Adamson, 2009b, Kummu et al, in publication). Given the properties of bed load grain size and weight it is likely that bed load trapping efficiencies will be greater than this with close to all bed load being trapped. Therefore, the bed load supply to the Zone 2 will be cut and given that there will not be a significant reduction in transport capacity (Carling, 2009), there will be a progressive downstream conveyance of bed load and erosion of in- channel storages zones (sand bars etc). However, the large number of deep pools will slow the rate of bed load conveyance so that effects will be begin to be seen within a few water seasons at the uppermost reaches of Zone 2, but will take a number of decades before effects are seen at Vientiane.

S5: Deep pools

Salient features/characteristics

This section draws heavily on the detailed field work undertaken by Conlan in 2008. Conlan (2008) identified 335 deep pools of >20m depth along the thalweg between Chiang Saen and Pakse. The characteristics of different types of deep pools are presented in figure 37, and are driven by:

1. Channel width
2. Variability in channel width
3. Channel gradient

- **Size range:** Deep pools reach a maximum of 90.5m and length of 9.9km (Conlan, 2008). The deepest pools are located in the wide bedrock-alluvial reach from Mukdahan to Pakse and the narrow bedrock channel between Pak lay and Vientiane (Conlan, 2008). Both of these zones correspond to the steepest water gradients and probable sites where the Mekong cuts major geological lineaments (Conlan, 2008). During in-filling at the onset of the flood season, pools can fill up to 20-30% of their depth (Conlan, 2008).
- Pool spacing is strongly influenced by channel width, while pool depth is most strongly influenced by variation in inner and outer channel width (Conlan, 2008). There is a clear distinction between the types of pools in bedrock reaches and alluvial reaches:
    1. Average bedrock pool spacing ~ 3.3km
    2. Average alluvial pool spacing ~ 8.3km

Sediment movement through deep pools

Detailed field work at the Ang Ngay deep pool revealed that sediment passed through the deep pool as a wave like perturbation in bed elevation, with sediment material moving as a aggregated unit (see for example, figure 38 in the previous section). The dynamics behind the propagation of the sediment wave are:

- Peak discharge and variations in river discharge
- Fluctuations in upstream sediment supply

Figure 39 below summarises the main phases in the migration of a sediment wave through a bedrock confined pool from Conlan (2008). The graph overlays the mean monthly flow at Vientiane for the baseline (current) and Definite Future (2015) conditions, with the estimated maximum velocities at the pool entrance, pool centre and pool exit. During the dry season velocity is greatest in the river bed (Conlan refers to these as 'crossings'), which results in the gradual scour of these areas and gradual infilling of deep pools. Then during the onset of the flood season, velocities peak at the entrance to the deep pool initiating a ~2month period of rapid pool infilling. At the peak of the flood season, the river bed maintains a stable elevation as the flows peak in the pool centre translating the sediment wave through the deep pool. By the end of the flood season the sediment wave has passed through the pool and begins to break up and deposit on the 'crossing' downstream. Then during the dry season the bed load in the crossing reconcentrates, consolidating into in-channel formations such as sand bars and siltation benches.

The translation for the sediment wave from crossing – deep pool – crossing (~10km) typically takes a full monsoon flood cycle (Conlan, 2008). This has important implications for the fate of sediment in the Mekong system. Suspended sediments are likely to move approximately at the same velocity as the flow as they remain entrained during the rising limb of the flood peak and reach downstream deposition sites in Zone 3-6. However, sediment moving close to the channel bottom tends to aggregate in a wave which moves under saltation and travels in the order of one pool crossing (~10km) per year. This means that though the pools are not sites of storage themselves, they act as buffers in the system regulating the downstream transport of coarser sediments and bedload, which produces the complex of in-channel features, which are themselves important habitats contributing to the productivity of the Mekong system. This is in agreement with Conlan's (2008) conclusion that deep pools do not store sediments during the dry season, rather, they act as conduits for sediment transport between storage zones ("crossings") and for the conveyance of wet season sediment loads.

Impacts of human activity

- **Bedrock blasting**: Clearing of rapids and the removal of bed rock outcropping, for navigation could transform pools from short deep pools to longer and shallower pools (Conlan, 2008).
- **Flood regulation:** Reduction in wet season flow will reduce bank full discharge, which could increase incision and reduce channel width. This would reduce the length and inter-pool spacing (Conlan, 2008).
- **Pool scouring:** Conlan (2008) hypothesized that in a regulated hydrological regime, bed load could be transported into the deep pools but may not reach the exit velocity required to scour during the peak flood period. For the Ang Ngay pool the max scour velocity required occurs at the pool centre and was in the order of 3.5-5m/s which begins to occur at ~60% of the annual peak flow. An exploration of the changes to transport capacity indicates that this 'filling' of deep pools is unlikely to be the case (Carling, 2009). This is reiterated in a fig 35 (shown previously) which suggests that with the complete Yunnan cascade peak flows will continue to induce sufficient velocity in the pool centre to facilitate seasonal scour.

PAST AND CURRENT TRENDS

There are at least 335 deep pools along the thalweg of the Mekong mainstream. These pools are dynamic features of the river channel consolidating sediment movement into a pulse-like wave which transports sediment between adjacent zones of sediment storage over the monsoon flood cycle. The deep pools play an important role in regulating the downstream progression of sediment and building in-channel features such as islands and sand bars, which are important for the river's biodiversity. No information is available on the past trends in either the location or number of deep pools.

FUTURE TRENDS TO 2015

Under the Definite Future scenario both the peak flows and sediment load will be reduced, however the reduction in peak flow is not expected to reduce the in-pool velocity enough to prevent entrainment. At Chiang Saen the duration of the flood season will be shortened by ~4weeks (25% of historic flood duration), this will affect the time over which scour velocities are reached resulting in only partial scouring of the deeper pools and increasing the time-step over which the sediment wave completely passes through the pool. The reduction in sediment load because of the reservoirs in the Definite Future is not likely to induce any changes in the functioning of the deep pool as their buffering effect on sediment movement has resulted in a significant volume of sediment stored within the channel banks. Therefore, in the short term the pools will continue to function naturally (with a potential reduced scouring efficiency) as 'crossings' continue to migrate downstream. In the long term, upstream crossings will disappear as they translate downstream and are not replaced, such that the deep pools eventually become static 'holes' and no longer dynamic components in the translation and storage of sediment and bed load.

S6: Bed and bank erosion

Bank erosion is a natural phenomena for alluvial reaches of the Mekong River and is balanced by deposition and consolidation of new channel features, for example the confluence between the Mekong and Tonle Sap Rivers shifts by up to 10m each year. In-channel islands of Z3 slowly migrate downstream by accreting sediment on their downstream banks while eroding at their upstream banks (Kummu et al, 2007).

The longest reach of alluvial channel roughly correlates to Zone3, starting approximately 40km upstream of Vientiane and extends downstream to Simphadon which marks the beginning of the Bolovens Plateau and an area of extensive bed rock outcropping (See Annex 1 for detailed morphology notes). The river alternates between a wide alluvial stretches divided into two unequal channels split by a series of large elongated islands within the channel and infrequent bed rock outcrops (Kummu et al, 2007; Conlan, 2008). This reach of river also acts as the international border between Lao PDR and Thailand. No definitive estimates are available for depth of sediment stored in-channel, however, Carling (2009) quotes an engineering study undertaken during the construction of the Friendship bridge which indicates a sediment lens of 5-15m deep at Vientiane.

Based on GIS analysis by Kummu (2007) over a 50km stretch of Zone 3, the table below presents the average erosion and accretion rates for the left and right banks as well as channel islands. These rates represent approximately 0.1% of the channel width in this reach which is low compared to other international rivers (Kummu et al, 2007).

Table 14: Erosion and accretion rates for a 50km section of Zone 3 (source: Kummu et al, 2007)

	1961 - 1992			1992 -2005		
	Left Bank (m/a)	Right Bank (m/a)	Channel islands (m/a)	Left Bank (m/a)	Right Bank (m/a)	Channel islands (m/a)

EROSION	0.7	0.9	1.2	1.2	0.8	2.3
ACCRETION	0.4	0.4	0.3	0.6	0.8	3.2

PAST AND CURRENT TRENDS

From Kummu's (2007) study the following past trends include:

- Since 1992, erosion has increased on the left bank, while accretion has increased on the right bank. This is part of the natural balance between erosion and deposition

- Both erosion and deposition have increased for in-channel islands, suggesting the rate of migration of channel islands may have increased since 1992.

- The banks of channel islands are more unstable than the river bank (Kummu et al, 2007). Therefore any changes to channel morphology due to increased erosion and accretion is likely to be experienced first by the channel islands.

FUTURE TRENDS TO 2015

Under the Definite Future scenario there is not likely to be an increase in the rate of erosion (Carling, 2009), however there will be an increase in nett erosion downstream of Vientiane as the river compensates for the reduced supply resulting from the hydropower developments (Sarkkula et al, 2010). Based on past erosion potential, this sediment uptake is likely to first affect channel islands and channel bed deposits, followed by river banks. In terms of channel geomorphology and using current estimates of in-channel storage, it would take many decades for the alluvial reaches to be completely eroded (Carling, 2009). However, local effects will be seen within 10years and regional effects within 20years (Carling, 2009). The uptake of sand sized particles from the river channel will also alter the particle distribution of the sediment load increasing the fraction of sand-sized materials, which will alter the downstream deposition dynamics in the Cambodian floodplain and the Mekong delta.

S7: Floodplain Nutrient and sediment dynamics

The Mekong floodplain covers 50,152km2, almost 60% of which is in Cambodia, and is home to 11.3million people (25% in Cambodia) (Kummu et al, 2009b). The seasonal cycle between aquatic and terrestrial environments and the input of nutrient-laden sediments make is one of the most productive inland ecosystems in the world.

Key characteristics

- Historic average seasonal water level fluctuations of up to 10m (Kummu et al, 2009b).
- During the wet season (May – October) flows overtop the Mekong channel flood the surrounding landscape. The main sites of flooding are:
    - **Kratie – Phnom Penh:** overbank flooding remains close to the mainstream channel
    - **Tonle Sap Lake:** Flood water levels in the Mekong system force a reversal of flow in the Tonle Sap River driving sediment rich Mekong floodwaters into the Tonle Sap Lake.
    - **Phnom Penh – Mekong Delta:** the terrain flattens in comparison to upstream areas and the mainstream splits into two channels. Flooding is becomes extensive

- During the Dry Season (November – April) the water from the floodplains drains back into the Mekong channel. In the Mekong floodplain overbank siltation can delay the timing of return flow providing surface water well into the dry season.

Sediment load

- Based on 8 years of data Kummu et al (2009b) estimate that the average annual sediment load at Kratie is 66-122Mt. However, there is at least +/- 30% error in this estimation (See figure 40 below). Sarkkula (2010) estimate that the sediment load at Kratie is 160Mt
- The peak sediment load at Kratie is more closely aligned with the flood peak than in upstream reaches of the basin, with both peaking in ~September.
- Approximately 4-7% of the SL at Kratie is deposited in the Tonle Sap Lake, while 8-20% of the SL settles on the Cambodian floodplain and the rest enters the Mekong Delta (Kummu et a, 2009b).
- This corresponds to ~8 – 35Mt/yr settling into the Tonle Sap and floodplain system (figure 47).
- Sediment deposition in the floodplain is likely to have a large component of clay sized particles (Sarkkula et al, 2010; Walling, 2005).

Indicative exploration of changes to the floodplain sediment load

The problem of sediment data uncertainty and gaps is exacerbated for the Mekong floodplain because the complex hydrodynamics, shifting channel bed make accurate and repeat sampling difficult. This subsection of the working paper presents an indicative picture of what is likely to

Figure 46 compares two stations Kratie and Tan Chau/Chau Doc which can be taken to represent the spatial extent of the Cambodian floodplain. Downstream of Kratie the river is navigable and velocities are low (in the order of 2m/s), downstream of Tan Chau/Chau Doc is the Mekong Delta and the influence of marine tidal dynamics begins to exert an influence on the hydrodynamics.

One study, reported by Walling (2009) suggests that the sediment load in the Mekong delta is predominantly fine silt with 15% clay, while the grain size distribution curve for Pakse (figure 31) indicates that 41% of the distribution is finer than coarse sand. Assuming that downstream of Kratie there is negligible transport of material larger than coarse sand because of decreasing gradients and decreasing bed shear stress, there is a progressive deposition of coarser materials at the entrance to the floodplain environment, with permanent settling and bed aggradation in the reach between Kratie and Phnom Penh. Some of this sand is extracted by the sand mining industry though no figures were available to properly quantify this. Figure 49 (top and bottom left figures) represents this for the past and current situation, with sand deposition resulting in no medium sized-sands entering the delta. Also there is a nett drop in the sediment load between the two stations accounting for the fraction of the load that is deposited in the Tonle Sap and floodplain (as discussed above).

The impact of the Yunnan cascade and other tributary developments is explored in the top and bottom right plots (figure 49).

- **Reduction in the nett load:** there will be a significant reduction of the majority of sediment sizes associated with the Yunnan cascade and other tributary projects.
- **No change in medium sand transport**: at Kratie there will be little reduction in medium sand transport because this will continue to be supplied by the erosion of upstream bed materials
- **Coarsening of the load at Kratie:** there will be a slight, but difficult to measure coarsening of the load at Kratie.

- **No coarsening of the load at Tan Chau/Chau Doc:** This coarsening of the sediment load will not arise at Tan Chau/Chau Doc, because it is not likely that medium sand is currently transported this far downstream.

PAST AND CURRENT TRENDS

- **Cambodian flood plain:** Sarkkula (2010) provide a summary of the fate of nutrients in the Mekong system. The high productivity of the Mekong floodplains is based on the load of cohesive sediments from upstream areas and on the nutrient loading associated with the sediment flux. Phosphorous is often the limiting nutrient and is locked into the geology of the upland areas until run-off and erosional processes transport it to the zones of deposition where conditions are favourable for deposition. Detailed studies of phosphorous in the Cambodian floodplain indicate that 31-42% of the bioavailable Phosphorous is transported into the floodplain with the sediment influx (Sarkkula et al, 2010). This equates to 21,500t/yr of bioavailable P, which is capable of fertilising 5,400-16,500km2 of rice paddy area (Sarkkula et al, 2010).
- **The Tonle Sap Lake:** The previous section demonstrated that sediment deposition in the Tonle Sap Lake is concentrated around Lake Chma, the braided Tonle Sap river channel north of Kampong Chnhang and the broad floodplains on the western extent of the lake's floodplain. During the flood season these are the shallowest areas of the lake and therefore encourage sediment deposition,

FUTURE TRENDS TO 2015

- **Extent of flooding:** The Cambodian floodplain will reduced by 4.8% (~1,034km2) due to the reduction in water levels predicted for the Definite Future.

- **Cambodian flood plain:** The trapping of sediment behind the Yunnan dams and the Three S dams proposed for the Definite Future will have a more immediate impact on finer sediment (Sarkkula et al, 2010). This is because the sustained transport energy of the Mekong will induce short and long term resuspension of coarse and non-cohesive sand-sized particles into the water column. Approximately 10,000 – 18,000t/yr of bioavilable P will be lost from the Mekong system (Sarkkula et al, 2010).
- **Tonle Sap Lake:** Productivity is reduced by 4 – 40% across the lake area (figure 41). The western perimeter of the dry season lake area is likely to face productivity reductions of up to 40% (Sarkkula et al, 2010).

S8: Sediment dynamics of the Tonle Sap Lake (TSL)

Tonle Sap Sediment loads

- The Mekong has a more dominant influence on TSL sediments than on the hydrology with most sediment entering the Tonle Sap being washload from the Mekong (MRC, 2007; Kummu, 2008b). The Mekong River contributes 72% of TSL average annual sediment load, which accounts for 4-7% of the annual sediment load at Kratie (Kummu, 2008a; Kummu 2008b)
- The lake retains ~80% of the sediment & nutrients, acting as a sink (MRC, 2007)

Table 15: Average annual sediment balance (x10^9 kg) (1997-2003) (adapted from: Kummu, 2008b)

DATE	FROM MEKONG	FROM TRIBS	TO MEKONG	REMAINING	% REMAINING
1997	5.72	1.99	-1.22	6.49	84
1998 (dry year)	2.54	0.95	-0.79	2.7	77

1999	4.42	2.05	-1.49	4.98	77
2000 (wet year)	5.88	3.43	-1.82	7.49	80
2001	6.62	2.2	-1.67	7.15	81
2002	7.11	1.77	-1.61	7.27	82
2003	3.35	1.33	-1.08	3.6	77
AVE	*5.09*	*1.96*	*-1.38*	*5.67*	*80*

- SL (MK – TS) = 4.5 - 6 million tons, based on 1950/51 – 1955/56 data (MRC, unpublished 2) and 5.1 x10^9 kg (based on 1997 – 2003 data)
- SL(TS – MK) = 3 – 6.7 million tons, 1950/51 – 1955/56 data (MRC, unpublished 2) and 1.4 x10^9 kg (based on1997-2003 data)
- Sedimentation rates in the lake bed have been estimated at 0.1mm/yr
- The Mekong channel south of Kratie is highly mobile with rapid accretion and lateral erosion along river channels and branches. The confluence of the Tonle Sap with the Mekong and the split into the Bassac and Mekong Rivers (known as the *Quatre Bras*) is estimated to be migrating southward at up to 10m/year (MRC, unpublished 2).
- The channel branching and braiding north of Kampong Chnhang is alluvial and evidence of sediment deposition and the area near Chnoc Trou is heavily anastomosed and difficult to navigate towards the end of the dry season.
- There is also evidence of sediment deposition in the northern extent of the Tonle Sap Lake (MRC, unpublished 2).
- The lake volume ranges between 1.3-75km3
- Little information is available on the grain size distribution of Tonle Sap sediments. Carling (2009) presents a distribution curve for Pakse (presented earlier in figure 31),According to this, 41% of the grain size distribution (D < 0.45mm) can be entrained at Pakse all year round (with a minimum entrainment velocity of 3,800 m3/s), while 99% of the sediment including the coarser material (D<4.75mm) can be entrained for at least half of the year (transition 1 + monsoon) (with Q(entrainment) ~ 5,600m3/s). The former grain size corresponds to coarse sand, while the latter is fine gravel or smaller.

outflows

Figure 42 below illustrates that outflows at Kampong Luong typically do not exceed the entrainment flow for fine gravels and this is an unlikely phenomena at present. The lower entrainment velocity is currently exceeded for 15% the year during outflow back into the Mekong. During the Definite Future, this will be reduced by ~2weeks (~one quarter reduction in time) which will affect the total sediment efflux from the Tonle Sap to the Mekong.

Flow at Prek K'dam does exceed the entrainment outflow for larger particles from the end of October to mid-December which will be reduced by 1-2weeks in the Definite Future Scenario. The entrainment outflow capable of exporting coarse sands starts after the second week of October and continues through to late January, the end of this period will be reduced by ~1week in the Definite Future, which represents a ~10% reduction in the time available for smaller particles to be flushed from the Tonle Sap system. Since the inflow at Kampong Luong (see below) only passes this larger load for a small proportion of the year, it is expected that under the definite future there will be a gradual accretion of sediment in the Tonle Sap River channel, particularly at current sites of in-channel deposition such as the delta near Kampong Chnhnang.

Therefore in terms of seasonal outflows from Tonle Sap, larger particles can be flushed from the Tonle Sap for a period of ~6weeks (29 OCT – 12 DEC) approximately 1-2 weeks less than under baseline scenario. Smaller particles will continue to be entrained from Tonle Sap Lake and conveyed through the river to the Mekong in the Definite Future, however the period over which this will occur will be reduced by ~2weeks (1 NOV – 11 DEC).

Inflows

Under the current situation flows at Prek K'dam and Kampong Luong would not be sufficient to entrain fine gravels during inflow periods and this would remain the case during the Definite Future. This means that current sediment storage in the TSL preferentially stores smaller than sand size sediments. These smaller sized particles will continue to pass through Prek K'dam during July, August and September, but the period of exceedance will be reduced by 2 – 4 weeks. Kampong Luong currently passes 41% of the sediment profile during the month of August, however, under the Definite Future flows in this area will no longer be sufficient to entrain all sediments in this range. The cumulative impact of these reductions is a 45-50% reduction in the time when Mekong sediments can enter the TSL system which will have implications for the sediment deposition rate and the TSL functioning as a site of sediment storage.

Table 16 Comparison of Baseline and Definite Future days in exceedance of required entrainment flow for 99% and 41% of Mekong sediments (based on Carling, 2009 and BDP modeling).

Q(ent)	STATION	SCENARIO	PERIOD EXCEEDING Q(ent)	TOTAL DAYS	REDUCTION IN TIME EXCEEDING Q(ent) (weeks)
OUTFLOW: TONLE SAP – MEKONG					
5,600	Prek K'Dam	BS	26 OCT - 18 DEC	54	
5,600	Prek K'Dam	DF	29 OCT - 12 DEC	45	1.3
5,600	Kampong Luong	BS	*does not exceed*		
5,600	Kampong Luong	DF	*does not exceed*		
3,800	Prek K'Dam	BS	10 OCT - 20 JAN	103	
3,800	Prek K'Dam	DF	11 OCT - 15 JAN	97	0.9
3,800	Kampong Luong	BS	27 OCT - 19 DEC	54	
3,800	Kampong Luong	DF	1 NOV - 11 DEC	41	1.9
INFLOW: MEKONG TO TONLE SAP					
5,600	Prek K'Dam	BS	*does not exceed*		
5,600	Prek K'Dam	DF	*does not exceed*		
5,600	Kampong Luong	BS	*does not exceed*		
5,600	Kampong Luong	DF	*does not exceed*		
3,800	Prek K'Dam	BS	20 JUL - 9 SEP	52	
3,800	Prek K'Dam	DF	29 JUL - 9 SEP*	35	2.4
3,800	Kampong Luong	BS	3 - 12 AUG, 24 - 29 AUG*	15	
3,800	Kampong Luong	DF	*does not exceed*		

* exceedance is intermittent during this period with up to 1 week of non-exceedance

Tonle Sap Sedimentation rates

- Based on the sedimentation retention volume of 5.7 x10^9kg per year, Kummu et al (2008b) estimated sedimentation rates varying between 1.42mm/yr to 0.27mm/yr. The former assuming all deposition occurs within the dry season lake area and the latter assuming deposition spans the entire average wet season lake area. Comparison with geologic coring estimates and modeling results indicate that the sedimentation rate is likely to be ~0.2mm/yr (see table below). This implies that current sediment deposition is not concentrated in the dry season lake bed but spreads out over the entire TSL floodplain
- Both the modeling undertaken for the 1997 water year and sedimentary core results suggest most of the sediment is concentrated in the lake floodplain (See figure 43), with the highest rates observed in Lake Chma, the western part of the lake and the Tonle Sap delta (Kummu et al, 2008b). Based on this, sedimentation rates are likely to be greater in the floodplain areas due to: (i) shallower water column during peak sediment loads, and (ii) increased entrapment caused by riparian and floodplain vegetation (Kummu et al, 2008). During the dry season the water column of the open lake drops down to 1m however TSS concentrations remain high, indicating active re-suspension of sediments contributing to the sediment efflux back into the Mekong. This maintained suspension in the dry season open lake area is likely to be the result of wind as well as turbulence and dispersion in the water column caused by the hydraulic gradient.

Table 17: Estimated sedimentation rates for Tonle Sap Lake (adapted from: Kummu et al, 2008b)

SOURCE OF ESTIMATE	AVERAGE ANNUAL SEDIMENTATION RATE
Empirical Calculation*	0.27 – 1.42mm/yr
Coring estimation A: long term range	0.05 – 2.55 mm/yr
Coring estimation B: long term average	0.66mm/yr
Coring estimation C: recent average (post-holocene)	0.19mm/yr
EIA model	0.2 – 0.4mm/yr
Ca. 550y. BP.	0.1 – 0.16mm/yr

**based on 1997-2003 observed lake area and sediment loads*

PAST & CURRENT TRENDS

Historic sediment balances for the Tonle Sap indicate that the lake is a net importer of sediment from the Mekong with 4.5-6million tons of washload entering the Tonle Sap, and 3 – 6.7 million tones exiting per year. Though the sediment yields and loads in the Mekong River are not likely to have changed significantly between the 1950s and the present, there is some question whether the sediment storage capacity of the Tonle Sap has decreased. One study in particular hypothesizes that the northern extent of the Tonle Sap is reaching storage capacity which is slowing down the deposition rate, other studies indicate that sediment deposition remains at 80% of inflow yields with the TSL storing 4-7% of the Mekong sediment load at Kratie (MRC, unpublished 2; Kummu et al, 2008b).

The window for sediment efflux from the TSL is on average mid-October to mid-January, with larger material capable of being transported from late October to mid December, and a one month smaller window at the Lake than in the Tonle Sap River. The window for sediment influx entering the TSL is currently mid July to early September, and larger materials are not likely to currently enter the system. This indicates that the complex hydrodynamics of the TSL system and flow reversal act as a 'sieve' preferentially passing smaller sized sediments into the Tonle Sap and accumulating at a rate of ~0.2mm/yr over the entire inundation plain of the

TSL. However, the comparatively lower flows at Kampong Luong suggest that transport capacity is not uniform throughout the system with preferential zones of deposition at Lake Chma, the 'delta' north of Kampong Chnhnang and the western shore line of the dry season lake area and amongst the lowest sedimentation rates in the dry season lake bed.

2015 TRENDS

There are two drivers of change for 2015 sediment dynamics in the Tonle Sap:

1. Changes to inflows and outflows on the Tonle Sap system
2. Changes to the sediment load in the Mekong River

The biggest change in sediment flux between the Baseline and Definite Future will occur during the infilling of the Tonle Sap Lake. During this time, flows up the Tonle Sap River will not be sufficient to entrain coarser materials, and there will be a reduction of 2-4 weeks of the 9week period in which finer materials consisting of 41% of the sediment profile will be passed. This will have significant implications for the volume of sediment entering the Tonle Sap Lake because the 2015 scenario will see an increase in the particulate size of sediments as hydropower developments trap sediments and more bed and bank material from Zone 3 is resuspended to compensate for reduced supply. Further, the period of sediment transport out of the Lake will be reduced by 1-2weeks reducing the connectivity of sediment transfer between the Tonle Sap and Mekong. From a geomorpological point of view this is likely to see increased sedimentation in the Tonle Sap River and the southern extent of the dry season lake area, which will build up in-channel features (e.g. at Chnoc Trou and the 'delta' area north of Kampong Chnhnang) and increase braiding near the outlet of the lake. The changes to the sediment flux will also reduce the proportion of sediment reaching the littoral zone of the TSL floodplain affecting the productivity of the flooded forests.

S9: The Mekong Delta and Marine sediment dynamics

Key features of the delta environment

- The Mekong delta is a flat flood plain (0-4 meters a.m.s.l) formed by eroded sediments from upstream. It is a zone of deposition, with the areas of greatest sediment deposition in the delta sediment profiles of 3 – 5km deep (ADB, 1999)
- Deltaic environment: Braiding of the mainstream and complex network of canals, as the river approaches the marine environment it fans out into a network of distributaries with high levels of siltation in the channel islands and inter-channel land mass.
- Overland flow during the flood season contributes approximately 30% of the total annual floodwaters and originates from the Cambodian floodplain.
- Overbank siltation traps flood waters sustaining pockets of remnant wetlands
- Extensive flooding (max. depth of 4m)
- Dry season saline intrusion: affects half of Vietnam's delta.
- High levels of erosion
- 7,000 km of main canals, 4,000 km of secondary canal, 20,000 km of protection dykes (preventing early flood) (MARD, 2003)

Key hydrological issues for the Mekong Delta

1. **Salinity intrusion:** Saline intrusion is greater on the eastern coastline of the delta, where the South China Sea tides are ~2m. In this area Intrusion is encouraged through river and distributary channels with very low elevation channel bottoms and can reach up to 60km in a dry year (eg 1998) averaging 30-40km between 1985-1996) (Miller, 2003). On the western coastline, tides are of smaller amplitude (~1m). On average 1.4-1.9million ha are affected for a period of 1-3months (SIWRP, 2009).

- **Floods:** 1.2 - 1.9 million hectares of the south-western part of the Delta is under annual flood. Flood levels exceed 0.42m ~ every 3-5years. Water levels peak near the Cambodian border and reduce with distance south. Peak levels of 3-5m are driven by overland flow from the Cambodian floodplain which can account for 30% of water volume entering the delta during a typical flood season.
- **Acid sulphate soils (ASS):** 1.6 million hectares (40%) of the Mekong Delta. Floods can transport toxic water from ASS areas to other non-ASS areas
    1. Acid sulphate soils cover 40 per cent of the delta and are sensitive to fluctuations in river discharge.
    2. In the rainy season, a large discharge from the rivers is necessary to leach and flush toxicity released from the soils before any crops can be cultivated. (Minh et al., 1997a).
    3. During the dry season, in order to maintain a certain groundwater level to prevent oxidization of pyritic substances, a certain minimum river discharge is needed.
    4. Alluvial soils concentrate around the river channels and adjoining Cambodian floodplain indicating that overbank siltation is an important component of the historic hydrology. Historically, overbank flooding was an important control on acid generation in acid sulphate soil areas as elevated ground levels in the alluvial zone prevented the return of flood waters during the flood recession and ponding large areas of the delta well into the dry season. The water column prevented the acidification of soils by minimizing contact with the air. Due to irrigation works many of these large flooded areas have been drained exacerbating the acid-sulphate soils problem.
- **Fresh water shortage:** discharge in dry season 1,700-2,500m3/s. Water scarcity for irrigation affects nearly 1.5 million hectares of cultivable land in the dry season. This water consumption by rice farming equals about one-half of flow rates of the Mekong during the dry season within Vietnam (Tin and Ghassemi, 1999).
- **Bank erosion:** The Vietnamese delta has the highest erosion rates in the basin (can be >10m). Areas of highest bank erosion potential are located on the Tien River and it's network of distributaries from Dong Thap to Tien Giang and Ben Tre provinces. In Dong Thap ~80% of the flow passes through the Tien River which accounts for the higher erosion potential as well as the noticeable erosion in the inter-channel zones of Dong Thap as the higher elevation of the Tien River and the larger flows sees flood season overland transfer from the Tien to the Hau River. However, downstream of the Vam Co River flow evens out resulting in a more even distribution of bank and in-channel erosion.
- **Marine sediment plume:** satellite images (fig 48) show that a substantial portion of the Mekong sediment load discharges into the South China Sea. The total load is unknown and cannot be estimated because of a lack of data, but it is likely to be mostly clay size (Walling, 2009). Kummu (2008) indicates that 75-85% of the of the Sediment Load at Kratie enters the Mekong Delta which amounts to 123 – 140Mt/yr. The rate of deposition in the delta is not well understood but there are in the order of 30,000km of canal and irrigation channels in the delta (primary, secondary and tertiary canals) and sediment deposition is known to be an important control limiting the life of these structures and requiring periodic maintenance and dredging.

PAST & CURRENT TRENDS

Flooding, saline intrusion and acidic flows from acid sulphate soils are a regular and seasonal occurrence for the Mekong Delta. All of which have undergone change in the past due to human management of the detlai environment:

- **Flooding:** in the order of 30,000km of primary, secondary and tertiary canals have divided the Mekong delta into a largely homogenous but highly productive region. This system of canals and sluice gates have escalated during the 1990s and allow local authorities to drain the larger floodplains of the Mekong Delta (the plain of reeds and the Long Xuyen Quadrangle) and provide suitable conditions for three rice crops per year in many areas of the delta. At present flooding affects 1.9million ha.
- **Saline intrusion:** the extent of saline intrusion is measured by the 4g/l isobar which represents the threshold between brackish and freshwater. An extensive network of dikes has been built – particularly on the western coastline to control saline intrusion. On average 1.4 – 1.9 million ha are affected for a period of 3-5months during the year.
- **Acid sulphate soils:** has emerged as an issue of the past 20-30years during a period of agricultural intensification. The draining of large areas of wetland exposed acid sulphate soils to the air and oxidation. After which the first flushes of the flood season would become acidic as the encountered acdic soils. Currently, 1.6million ha (40% of the delta) is seasonally affected by acid sulphate soils.
- **Marine sediment plume:** A significant proportion of the sediment load enters the marine environment, where tidal forcing drifts the sediment plume southward loosely tracking the eastern coastline of the delta. The youngest region of the delta is the Ca Mau Pennisula and sediment deposition is concentrated on the eastern and western face of the tip. Very little is known about the trends in the fate and size of the Mekong sediment plume, but it plays two important functions for the delta:
    1. The plume introduces nutrient rich silt into the marine environment which plays an important role in the highly productive marine fisheries of the Mekong delta. Trash fish from marine fisheries are also an important source of food-pellets used extensively in the Mekong Delta to support its large aquaculture industry.
    2. The plume is also responsible for delta building and the preservation of mangrove coastlines – particularly in Ca Mau province.

2015 TRENDS

- **Flood area:** The Definite Future will see a typical reduction of 20,000ha in the flooded area of the Mekong Delta (table below).
- **Flood depth:** Water regulation will also shift the distribution of flooded depths in the delta, with an increase of ~90,000 – 100,000ha experience lower water level (<1.0m) during the flood season.
- **Flood duration:** As discussed in the analysis of hydro-biological seasons, there will be a reduction in the duration of the flood season and also the transitions seasons, with an increase in dry season. Specifcally, the border area of the Mekong Delta (Kieng Giang, An Giang, Dong Thap provinces) will experience 2-4week shortening of the flood season. A significant proportion of flood volumes for these areas (~20-30% of total flood volume) is generated by overland flow from Cambodia.
- **Saline intrusion:** BDP modeling suggests that the are affected by saline intrusion would reduce by ~15% because increased dry season flows will reduce the effectiveness of the hydraulic gradient driving saltwater into the delta (Piman, 2010). In principle this is likely to be the case, however further study is needed to understand the morphological implications of the reduced sediment load arriving in the delta to better understand the future saline intrusion dynamics. The current delta river channels lie close to and even below sea level and are cut through 3-5km of sedimentary material.

Changes to the nett erosion from Z6 channel reaches may cause incision of the channel which may enhance saline intrusion. Detailed hydrodynamic modeling is required to better understand the implications of the Definite Future on saline intrusion.

- **Marine sediment plume:** there is likely to be an 80% reduction in the supply of fines to the Mekong delta – based on the trapping efficiencies of the Yunnan and Three S projects. It is unlikely that larger sand-sized particles will remain in suspension through the Cambodian floodplain. Therefore, although the reduction in sediment load will undergo a lag of several decades before it becomes a problem in the upstream areas. The Delta's reliance on clays and fine silts suggest that the impact of an 80% reduction in load will begin to manifest changes in the marine sediment plume over shorter time scales. Based on an indicative assessment of the changed sediment load (Figure 46) , some likely changes are:
    - **Reduction in the size:** the sediment plume will be supplied with significantly less material and will therefore disperse quicker with a reduced range of littoral migration.
    - **Reduction in delta building:** the reduce load and range of marine transport will stunt delta building on the Ca Mau Pennisula, and increase coastal erosion along the entire eastern coastline of the delta.
    - **Collapse of nutrient transport:** there is likely to be a collapse in the nutrient transport pathway connecting the Upper Mekong Basin to the marine environment. Modelling on Tonle Sap suggested that a 4-40% reduction in primary productivity will be experienced in the lake with an 80% reduction in sediment load (Sarkkula, et al, 2010). While the hydrodynamics are completely different the reduced washload in the marine environment will also see a reduction in primary productivity, which will have major implications for the Delta's marine fisheries, as well as the aquaculture industry which uses marine trash-fish to produce fish pellets.

Table 18: Change to flooded areas of the Mekong Delta (adapted from: Piman, 2010)

Flood depth	BDP Baseline ('000ha)	BDP Definite Future ('000 ha)
< 0.5m	307	374
0.5 – 1.0m	668	712
2.0 – 3.0m	795	666
> 3.0m	5	3
Totals	**1,773**	**1,756**

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ANNEX I: TEMPORAL AND SPATIAL FRAMEWORK OF THE SEA BASELINE

TEMPORAL FRAMEWORK

In the SEA impact assessment, the mainstream projects are assessed against a baseline of economic, social and environmental conditions. The baseline "without" the mainstream dams should represent an accurate description of the past and current situation and present a realistic projection of future conditions for a period when the mainstream dams might be constructed and operational. For the Mekong hydrological regime, the BDP Baseline has been taken as an accurate description of the past and current situation. For the projected baseline, the hydrological assessment selected two BDP scenarios – the Definite Future to 2015 and the LMB 20 Year Scenario to 2030. In this paper only the Definite Future is analysed. The LMB 20 Year baseline will be analysed during the impact assessment phase so that the mainstream project can be assessed for their effects against two sets of baseline conditions. The SEA team considers the Definite Future development scenario to be the most likely baseline conditions for the mainstream project, which if they were to proceed, would only be a reality in a post-2016-2020 Mekong basin. The LMB 20 Year scenario enables the mainstream projects to be assessed against a more extreme projected development baseline.

SPATIAL FRAMEWORK

Due to the length of the Mekong River and the topographic, climatic and geologic diversity of the basin, it is convenient to divide the river into zones which manifest an identifiable, cohesive set of features. However, identification of these reaches depends on the perspective with which the river is being investigated, and can include: hydrology, sediment transport, topography, drainage patterns and surface slope, soil composition, climate, changes in flow, and land cover. Several approaches have been attempted in the past and they are summarized below.

Geographical/political boundaries: Upper and Lower Mekong Basins

The Mekong River is commonly divided into the Upper and Lower Mekong Basin. While there are climatic and topgraphical distinctions between the UMB and LMB, the demarcation historically acknowledges a changes in regional cooperation and state-actors in basin management. From a hydrological point of view, the following differences are important between the UMB and LMB:

- UMB catchment is characterized by confined narrow gorges with steep gradients.
- There are comparatively few tributaries in the UMB and only 14 of which have catchments greater than 1,000km2 in the UMB (MRC, 2005).
- There has also been extensive land-clearing in the UMB, one estimate indicates that between the 1960s and the 1980s forest cover in Yunnan province[6] dropped from ~55% to 30% (MRC, 2007)
- Snow-melt and to a lesser extent glacial flows account for a greater proportion of dry season flows in the UMB, dropping to ~16% of the mean annual flow at Kratie (MRC, 2005).
- Suspended Sediment Yields are higher in the UMB than all other Mekong subcathments (Kummu et al, in publication) with the exception of the Central highlands.

[6] The Lancang River catchment is just one areal component of Yunnan province. This figure relates to the entire province and should only be considered as indicative of the scale of deforestation for the Lancang catchment

Six IBFM flow zones of the LMB (MRC, 2005)

Six IBFM flow zones were developed based on consideration of: (i) hydrological regime, (ii) physiography, (iii) land use, and (iv) existing planned and potential resource developments (table 20).

6 zones based on drainage pattern (SOB, unpublished)

The Mekong River Basin has a complex and varied tributary network because of an active history of geologic events such as tectonic shear, uplift, headwards erosion and river capture (SOB, unpublished). This heterogeneity in drainage patterns allows for zonation based on the nature of drainage.

12 geomorphological zones between Chiang Saen and Khone Falls

A study on deep pools defined 12 gemorphic zones in the LMB north of Khone Falls. These zones are described in the second table below, together with their relationship with the 6 IBFM flow zones.

Table 19 Hydrological spatial zoning for the Mekong Basin (adapted from MRC, 2005; MRC, unpublished)

ZONE	IBFM FLOW ZONE	DESCRIPTION	DRAINAGE PATTERN	GEOLOGIC ZONE	LENGTH & FALL	% of MEKONG BASIN AREA	% of MEKONG MEAN ANNUAL FLOW
1	**Lancang River**	• Major source is Tibetan plateau • Narrow steep gorges	Parallel, no tributaries, recticular	Gorges, Ailao Shan Shear Zone	~1,900km with a fall of ~4,200m		
2	**Chiang Saen to Vientiane**	• Mountainous with large areas of remaining forest • Hydrological response to disturbances is likely to be most likely to be most natural	parallel	Gorges, Wang Chao fault zone	~1,100km with a fall of 200-300m		
3	**Vientiane to Pakse**	• Increasing influence of tributaries to flow •	dendritic	Gorges, central highlands & Khorat plateau	~600km with a fall of 100-200m		
4	**Pakse to Kratie**	• 3S contributions (>25% of annual flow volume)	dendritic	Gorges, central highlands	~200-300km, with negligible fall		
5	**Kratie to Phnom Penh**	• Cambodian floodplain and the Tonle Sap system • Furtherest extent of influence for saline intrusion and coastal process	dendritic	Gorges	~200-300km, with negligible fall		
6	**Phnom Penh to South China Sea**	• Braiding of the mainstream and complex network of canals • Extensive flooding and saline intrusion	distributary	gorges	~100-150km with negligible fall		

The SEA will predominantly use the IBFM flow zones to frame the baseline assessment, drawing on the other zoning as appropriate for specific issues.

ANNEX II: SALIENT CHARACTERISTICS FOR SUB CATCHMENTS OF THE MEKONG BASIN

Table 20: Salient characteristics for 31 sub catchments of the Mekong Basin (adapted from: Kummu et al, in publication)

	Sub-basin information				Reservoirs				TE Results						zone totals				
		Asb	Qsb	SLa	tot	Vreg	Areg	Qreg	Δtreg	TEreg	Δτsb	TEsb	SLtrap	CI	Asb	Qsb	Sla	Tot. Zone Area	% of TA considered
Sub-basin	ZONE	km2	km3·yr-1	Mt·yr-1		km3	km2	km3·yr-1					Mt·yr-1	Mt·yr-1	km2	km3·yr-1	Mt·yr-1		
Lancang	Z1	184,845	73.6	90.3	8	23.948	160,000	63.7	0.38	0.92	0.33	0.8	71.8	70.2-73.3	185,973	75	91		
Nam Ma	Z1	1,128	1	0.3	1	0	156	0.14											
Nam Beng	Z2	2,193	0.9	0.5	1	0.098	1,908	0.8	0.12	0.86	0.11	0.75	0.38	0.36-0.39					
Nam Khan	Z2	7,409	4.2	0.8	4	2.239	7,300	4.1	0.55	0.93	0.54	0.92	0.77	0.75-0.78					
Nam Nhiam	Z2	1,952	3.2	0.1	1	0.339	1,700	2.76	0.12	0.86	0.11	0.75	0.04	0.04-0.04					
Nam Ou	Z2	26,130	19.5	6.2	14	3.784	25,979	19.36	0.2	0.89	0.19	0.88	5.46	5.29-5.62					
Nam Pho	Z2	3,431	2.9	0.9	1	2.738	2,837	2.41	1.13	0.95	0.94	0.79	0.68	0.66-0.68	61,970	45	12		
Nam Phoul	Z2	2,057	1.2	0.1	1	0.499	1,680	0.95	0.53	0.93	0.43	0.76	0.05	0.04-0.04					
Nam Phuong	Z2	3,420	5.4	0.3	4	0.04	714	1.13	0.04	0.73	0.01	0.15	0.04	0.03-0.04					
Nam Suong	Z2	6,687	2.8	1.1	2	2.102	5,755	2.41	0.87	0.95	0.75	0.81	0.93	0.91-0.93					
Nam Tha	Z2	8,691	5.2	2.1	1	0.676	8,990	5.3	0.13	0.86	0.13	0.89	1.86	1.78-1.92					
Huai Bang Lieng	Z3	657	1.7	0.1	1	0.035	80	0.2	0.17	0.88	0.02	0.11	0.01	0.01-0.01	207,745	149	11		
Nam Chi	Z3	49,067	29.5	0.9	3	0.002	12,104	7.28											
Nam Hinboun	Z3	2,702	1.1	0.2	2	1.25	1,380	0.58	2.17	0.97	1.11	0.49	0.08	0.07-0.08					
Nam Kam	Z3	3,506	4.7	0.1	1	0	296	0.39											
Nam Mang	Z3	1,788	3.2	0.1	2	0.551	577	1.02	0.54	0.93	0.17	0.3	0.02	0.01-0.03					

Nam Mun	Z3	70,827	4.6	1.8	3	0.002	117,000	7.57											
Nam Ngum	Z3	17,169	20.7	0.6	10	10.386	16,900	20.4	0.51	0.93	0.5	0.92	0.57	0.55-0.57					
Nam Nhiep	Z3	4,496	6.2	0.2	5	1.269	3,750	5.17	0.25	0.9	0.2	0.75	0.13	0.13-0.13					
Nam Sane	Z3	2,224	2.9	0.1	3	2.08	1,429	1.83	1.14	0.95	0.73	0.61	0.05	0.05-0.05					
Nam Theun	Z3	14,894	15.4	0.6	8	10.986	14,070	14.51	0.76	0.94	0.72	0.89	0.54	0.53-0.55					
Se Bang Fai	Z3	10,188	31.9	0.8	2	0.624	6,350	19.87	0.03	0.72	0.02	0.45	0.36	0.32-0.39					
Se Bang Hieng	Z3	19,412	17.4	3.2	4	1.464	1,415	1.27	1.15	0.95	0.08	0.07	0.22	0.21-0.22					
Se Bang Nuoan	Z3	3,085	2.3	0.5	1	1.477	474	0.35	4.25	0.98	0.65	0.15	0.07	0.06-0.06					
Se Done	Z3	7,730	7.1	1.6	5	1.757	6,360	5.85	0.3	0.91	0.25	0.75	1.19	1.16-1.21					
Se Kong	Z4	28,766	29.6	4	20	11.067	9,700	9.98	1.11	0.95	0.37	0.32	1.29	1.27-1.30					
Se San	Z4	18,684	41.1	2.2	14	6.855	18,684	41.12	0.17	0.88	0.17	0.88	1.97	1.90-2.03	78,529	100	10		
Sre Pok	Z4	31,079	29	3.7	7	8.1	26,200	24.44	0.33	0.91	0.28	0.77	2.87	2.80-2.93					
St. Pursat	Z5	5,920	5.3	0.4	2	0.985	2,080	1.85	0.53	0.93	0.19	0.33	0.14	0.13-0.14					
St. Sangker	Z5	4,338	5	0.4	2	1.15	2,135	2.48	0.46	0.93	0.23	0.46	0.19	0.18-0.19	26,490	17	1		
St. Sen	Z5	16,232	7	0.5	1	2.89	10,540	4.57	0.63	0.94	0.41	0.61	0.33	0.32-0.33					
TOTAL		**560,708**	**385**	**125**	**134**	**99.39**							**92.1**	**90-94**	**560,707**	**386**	**125**		
% of basin		**69%**	**76%**	**89%**		**20%**							**66%**						

ANNEX 3: FIGURES

Figure 1: The hydro-ecological zones of the Mekong Basin

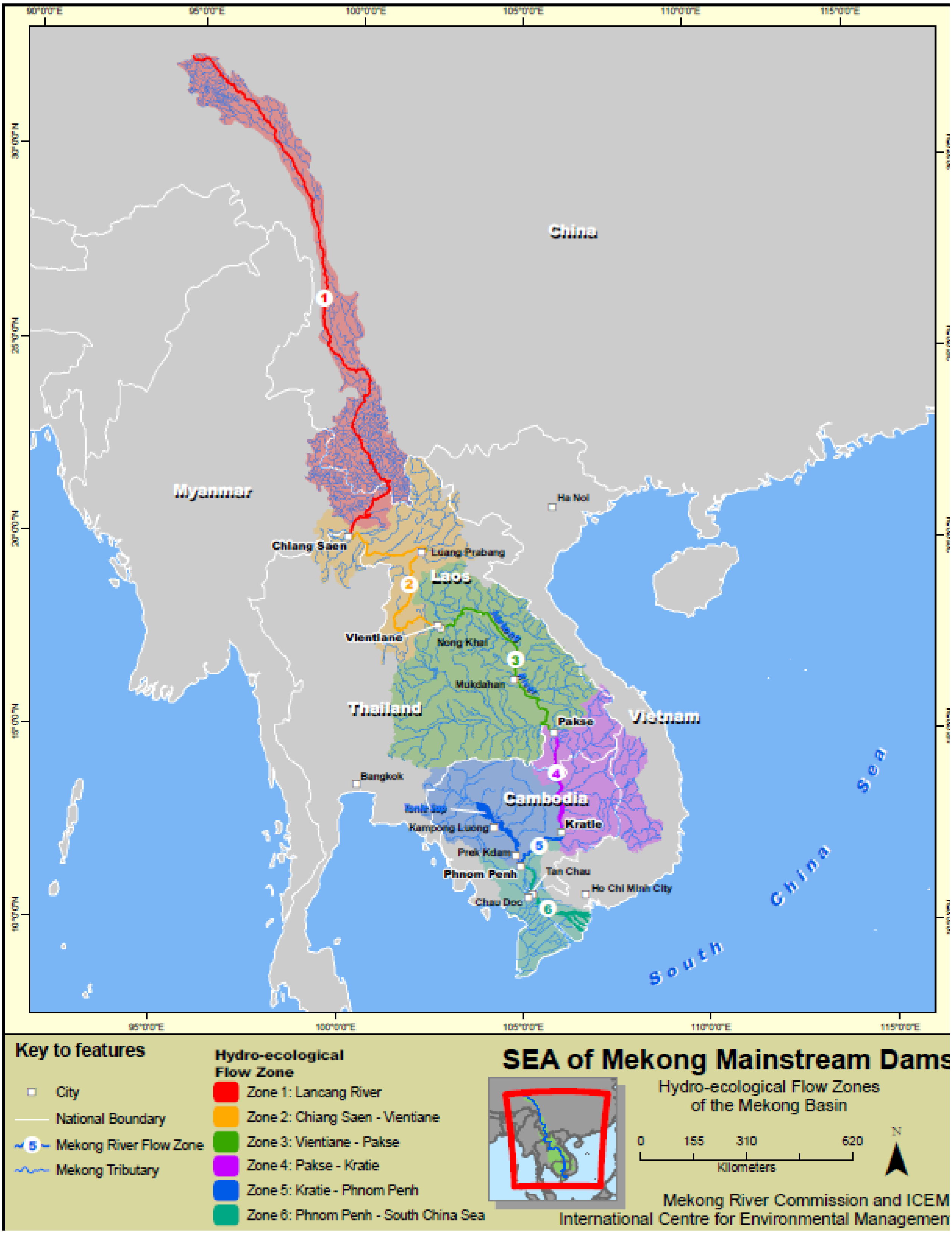


Figure 2: SEA relationship to the BDP scenarios

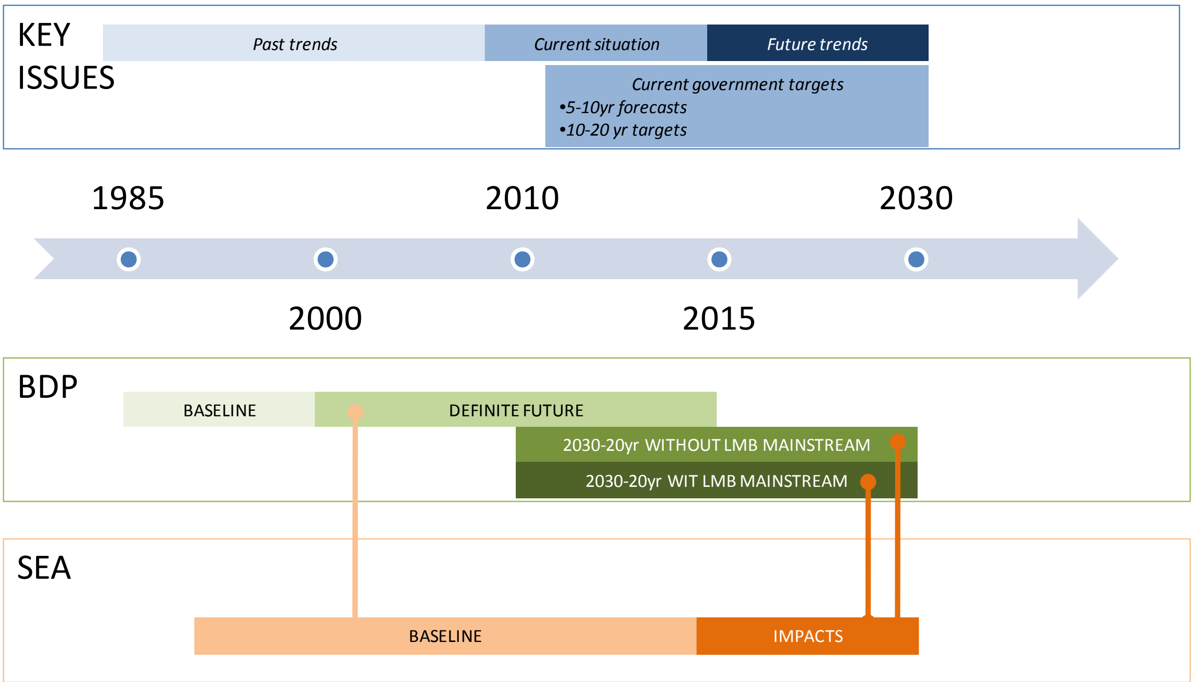


Figure 3: Average daily flow hydrographs for the Mekong River for the MRC Baseline (1986 – 2000)

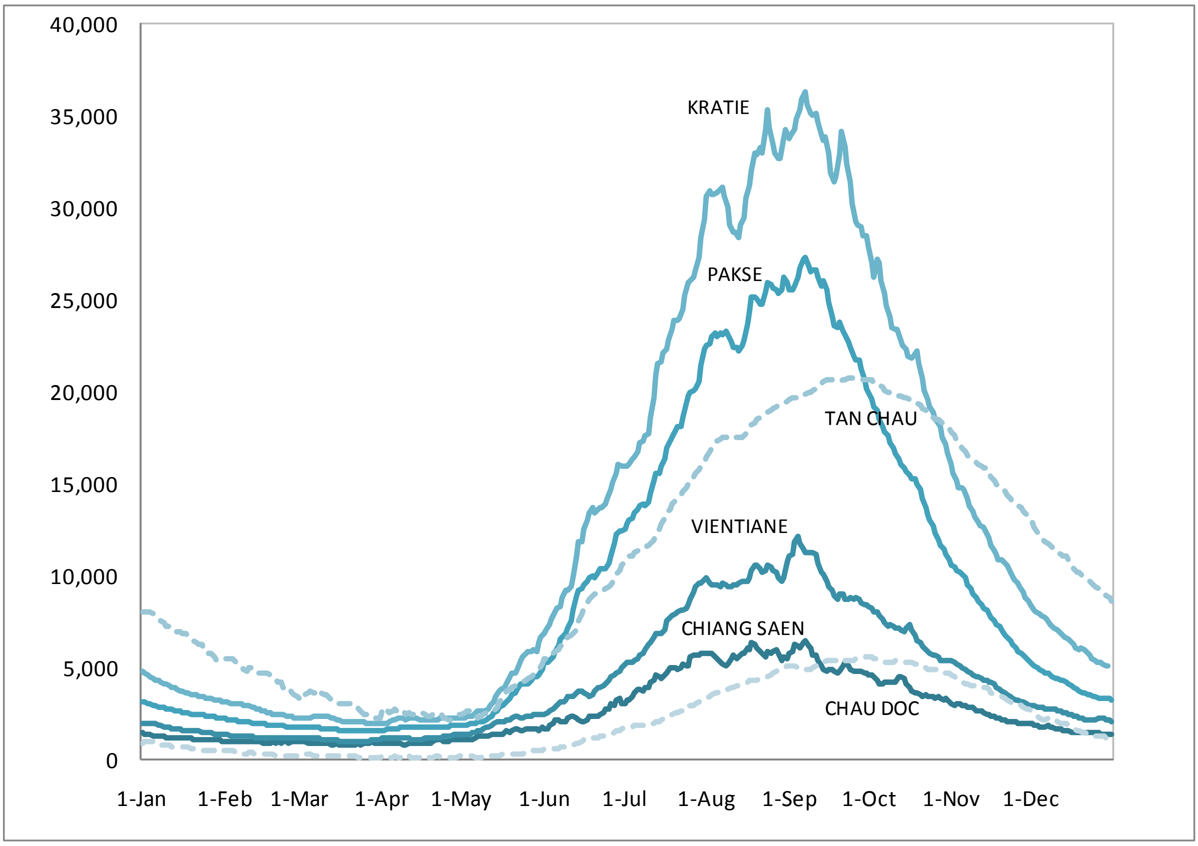
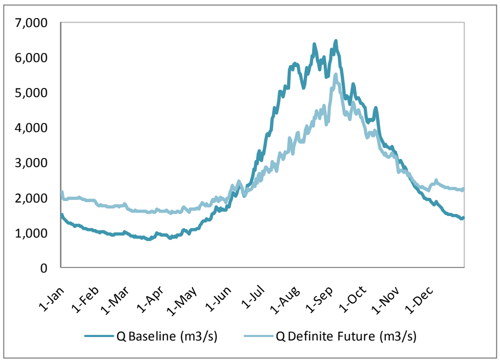
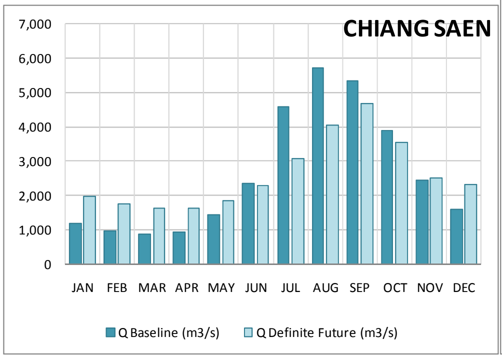
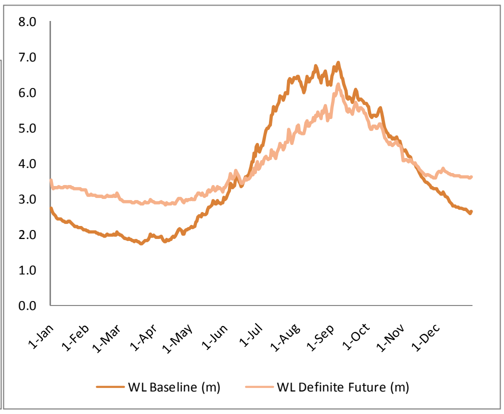


Figure 4: CHIANG SAEN: changes to the hydrograph between the Baseline and Definite Future scenario (adapted from BDP modelling): Top Left - Mean daily flows; Top Right - mean monthly flows; Bottom Left - mean daily water levels; Bottom Right - mean monthly water







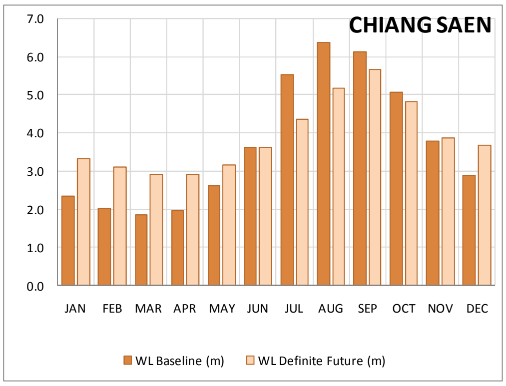


Figure 5: VIENTIANE: changes to the hydrograph between the Baseline and Definite Future scenario (adapted from BDP modelling): TL - Mean daily flows; TR - mean monthly flows; BL - mean daily water levels; BR - mean monthly water levels

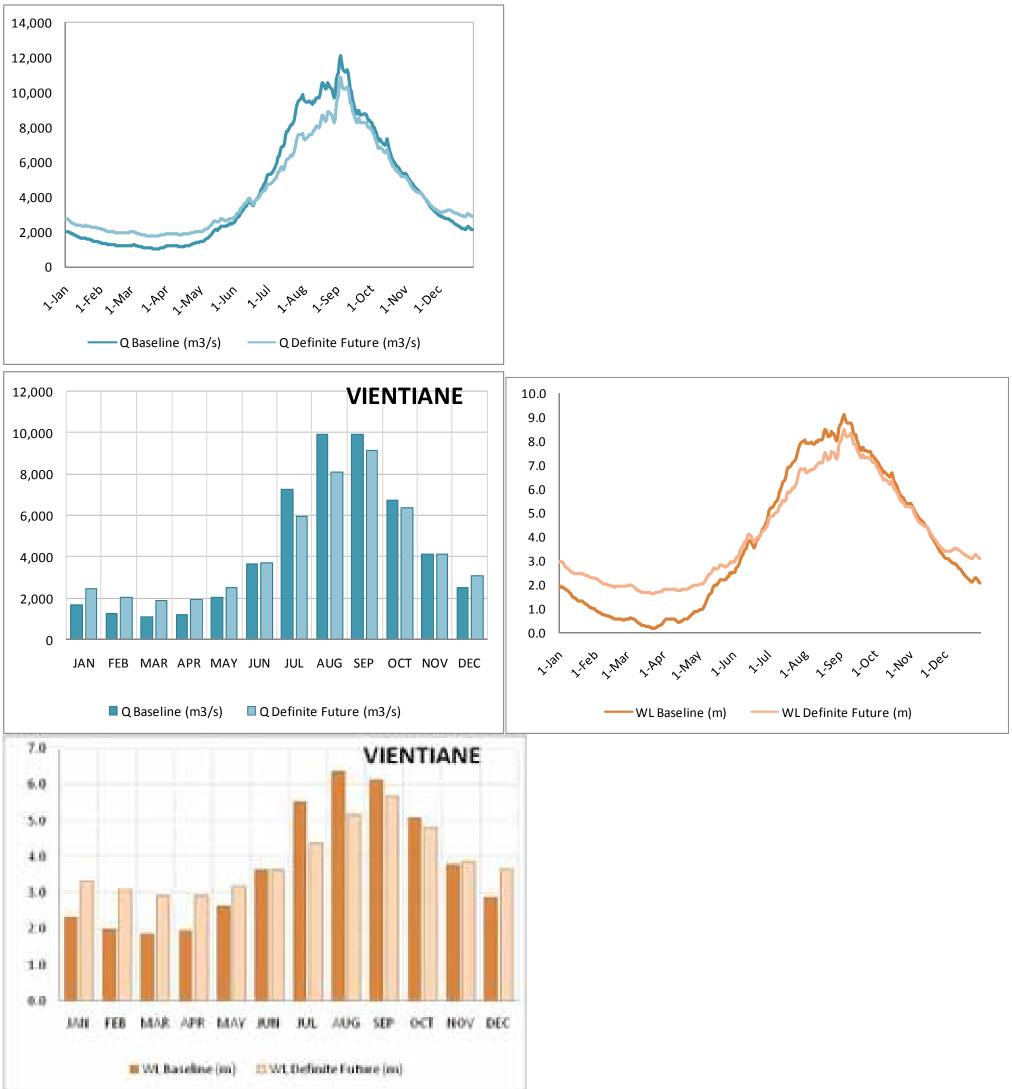


Figure 6: PAKSE: changes to the hydrograph between the Baseline and Definite Future scenario (adapted from BDP modelling): TL - Mean daily flows; TR - mean monthly flows; BL - mean daily water levels; BR - mean monthly water levels

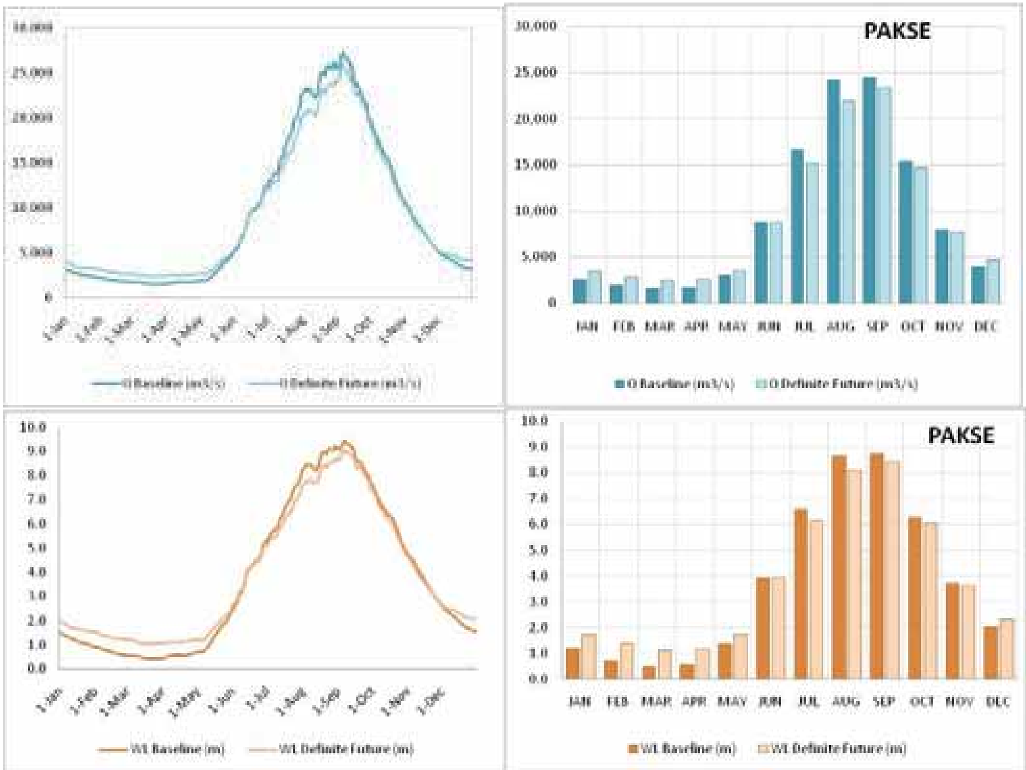


Figure 7: KRATIE: changes to the hydrograph between the Baseline and Definite Future scenario (adapted from BDP modelling): TL - Mean daily flows; TR - mean monthly flows; (NOTE: no water level data is available for Kratie)

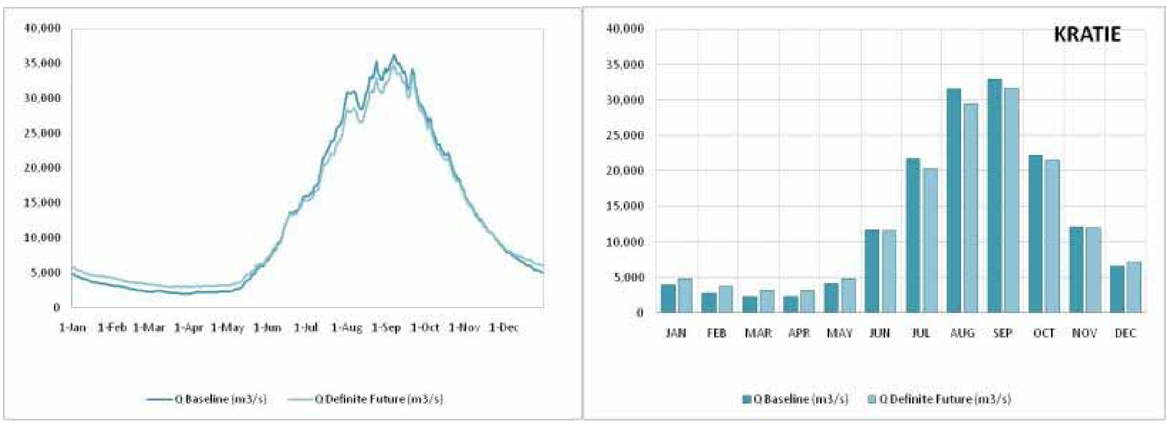


Figure 8: TAN CHAU: changes to the hydrograph between the Baseline and Definite Future scenario (adapted from BDP modelling): TL - Mean daily flows; TR - mean monthly flows; BL - mean daily water levels; BR - mean monthly water levels

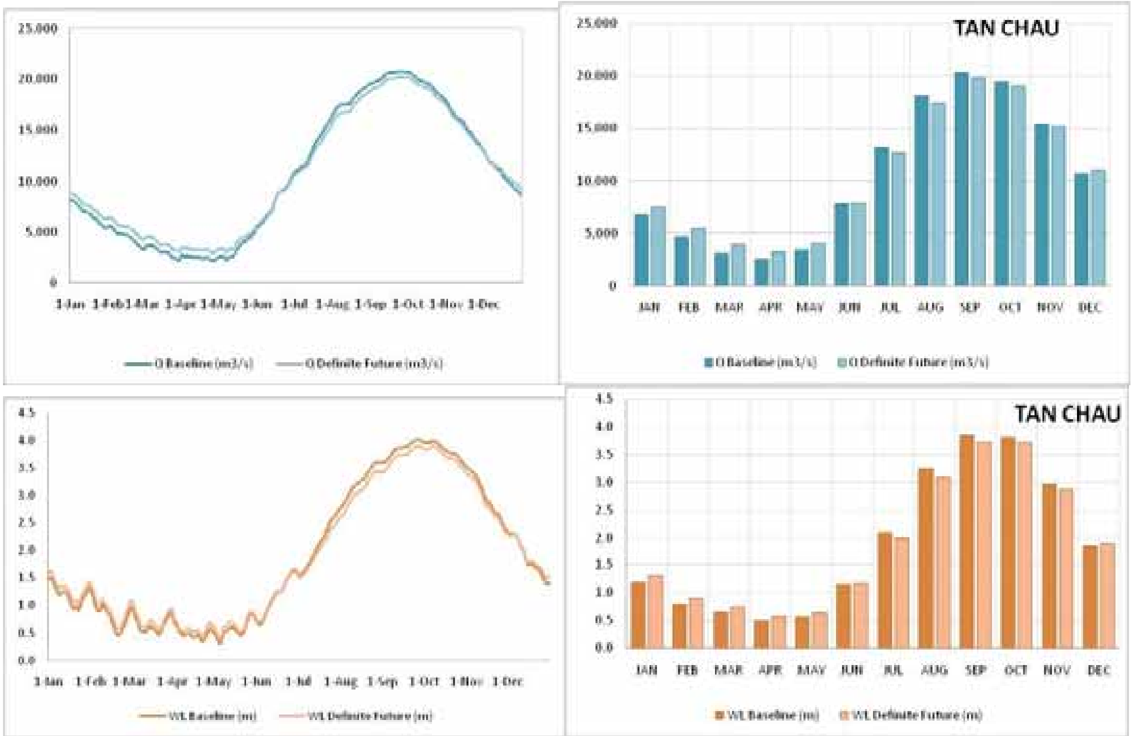
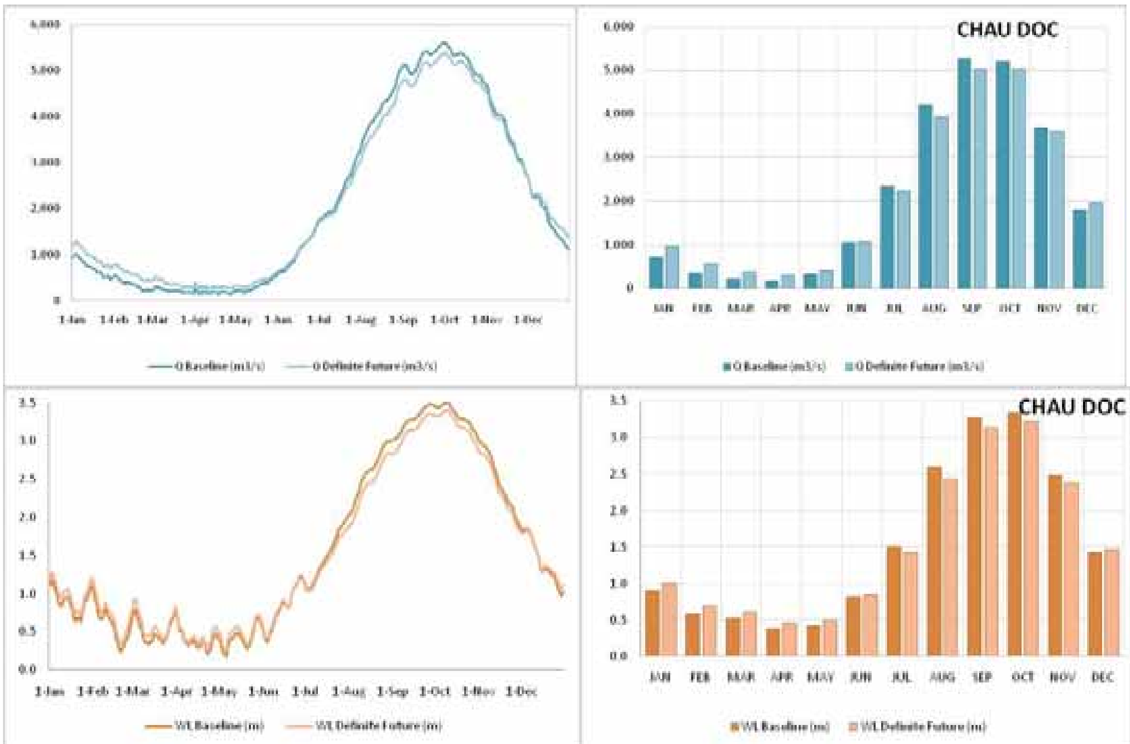
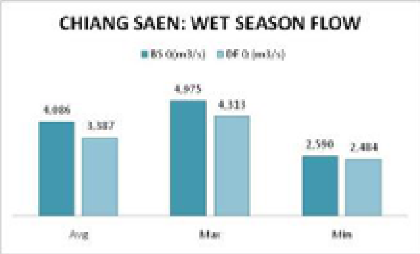
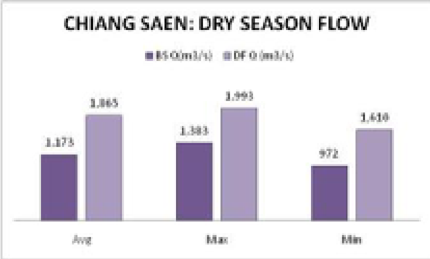
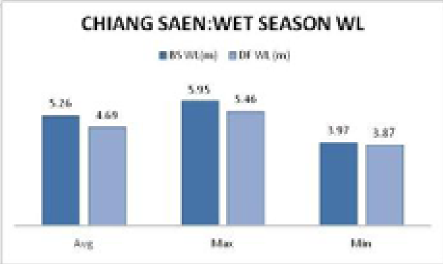


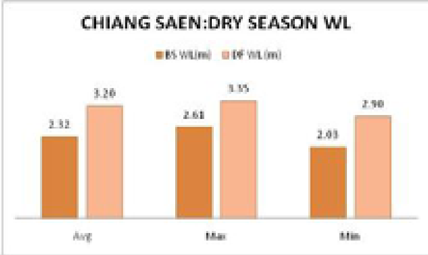
Figure 9: CHAU DOC: changes to the hydrograph between the Baseline and Definite Future scenario (adapted from BDP modelling): TL - Mean daily flows; TR - mean monthly flows; BL - mean daily water levels; BR - mean monthly water levels




CHIANG SAEN: WET SEASON FLOW
4,975
4,313
2,590
2,484
Avg
Max
Min


CHIANG SAEN: DRY SEASON FLOW
972
1,610
Avg
Max
Min


CHIANG SAEN:WET SEASON WL
5.26
4.69
5.95
5.46
3.97
3.87
Avg
Max
Min


CHIANG SAEN:DRY SEASON WL
3.20
2.61
2.03
2.90
Avg
Max
Min

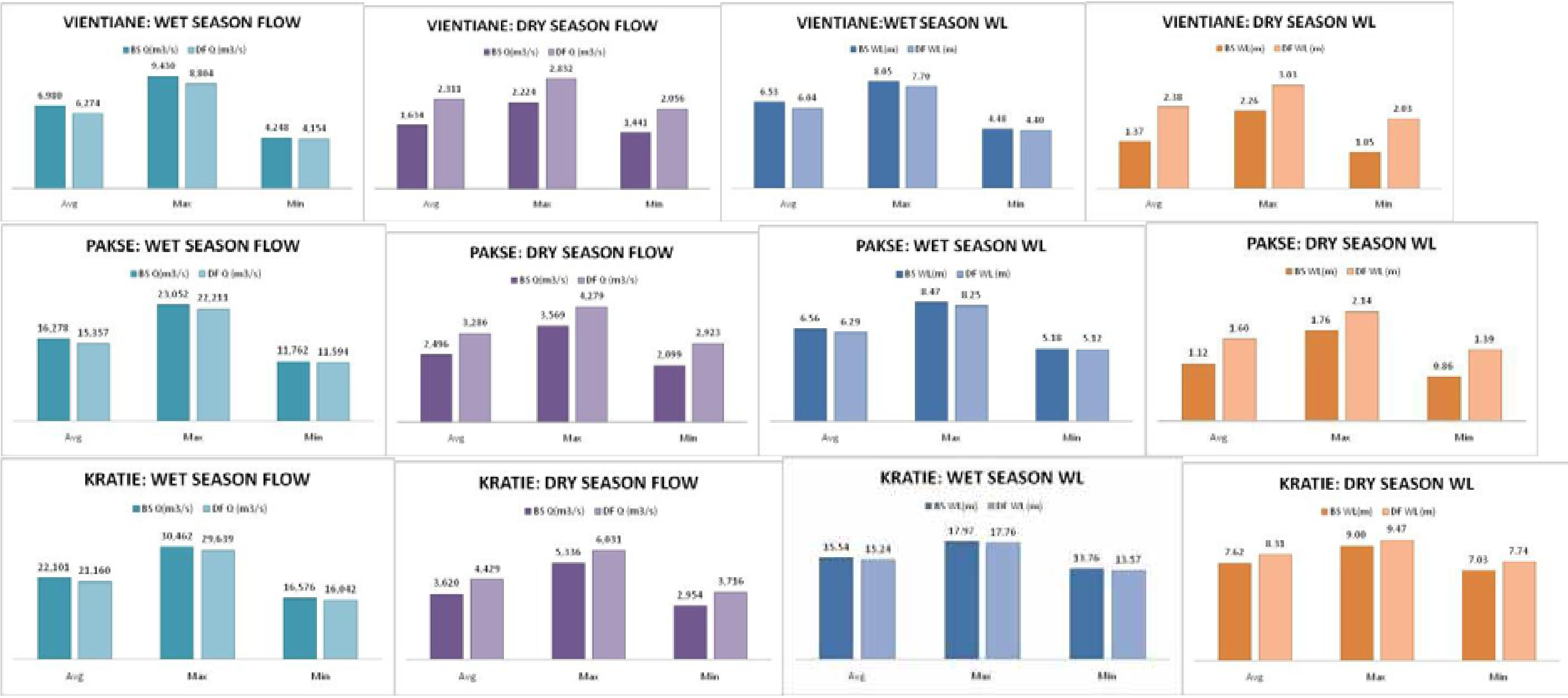


Figure 10: Chiang Saen - Kratie: Seasonal flow and water levels for Baseline and Definitie Future scenario (Based on BDP model scenarios)

Figure 11: Tan Chau – Chau Doc: Seasonal flow and water levels for Baseline and Definitie Future scenario (Based on BDP model scenarios)

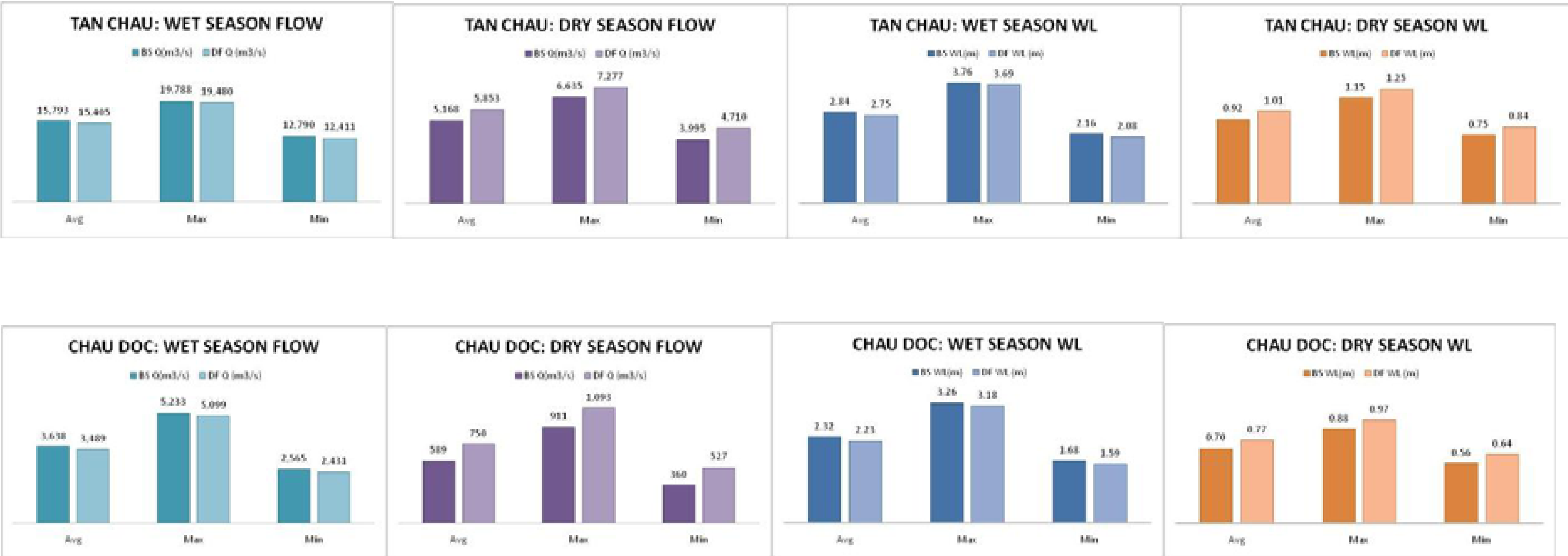


Figure 12: (left)) percentage increase in average dry season flows and (right) percentage decrease in average wet season flows

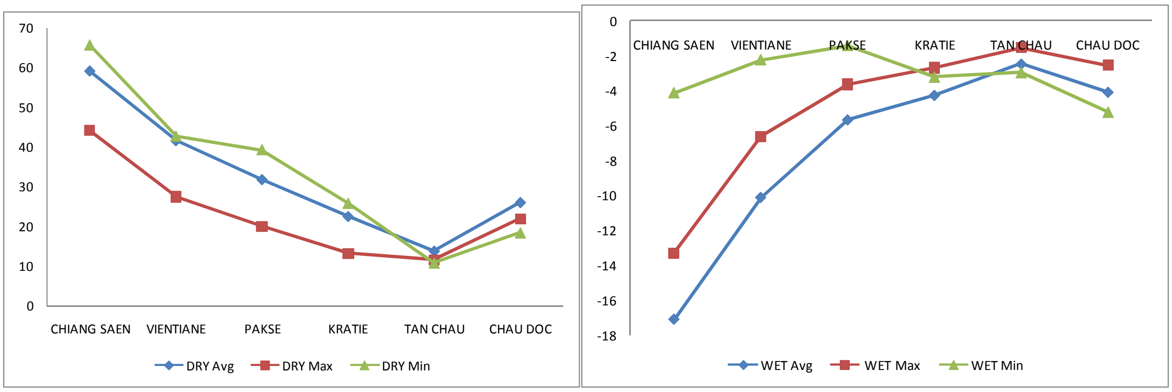


Figure 13: Variation in the start date of the Mekong hydro-biological seasons. Positive values show a delay (in days) in the onset of the season, negative values show the early arrival of the season

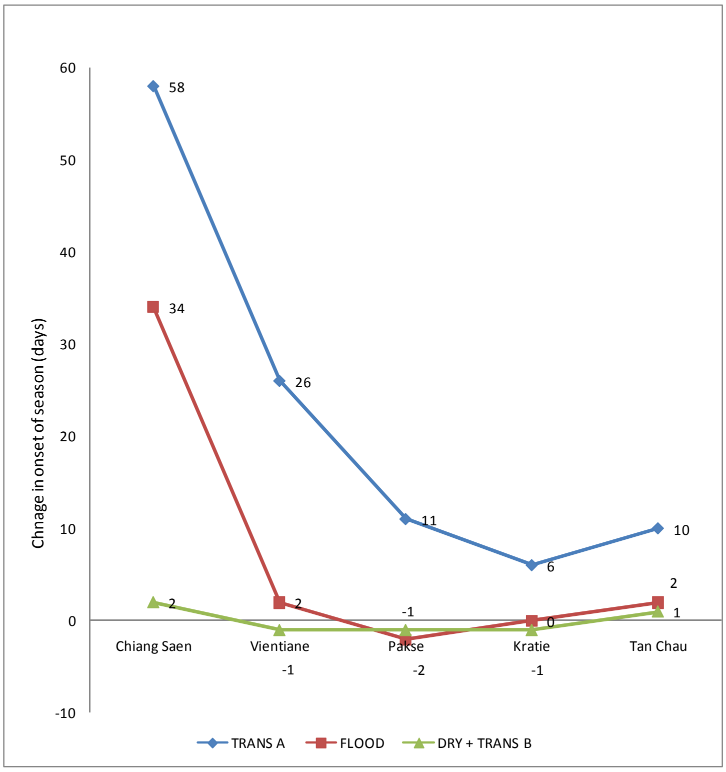


Figure 14: Duration of the Mekong Hydro-biological seasons (days) form Baseline (BS) to Definite Future (DF). Chiang Saen will see an ~25% reduction (4week) reduction in the duration of the flood season which will not be seen at downstream stations. There will be a decrease in the duration of transition seasons and an increase in the duration of the dry season (see next figure for further exploration of change).

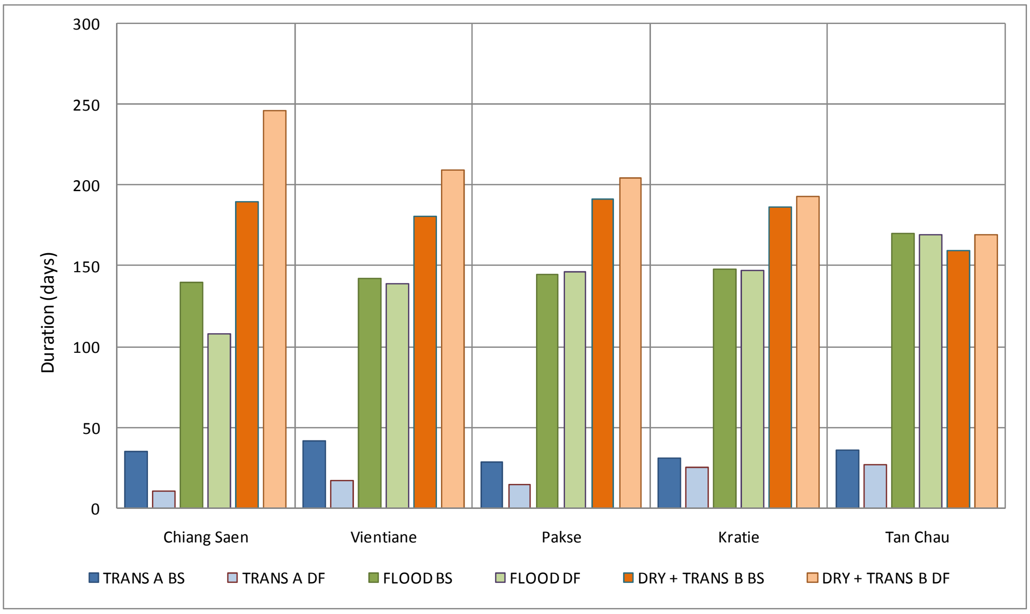


Figure 15: Change in the Duration of the Mekong seasons between the Baseline and the Definite Future.

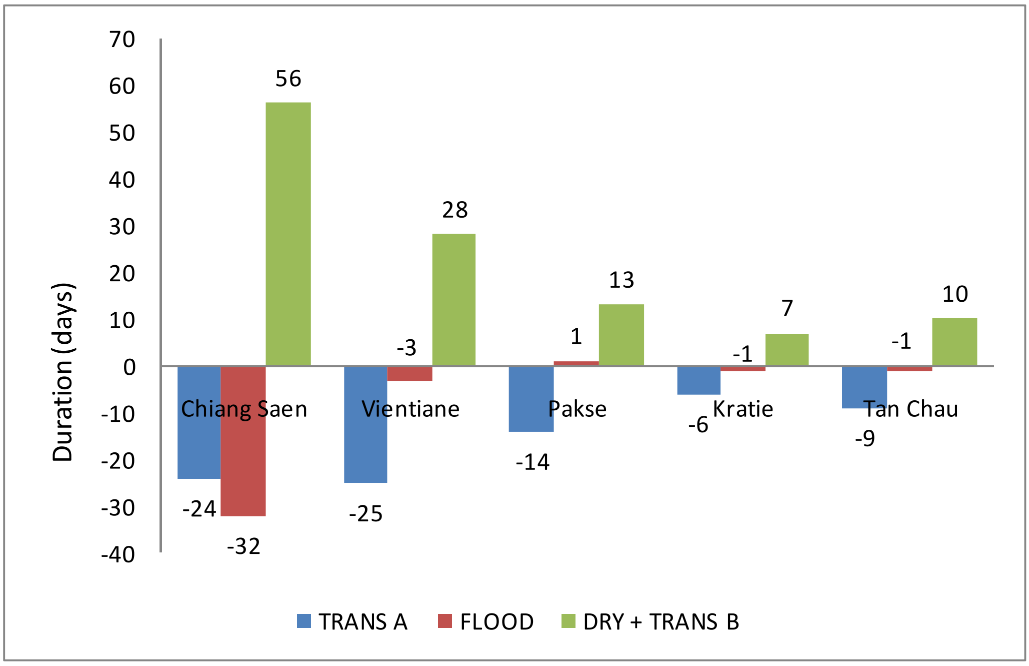


Figure 16: Mean monthly rainfall (mm) for key zones of the LMB (source: MRC, 2005)

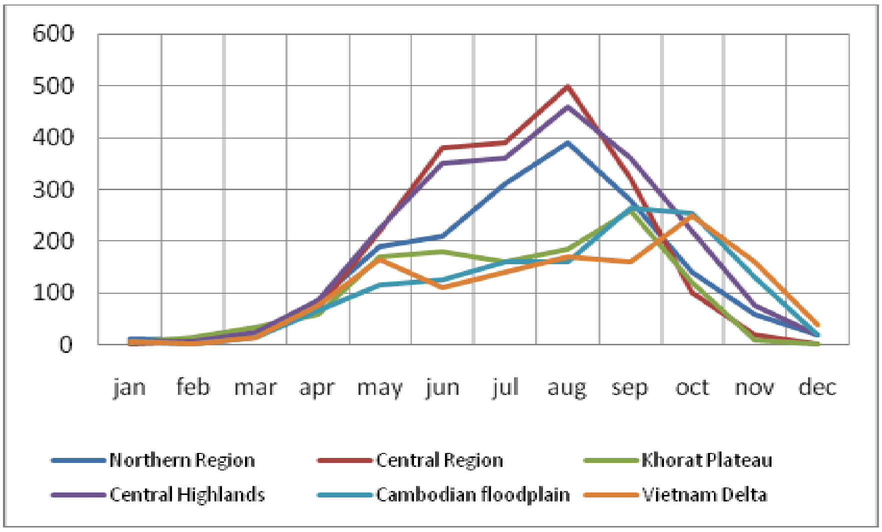


Figure 17: Tributary contribution to Mekong annual flow (ADB, 1999)

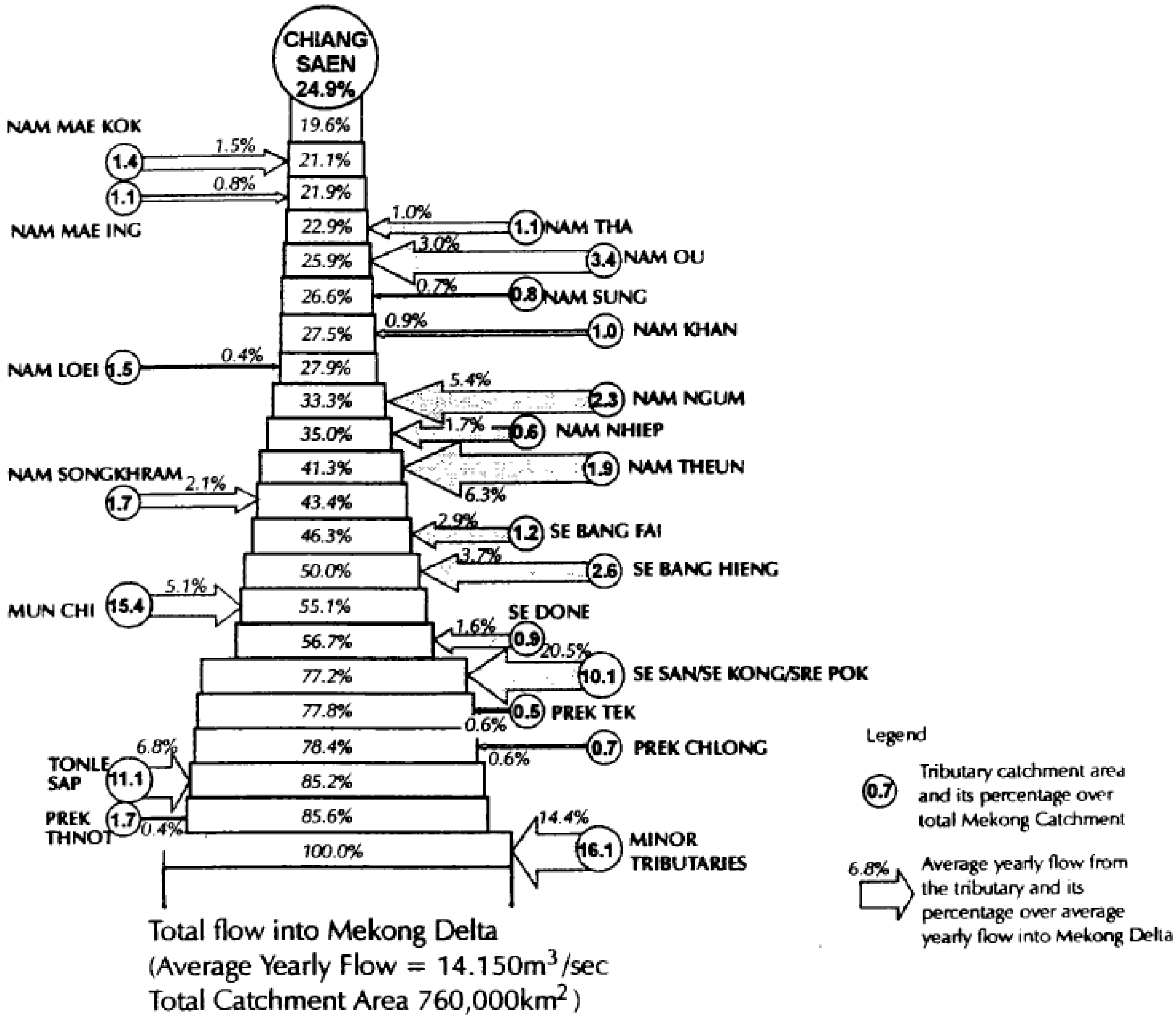


Figure 18: Comparison of the current hydraulic gradient between Phnom Penh and the Tonle Sap Lake (dark blue) and Tonle Sap River and Lake (light blue). The gradient is greater at Phnom Penh because water levels there are directly connected to the Mekong mainstream, while Prek K'dam on the Mekong River is lies on the Tonle Sap River channel. The difference is greatest during the beginning of the dry season as water levels in the Mekong channel recede quicker than those in the smaller Tonle Sap channel.

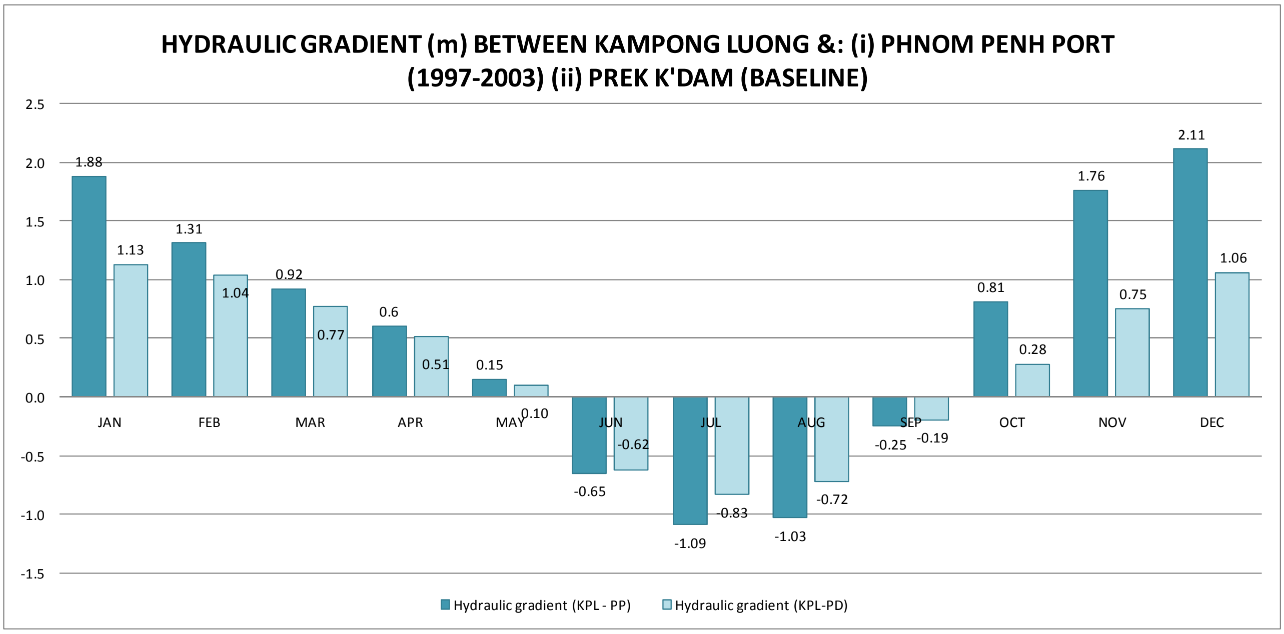
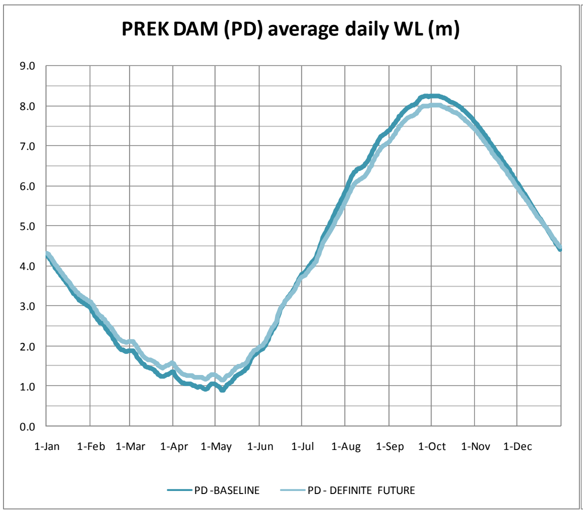


Figure 19: Average daily fluctuation in WLs (1986 -2000) and predicted 2015 fluctuations for: (left) Prek K'dam, (right) Kampong Luong



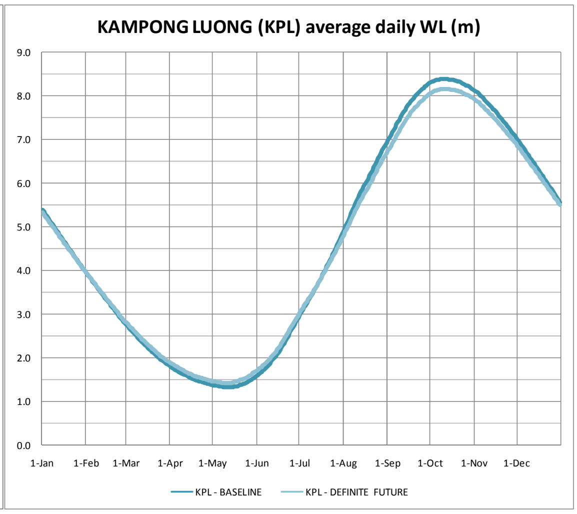


Figure 20: Change in WLs at Kampong Luong & Prek K'dam expected by 2015

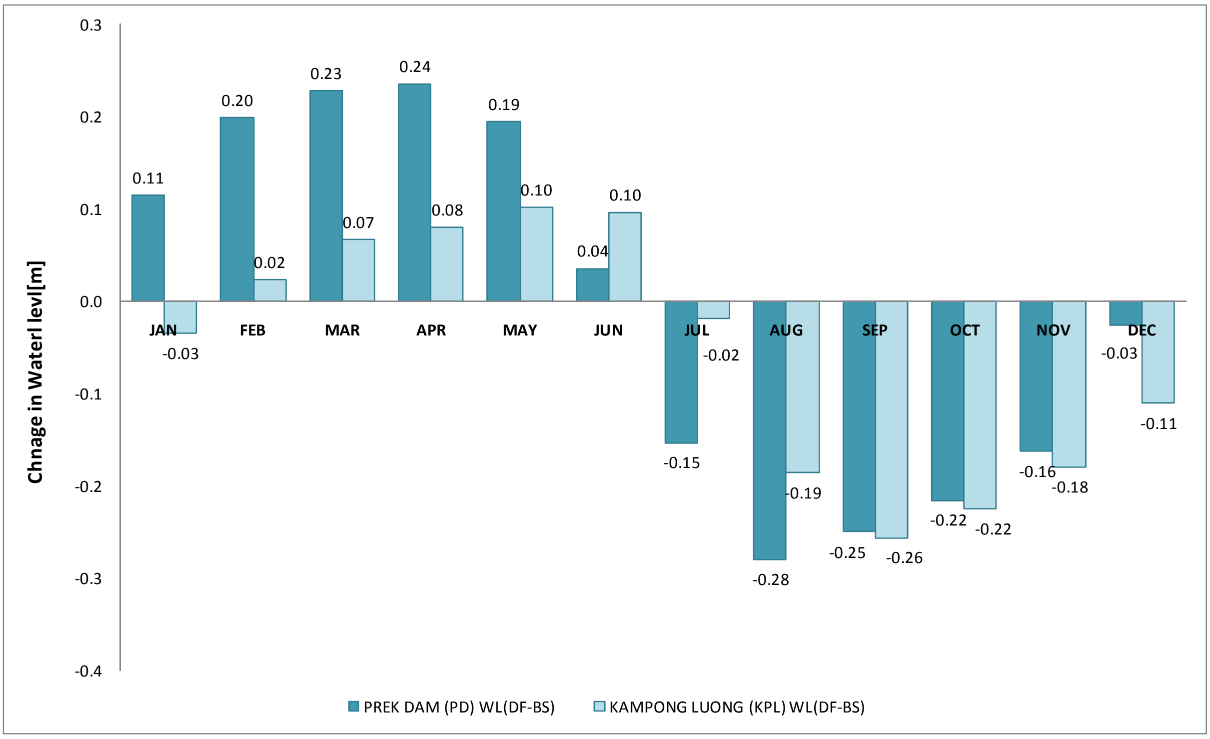


Figure 21: Daily fluctuation in the hydraulic gradient of the Tonle Sap River (PD - KPL) for both BDP baseline and Definite Future Scenarios

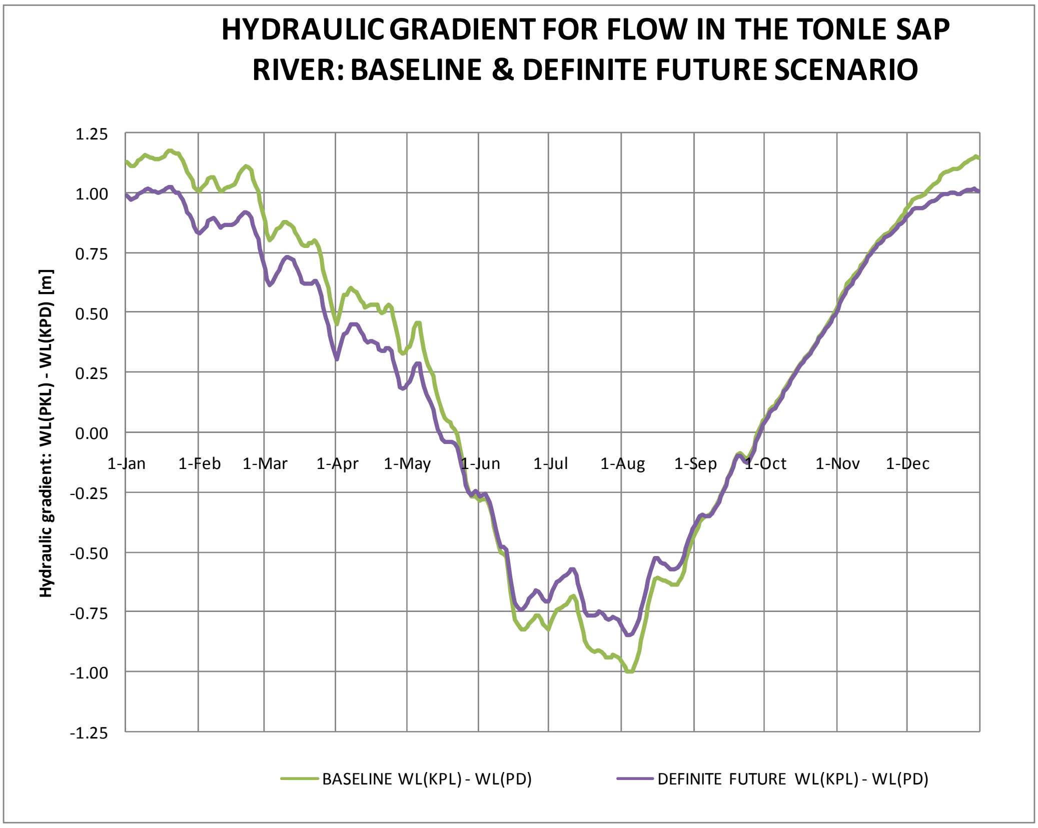


Figure 22: Decrease in the hydraulic gradient (PD-KPL) between the BDP Baseline & Definite Future scenarios

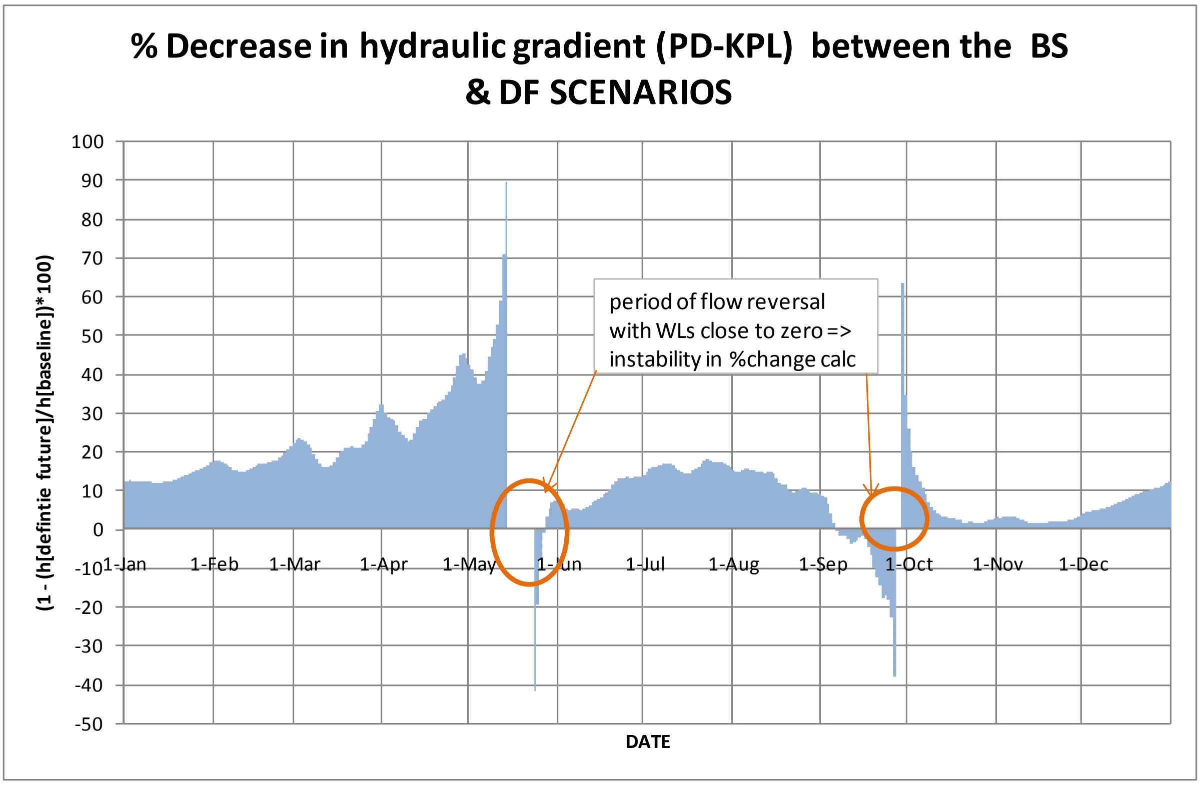
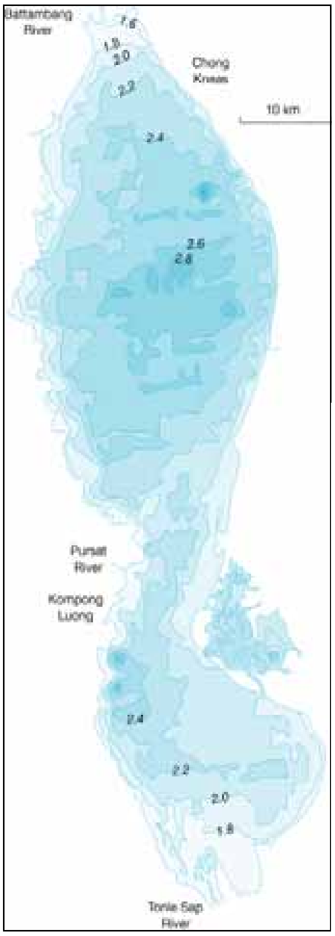


Figure 23: Hydro-physical characteristics of the Tonle Sap Lake: (left) bathymetry of the dry season lake bed (MRC, 2007), and; (right) Dry and wet season open water area of the Tonle Sap Lake (MRC, 2006)



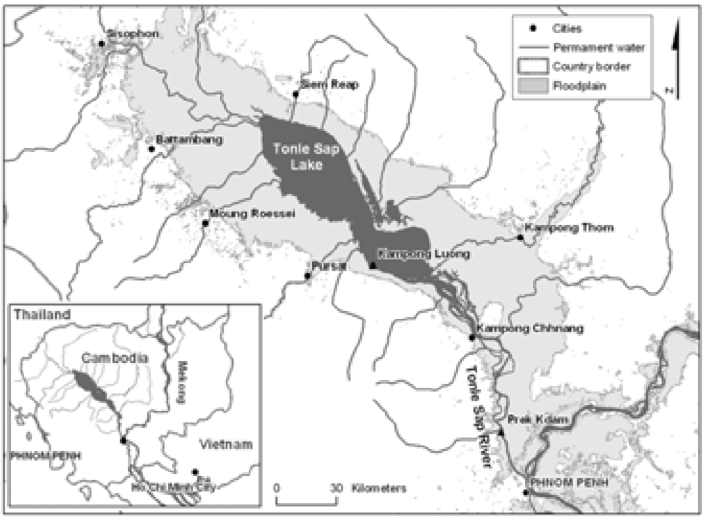
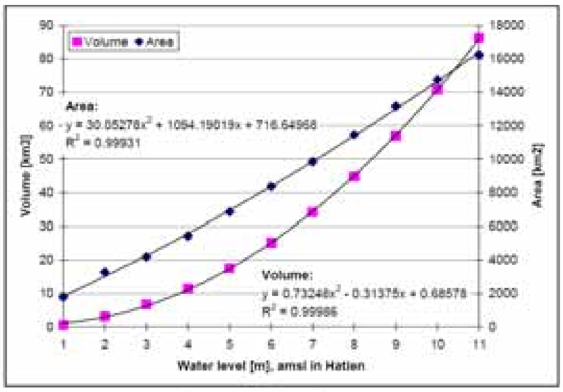


Figure 24: (Left) Empirical WL:SA:V rating curves for the Tonle Sap Lake (1997-2003 data) (MRC, 2006); (Right) compares the SA rating curve calculated in 2006, with a 2010 revised estimate which used GIS techniques to interpolate between the 1m contours of the DE



Open water area (km²) and volume (km³) of the Tonle Sap Lake as a function of water level (masl).

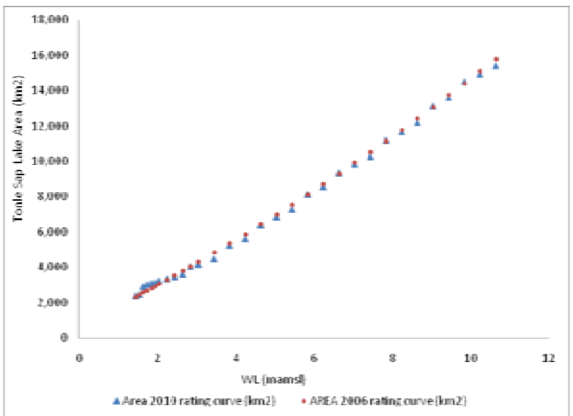


Figure 25: Decrease in Tonle Sap Lake Area based on 2015 changes to average monthly WLs at Kampong Luong. Lake areas were calculated using the above rating curves. The peak decrease in lake area occurs during the flood peak and just before the reversal of flow, similarly the peak increase in area occurs at the time of the dry season flow reversal.

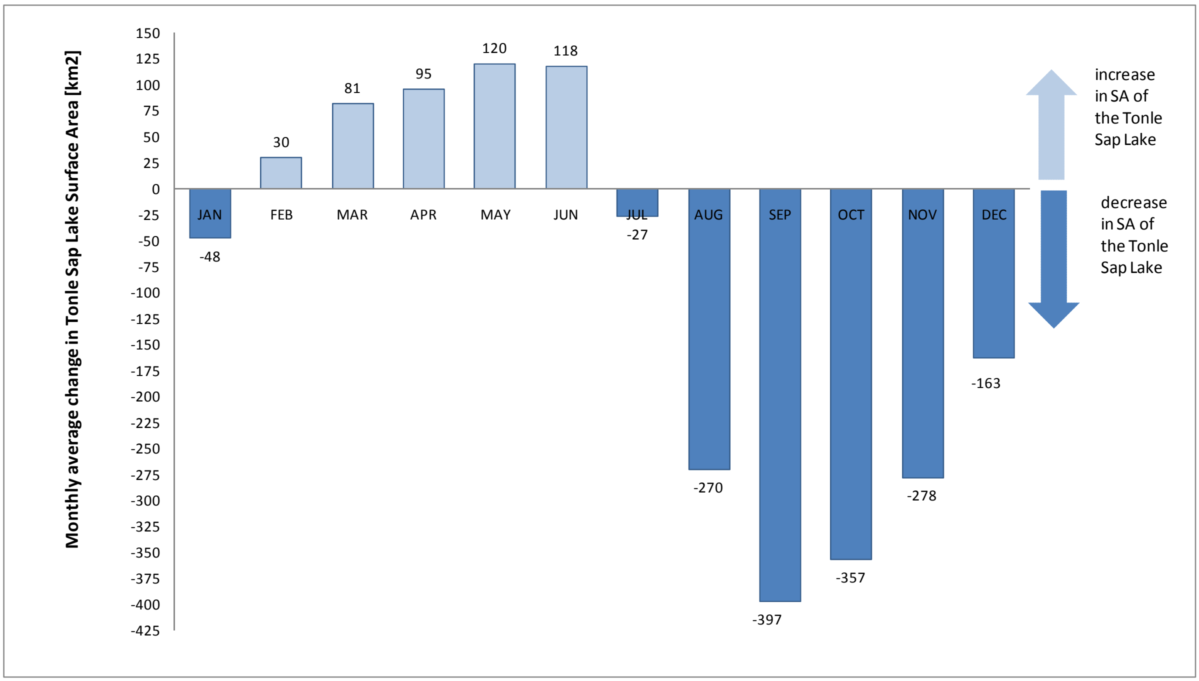


Figure 26: Percentage decrease of Tonle Sap Lake Surface Area between 2015 and current. Based on the rating curve presented above. Although the absolute increase in area is less than the decrease, as a proportion of current lake area, the dry season increase in lake area is larger than the wet season decrease.

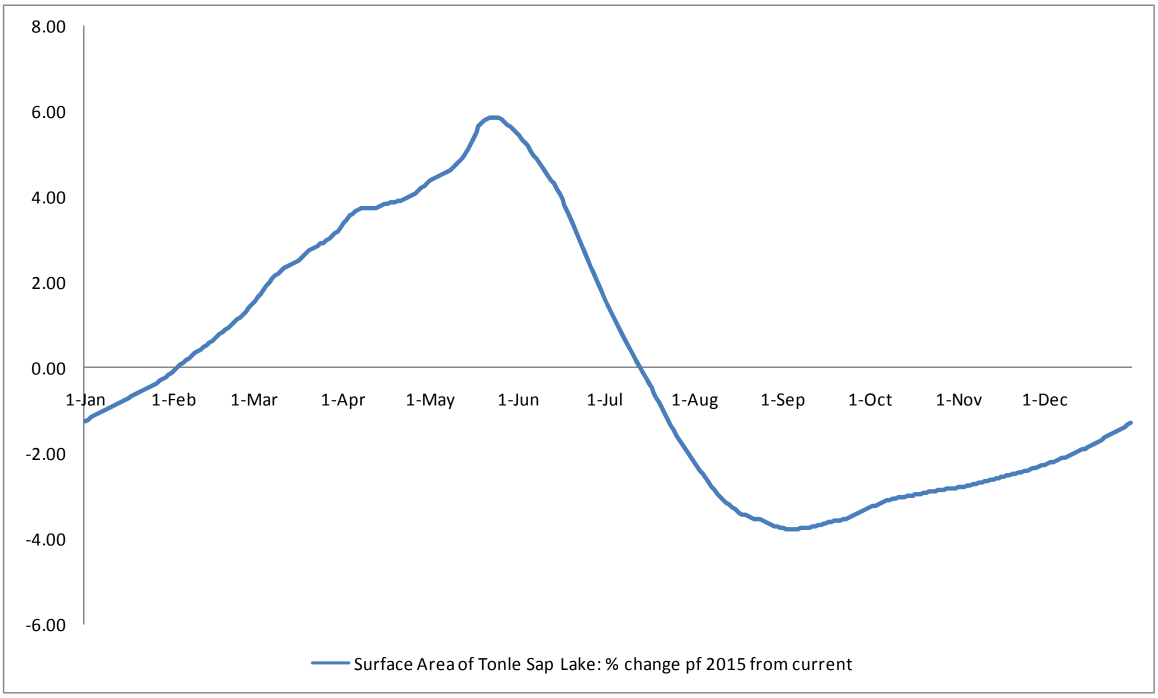


Figure 27: Sources of sediment provenance in the Mekong Basin (adapted from: MRC, un published). The UMB and the central highlands dominate current sediment supply to the Mekong system

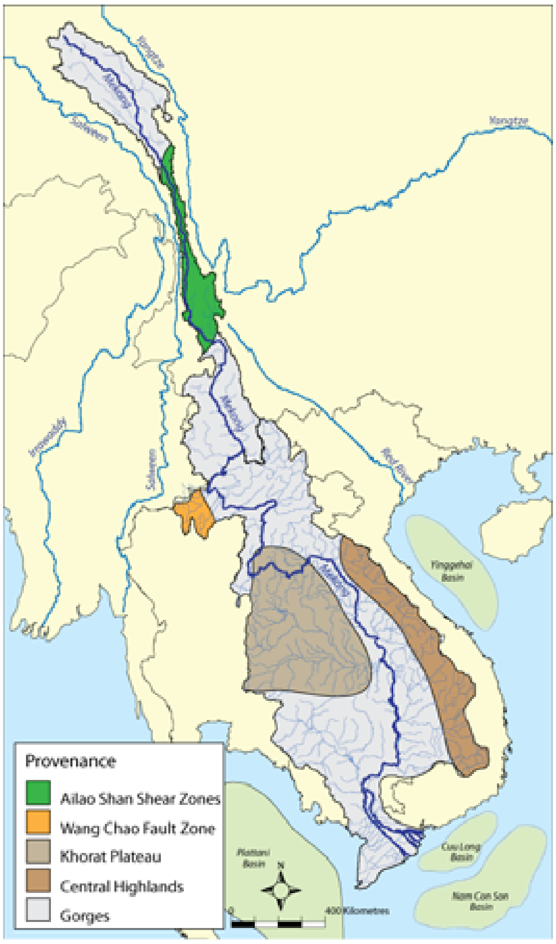


Figure 28: Some estimates of the Sediment Load at Chiang Saen: pre and post Manwan (MCM/yr) (adapted from: Walling, 2005; Carling, 2009)

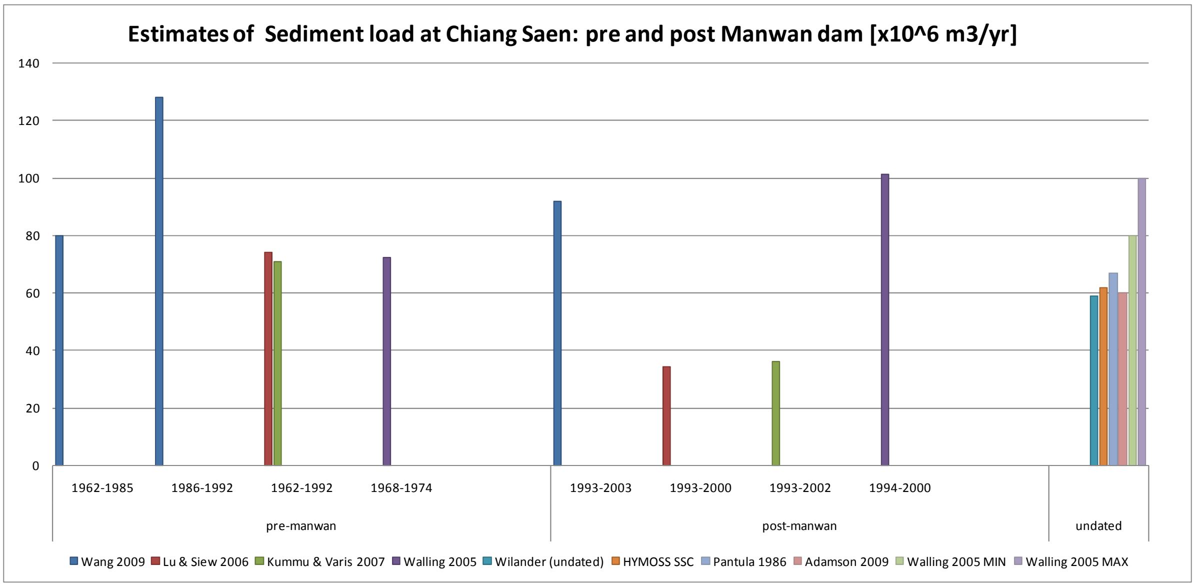


Figure 29: Average annual mainstream sediment load (adapted from: Walling, 2005; Carling, 2009)

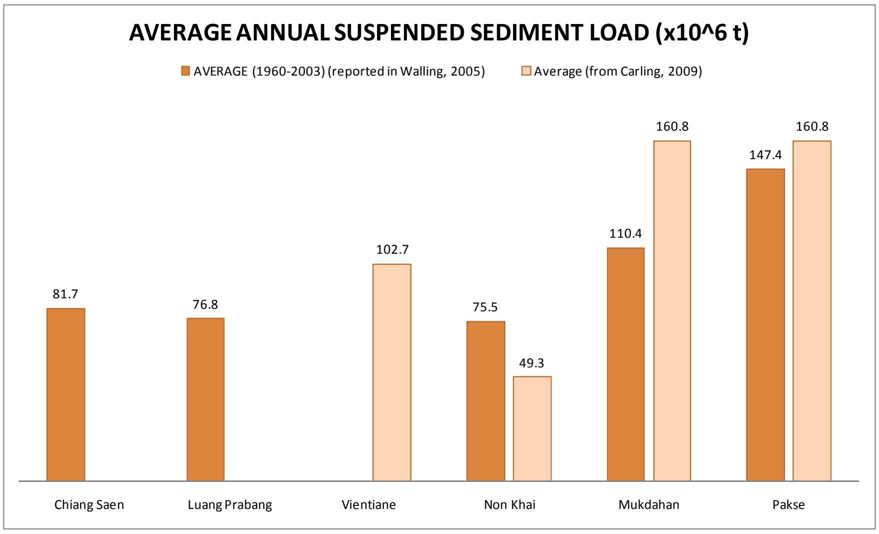
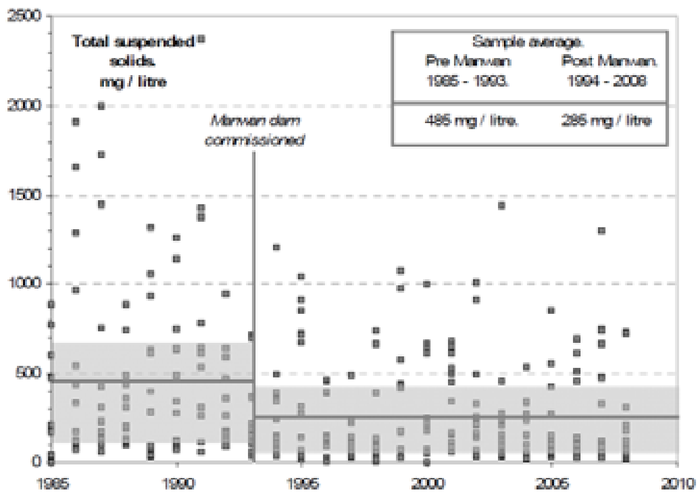


Figure 30: Comparison of pre- and post-Manwan dam TSS concentrations at: (top) Chiang Saen and, (bottom) Luang Prabang (Adamson, 2009b). There is a clear drop in the sediment load, but the high variance within the data set means that it is statistically difficult to quantify exactly



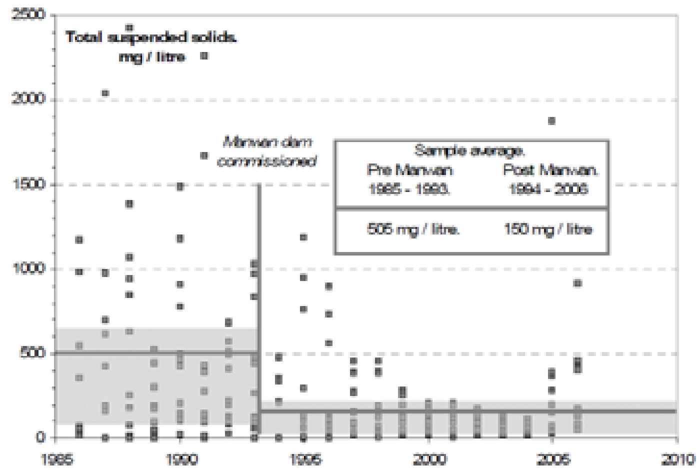


Figure 31: Sample grain size distribution curve for Pakse (Carling, 2009). The curve shows that 99% of the sediment has a grain size smaller than 4.75mm (fine gravel) and 41% of the distribution is finer than 0.45mm (coarse sand). This implies that the current conveyance of bed load is largely confined to Z2 and Z3 and that the current sediment composition at Pakse is highly mobile

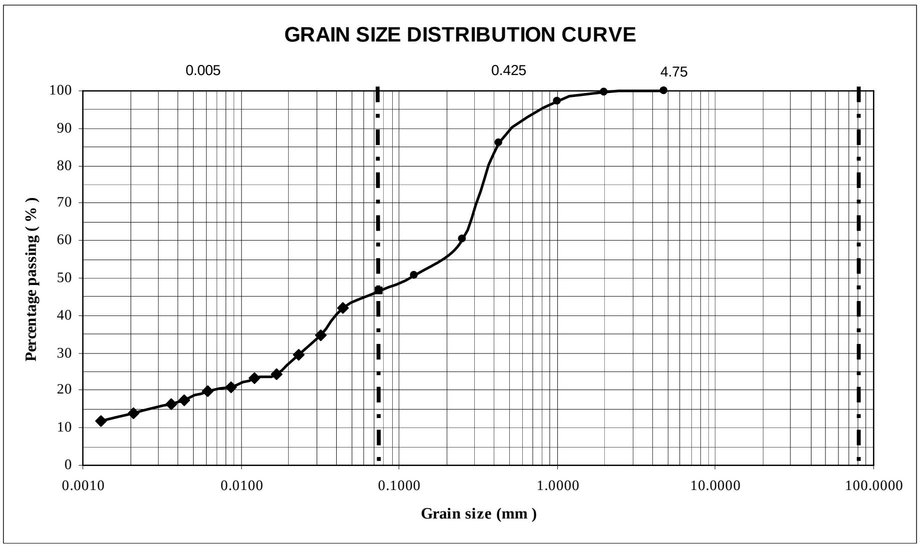


Figure 32: Chiang Saen - Khone Falls: Mean channel width (m) and water surface slope along thalweg (adapted from: Conlan, 2008)

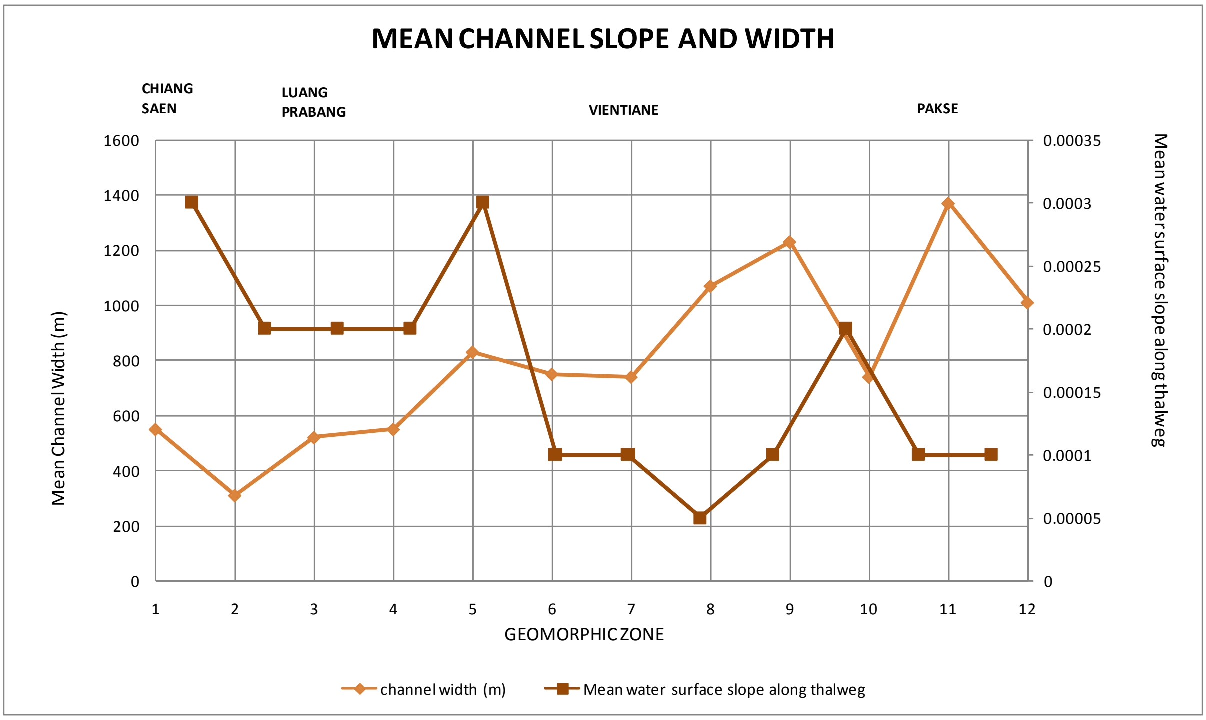


Figure 33 :Ratio of Average Annual SL at Nong Khai over Jinghong for 1972-1990 (Source: Walling, 2009). Deposition is likely to occur when the load ratio is less than 1. This has been a regular occurrence since 1980

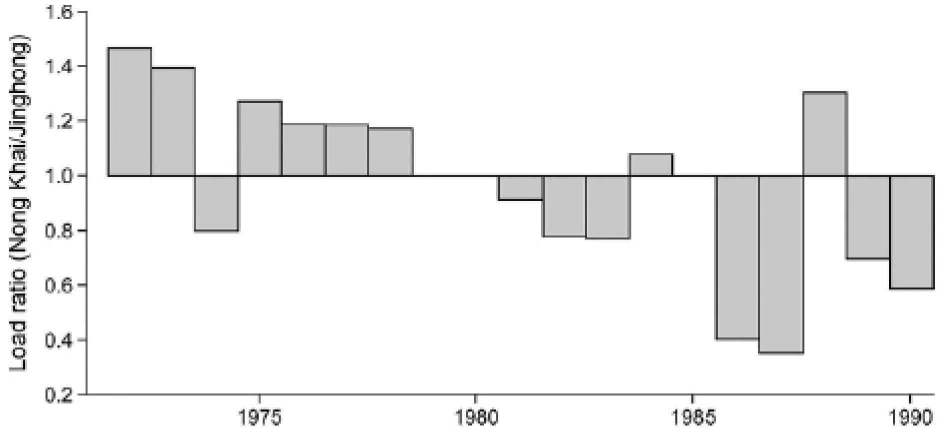


Figure 34: Comparison of sediment load and discharge in the Mekong Basin (Wang et al, 2009). All periods show a decrease in sediment load between Luang Prabang and Nong Khai contrary to the increased discharge and Basin area. Wang et al (2009) interpret this by identifying the Luang Prabang – Nong Khai reach as as an important zone of sediment deposition

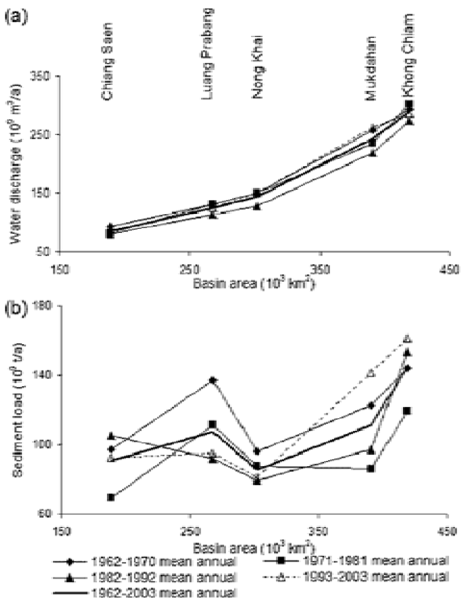


Figure 8. Variations of the (a) water discharge and (b) sediment load along the Lower Mekong River. The five stations are Chiang Saen, Luang Prabang, Nong Khai, Mukdahan and Khong Chiam from left to right. Note that the solid and empty symbols represent the pre-dam and post-dam periods, respectively

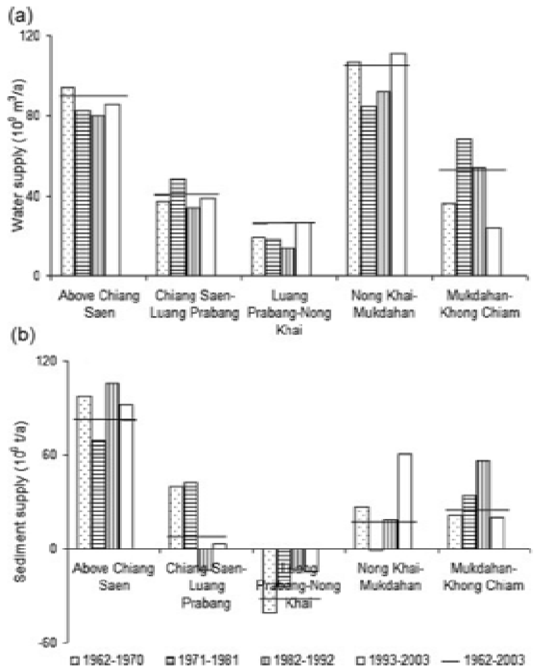


Figure 9. The water and sediment supplies of the Mekong River sections during the entire period of 1962–2003 and the four sub-periods

Figure 35: Comparison of the average peak daily flows at Chiang Saen (CS), Vientiane (VT) and Pakse (PK) for the Baseline and Definite Future scenarios. The changes in the peak flow are compared to: (i) an indicative estimation of the peak flow required at the center of deep pools to mobilize the in-pool sediment wave for pools in the vicinity of the station, and (ii) the flow required to mobilize 99% and 41% of the sediment distribution as measured at Pakse. The required peak flow at the pool centre was extrapolated from Ang Ngay pool where the pool centre flow during wave translation was 60% of the average peak daily flow.

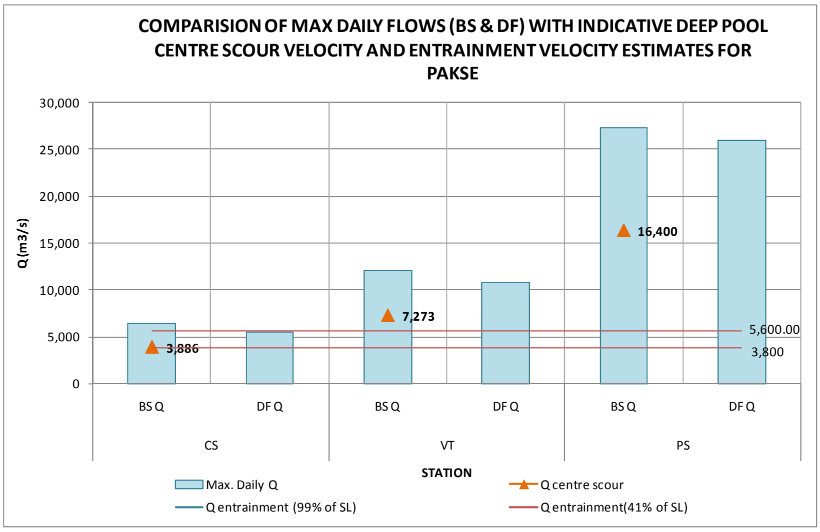


Figure 36: Comparison of average daily discharge with suspended sediment concentrations for 1961 at: (A) Luang Prabang, (B) Pakse (source; Walling, 2009).The figure illustrates that sediment concentrations peak ~ 1month before the flood peak and are centred on the rising limb of the flood. Changes to the duration and variability of the seasons will impact the sediment load.

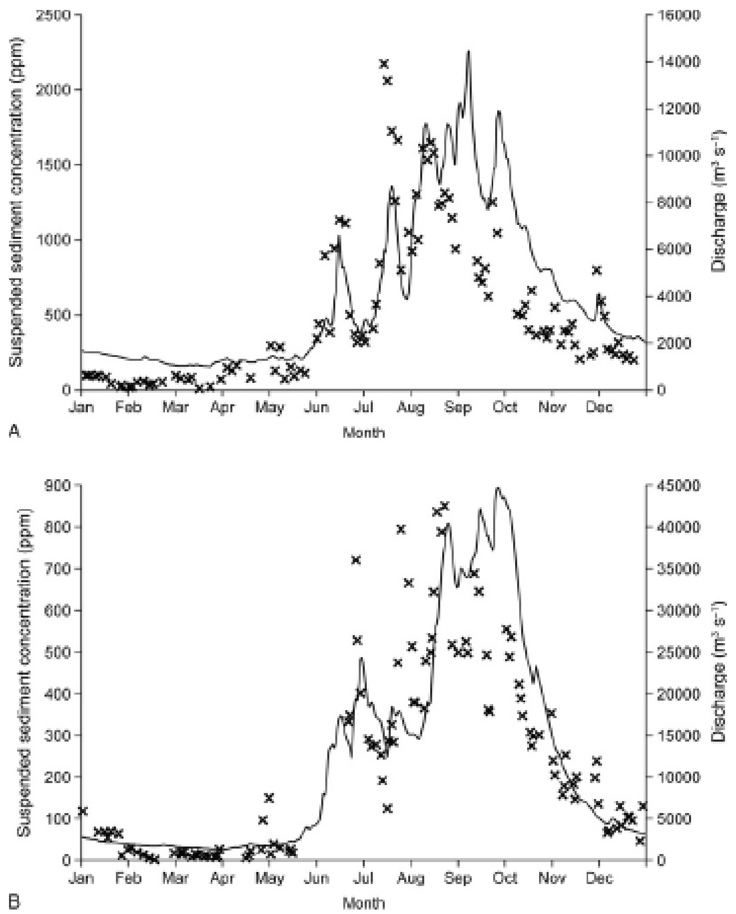


Figure 37: Major pool types of the Mekong mainstream (Source: Conlan, 2008)

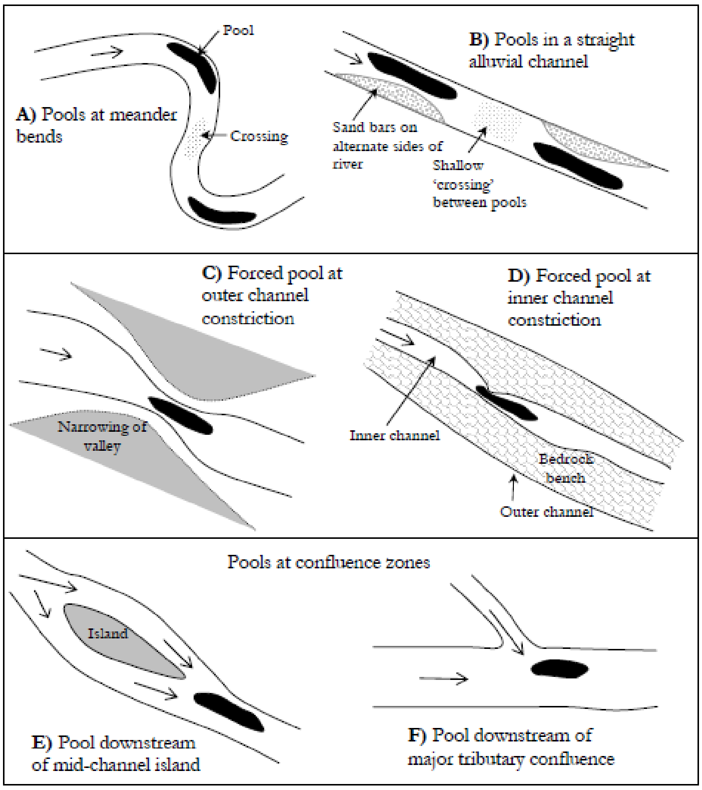


Figure 38: Comparison of discharge and bed sediment volume per unit channel length (Conlan, 2008). Temporal comparison of the pool entry, centre and exit volumes clearly show a sediment wave moving along the channel bed through the deep pool. The study reveals that deep pools are dynamic sites of sediment flux connecting up and downstream storage sites (e.g. in-channel islands, sand bars and benches), but the slow progression through the deep pools reduces bed load saltation rates to one pool crossing per year (~10km) slowing down the downstream conveyance of sediment in Z2

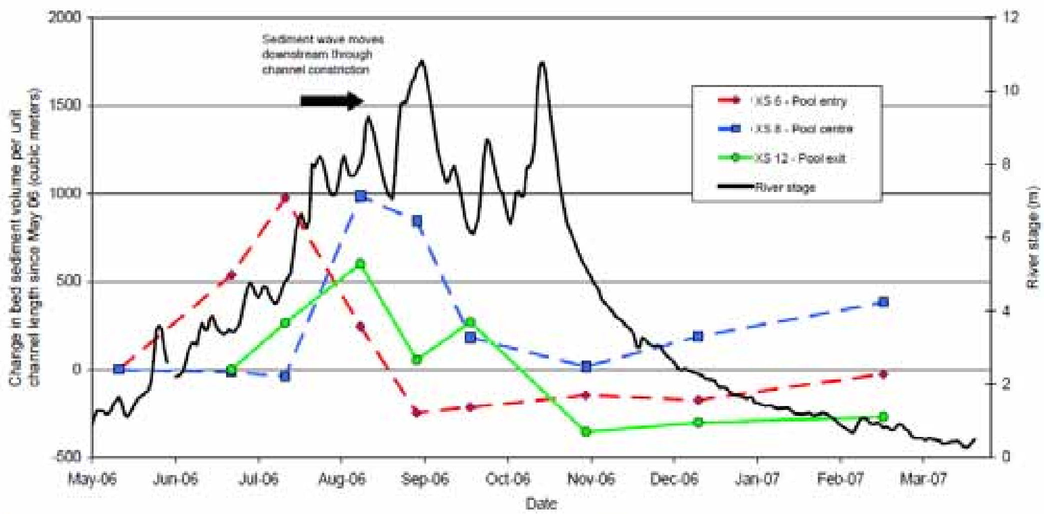


Figure 26 Changes in mean bed sediment volume per unit length of channel at the pool entry, centre and exit at Ang Nyay site from the first survey period in May 06 (XS 6 and 8); and June 06 (XS 12).

Figure 39: Timing of the sediment wave translation through Deep pools of Z2. (adapted from; Conlan, 2008). The graph overlays the mean monthly flow at Vientiane for the baseline (current) and Definite Future (2015) conditions, with the estimated maximum velocities at the pool entrance, pool centre and pool exit. During the dry season velocity is greatest in the river bed (Conlan refers to these as 'crossings'), which results in the gradual scour of these areas and gradual infilling of deep pools. Then during the onset of the flood season, velocity peak at the entrance to the deep pool initiating a ~2month period of rapid pool infilling. At the peak of the flood season, the river bed maintains a stable elevation as the flows peak in the pool centre translating the sediment wave through the deep pool. By the end of the flood season the sediment wave has passed through the pool and begins to break up and deposit on the 'crossing' downstream. Then during the dry season the bed load in the crossing reconcentrates, consolidating in-channel formations.

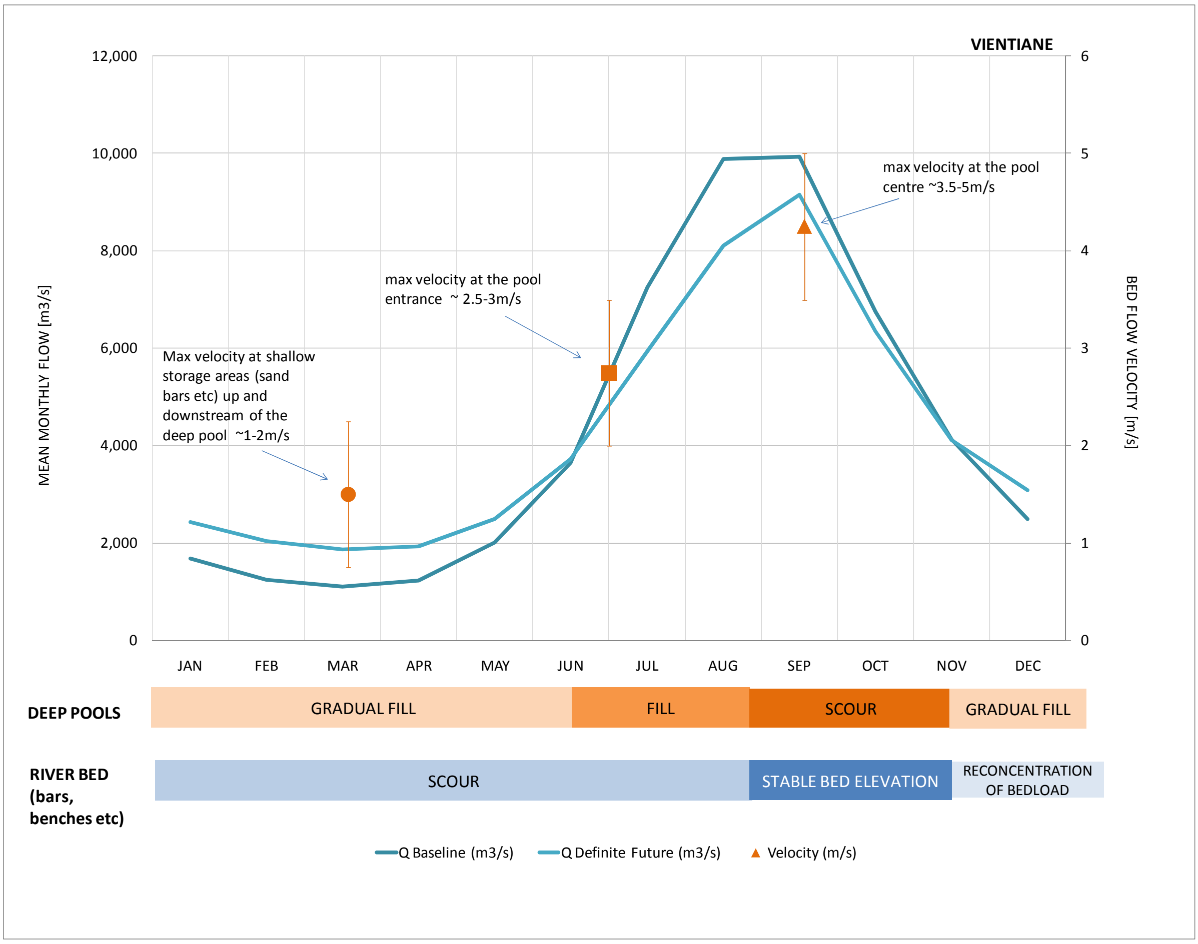


Figure 40: Annual average sediment load (1997 - 2004) at Kratie (source: Kummu at al, 2009b)

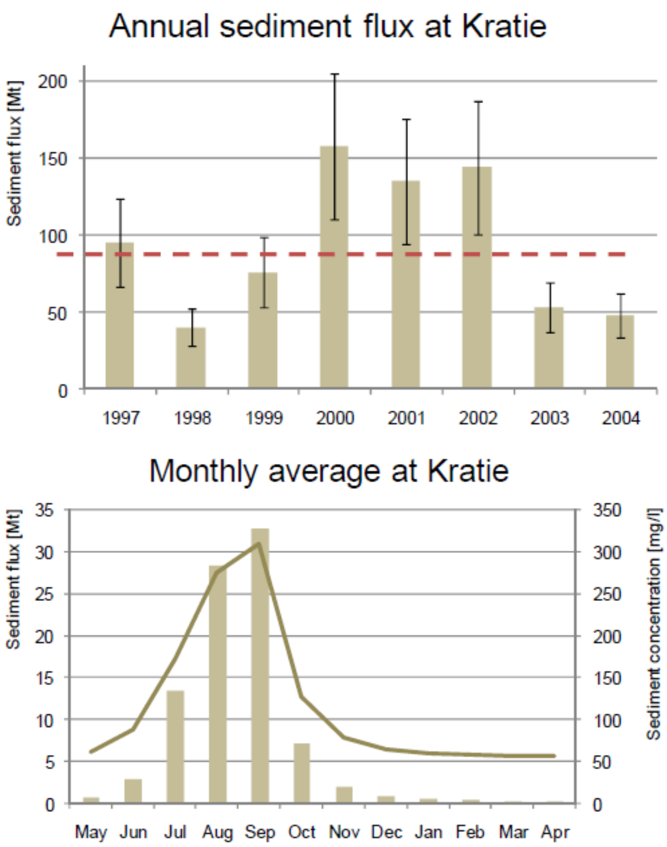


Figure 41: Reduction in primary production of Tonle Sap, based on an 80% reduciton in sediment load (Sarkkula et al, 2010)

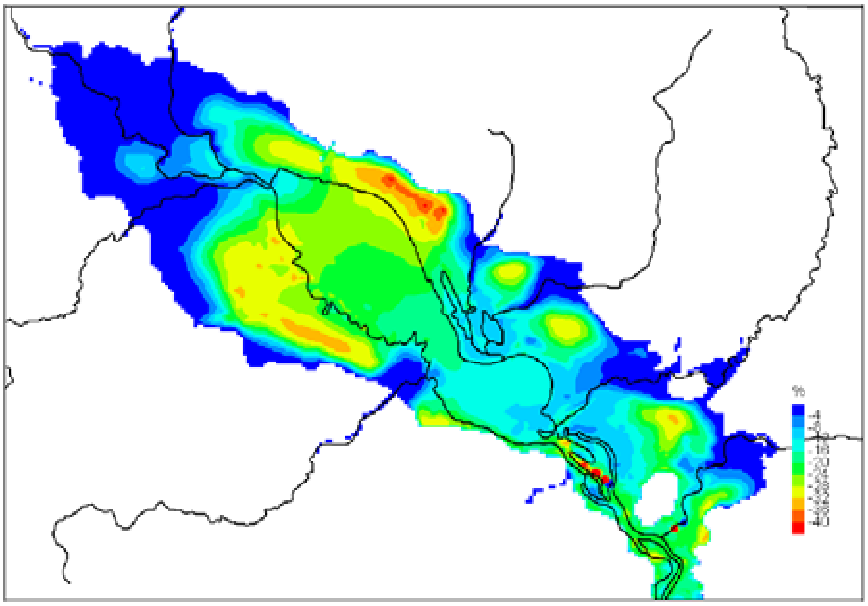


Figure 34. Modelled impact of Mekong sediment dam trapping on average total primary production. Red areas are most impacted in relative terms, blue ones least. Simulation period 1.5.1993 - 31.12.1997. Observe that the model results are ***only indicative*** because model verification, calibration and development are ongoing.

Figure 42: Exceedance of the entrainment flow for coarse sands and fine gravels at Prek K'dam and Kampong Luong.

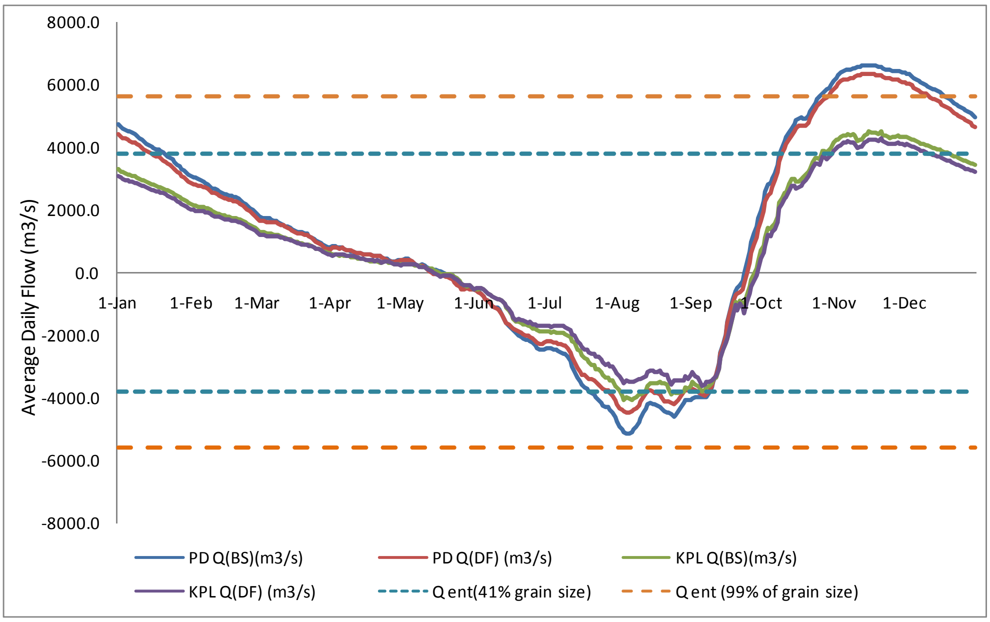


Figure 43: Net sedimentation in Tonle Sap Lake (1997) (Kummu et al, 2008b). Max sedimentation rates (up to ~0.5mm/yr) were observed at the extremity of the dry season lake area, particularly in Lake Chma, the braided reach north of kampong Chnhang and on the Western edge. Mekong River sediments are an important contribution to all three of these zones, particularly Lake Chma and Kampong Chnhnang.

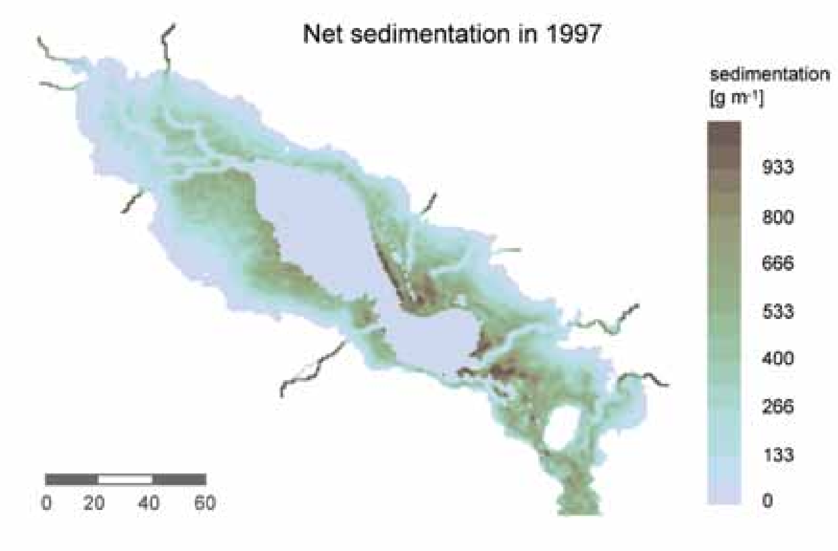


Figure 7. Simulation results of the net sedimentation during the period 01 May 1997–30 April 1998; 1600 g m⁻² represents around 1 mm of net sedimentation.

Figure 44: Key features of the Mekong Delta hydrological regime (SIWRP, 2009): (left) max flood depths during a wet year. WLs peak near the Cambodian border and reduce with distance south. peak levels of 3-5m are driven by overland flow from the Cambodian floodplain which can account for 30% of water volume entering the delta during a typical flood season. On average 1.2-1.9million ha are affected for a period of 3-5months (SIWRP, 2008): (right) maximum saline intrusion during a dry year. Saline intrusion is greater on the eastern coastline of the delta, where the South China Sea tides are ~2m. In this area Intrusion is encouraged through river and distributary channels with very low elevation channel bottoms and can reach up to 60km in a dry year (eg 1998) averaging 30-40km between 1985-1996) (Miller, 2003). On the western coastline, tides are of smaller amplitude (~1m). on average 1.4-1.9million ha are affected for a period of 1-3months (SIWRP, 2009)

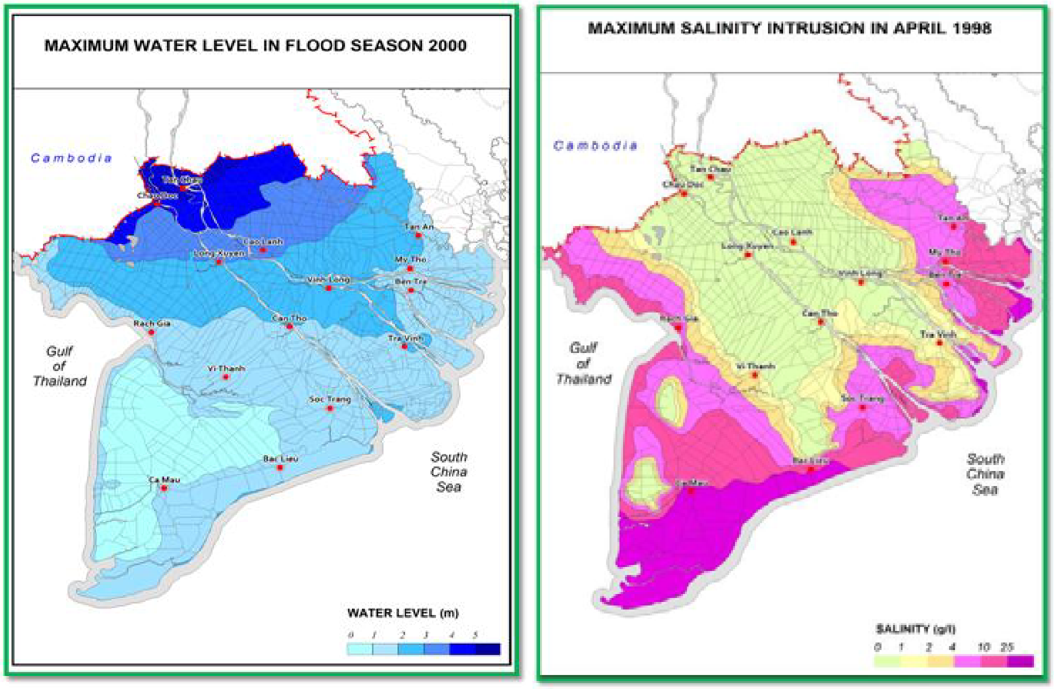


Figure 45: change in salinity intrusion for the Mekong Delta between the Baseline and the Definite Future

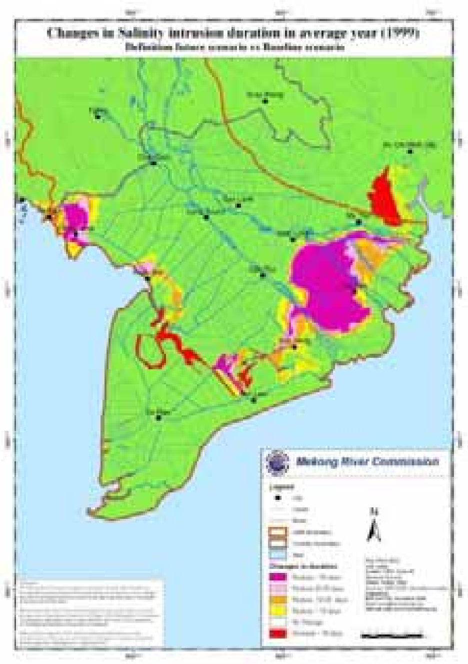


Figure 46: Indicative changes to the sediment load composition for Kratie and Tan Chau/Chau Doc..The left hand figure represent the current and past situation, while the right hand figures present the best estimate of the 2015 situation.

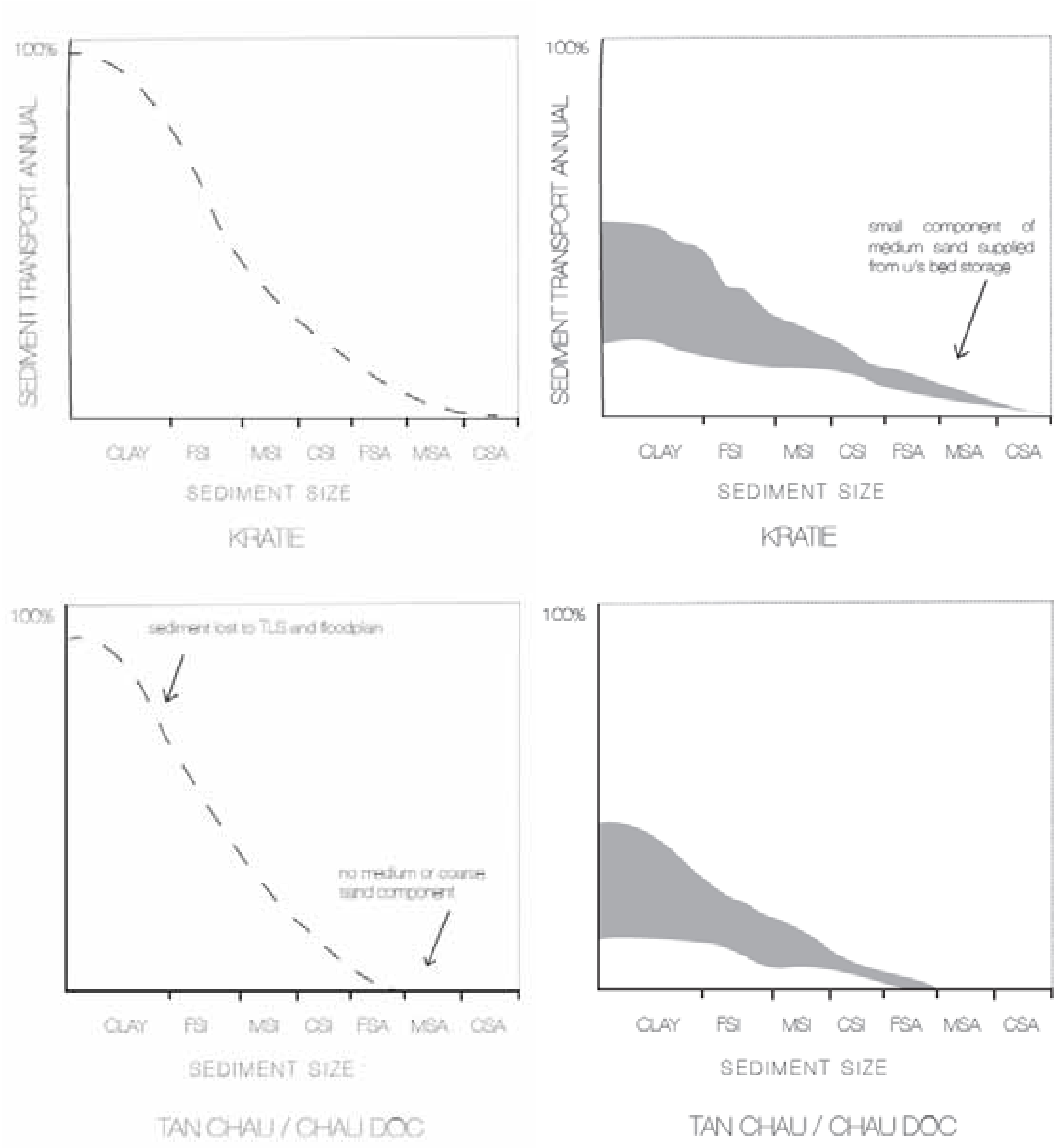


Figure 47: Sediment dynamics of the Cambodian floodplain (source: Kummu et al, 2008). There is some uncertainty of the sediment load at Kratie however, there is reasonable confidence that between 15-25% of sediments deposit on the floodplain (4-7% in the Tonle Sap system). The remaining 75-85% enters the Mekong Delta

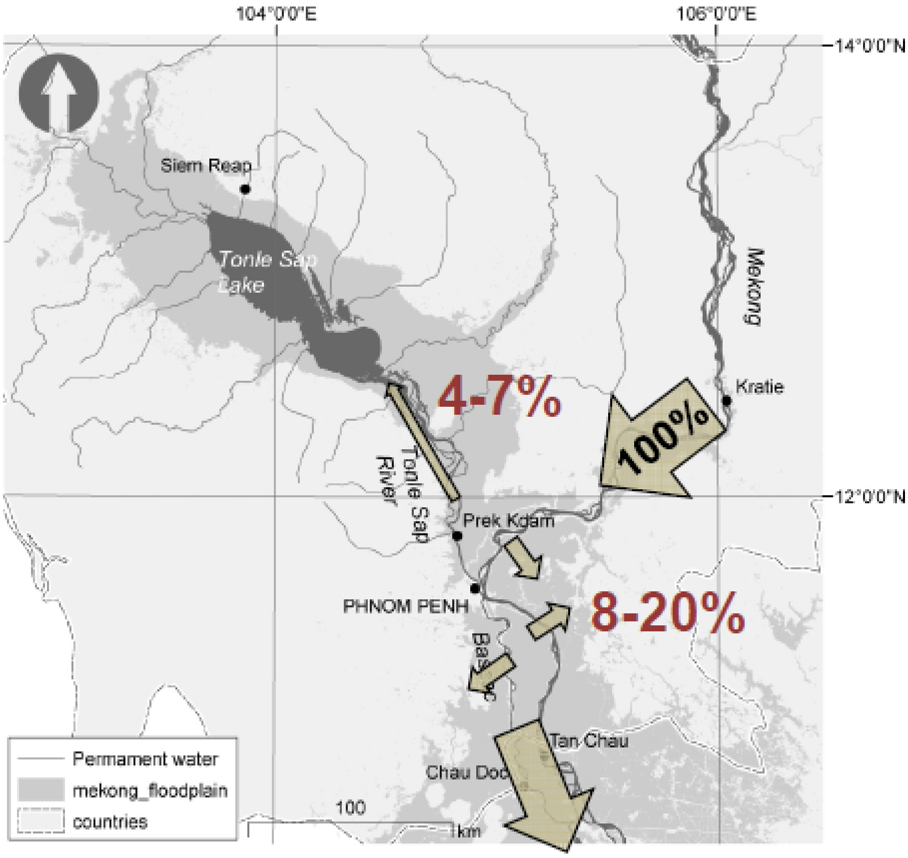


Figure 48: Satellite image of the Mekong Sediment plume taken in September. There are two main discharge sites: (i) the delta fan near the mainstream outlet which discharges into the South China Sea and transported along the delta coast in littoral drift before depositing at on the tip of the Ca Mau Penninsula, (ii) small bay in Kien Giang province near the Cambodian border