Available online at www.sciencedirect.com
ScienceDirect
Geomorphology 85 (2007) 275–293
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

Sediment-related impacts due to upstream reservoir trapping, the Lower Mekong River

Matti Kummu *, Olli Varis

Laboratory of Water Resources, Helsinki University of Technology (HUT), P.O. Box 5200, FIN-02015 HUT, Finland

Received 9 December 2004; received in revised form 8 July 2005; accepted 15 March 2006
Available online 12 October 2006

Abstract

A sharp decrease in total suspended solids (TSS) concentration has occurred in the Mekong River after the closure of the Manwan Dam in China in 1993, the first of a planned cascade of eight dams. This paper describes the upstream developments on the Mekong River, concentrating on the effects of hydropower dams and reservoirs. The reservoir-related changes in total suspended solids, suspended sediment concentration (SSC), and hydrology have been analyzed, and the impacts of such possible changes on the Lower Mekong Basin discussed. The theoretical trapping efficiency of the proposed dams has been computed and the amount of sediment to be trapped in the reservoirs estimated. The reservoir trapping of sediments and the changing of natural flow patterns will impact the countries downstream in this international river basin. Both positive and negative possible effects of such impacts have been reviewed, based on the available data from the Mekong and studies on other basins.
© 2006 Elsevier B.V. All rights reserved.

Keywords: Sediment yield; Reservoirs; Hydrology; Sediment deposition; Dams; Mekong

1. Introduction

Dam construction has increased secure water supply by 28% globally, a figure expected to grow to 34% by 2025 (Postel et al., 1996). Currently, 2.2% of the world's primary energy production is generated by hydropower installations. As a consequence of dam and reservoir consumption, the water renewal time of the world's rivers has increased dramatically from 20 to 100 d (Golubev, 1993). The self-purification capacity of rivers has decreased. Pronounced environmental consequences are expected, following profound in riverine hydrology and ecology.

Reservoir construction currently represents the most important influence on land–ocean sediment fluxes (Walling and Fang, 2003). Around 70% of the world's rivers are intercepted by large reservoirs. A notable threat to the sustainability of reservoirs is sedimentation. It is estimated, that 1% of the existing storage volume in the world is lost each year. The theoretical sediment trapping efficiency in these reservoirs are high, half of the reservoirs showing a local sediment trapping efficiency of 80% or more (Vörösmarty et al., 2003). In some basins, such as the Colorado and Nile, sediment is trapped completely due to large size of the reservoirs and flow diversion (Vörösmarty et al., 2003; Walling and Fang, 2003). According to Williams and Wolman (1984) and Graf (2005) the trapping efficiency of large reservoirs (Volume $>10^7$ m^3) is commonly greater than 99%,

* Corresponding author. Fax: +358 9 451 3827.
E-mail address: matti.kummu@iki.fi (M. Kummu).

0169-555X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2006.03.024

depending on the characteristics of the sediment, inflow, and the reservoir. Trapping efficiency for smaller dams ranges between 10 and 90% (Brune, 1953).

In the Mekong region, especially in countries such as China and Thailand, rapid economic growth has increased the pressure for greater hydropower production and other water-related developments, such as large-scale irrigation. In 2005, China had completed two hydropower dams on the Mekong, and has two dams under construction and four dam planned (Plinston and He, 1999; McCormack, 2001; Dore and Yu, 2004). Thailand, Laos, and Vietnam have build several dams on the Mekong tributaries (e.g. Australian Mekong Resource Centre, 2003; Mekong River Commission, 2003), and plan more, while the

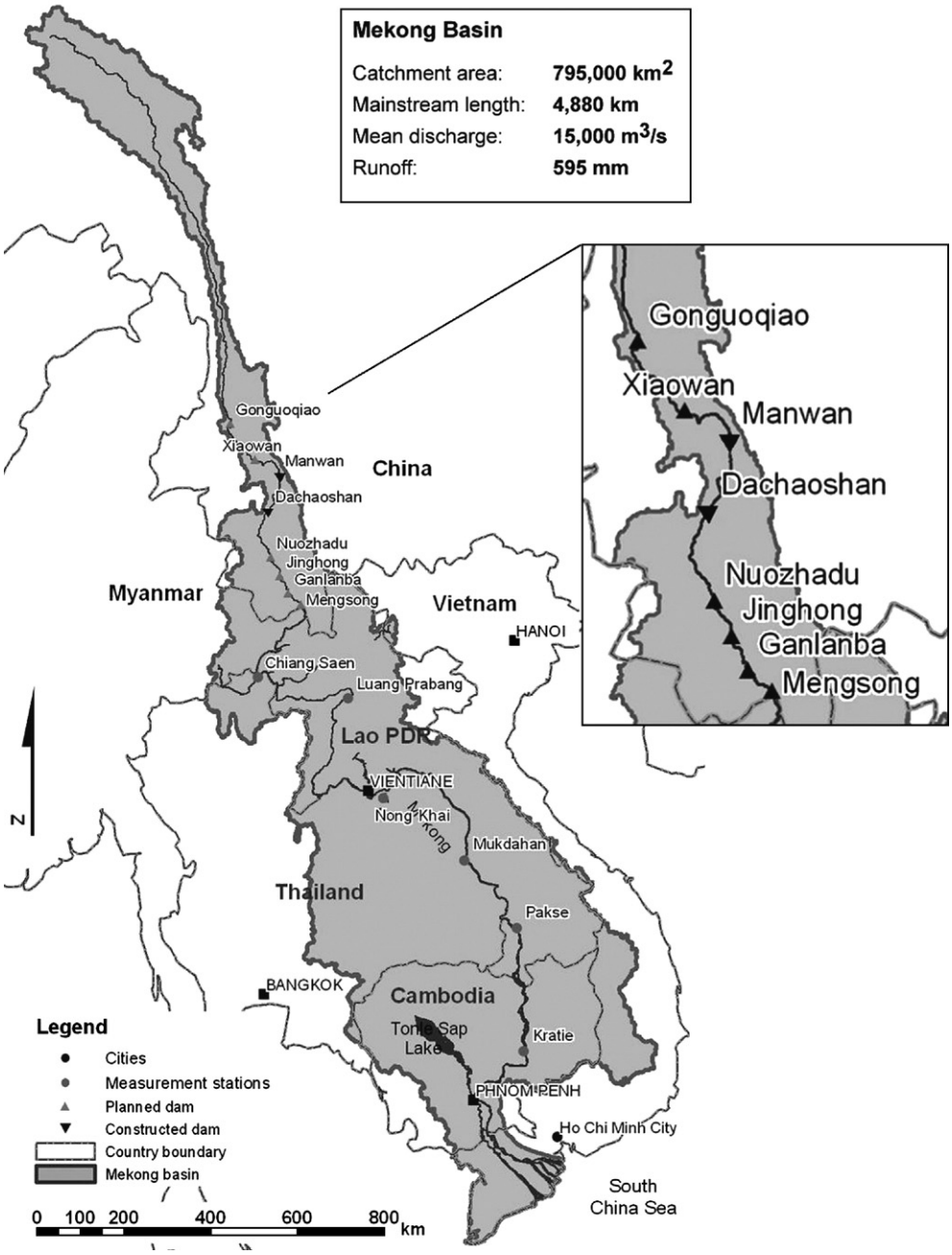

Fig. 1. The Mekong Basin and the constructed and projected dams in the mainstream and measurement stations. The locations of the dams (inset) are not georeferenced. Source for the GIS data: Mekong River Commission (2004); source for the basin information: Meade (1996), Milliman and Meade (1983), Mekong River Commission (1996), and Mekong River Commission (2003).

irrigation structures in both the tributaries and the mainstream are also increasing (Hori, 2000).

This paper focuses on the hydropower dams and their reservoirs in the Upper Mekong, and their impacts on the Lower Mekong Basin (LMB). It also reviews the importance of impacts of tributary-based hydropower developments on the Mekong Basin. The main objectives of the paper are:

- to provide an overview of the impacts of dams and reservoirs on sediment transportation and analyze the existing total suspended solids (TSS) and suspended sediment concentration (SSC) data in selected stations in LMB;
- to estimate the theoretical trapping efficiency of the proposed dams in Yunnan;
- to analyze potential and observed changes in sediment transportation, geomorphology, and hydrology in the Lower Mekong River, due to construction of hydropower dams on the Upper Mekong in south China.

The Mekong is a transboundary river, which raises political and economic questions among the basin's countries. However, this paper focuses specifically on impacts of the Yunnan hydropower development on the environment, and does not discuss the political and economic issues. These issues have been addressed in recent studies (see e.g. Bakker, 1999; Plinston and He, 1999; Öjendal, 2000; Dore and Yu, 2004; Feng et al., 2004; Makkonen, 2005; Keskinen et al., 2007; Yu, 2003).

This paper consists of five parts. First, the Mekong River and its basin are introduced, followed by a description of upstream hydropower dam construction in southern China. Next the data and methodology are presented, followed by an analysis of changes in suspended sediment concentration and hydrology. Finally, the paper discusses the impacts of these changes to the Lower Mekong Basin.

2. The Mekong River and its basin

With approximately 475 km^3 of water that it carries each year from a basin of 795,000 km^2, the Mekong is the world's 8th largest river (Mekong River Commission, 2003; Campbell, 2005). It is also one of the world's most pristine large rivers. The Mekong Basin is shared by six countries, and is usually divided into two parts which are:

- Upper Mekong Basin (including parts of the basin in China and Myanmar).
- Lower Mekong Basin (including parts of the basin in Lao PDR, Thailand, Cambodia and Vietnam).

The Mekong originates in the eastern Tibetan highlands, at an altitude of 4970 m above mean sea level. From Tibet, the river crosses the Chinese provinces of Qinghai and Yunnan, flowing through narrow gorges in a very steep topography for most of its upper course. After leaving China, the Mekong marks the border between Myanmar and Lao PDR. Further downstream, the river runs through Lao PDR, Thailand, Cambodia, and Vietnam to the South China Sea (Fig. 1).

Altogether, more than 70 million people live in the basin, about 54.8 million in the lower Basin (Mekong River Commission, 2003). A large part of the lower basin population directly depends on natural ecosystems for their livelihood. Fisheries and croplands are important sources of food and income. For China, the Mekong is especially important as a source of hydropower and for transportation (Makkonen, 2005).

2.1. Hydrology of Mekong

The climate in the Mekong Basin varies from tropical to cool temperate. On the Tibetan plateau the high peaks are permanently snow-capped, while most of the lower basin is tropical. Part of the dry season flow and the rise to the wet season stage come from snowmelt. In the lower parts of the basin, the climate is seasonal. Between November and February the Northeast Monsoon brings dryness and cooler temperatures, while the Southwest Monsoon dominates the hot wet season from June to September.

Table 1
Mekong mainstream: mean annual flows at selected locations (modified from Plinston and He, 1999; WUP-A, 2001)

Mainstream site	Years of record	Catchment area (10^3 km^2)	Mean annual flow		
			Volume (km^3)	Discharge (m^3 s^{-1})	Runoff (mm)
Xiaowan	30	113	38	1220	336
Jinghong	30	141	59	1870	418
Chinese border		168	74	2340	440
Chiang Saen	36	189	85	2700	450
Luang Prabang	48	268	121	3800	450
Vientiane	84	299	143	4500	480
Nakhon Phanom	70	373	232	7300	620
Mukdahan	71	391	251	8000	640
Pakse	73	545	318	10,000	580
Kratie	44	646	440	14,000	680

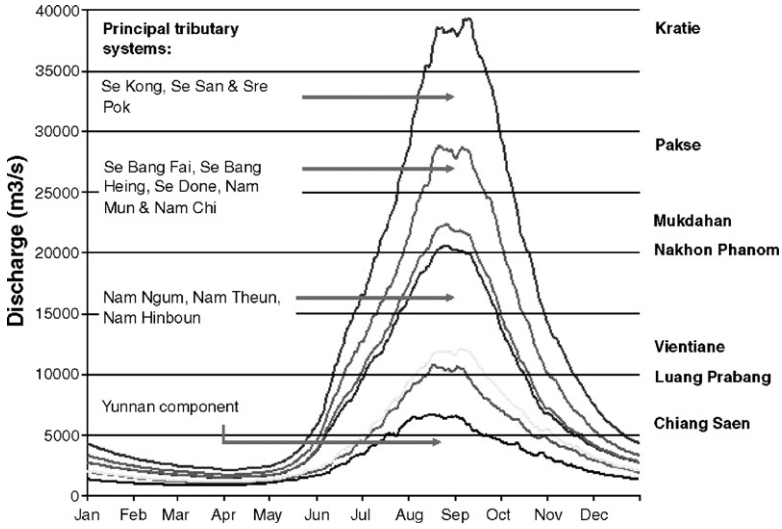

Fig. 2. Mean flows at selected sites in the Mekong mainstream, and an indication of the major tributaries and their contribution in each reach. Hydrographic data from 1960–2000 from Mekong River Commission (2004).

Table 1 summarises the average annual discharges for the Mekong River at selected stations. The locations of each site are in Fig. 1. The tributaries in central and southern Laos are the most important contributors to the Mekong's flow in the lower basin (Fig. 2). The Cambodian floodplains and Mekong Delta receive more than 90% of the available water resources and 95% of the total suspended sediment flux from upstream. This part of the basin is directly dependent on the conditions of the Upper Mekong.

The 189,000 km^2 catchment area of the Upper Mekong Basin in China and Myanmar is 24% of the total area, and contributes 18% (mean annual discharge 2710 m^3 s^{-1}) of the total runoff (Mekong River Commission, 2003). Although only 18% of the flow comes from the upper basin, it is important for the lower basin south of the China border (WUP-A, 2001) for the following two reasons:

- runoff from Yunnan, China, dominates the dry season flow throughout much of the overall Mekong system. Although the average yearly runoff from Yunnan is only 16% of the total runoff, it is over 35% for April and May. Any modification of the seasonal regime of the upper river therefore may have significant consequences as far downstream as Mekong Delta in Vietnam (Fig. 3).
- proposed Lancang Cascade with 8 dams will have a total storage capacity of over 40 km^3 and an active storage of over 23 km^3.

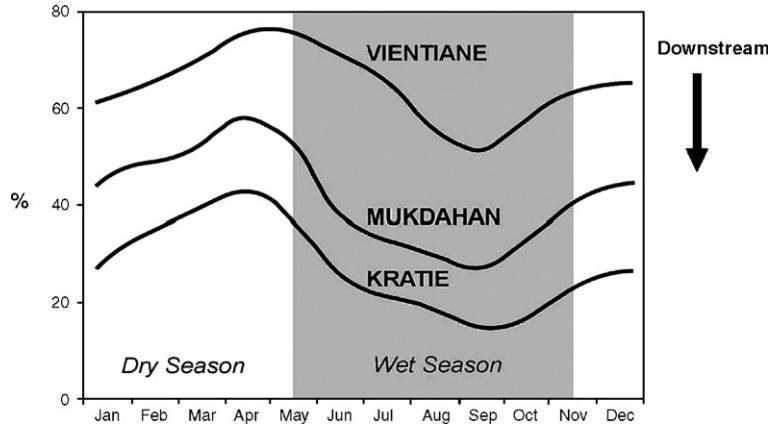

Fig. 3. Mekong River: percentage contribution of the Upper Mekong Basin to mean monthly flow at selected sites (Adamson, 2001). Reproduced with permission from International Water Power and Dam Construction.

Table 2
Estimations of mean annual sediment transport rates in Mekong

Source	From China (% / $\times 10^9$ kg)	Total in Mekong ($\times 10^9$ kg)
Milliman and Meade (1983)		160
Milliman and Syvitski (1992)		160
ADB (1997; ref Plinston and He, 1999)	50%	150–170
Roberts (2001)	50%	150–170
You (1998; ref Plinston and He, 1999)	84.8×10^9 kg	
Department of Hydrology, Ministry of Water Resources, China (1992; ref Plinston and He, 1999)	74×10^9 kg	

2.2. Sediment transport in the Mekong River

Sediment transport rates in the Mekong are poorly documented and there is no reliable definitive study. A few estimates of transport have been made, without reference to the original data or method (e.g. Milliman and Meade, 1983; Milliman and Syvitski, 1992; Roberts, 2001). Estimates of annual sediment flux of Mekong range from 150×10^9 kg to 170×10^9 kg (Table 2). Even though the estimates are consistent, no reliable picture of the total sediment flux of Mekong can be given as the referred sources haven't mentioned the original source or method of the estimate. The only source of data from China (Table 2) are the studies summarized in Plinston and He (1999).

In contrast, data from a number of measurement stations on the Mekong mainstream are available for suspended solid concentrations, starting from the 1960s (Mekong River Commission, 2004). Part of this data is presented and analyzed in this paper. Walling (2005) gives also good overview and evaluation of the available sediment data in Mekong.

According to Gupta and Liew (2007-this issue) most of the sediment in the Mekong upstream of Cambodia appears to be stored inside the channel, either on the bed or as insets against rock-cut banks. Unlike certain other large alluvial rivers such as the Amazon and Fly, little sediment exchange occurs between channel and floodplain in the Mekong, except in the Cambodian lowlands and the Mekong Delta in Vietnam, where the river overtops its banks during the rainy season and also has a laterally-shifting channel (Gupta et al., 2002; Gupta and Liew, 2007-this issue).

No reliable data on bedload is available for the Mekong Basin. Thus, with the current information, one very important part of the sediment transport and impacts of dams cannot be analyzed.

3. Dams on the Upper Mekong in Yunnan

The Lancang (as the Mekong is known in Yunnan) Cascade of dams in Yunnan, China, is a very large engineering project. Eight hydropower dams (Fig. 1) have been planned taking the advantage of an 800 m drop over 750 km of river in the middle and lower sections of the Yunnan stretch of the Mekong (Plinston and He, 1999).

3.1. Lancang Cascade

The first dam on the Mekong was completed in 1993 at Manwan, China (Fig. 1). Manwan started generating power three years later in 1996 (Dore and Yu, 2004; Plinston and He, 1999). The second dam was completed in October 2003 in Dachaoshan (Dore and Yu, 2004). The total storage of the Manwan and Dachaoshan dams are 0.92 km^3 and 0.89 km^3 respectively (Plinston and He, 1999).

Table 3
Completed and proposed dams and reservoirs on the Upper Mekong (Lancang) River in Yunnan (adapted from Dore and Yu, 2004; McCormack, 2001; Permpongsacharoen, 2002; Plinston and He, 1999) (n/a means *not available*)

Dam site	Elevation asl (m)	Watershed area (km^2)	Average inflow (mcm)	Total storage (mcm)	Active storage (mcm)	Installed capacity (MW)	Annual energy (GWh)	Inundated area (ha)	Dam height (m)	Progress
Gonguoqiao	1319	97,200	31,060	510	120	750	4060	343	130	Designed
Xiaowan	1236	113,300	38,470	14,560	9900	4200	18,990	3712	300	Building 2001–10
Manwan	994	114,500	38,790	920	257	1500	7805	415	126	Building 1986–93
Dachaoshan	895	121,000	42,260	890	367	1350	7021	826	118	Building 1996–2003
Nuozhadu	807	144,700	55,190	22,400	12,300	5500	23,777	4508	254	Designed
Jinghong	602	149,100	58,030	1233	249	1500	8059	510	118	Building 2004+
Ganlanba	533	151,800	59,290	n/a	n/a	250	780	12	n/a	Designed
Mengsong	519	160,000	63,700	n/a	n/a	600	3380	58	n/a	Designed

China plans to build six more dams on the Mekong mainstream (Table 3). The Xiaowan Dam, the second largest dam in China after the Three Gorges (dam height 292 m, reservoir length 169 km), has been under construction since 2001. According to CPN (2004), construction of the Jinghong Dam also has started. The total storage volume of the constructed and projected reservoirs in the eight-dam cascade would be around 40 km^3 which is more than half of the current total annual discharge of 73.6 km^3 from the upper basin up to the Chinese border. Hence, the reservoirs of the cascade would be able to store more than half the current annual discharge of the Mekong flowing out of China.

3.2. Sediment trapped by Manwan Dam

Little information is available on sediment trapping rates by the Manwan Dam. Analysis of bathymetric surveys at Manwan hydropower station in 1996, three years after the closure of the dam, determined the elevation of the bottom of the reservoir as 913.8 m, 30 m higher than when it was constructed (He et al., 2004). The same survey found that after three years, the silting rate and loss of active storage had reached rates expected for the 5th and 15th years of operation respectively. The mean annual sediment deposition in the reservoir was estimated to be 60×10^9 kg (He et al., 2004). This can be compared to the total annual suspended sediment (SS) load at Gaiju (15 km downstream from the Manwan Dam), which is 50.5×10^9 kg as calculated from the SSC data between 1953–1991 (He et al., 2004). These figures suggest that the dead storage of the dam (0.662 km^3) might be reached in about 15–17 years.

If the Xiaowan Dam is not built upstream of the Manwan and Dachaoshan dams (Fig. 1), these will fill up with sediment relatively fast. Xiaowan, with its large reservoir capacity of 14 km^3, has a much longer life span than the considerably smaller reservoirs of Manwan and Dachaoshan. Thus, apart from producing hydroelectricity, Xiaowan would act as a sediment buffer for downstream reservoirs.

3.3. Possible impacts of the dams

The hydropower potential of the Lancang River is unquestionable, and the dams probably would have some positive impacts downstream (Plinston and He, 1999; Hori, 2000; Mekong River Commission, 2003). However, strong concerns have been expressed about the negative impacts of the dams on the lower basin and the river (e.g. Blake, 2001; Mekong River Commission, 2003; Pearce, 2004a,c). Table 4 summarises such possible impacts.

4. Materials and methods

4.1. Data

The data used for the analysis of concentration and fluxes of suspended sediment concentration (SSC) and total suspended solids (TSS) in the Mekong mainstream are from the Mekong River Commission's databases (Mekong River Commission, 2004). The following two databases were used:

- The MRC hydrological database (HYMOS) includes SSC data from 1962 until 2002. Measurements are based on the depth integrated method, with varying sampling frequency. There are 14 stations in the Mekong mainstream and 46 in the tributaries, all within Thailand or Lao PDR territory.

Table 4
Possible positive and negative impacts of the hydropower projects in China on LMB (Blake, 2001; Hori, 2000; Mekong River Commission, 2003; Pearce, 2004a,b; Plinston and He, 1999)

Action	Positive impacts	Negative impacts
Controlling the flow	Increase capacity for flood control	Changes in the river's natural flow pattern, and possible increase of flow fluctuation
	More assured dry-season flows	Increase average downstream dry-season flows; permanent flooding of important ecosystems
	Increase navigation options	Decrease wet season flows
	Reduce saline intrusion in Delta (higher dry-season flow)	Shift of the flood regime, flood arrival delays, shorter flooding period
	Creation of extra irrigation opportunities	
Trapping of sediments	Ease navigation in LMB, less problems with sedimentation	Decrease flux of sediments and nutrients
		Increase geomorphological changes, such as bank erosion and bed degradation
Blocking the river		Block migration routes of fishes
		Divide/fragment river ecosystems, disturb local biodiversity

Table 5
Summary of the suspended sediment data availability in LMB

Database	Station	Pre-dam (1962–1992)		Post-dam (1993–2002)	
		Years	Samples	Years	Samples
MRCS hydrological database (HYMOS) Parameter: SSC	Chiang Saen	62, 68–75	414	N/A	N/A
	Luang Prabang	62, 85–92	270	97–02	51
	Nong Khai	72–78, 81–92	588	94–02	280
	Mukdahan	62–82, 84–92	1030	93–02	326
	Pakse	62, 90	66	97–02	60
MRCS Water Quality Monitoring Network database (WQMN) Parameter: TSS	Chiang Saen	85–92	92	93–00	96
	Luang Prabang	85–92	71	93–00	87
	Pakse	86–92	68	93–00	84
	Kratie	N/A	N/A	95–00	50

- The MRC Water Quality Monitoring Network (WQMN) database includes TSS data from 1985 until 2000. TSS is sampled just below the water surface once per month. There are 18 stations in the Mekong mainstream and 37 stations in Mekong tributaries in all four LMB countries.

The stations selected for this analysis were based on the years when data was available and the location of the station. Data from five HYMOS and four WQMN stations in the Mekong mainstream were used (Table 5). No data were available from stations in China and thus the data summarised by Plinston and He (1999) were used.

The datasets included daily discharge ($m^3\ s^{-1}$) and either the SSC (HYMOS) or TSS (WQMN) concentrations ($mg\ l^{-1}$). Analysis time was divided into the periods before and after the Manwan Dam closure in 1993. A complete time series of discharge were available for the whole period (1962–2002). A major gap exists in the SSC data between the mid-1970s and 1985, because of the unstable political situation in the Mekong area. Collection of TSS samples started in 1985. The extent of the data available from each station is presented in Table 5. The location of each station is presented in Fig. 1.

Sediment sampling for the MRC hydrological database (HYMOS) follows the United Stated Geological Survey procedures, with special modifications for conditions in the Mekong (Mekong River Commission, 1992). Samples are normally taken from three vertical sections, each representing an approximately equal portion of the total stream discharge. Samples are taken with USD 49, USP 46 and P 61 point integrated samplers. The depth-integrated method is employed whenever it can be used with a single traverse of the vertical. If the depths are such that two or more traverses are required to sample the complete depth, point samples at 0.2 and 0.8 of the total depth are taken instead of depth-integration and combined by the Straub method. Exceptions to this rule are the samples analyzed for particle-size determination. These are collected by the depth-integration method, even when two or more traverses are required (Mekong River Commission, 1992).

In MRC Water Quality Monitoring Network (WQMN) database the TSS samples were collected at 0.3 m below the water surface in the middle of the mainstream cross section at each station. The samples were filtered (e.g. Morris and Fan, 1998) on 0.45 μm (Millipore™) and the sediment concentration of the sample was calculated from the dry weights (Tin, 2004).

The HYMOS and WQMN datasets were processed separately, as the measurement techniques and analyzed parameters were different. Rating curves for SSC and TSS against the flow of the measured day were constructed for both datasets. The Power type of rating curve was used. TSS and SSC concentrations were calculated at selected stations for each day of the year for which the sediment data were available.

The SSC and TSS concentrations and fluxes were compared before and after the Manwan Dam closure in 1993. Also, if both measurements (SSC and TSS) were available for a station, the results have been compared and used for mutual validation.

4.2. Computing sediment trapping efficiency of reservoirs

The suspended sediment load trapped by the Manwan reservoir can be compared to the theoretical amount calculated with the following sediment retention function. The same method can be used for predicting the total trapping efficiency of the eight-dam cascade in Yunnan.

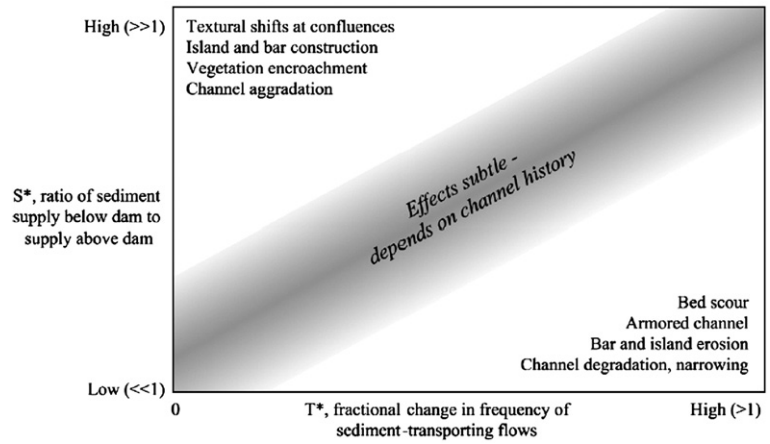

Fig. 4. Response domain for predicted channel adjustment in relation to the fractional change in T^* and S^* (Grant et al., 2003). Reproduced with permission from American Geophysical Union.

The theoretical trapping efficiency (TE) for an individual reservoir or for a group of reservoirs is determined by the following empirical relationship of Brune (1953).

$$\mathrm{TE} = 1 - \frac{0.5}{\sqrt{\Delta\tau_R}} \quad (1)$$

Where, $\Delta\tau_R$ is the local residence time change calculated with Eq. (2)

$$\Delta\tau_R = \frac{\sum_{1}^{n_j} V_i}{Q} \quad (2)$$

Where, V_i is the storage capacity of the ith reservoir in the jth regulated sub-basin (km^3) and Q the discharge at the mouth of the jth sub-basin ($km^3\ a^{-1}$). The Brune method for calculating the theoretical TE is simple and does not require any detailed data of the reservoir or sediment. Thus, this technique can be applied for the dams of the Lancang Cascade where available data are extremely scarce.

This methodology was originally developed for reservoirs in the United States, but is widely used for other parts of the world as well (e.g. Siyam et al., 2001). It provides reasonable estimates of long-term mean trapping efficiency (Morris and Fan, 1998; Vörösmarty et al., 2003). Thus, among the available methods (e.g. US Army Corps of Engineers, 1989; Siyam et al., 2001) Brune's was deemed most suitable for estimating the trapping efficiency of the reservoirs on the Upper Mekong.

4.3. Analysing downstream morphological changes

Dams change two critical elements of the geomorphic system: the ability of the river to transport sediment, and the amount of sediment available for transport (e.g. Grant et al., 2003). If the transport capacity exceeds the available supply, the flow may become sediment-starved and the channel can be expected to erode sediment from its bank and/or bed. If the transport capacity is less than the available supply, the channel can be expected to

Table 6
Water discharge, SSC and TSS concentrations and fluxes in analyzed stations along the Lower Mekong River divided to pre-dam and post-dam periods

Station	Discharge		HYMOS				WQMN			
	Pre-dam	Post-dam	Pre-dam		Post-dam		Pre-dam		Post-dam	
	Q	Q	SSC	Flux	SSC	Flux	TSS	Flux	TSS	Flux
	($m^3\ s^{-1}$)	($m^3\ s^{-1}$)	($mg\ l^{-1}$)	($\times 10^9$ kg)	($mg\ l^{-1}$)	($\times 10^9$ kg)	($mg\ l^{-1}$)	($\times 10^9$ kg)	($mg\ l^{-1}$)	($\times 10^9$ kg)
Chiang Saen	2741	2648	449	71			484	71	215	31
Luang Prabang	3623	4300	555	133	284	71	440	93	183	48
Nong Khai	4309	4757	297	76	219	72				
Mukdahan	7452	7724	196	88	247	129				
Pakse	8551	9913			136	101	218	133	156	111
Kratie		13732							90	81

accumulate sediment. Typical downstream responses are channel bed degradation or incision, textural changes such as coarsening or fining of surface grain-size distribution, and lateral adjustments, including both expansion and contraction of channel width (e.g. Williams and Wolman, 1984; Kondolf, 1997; Brandt, 2000; Grant et al., 2003). The form and intensity of the downstream morphological changes due to dams depend on the characteristics of the river, and on the pre- and post-dam conditions in flow regimes and sediment load.

Grant et al. (2003) developed a conceptual and analytical framework for predicting geomorphic response of rivers to dams. Their analytical framework is based on two dimensionless variables: ratio of sediment supply below to above the dam (S^*), and fractional change in frequency of sediment-transporting flows (T^*). Predicted downstream effects of dams in relation to these two variables can therefore be presented as a bivariate plot of T^* and S^* (Fig. 4).

Brandt (2000) developed a classification of the geomorphological effects downstream of dams, based on the balance between water discharge and sediment load. According to this classification it is possible to estimate the resulting cross-sectional morphology, depending on changes in released water flow and sediment load relative to the transport capacity of the flow.

5. Suspended sediment, the Lower Mekong

5.1. Suspended sediment load

Prior to the closure of the Manwan Dam, around 71×10^9 kg, or roughly 50%, of the total suspended sediment flux of the Mekong Basin annually originated from China. The post-Manwan Dam TSS flux is only 31×10^9 kg, a TSS flux drop of 56% after the closure of the first dam in the Lancang Cascade (Fig. 6). However, based on the analysis presented in report by Walling (2005) the suspended sediment flux has not been decreased in Chiang Saen after the closure of the Manwan Dam. The analysis is based on the SSC data.

Table 6 presents the average annual discharge, and SSC and TSS concentrations and fluxes, at stations (Table 5) on the Lower Mekong River. The first set of columns summarizes the discharge data, the following two set of columns the HYMOS and WQMN data. Both datasets separate the situation before the Manwan Dam was closed (1962–92) from the conditions after 1993.

After the dam at Manwan was closed in 1993, a sharp decline in the suspended sediment flux was seen at Chiang Saen, the most upstream MRC gauging stations on the Mekong, approximately 660 km downstream from the Manwan Dam and 290 km from the China border. The annual SS flux dropped from 71×10^9 kg to 31×10^9 kg (Fig. 6), while the TSS concentration dropped from 484 mg l^{-1} to 216 mg l^{-1}. The same trend was seen at Luang Prabang (647 km downstream from China) and Nong Khai (1104 km downstream from China), next stations downstream from Chiang Saen. In Mukdahan (1534 km downstream from China) and Pakse (1787 km downstream from China), the HYMOS data show an increasing trend in sediment flux after the closure of Manwan. Interestingly, the data for Pakse in WQMN database show a decreasing trend in sediment concentration. Only data for post-dam period are available for Kratie (2095 km downstream from China), the furthest downstream station considered.

The average suspended sediment fluxes from the HYMOS and WQMN datasets, of pre- and post-dam period, and their relative change, are presented in Fig. 5.

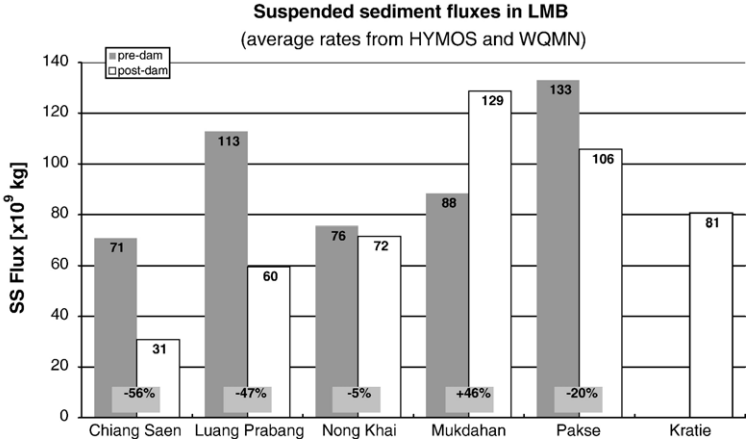

Fig. 5. Suspended sediment fluxes in the lower basin (LMB), before and after dam closure: averages from HYMOS and WQMN datasets.

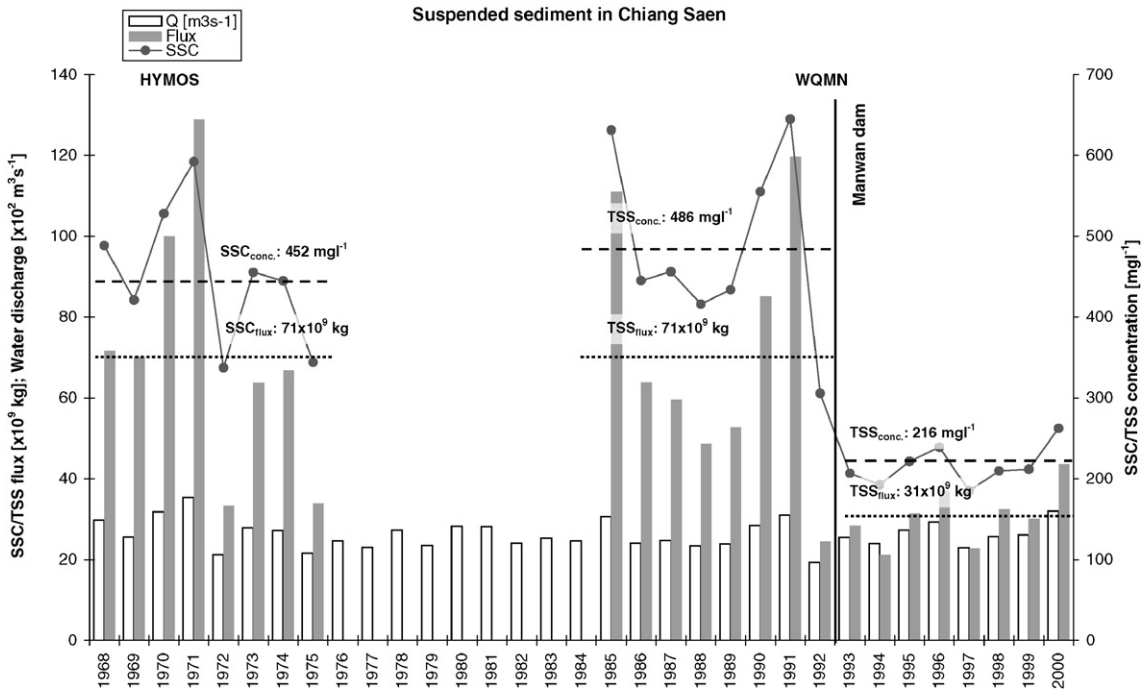

Fig. 6. Annual SSC and TSS flux (x10^9 kg), SSC and TSS concentrations (mg l^{-1}), and discharge (m^3 s^{-1}) at Chiang Saen, northern Thailand. Annual average SSC and TSS concentrations and fluxes are presented for three periods (1968–1975, 1985–1992, and 1993–2000).

The biggest change is at Chiang Saen, where the suspended sediment flux dropped by 56%. The changing situation at Chiang Saen is illustrated in Fig. 6. In Fig. 7, the SSC and TSS are plotted against the discharge, for all stations used in the analysis. The pre- and post-dam periods are shown separately.

The monthly average TSS flux and concentration at Chiang Saen and Pakse are presented before and after 1993 (Fig. 8). The reduction in the TSS flux and concentration is clear. The greatest difference in the TSS concentration between pre- and post-dam periods occurred in August and January in Pakse and October and June in Chiang Saen. At Chiang Saen, 86% of the total sediment flux occurred during the wet season (July–October), whilst in Pakse the same figure was 93%.

5.2. Computing theoretical trapping efficiency in the upper basin

The theoretical trapping efficiency was calculated using Brune's method as discussed earlier. The trapping efficiency was calculated for each dam separately, using the data of flow discharges and storages from Plinston and He (1999). For calculations regarding the total cascade, the volumes of active storage of individual dams were summarized. The discharge figure used is from the proposed Mengsong damsite, which is the most downstream dam in the Lancang Cascade (Plinston and He, 1999).

The theoretical values of TE (Table 7) vary from 0.61 to 0.66 for the large reservoirs (10^7 m^3 < Volume < 10^9 m^3) and from 0.66 to 0.92 for the very large reservoirs (Volume > 10^9 m^3). The classification of large and very large reservoirs is based on Graf (2005). On completion of the whole cascade of dams it would theoretically trap 94% of the suspended sediment load coming from China (Table 7).

Plinston and He (1999) reported that the average annual sediment load at Gaiju (15 km downstream from Manwan) was 50.5×10^9 kg. Based on the analysis made in this study the annual suspended sediment flux at Chiang Saen has dropped to around 38×10^9 kg after the closure of Manwan Dam which would correspond to a trapping efficiency of 0.75. The theoretical trapping efficiency computes to 0.68 (Table 7). However, the possible increased bank and bed erosion between Manwan and Chiang Saen may have had some effect on the changes in suspended sediment flux. Nonetheless, the result of theoretical trapping efficiency is in the same order of magnitude and therefore can be taken to approximate the real trapping efficiency.

The trapping efficiencies for the eight-dam cascade calculated here are of the same order of magnitude as observed for efficiencies from other regulated basins

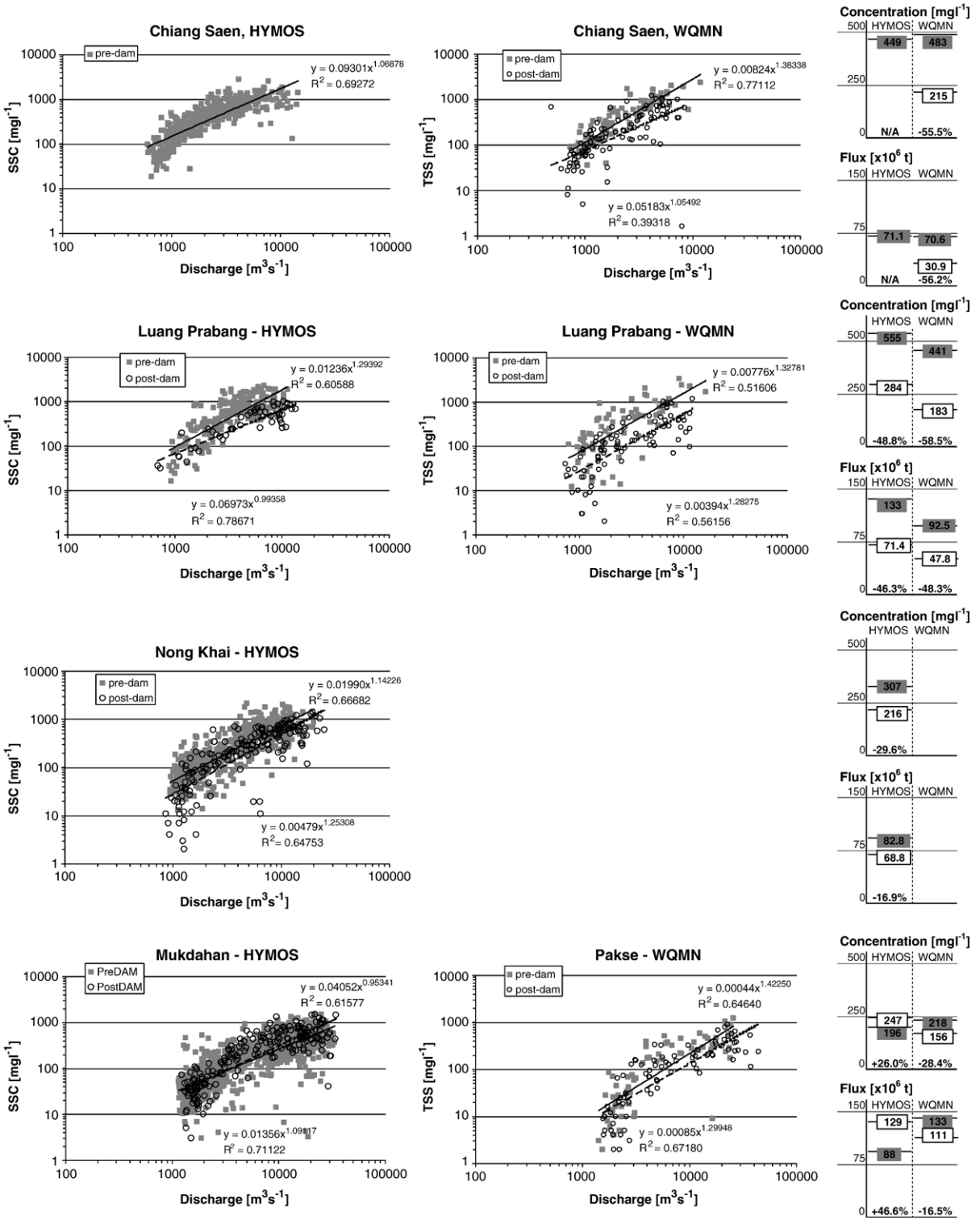

Fig. 7. The suspended sediment concentration plotted against the discharge for selected stations.

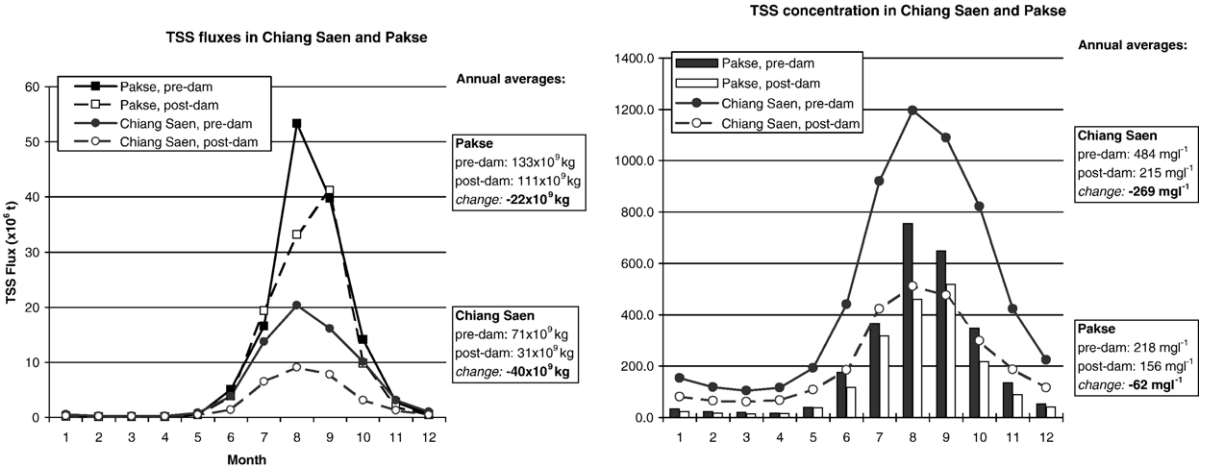

Fig. 8. TSS fluxes (right) and TSS concentrations (left) at Chiang Saen and Pakse (monthly averages).

round the world (Vörösmarty et al., 2003; Walling and Fang, 2003), and parallel the results of Williams and Wolman (1984) and Graf (1999).

The profile of the cascade of dams is presented in Fig. 10, with height, head, approximate location and water level, and elevation of each dam. The theoretical trapping efficiency figures for each dam (Table 7) are also included. It must however be noted that trapping in downstream dams is influenced by what gets trapped upstream. For example, even though the Nuozhadu Dam, expected to be in operation in 2017 (Permpongsacharoen, 2002), has a very high theoretical trapping efficiency (92%), most probably it would not trap much sediment, because of its most downstream location.

6. Impacts on the Lower Mekong Basin

Upstream development may have both positive and negative downstream impacts. The operation of the reservoirs probably would lead to an increase in the dry season flow and a decrease in flood peaks. Furthermore, it may shift the period of flooding earlier in the year and increase the fluctuation of the water level in the lower basin. The two operating reservoirs are already trapping a significant amount of sediment and trapping will increase if the two dams construction are closed during the next decade. This may lead to changes in hydrology, geomorphology, and biological productivity in the lower basin.

Table 7
Results of the theoretical trapping efficiency calculations for individual dams and the cascade

	Q^a (km^3 a^{-1})	V^b (km^3)	dtR^c (a)	Brune^d (TE)
Gonguoqiao	31.1	0.51	0.016	0.61
Xiaowan	38.5	14.56	0.378	0.92
Manwan	38.8	0.92	0.024	0.68
Dachaoshan	42.3	0.89	0.021	0.66
Nuozhadu	55.2	22.40	0.406	0.92
Jinghong	58.0	1.23	0.021	0.66
Cascade	63.7	40.51	0.636	0.94

[a] Discharge at the dam location (Plinston and He, 1999).
[b] Storage volume (Plinston and He, 1999).
[c] Eq. (2).
[d] TE calculated using the original Brune's method, Eq. (1).

6.1. Hydrological changes

The possible effects of Chinese dams to the hydrology of the lower basin have been analyzed by Adamson

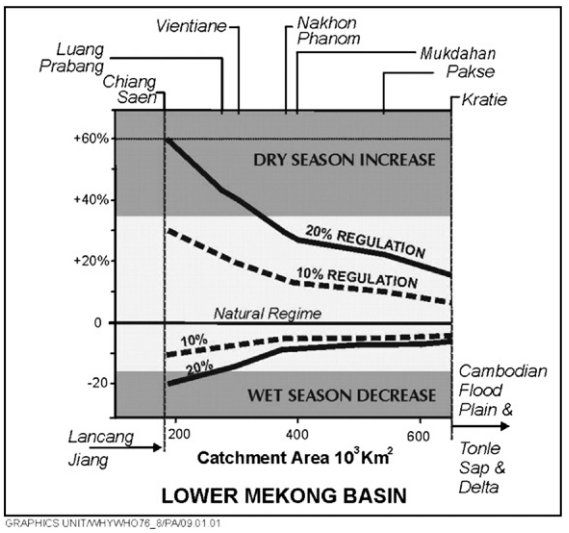

Fig. 9. Potential changes to average wet and dry season flows in the Lower Mekong channel, given 10 and 20% regulation by hydropower dams in Yunnan (Adamson, 2001). Reproduced with permission from International Water Power and Dam Construction.

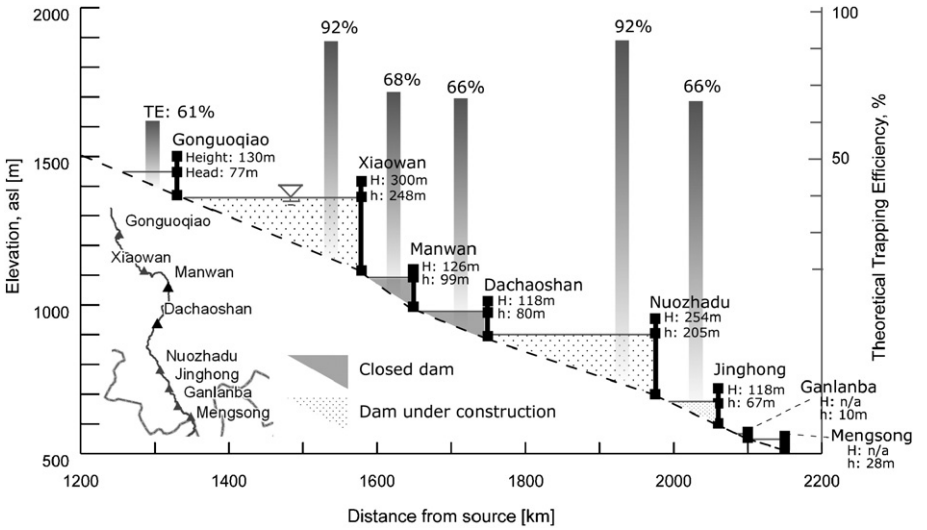

Fig. 10. Profile of the Lancang Cascade of dams plotted with the location, height, head, and average theoretical trapping efficiency of each reservoir (source: Dore and Yu, 2004; McCormack, 2001; Plinston and He, 1999).

(2001). The impacts of the Manwan Dam has been reported by Lu and Siew (2006). Adamson's (2001) results are summarized in Fig. 9, showing the potential changes to average wet and dry season flows in the Lower Mekong (see also Fig. 3). The 10% and 20% regulation, used in the analysis of Adamson (2001), represent reallocation from the wet to the dry season at Chiang Saen of 6.8 and 13.6 km^3 of discharge respectively. The long term wet season flow volume at Chiang Saen (1960 to 1991) is 68 km^3 (Adamson, 2001).

The most significant effect of the dam operation would be seen in northern Thailand and Laos, downstream of the Yunnan cascade of dams. As presented in Fig. 9, regulation increases the dry season flow and correspondingly decreases the wet season flow. During the dry season, the impacts are greater because the Chinese part of dry season flow is proportionally much larger than during the wet season (Fig. 3). However, the areas most sensitive to flood level change are the major Mekong floodplains downstream from Kratie (see Fig. 1) (e.g. Kummu et al., 2004, 2005).

Lu and Siew (2006) conclude that water discharge of the Mekong River has been influenced by the construction of Manwan Dam, although the extent of influence remains relatively small at this point. The mean discharge and seasonal discharge regimes have remained within the recorded range, but the frequency and magnitude of water level fluctuations have increased considerably in the post-dam period (1993–2000).

6.1.1. Positive impacts

Increased dry season flow decreases the risk of water shortages and increases the options for dry season irrigation. In the Mekong Delta in Vietnam, increasing dry season flow may reduce saline water intrusion, benefiting rice farming and aquaculture. Higher water levels during the dry season may also ease navigational activities in many places.

6.1.2. Negative impacts

Regulation by dams changes the pattern of natural flow in rivers, with potential negative impacts on riverine habitats. The likely increase in average downstream dry-season flow may flood important ecosystems, while decreasing wet season flow may impact biological productivity of smaller floodplains. Also, the shift of the flood regime may result in delays in flood arrival and shorter flood periods, both having a negative effect on ecosystem productivity, according to Junk's (1997) studies from Amazon.

A 20% regulation at the Yunnan cascade would result in a 50% increase in average discharge in March at Kratie (Adamson, 2001). Such an increase in the dry season flow would affect the lower basin floodplains, especially the Tonlé Sap system, where the minimum water level would increase from 1.57 m to 1.81 m above mean sea level according to Danish Hydraulic Institute (2004). This increase corresponds to the 26% of the water depth, the bottom of the lake being at an elevation of 0.6 m. This rise in water level would increase the minimum area and volume of the lake from 2500 km^2 to 2976 km^2 and from 1.62 km^3 to 2.37 km^3 respectively. ADB (2004) estimates that the dry season water level in Tonle Sap would rise as much as 0.6 m due to the reservoir construction in Mekong mainstream and tributaries. This would mean

Table 8
Calculation of S^* for the Mekong in present conditions (after Manwan Dam) and in the future (assuming that the whole cascade of dams have completed)

	Catchment area [km^2]	Post-Manwan Dam				Cascade			
		Sediment supply [$\times 10^9$ kg]				Sediment supply [$\times 10^9$ kg]			
		Pre-dam	Post-dam	S^* (pre)	S^* (post)	Pre-dam	Post-dam	S^* (pre)	S^* (post)
Chiang Saen	189,000	71	31	1.42	0.62	71	4.26	1.42	0.09
Pakse	545,000	133	106	2.66	2.12	133	66.26	2.66	1.33

even more dramatic change on the Tonle Sap ecosystem. Large areas of seasonally flooded forest, situated on the shore of the present dry season lake, would become permanently flooded with presumable changes to the ecosystem as the forest currently offers physical shelter on the floodplain. Important habitats in other areas maybe flooded permanently as well, with similar negative impacts on the ecosystem.

The filling of new reservoirs in the cascade may have short-term impacts downstream, depending on the time taken to fill. Plinston and He (1999) report unusual low water levels during the filling of the Manwan Dam in 1992–1993. During the dry season of 2004, just after the Dachaoshan Dam was closed, extremely low water levels were also measured in Laos and Thailand, as reported by Pearce (2004b) among others. However, at the same time extremely low rainfalls were reported in China, which also partly explains the low dry-season water level.

6.2. Geomorphological changes

6.2.1. Downstream geomorphological changes

Following the construction of Manwan Dam, the sediment concentration in the Mekong River was reduced downstream. Thus following completion of the cascades, sediment transport capacity will exceed available supply in both dry and wet seasons, especially close to the damsites as large amount of sediment would be trapped by the dams. This would lead to downstream impacts such as channel bed degradation, textural changes involving coarsening of surface grain-size distribution, and lateral expansion. The channel bed degradation and lateral expansion (e.g. bank erosion) may harm local ecosystems (and hamper the human use of the river) in many ways. According to Gupta and Liew (2007-this issue) the trapping of sediments by dams in China may eventually lead the Mekong to be a rock-cut canyon because very little exchange of sediment occurs between the main channel and floodplain upstream from Cambodian lowlands.

Higher dry season flows due to the pattern of dam operation have more capacity to transport sediment. However, lower wet season flows also have less capacity to transport. This impact on the geomorphology of the river is difficult to evaluate at present.

On the other hand, Hori (2000) argues that trapping of sediment by reservoirs may also have positive impacts on navigation by reducing sediment in the navigable routes, thus making it easier to keep the channels clear. Also, in many watersheds, increasing erosion due to land-use changes, especially deforestation, causes problems (e.g. Ananda and Herath, 2003). Hence, trapping of sediments upstream might reduce such problems downstream. To date, there is no available information in the Mekong Basin as to whether intensive deforestation in the region, especially in Lao PDR, Myanmar, and Thailand (e.g. Shmueli, 1999), has increased erosion and suspended sediment fluxes to the mainstream.

6.2.2. Grant et al. (2003) method

The analytical framework developed by Grant et al. (2003) was applied to evaluate downstream morphological changes in the Mekong (see Section 4.3). Table 8 shows the ratios of sediment supply below dams to the supply above dams (S^*). The time periods analyzed are (1) pre- and post-Manwan Dam and (2) post-Lancang Cascade. Sediment supply above the Manwan is 50.5×10^9 kg (He et al., 2004). The sediment supplies below the dam at Chiang Saen and Pakse are based on the analysis made in this study for the pre- and post-Manwan Dam time periods. The suspended sediment rate of the post-cascade period is based on the trapping efficiency calculations for the cascade, with the assumption that no new sediment supply is available downstream, i.e. bank and bed erosions do not increase significantly.

The fractional change in frequency of sediment-transporting flows (T^*) in present conditions is 1.0 throughout the river. Using the hydrological analysis made by Adamson (2001) for the impact of the cascade, T^* would be around 0.8 at Chiang Saen and close to 0.9 at Pakse, based on the wet season results, when most of the discharge and sediment transport occur (Fig. 10). Predicted downstream effects of the dams, in relation to S^* and T^*, are presented as a bivariate plot for two stations: Chiang Saen and Pakse (Fig. 11).

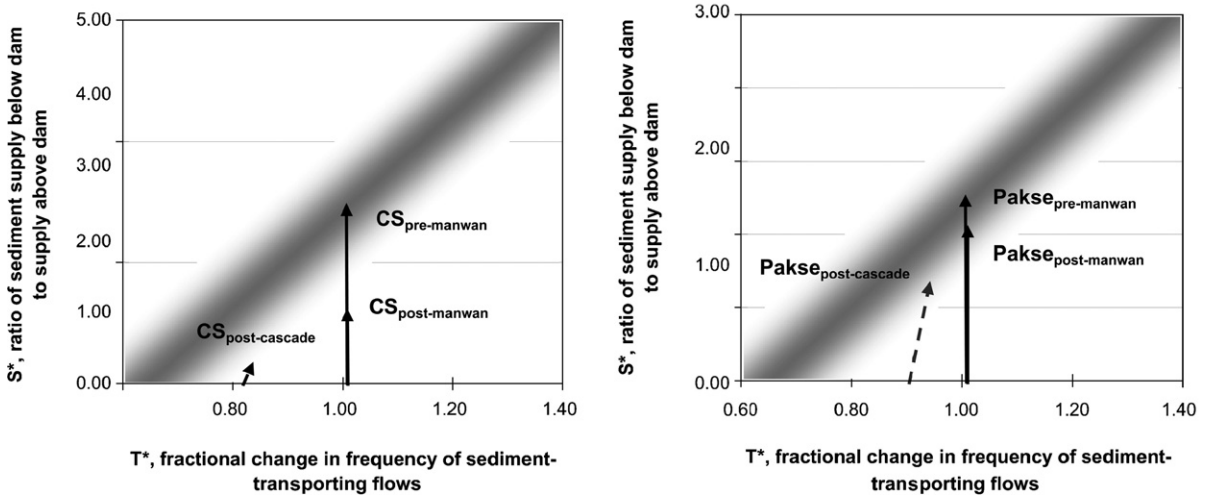

Fig. 11. Endpoint trajectories of downstream change for Chiang Saen (CS) (left) and Pakse, pre- and post-Manwan Dam, and post-cascade conditions. See Fig. 4 for expected morphological adjustments to the channel.

According to the method (Fig. 4) developed by Grant et al. (2003) the impacts of the dams on the Mekong downstream (bed scour, armoured channel, bar and island erosion, channel degradation and narrowing) are high close to dams and then decrease downstream, (Fig. 11).

6.3. Brandt (2000) method

The dry and wet seasons were considered separately for the morphological changes analysis developed by Brandt (2000). The results of the analysis are presented in Table 9. In dry season, the discharge increases and the sediment load is smaller than the transport capacity, because of the trapping effect of the dams in China. Thus, for dry season the Brandt's Case 7 (Brandt, 2000) has been used. During the wet season, the discharge slightly decreases but not enough to affect the transport capacity, and the resulting sediment load is smaller than the transport capacity. Hence, for the wet season, the Brandt's Case 1 (Brandt, 2000) has been used.

Table 9
Morphological changes in Mekong downstream due to the Chinese dams: based on/results of using Brandt's (2000) method

	Wet season (Case 1)	Dry season (Case 7)
	Decrease Q	Increase Q
	$L<K$	$L<K$
Cross-section area	–	+
Width	±	±
Depth	±	±
Bed level	0/degradation	Degradation
Terrace	Formation	Disappearance
Riffles	Erosion	Erosion/deposition
Pools	Erosion/deposition	Erosion

K = transport capacity, L = sediment load, and Q = water discharge.

The peak flows, especially close to China border, may be reduced because of the dams, and the cross-section of the channel may decrease. The nature of the decrease in cross sections (depth and width ratio) depends on the local conditions. It appears that the level of the river bed would degrade due to sediment trapping. Impact on floodplains is difficult to predict but riffles and pools will most probably undergo erosion.

6.4. Biodiversity and biological productivity

The dams are trapping a large portion of the sediments, which in turn may decrease the biological productivity as part of nutrients are attached to the sediment. Fish and other aquatic species are adapted to sediment-rich and turbid conditions of the Mekong. It is possible that the feeding and spawning conditions would be disturbed and lead to declining biodiversity and productivity (Blake, 2001). The dams could also block the natural migration pathways as none of the finished or projected dams have a fish ladders or diversion channels.

In floodplains, the driving force for biological productivity is the flood pulse. Junk's (1997) flood pulse concept, developed for the Amazon, has been widely accepted as describing highly productive floodplain environments and the ecology of pulsing systems in Mekong (see, for example, Lamberts, 2001; Bonheur and Lane, 2002; Sverdrup-Jensen, 2002). Due to regulation, the total area of floodplains would be reduced due to the higher dry season and lower wet season water levels. This would have direct impact on the productivity and also on

fish feeding, spawning and nursery grounds. It may also decrease the area of possible agricultural activities fertilized by the silt and nutrients provided by the seasonal flooding of the Mekong.

7. Discussion

In many stations the TSS and SSC data are dispersed and available data limited. Quality of the data may also vary from one station to another, as water samples from different stations are not analyzed in the same laboratory. This may increase the possible error in determining the changes in suspended sediment fluxes and comparing the results between different stations.

Two different methods were used to collect samples for determining the concentration of suspended material in water. The Suspended Sediment Concentrations (SSC) in the HYMOS database were produced by measuring the dry weight of all the sediment in a known volume of water–sediment mixture collected as an integrated vertical sample. The total suspended solids (TSS) data were produced by several methods, most of which entail measuring the dry weight of sediment from a known volume of a subsample of the original collected from the surface water.

If particles are uniformly distributed in both the vertical and horizontal dimensions then the TSS and SSC would give the same results. However, if we hypothesise that particles are not uniformly distributed because heavier particles are closer to the bed in the vertical and particle concentrations vary with flow rate in the horizontal dimension, then SSC should better represent the flux through a channel section as it is closer to a vertically and horizontally integrated sample of the entire channel than TSS. The TSS is collected at only one location mid-channel at 0.3 m below the surface. Therefore, if sediment particles are non-uniformly distributed in the vertical dimension, and heavier ones remain closer to the bed, then TSS would underestimate the total sediment flux. This underestimation may be greatest when flows are highest and the channel deepest during the flood season (when fluxes are also at their peak).

In general, Gray et al. (2000) concluded that SSC values tend to increase at a greater rate than the correspondingly paired TSS values and data produced by the SSC technique are more reliable according to his study in the United States. SSC and TSS data collected from natural water are not comparable and should not be used interchangeably. Thus, the two datasets were analyzed separately in this paper.

The sediment volume of the Mekong has been estimated in other studies as $150–170 \times 10^9$ kg (e.g. Milliman and Meade, 1983; Milliman and Syvitski, 1992; Roberts, 2001). However, no reliable calculations or source data have been presented. To estimate the total flux of Mekong is difficult as after Kratie large amount of the flood water enters the floodplain where a part of the sediment is deposited. Thus, the amount of sediment which finally reaches the South China Sea is less than the total sediment carried by the Mekong. According to the results of this study, the suspended sediment flux in Kratie was 81×10^9 kg between 1995 and 2000. However, this is based only surface TSS concentration calculations and thus, the real suspended sediment flux may be higher. More research and field work need to be done to predict the total sediment flux in Mekong.

So far, we have only presented and analyzed the effect of actual and proposed mainstream dams on the total suspended sediment flux in the Mekong River. The effect of dams on bed load transport is even more dramatic because it is fully trapped by reservoirs (e.g. Kondolf, 1997). The accurate measurement of the bed load transport is very difficult and there are no reliable data available from China or the Lower Mekong Basin. Also there is limited information on the geomorphology in Lower Mekong Basin. This makes prediction of downstream impacts of bed load interception difficult.

Another issue, which may alter the suspended sediment flux from China, is reforestation. This is a key element of the Chinese Government's strategy for forestry and watershed management. The Chinese Government launched a reforestation programme in the Mekong River basin in 1996, with the objective of watershed protection (Puustjärvi, 2000). The effect of reforestation programs on the sediment transport in the Mekong downstream of the existing mainstream dams is unknown, but it may have further reduced the sediment flux from bank erosion and landslides. Thus, in order to be able to analyze in more depth the impacts of the dams on the suspended sediment fluxes the impact of reforestation in the upper basin needs to be studied.

Brune's (1953) method was used for theoretical trapping efficiency calculations. It has originally been developed for the dams in the United States but later applied with relatively good results to rivers in other areas. According to the validation results made in this study for Manwan Dam and Reservoir, the Brune's (1953) method can be applied to the reservoirs on the Mekong. The methods developed by Grant et al. (2003) and Brandt (2000) were used to predict the possible morphological changes in the lower basin due to upstream sediment trapping. However, it has not been possible to validate the results.

8. Conclusions

The study on the possible impacts of the Lancang Cascade in the Mekong has concentrated so far on the hydrological effects. However, the possible changes in sediment transportation due to the sediment trapping in reservoirs are also very important, and along with the hydrologic changes may have large impacts on the downstream ecosystems.

This paper explores the potential and observed downstream changes related to hydrology, sediment flux, and geomorphology in the Lower Mekong Basin due to hydropower dam construction on the Upper Mekong, where China has completed two hydropower dams to Mekong mainstream since 1993 and six more are either under construction or proposed. The suspended sediment data from seven stations along the Mekong River downstream have been used to compare the suspended sediment fluxes before and after the Manwan Dam. The theoretical trapping efficiency of the reservoirs has been calculated with Brune's (1953) method. The possible downstream morphological changes due to dams on the Upper Mekong are predicted by using methodologies developed by Brandt (2000) and Grant et al. (2003).

Manwan, the first dam in the Lancang Cascade, was closed in 1993. Following its completion, it impacted on the sediment flux downstream along the Lower Mekong. In Chiang Saen, 660 km downstream from the dam, the measured annual sediment flux based on TSS data has been more than halved from 70×10^9 kg to 31×10^9 kg. In other stations the sediment flux has changed as well after the closure of the Manwan Dam but not statistically significantly. In some stations sediment fluxes have even increased in post-dam period. It should be noted that a number of tributaries of the Mekong have dams and reservoirs on them, but, the effects of these are not analyzed or have been excluded from this study. Thus, the decline of the sediment fluxes in stations downstream from Chiang Saen may also be partly explained by the impact of these reservoirs. Other problems are the limited data at some stations and the variation in the quality of data between stations.

It is possible to calculate the theoretical trapping efficiency for the dam and its reservoir by using the Brune (1953) method. Theoretical trapping efficiency for Manwan is 68%, which correlates well with the measured trapping efficiency of 75%. The Dachaoshan Dam, closed in 2003, has a theoretical TE of 66%, while the bigger dams Xiaowan and Nuozhadu at present under construction, have trapping efficiencies as high as 92%, basically trapping all the sediment. The whole cascade of eight dams has a total theoretical trapping efficiency of 94%.

The major hydrological impacts of the these reservoirs on the Lower Mekong are (1) increasing average downstream dry-season flow, (2) decreasing wet-season flow (Adamson, 2001), and (3) increasing water level fluctuations (Lu and Siew, 2006). These hydrological changes may impact negatively on the ecosystem but at the same time may reduce saline intrusion in delta, ease navigation, and increase irrigation opportunities during the dry season. Flux of sediment from the upper basin is decreasing due to sediment trapping by dams. This will likely increase bed and bank erosion downstream and have negative impacts on ecosystem productivity. The changes are greater close to the dams and reduce in scale moving downstream.

According to the technique developed by Grant et al. (2003), the geomorphological impacts of the dams include bed scour, armouring of channel, bar and island erosion, and channel degradation and narrowing, the intensity of change decreasing in the downstream direction. Based on the method developed by Brandt (2000) the possible impacts are a degrading bed level and cross-sectional changes, depending on the local condition. Impact on floodplains is difficult to predict, but riffles and pools are likely to be eroded. Grant et al. (2003) and Brandt (2000) methods for impact estimation are highly useful. However further studies are more than justified. An unrestricted flow of information between the countries of the lower and Upper Mekong Basin is urgently needed, to enable more quantitative estimations of possible development-related impacts.

Acknowledgements

The authors would like to thank Professors Pertti Vakkilainen, John Dore, Avijit Gupta, Gordon Grant, and Peter Hawkins, Juha Sarkkula, Marko Keskinen, Jorma Koponen, Charlotte MacAlister, Katri Makkonen, Mohammed Mizanur Rahaman, and Monika Schaffner for their extremely useful comments, support, help, and advice during the research and writing process. The first author was supported financially by a Helsinki University of Technology Research Grant.

References

Adamson, P.T., 2001. Hydrological perspectives on the Lower Mekong Basin — the potential impacts of hydropower developments in Yunnan on the downstream flow regime. International Water Power and Dam Construction, pp. 16–21 (March 2001).

ADB, 2004. Cumulative Impact Analysis and Nam Theun 2 Contributions, Final report. Prepared by NORPLAN and EcoLao for Asian Development Bank (ADB), 143 pp.

Ananda, J., Herath, G., 2003. Soil erosion in developing countries: a socio-economic appraisal. Journal of Environmental Management 68 (4), 343–353.

Australian Mekong Resource Centre, 2003. Hydropower development in the Se San Watershed. Australian Mekong Resource Centre (AMRC), Sydney. Accessed through internet on July 2005: http://www.mekong.es.usyd.edu.au/case_studies/sesan/index.htm.

Bakker, K., 1999. The politics of hydropower: developing the Mekong. Political Geography 18 (2), 209–232.

Blake, D., 2001. Proposed Mekong dam scheme in China threatens millions in downstream countries. World Rivers Review 16 (3), 4–5.

Bonheur, N., Lane, B.D., 2002. Natural resource management for human security in Cambodia's Tonle Sap Biosphere Reserve. Environmental Science & Policy 5, 33–41.

Brandt, S.A., 2000. Classification of geomorphological effects downstream of dams. Catena 40 (4), 375–401.

Brune, G.M., 1953. Trap efficiency of reservoirs. Transactions of American Geophysical Union 34 (3), 407–418.

Campbell, I.C., 2005. Integrated water resources management for the Mekong River Basin. In: Biswas, A.K., Varis, O., Tortajada, C. (Eds.), Integrated Water Resources Management in South and South-East Asia. Oxford University Press, New Delhi, p. 353.

China Power News, 2004. Yunnan to speed up Lancang dam building. China Power News. (May 24, 2004).

Danish Hydraulic Institute, 2004. Study on natural reverse flow in the Tonle Sap River, Prepared by DHI (Danish Hydraulic Institute) Water and Environment for the Mekong River Commission Secretariat. Financed by World Bank., Vientiane, Lao PDR.

Dore, J., Yu, X., 2004. Yunnan hydropower expansion — update on China's energy industry reforms and the Nu, Lancang and Jinsha hydropower dams, Chiang Mai University's Unit for Social and Environmental Research and Green Watershed, Kunming, PR of China. 38 pp.

Feng, Y., He, D., Bao, H., 2004. Analysis on equitable and reasonable allocation models of water resources in the Lancang–Mekong River basin. International Water Resources Association 29 (1), 114–118.

Golubev, G., 1993. Sustainable water development: implications for the future. Water Resources Development 9 (2), 127–154.

Graf, W.L., 1999. Dam nation: a geographic census of American dams and their large-scale hydrologic impacts. Water Resources Research 35 (4), 1305–1311.

Graf, W.L., 2005. Geomorphology and American dams: the scientific, social, and economic context. Geomorphology 71 (1–2), 3–26.

Grant, G.E., Schmidt, J.C., Lewis, S.L., 2003. A geological framework for interpreting downstream effects of dams on rivers. In: O'Connor, J.E., Grant, G.E. (Eds.), A Peculiar River. Water Science and Application, vol. 7. American Geophysical Union, pp. 203–219.

Gray, J.R., Glysson, G.D., Turcios, L.M., Schwarz, G.E., 2000. Comparability of Suspended-Sediment Concentration and Total Suspended Solids Data, U. S. Geological Survey, Water-Resources Investigations Report 00-4191. Reston, Virginia, 20 pp.

Gupta, A., Liew, S.C., 2007. The Mekong from satellite imagery: a quick look at a large river. Geomorphology 85, 259–274 (this issue). doi:10.1016/j.geomorph.2006.03.036.

Gupta, A., Hock, L., Xiaojing, H., Ping, C., 2002. Evaluation of part of the Mekong River using satellite imagery. Geomorphology 44 (3–4), 221–239.

He, D., Zhao, W., Chen, L., 2004. The ecological changes in Manwan reservoir area and its causes, Asian International Rivers Centre, Yunnan University, Kunming, Yunnan, China. Accessed through internet on July 2004: http://airc.ynu.edu.cn/English_site/Eng_publicat/Manwan.pdf.

Hori, H., 2000. The Mekong: Environment and Development. United Nations University Press, Tokyo. 398 pp.

Junk, W.J., 1997. The central Amazon floodplain: ecology of a pulsing system. Springer, Berlin, Ecological Studies, vol. 126. 525 pp.

Keskinen, M., Makkonen, K., Varis, O., 2007. The role of China and Cambodia in the Mekong Region. In: Jansky, L., Nakayama, M. (Editors), Endangered International Waters: Lessons from Domestic Security Issues. UNU Press, Tokyo.

Kondolf, G.M., 1997. Hungry water: effects of dams and gravel mining on river channels. Environmental Management 21 (4), 533–551.

Kummu, M., Koponen, J., Sarkkula, J., 2004. Upstream impacts on Lower Mekong floodplains: Tonle Sap case study. Proceedings of the International Conference on gAdvances in Integrated Mekong River Management". Lao PDR, Vientiane. 347–352 pp.

Kummu, M., Koponen, J., Sarkkula, J., 2005. Assessing impacts of the Mekong development in the Tonle Sap Lake. International Symposium of Role of Water Sciences in Transboundary River Basin Management. Ubon Ratchatani, Thailand.

Lamberts, D., 2001. Tonle Sap fisheries: a case study on floodplain gillnet fisheries in Siem Reap, Cambodia. FAO Regional Office for Asia and the Pacific, Bangkok, Thailand. RAP Publication 2001/11. 133 pp.

Lu, X.X., Siew, R.Y., 2006. Water discharge and sediment flux changes over the past decades in the Lower Mekong River: possible impacts of the Chinese dams. Hydrology and Earth System Sciences 10, 181–195.

Makkonen, K., 2005. Integrated water resources management in China. In: Biswas, A.K., Varis, O., Tortajada, C. (Eds.), Integrated Water Resources Management in South and South-East Asia. Oxford University Press, New Delhi, pp. 267–296.

McCormack, G., 2001. Water margins: competing paradigms in China. Critical Asian Studies 33 (1), 5–30.

Meade, R.H., 1996. River-sediment inputs to major deltas. In: Milliman, J.D., Haq, B.U. (Eds.), Sea-Level Rise and Coastal Subsidence: Causes, Consequences, and Strategies. Kluwer Academic Publishing, Dordrecht, pp. 63–85.

Mekong River Commission, 1992. Lower Mekong Hydrologic Yearbook. Mekong River Commission (MRC), Phnom Penh, Cambodia. 467 pp.

Mekong River Commission, 1996. Lower Mekong Hydrologic Yearbook. Mekong River Commission (MRC), Phnom Penh, Cambodia. 467 pp.

Mekong River Commission, 2003. State of the Basin Report: 2003. Mekong River Commission (MRC), Phnom Penh, p. 316. 1728:3248.

Mekong River Commission, 2004. Databases of Mekong River Commission. Mekong River Commission (MRC), Vientiane, Lao PDR.

Milliman, J.D., Meade, R.H., 1983. World-wide delivery of river sediment to the oceans. Journal of Geology 91, 1–21.

Milliman, J.D., Syvitski, J.P.M., 1992. Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. Journal of Geology 100, 525–544.

Morris, G.L., Fan, J., 1998. Reservoir Sedimentation Handbook: Design and Management of Dams, Reservoirs, and Watersheds for Sustainable Use. McGraw-Hill, New York. 848 pp.

Öjendal, J., 2000. Sharing the good: modes of managing water resources in the Lower Mekong Basin. PhD Thesis, Göteborg University, Sweden, 325 pp.

Pearce, F., 2004a. China drains life from Mekong River. New Scientist 182 (2441), 14.

Pearce, F., 2004b. Chinese dams blamed for Mekong's bizarre flow, NewScientist.com. Published 25 March 04.

Pearce, F., 2004c. Where have all the fish gone? Independent.co.uk. Published on web 21 April 2004.

Permpongsacharoen, W., 2002. Trust, hope and common sense. Watershed 8 (1), 44.

Plinston, D., He, D., 1999. Water Resources and Hydropower. ADB TA-3139 Policies and Strategies for Sustainable Development of the Lancang River Basin. Asian Development Bank, Manila. 35 pp.

Postel, S.L., Daily, G.C., Ehrlich, P.R., 1996. Human appropriation of renewable fresh water. Science 271, 785–788.

Puustjärvi, E., 2000. Review of policies and institutions related to management of upper watershed catchments — Yunnan, China. Poverty and environmental management in the remote GMS. Watersheds Project, Phase I. ADB Regional Environmental TA-5771. 33 pp.

Roberts, T., 2001. Downstream ecological implications of China's Lancang Hydropower and Mekong Navigation Project. International Rivers Network, accessed through internet on July 2005: http://www.irn.org/programs/lancang/.

Shmueli, D.F., 1999. Water quality in international river basins. Political Geography 18 (4), 437–476.

Siyam, A.M., Yeoh, J.S., Loveless, J.H., 2001. Sustainable reservoir sediment control. XXIX IAHR Congress. Beijing. Accessed through internet on July 2005: http://www.iahr.org/e-library/beijing_proceedings/Theme_E, 5 pp.

Sverdrup-Jensen, S., 2002. Fisheries in the Lower Mekong Basin: status and perspectives. MRC Technical Paper No. 6. Mekong River Commission, Phnom Penh. 103 pp. 1683-1489.

Tin, N.T., 2004. Personal communication. Tin is the water quality specialist in Mekong River Commission Secretariat, Vientiane, Lao PDR.

US Army Corps of Engineers, 1989. Trap efficiency of reservoirs, EM 1110-2-4000: engineering and design — sedimentation investigations of rivers and reservoirs. US Army Corps of Engineers (USACE), accessed through internet on July 2005: http://www.usace.army.mil/inet/usace-docs/eng-manuals/em1110-2-4000/, pp. 9.

Vörösmarty, C.J., Meybeck, M., Fekete, B., Sharma, K., Green, P., Syvitski, J.P.M., 2003. Anthropogenic sediment retention: major global impact from registered river impoundments. Global and Planetary Change 39 (1–2), 169–190.

Walling, D.E., 2005. Evaluation and analysis of sediment data from the Lower Mekong River, Report prepared for the Mekong River Commission, 61 pp.

Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global and Planetary Change 39 (1–2), 111–126.

Williams, G.P., Wolman, M.G., 1984. Downstream effects of dams on alluvial rivers. Geological Survey Professional Paper 1286. USGS, Washington DC. 61 pp.

WUP-A, 2001. Working paper 1 — hydrological review. Water Utilisation Project Component A: Development of Basin Modelling Package and Knowledge Base.

Yu, X., 2003. Regional cooperation and energy development in the Greater Mekong Sub-region. Energy Policy 31 (12), 1221–1234.