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Sediment storage and transfer in the Mekong: generalizations on a large river

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Abstract Our knowledge regarding sediment transfer and storage by a large river is limited. The morphology of the Mekong River and the physiography of its basin restrict sediment storage to its channel, or very close to it, for 4000 km, due to limited overbank accommodation space. Only for the last 600 km does the river move laterally to deposit sediment. This paper reviews: (a) the nature of sediment storage in the upper and middle Mekong; (b) sediment deposition in a wide flood basin in its lower course; (c) transfer of flood sediment into Tonlé Sap Lake; and (d) the seasonal pattern of sediment collection, transfer and storage along the river and into the South China Sea. The discussion is based mainly on satellite imagery at various resolutions, hydrological information from the Mekong River Commission, and field visits. It is suggested that the sediment storage pattern and the volume stored in the Mekong can be extensively disturbed by anthropogenic environmental alteration, such as the ongoing series of dam construction in the upper reaches.

Key words dam; Mekong; satellite imagery; sediment storage; sediment transfer

INTRODUCTION

Large rivers do not always demonstrate organized downstream transfer of sediment or progressive diminution of its texture. Meade (2006) has described the episodic transfer of sediment for thousands of kilometres by the Amazon and the Orinoco. The opportunity for storage is high along this vast distance and the lateral flux is comparable to the downstream transfer (Dunne *et al*., 1998). Blum & Tornqvist (2000) have generalized sediment transfer in terms of the vacuum cleaner model and the conveyor bed model, thereby indicating that variations occur in the sediment transfer mechanism. Sediment transfer is also complicated by varying physiography: rivers like the Zambezi or Irrawaddy flow in and out of gorges into flood basins. Sediment transfer and storage vary following changes in stream power and accommodation space.

For about 4000 km, the morphology of the Mekong and the physiography of its basin restrict sediment storage to the channel or an area very close to it. The river then moves freely to deposit sediment for the last 600 km of its course. The transfer and storage pattern is further complicated by the seasonality of river flow, episodic flood discharges, transfer of sediment during high flow upstream along a tributary to the Tonlé Sap Lake, and the cumulative pattern of water and sediment supply to the main river. The pattern, however, may change following construction of a series of dams in the upper Mekong, deforestation on slopes, and a probable increase in storminess and sea-level rise driven by climate change.

This paper constructs a general picture of sediment transfer and storage on the Mekong, a river ranked 12th in length, 8th in water discharge, and 10th in annual suspended sediment discharge. Sediment data on the Mekong are limited, unlike the data on discharge. This discussion is based primarily on satellite imagery at various resolutions supported by field visits, topographical maps, a limited description in the available literature, the hydrographic atlas of the river, the long-term hydrological records of the Mekong River Commission, and the sporadic and discrete sediment measurements taken also by the Commission.

THE MEKONG: A DESCRIPTION

The 4880 km long Mekong rises at an elevation of near 5000 m in Qinghai (China) to flow through a narrow and elongated basin in the highlands of eastern Tibet and Yunnan.

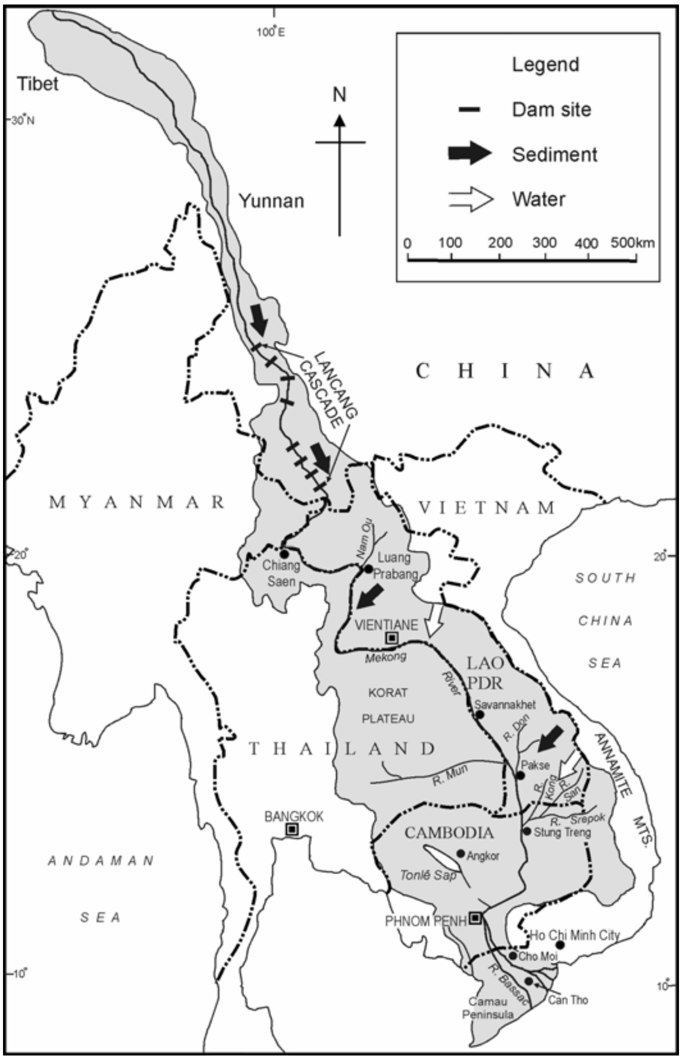

Fig. 1 Map showing the Mekong Basin with the places mentioned in the text. The locations of the eight dams of the Lancang Cascade are marked by lines across the river. In the downstream direction they are Gonguoqiao, Xiaowan, Manwan, Dachaoshan, Nuozhadu, Jinghong, Ganlanba, and Mengsong. The principal source areas for supplying water to the river are marked by open arrows and those of sediment by solid arrows.

The rest of the basin is much wider, and includes parts of Myanmar, Lao People's Democratic Republic, Thailand, Cambodia, and Viet Nam. The river runs for the first 3000 km on rock through narrow valleys in mountainous regions. The next 1000 km is on both rock and alluvium, with the mountain slopes always close. The river then emerges on to a 500 km wide lowland where it can move laterally for the last 600 km of its course, finally flowing through a large delta to the South China Sea (Fig. 1).

The locally complex geology of the Mekong is patchily known. Depressed lowlands in Southeast Asia and the South China Sea probably opened up due to extrusion tectonics associated with the collision of the Indian plate with the Eurasian one that led to the formation of the Himalaya Mountains (Tapponier *et al.*, 1982; Peltzer & Tapponier, 1988). This created a number of structural lineations and faults, confining the major rivers of Southeast and East Asia to a fault-controlled course. The Sông Hóng (Red) in northern Viet Nam is a classic example. The Mekong follows the line of several faults and the Loei Fold Belt in Lao PDR (Fenton *et al*., 2003). This restricted the river to a rock-cut channel with high banks for long stretches and also prevented the formation of a wide flood plain. The valley flat widens only in selective places such as near confluences with larger tributaries, or as Fenton *et al.* (2003) have described, near faults such as the Mae Chan Fault east of Chiang Saen in northern Thailand. Here the valley flat of the Mekong River widens to 4 km in a marshy depression at the mouth of the tributary, Kok, in a tectonic sag basin. The channel morphology of the Mekong in rock falls into three different classes. In cross-section the channel can be trapezoidal but more commonly it displays a 100 m wide inner channel flanked by rock shoulders summing to a total channel width of 600–700 m. The incision of the inner channel is in tens of metres, although a figure close to 10 m is common. Pools and rock ribs occur on top of the rock shoulder, stretching parallel to the inner channel. A third type of cross-section is seen where the channel widens and cross-channel rock ribs tens of metres high, isolated transverse rock piles, and lines of rapids characterize the river (MRC, 1996–1999; Gupta *et al*., 2002).

The Mekong also flows through a number of U-bends of various dimensions in rock. A tributary tends to join the main river at the top of the larger bends. Such bends are marked by rapids, exposed rock, deep inner gorges, scour pools on bed, and strongly-developed eddies on the surface. Lacassin *et al*. (1998) have proposed a slip-sense inversion, at a time subsequent to the extrusion tectonics that produced the large faults mentioned above, to account for several such U-bends. This probably explains the number of U-bends on the Mekong and its pattern of direction change along its course.

Except for a 500 km length of the river that starts several kilometres above Vientiane where the river flows through Quaternary alluvium, the Mekong is on rock up to the Lao PDR-Cambodia border. Near the border it flows through a 50 km long, 15 km wide anastomosed channel in rock that ends in a zone of rapids and waterfalls. Below this zone, the Mekong is on alluvium although its lateral movements are limited, suggesting that the river is still cut into rock underneath the alluvium. Below this is a short stretch of the freely-moving Mekong upstream of the delta.

The discharge of the Mekong is seasonal. Eighty percent of its annual discharge arrives between June and November with the southwest monsoon. A short rise happens earlier in May, associated with the arrival of summer snowmelt on the Tibetan Plateau.

Large floods tend to occur late in the wet season tailing off very slowly, and often triggered by the arrival of tropical storms over the Annamite Mountains when the Mekong is already high. The tributaries are highly seasonal, with spikes of high flow rising from a low stage immediately following rainfall (MRC Hydrologic Yearbooks, various dates). The runoff contribution is uneven across the basin, a disproportionally high amount of water arriving from two sources: (a) the steep northern hills of Lao PDR and northern Annamite Mountains, and (b) the southern Annamite slopes (MRC Hydrologic Yearbooks, various dates). A detailed description of the river and its basin is provided in Gupta & Liew (2006).

ACCOMMODATION SPACE

For almost its entire course in China, the Mekong flows in a steep rocky gorge. Its regional names, Dza Chu (River of Rocks) in Tibet and Lancang Jiang (Turbulent River) in Yunnan, correctly describe the channel morphology and behaviour. There is very little space to accommodate the gravelly alluvium outside the channel except at tributary mouths. Further downstream in Thailand and northern Lao PDR the river flows through a steep (0.0003 gradient) and narrow valley where only a limited amount of sediment can be stored. The volume of this sediment has not been properly determined but it appears to be wedge-shaped on both sides, with the maximum thickness on the banks being in the order of several metres over exposed rocks. The distance between the river and the steep hills varies between 10 m and about 2 km. Sediment is therefore stored primarily inside the channel as insets against banks, against transverse rock features described earlier, on rock shoulders, and as a mobile belt on the rock bed.

Although the Mekong traverses east and southeast across Quaternary alluvium that starts near Vientiane, signatures of a mobile channel are not visible. The river meanders with low amplitude bends near Vientiane where sand and pebbles in the channel form braid bars with falling discharge in the dry season. Point bars and bank erosion are seen near Vientiane but further downstream the river consists of 50–60 km near-straight reaches joined by sharp bends on a very low gradient (0.00006). It is likely that the river is rock-controlled underneath the alluvium. The major sedimentation form is a 1–3 km long and 200–400 m wide lozenge-shaped bar with pointed ends. Such bars could be in mid-channel but commonly they have a skewed location, and the narrower part of the channel probably silts up anchoring the bar to the valleyflat alluvium. Past attachment of such bars can be identified from satellite imagery but the alluvial surface next to the river does not display striking signs of a laterally-moving channel.

Downstream of this alluvium, the Mekong is back on rock and sediment accommodation inside the channel again becomes common. Even the banks for some distance are mostly rock cut. The valley widens downstream, and although in-channel sedimentation occurs forming bars and islands, thicker alluvial layers begin to appear on top of rocky banks and fans are seen at tributary mouths. Further downstream is the anastomosed reach on Mesozoic basalt, on which the river deposits sediment to form rock-cored low islands.

In contrast, the river deposits a considerable amount of sediment overbank in the alluvial basin of Cambodia: first, in a narrow belt along the channel as identified by attached bars and filled old channels and then over a wide area that is flooded periodically and across which the river moves laterally. The unique phenomenon here is the connection of the Mekong River with the lake of Tonlé Sap via the Tonlé Sap River. During the dry season when the Mekong is low, water drains from the lake to the Mekong. The flow in the link river is reversed during the high stage of the wet season, and sediment-laden water from the Mekong flows into the lake which acts as deposition space for Mekong-borne sediment. Further downstream, sediment is deposited on the upper parts of the delta and then via the distributary channels to the South China Sea.

SEDIMENT TRANSFER AND STORAGE ON THE MEKONG

The sediment of the Mekong is sourced from: (a) mass movements on steep valley slopes in China and northern Lao PDR that end directly in the channel; (b) sediment contributed by short tributaries draining steep side slopes that form small steep fans of gravel and sand at confluences with the Mekong; (c) sediment contributed by large rivers such as the Nam Ou, Mun, and the Kong, San and Srepok; and, recently, (d) sediment from accelerated erosion on the slopes following deforestation and shifting agriculture. Unlike discharge, the sediment load of the Mekong is not well documented and constructing a sediment budget for the river is not feasible at present. It is probably reasonable to assume that sediment input is directly related to steep and tectonic landforms and areas of high runoff. Given this assumption, high sediment contribution may be expected from the narrow steep part of the basin in China, the hills of northern Lao PDR, and the Annamite Mountains.

Some sediment measurements are available. A publication of the Mekong River Commission (MRC, 1997) mentions 75–85 × 10^6 t arriving from the Chinese part of the Mekong and 150–170 × 10^6 t being discharged into the South China Sea. The amount discharged into the sea is comparable to Meade's (1996) estimate of 160 × 10^6 t or the annual rate of 144 ± 36 × 10^6 t calculated by Ta *et al.* (2002) based on the rate of delta progradation from borehole data. When its sediment yield is plotted against the drainage area, the Mekong is very close to the regional average for South and Southeast Asian rivers (Gupta & Krishnan, 1994), indicating that the Mekong does not carry an amount of sediment comparable to that of the Ganga or the Yangtze. The hydrological yearbooks of the Mekong River Commission list sediment measurements that range from very low concentrations in the dry season to 10^3 mg L^{-1} during the wet. Sediment concentration during a high flood probably has not been recorded. Wood *et al.* (2006) have measured suspended sediment load near Chiang Saen, northern Thailand. Their figures exceeded 350 mg L^{-1} in the high stage of the wet season, reaching 1200 mg L^{-1} during the rising hydrograph of a flood in 1994. They also describe a clockwise hysteresis effect marked by higher sediment concentration at the onset of the rainy season when the river remobilizes sediment already present in the channel. They refer to an MRC measurement of 1600 mg L^{-1} during the flood of 1968 when the discharge at Chiang Saen (drainage area 189 000 km^2) peaked at 11 000 $m^3 s^{-1}$.

The flood of 2000 which roughly had a recurrence interval between 5 and 10 years (the exact RI varied at different stations on this long river) generally did not top the banks until the alluvial basin of Cambodia was reached where the lowland was inundated for 6–8 weeks. SPOT satellite images displayed a high reflectance from the water overland that gradually disappeared, the water turning dark indicating overbank sedimentation being complete by the early stage of flooding. Bed load on the Mekong has not been measured but field observations indicate transportation of the sand, pebble and cobbles resting on the rocky bed of the channel. Even small boulders (less than a metre) were seen on sand bars after the flood of 2000.

Sediment transport in the Mekong is episodic, related to the high flows of the wet season when the water depth increases to 10–30 m depending on whether the inner channel is present or not. Measured data are rather limited but the reddish brown colour of the water indicates significant sediment transfer. The Mekong River Commission (1997) recorded that the tributaries in Lao PDR may carry 50–100 t day^{-1} in the dry season, a figure that may rise to 170 000 t day^{-1} during the wet monsoon. It is, however, difficult to determine bed load behaviour in the inner channel and scour pools because of their depth. The maximum depth recorded for a scour pool at a bend is 60 m below the low water level (MRC, 1996–1999).

The episodic transfer of the sediment is supported by bank stratigraphic sections. In general, the banks consist of 5–10 m of sandy silt and silty sand over several metres of gravel that rest on bedrock. The silt and sand beds are generally structureless and between 0.5 to 2 m thick (Fig. 2). Their stratigraphy suggests deposition in episodic flood events. Wood *et al*. (2006) estimated deposition of 5 m of silt in several floods over a period of 85 years, based on a radiometric date from buried charcoal and burnt bones and a known date for structures on the bank of the river. The seasonality of downstream transfer is also seen by the changing volume of sediment released by the Mekong at the delta face (Fig. 3). This has been determined by mapping backscattering in coastal water from MODIS images at the Centre of Remote Imaging, Sensing and Processing, National University of Singapore. Sediment transfer in the Mekong is seasonal, complemented episodically by large floods.

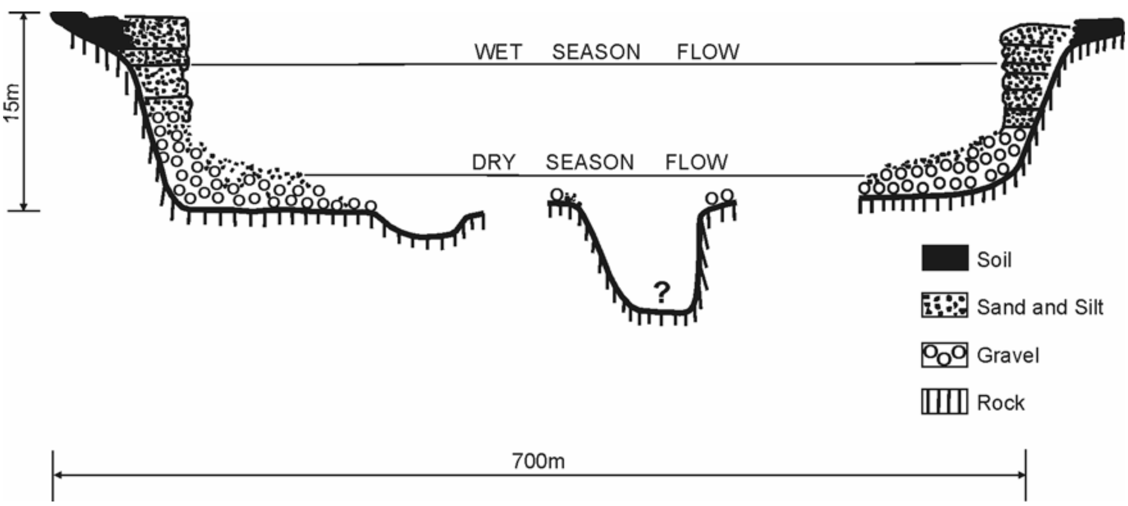

Fig. 2 A generalized stratigraphy and cross-section of the Mekong in rock.

(a)

(b)

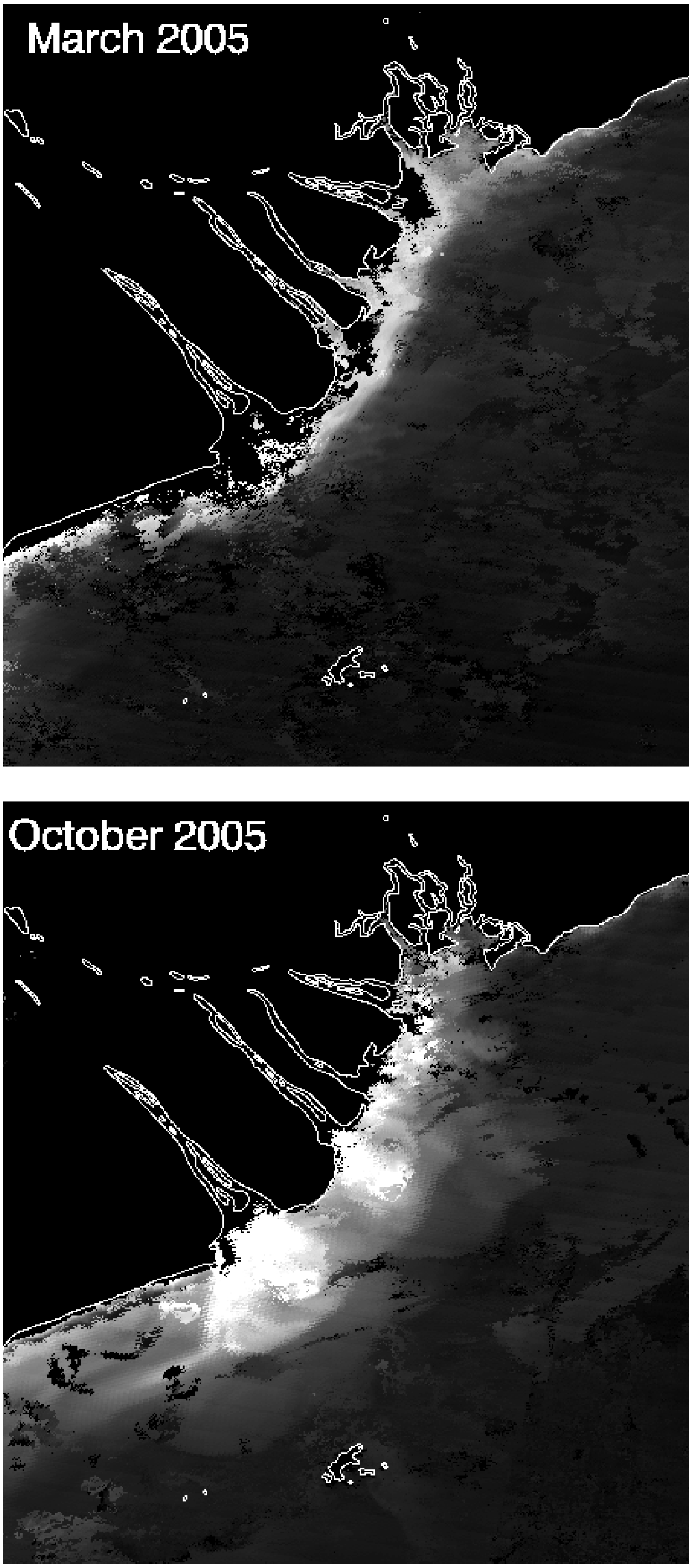

Fig 3 Seasonal pattern of sediment discharge by the Mekong to the South China Sea, derived from MODIS images: (a) March 2005 (dry season), (b) October 2005 (wet southwest monsoon). Land area masked for better viewing.

The storage of the Mekong sediment between seasonal and episodic transfers is unusual. Upstream of the Cambodian lowland, the sediment is stored mainly in the channel; a fraction may be welded as large islands to the bank thereby extending the valleyflat. In-channel storage is determined less by channel geometry and more by channel relief. Sediment is stored as a quasi-mobile belt of sand and gravel resting on or against bedrock, transverse rock ribs, rock shoulders flanking the inner channel, and accumulations of boulders and cobbles on the bed. Finer material comes to rest against such piles of boulders and extends and builds up the feature to form islands that, after emergence, are further consolidated by vegetation. These are the mid-channel elongated rock-cored islands (Fig. 4) described earlier. The best examples are seen in the anastomosed reach upstream of the Lao PDR-Cambodia border. Here all the islands occupy relatively higher flows in Mesozoic basalt, separated by the water of the Mekong dividing into a number of channels that occupy the lower flows in the rock. Only two of the islands carry low hills in weathered basalts. The rest are low, rising 2–3 m above the water level with fresh sand and silt extending their size. The islands, however, are permanent features. They carry large trees and settlements, and were described about 150 years ago by travellers along the Mekong.

Fig. 4 Rock-cored island in the Mekong (photo: Avijit Gupta).

It is possible that the Mekong has built only a part of the 500 km wide alluvial plain of Cambodia. In the upper part of this plain, abandoned former courses and past scroll bars welded to the bank are seen next to the river. In contrast, near Phnom Penh, the Mekong displays the standard morphology and sedimentary features of a mobile meandering river with levees, crevasse splays, backswamps, abandoned channels and shifting point bars over a zone of several kilometres. Sediment is transported downstream but also carried laterally by overbank floods, channel shortening, and crevasse splays. Sediment in overbank flooding reaches tens of kilometres.

CONSEQUENCES OF ANTHROPOGENIC CHANGES

Even several years ago, the Mekong was a river without any impoundment. Anthropogenic alterations that caused concern were limited to deforestation and shifting cultivation on steep slopes. Gupta & Chen (2002) suggested that erosion from such land practices was limited to the first several weeks of the wet season prior to the growth of new vegetation cover. The fresh yellow sand seen in the tributaries, especially in northern Lao PDR, and as insets against banks and on top of bars, are probably associated with deforestation and shifting cultivation.

A set of eight dams, collectively known as the Lancang Cascade, is being built by China on the Mekong in Yunnan. Of these, two small dams, Manwan (1500 MW) and Dachaoshan (1350 MW) are complete and work on three others (Xiaowan, Jinghong and Nuozhadu) has started. The 300 m high Xiaowan with an active storage of 990×10^6 m^3 and a power-generating capacity of 4200 MW will be the second largest dam in China on completion, being second only to the Three Gorges. The scheduled date for completion of all the dams is 2020 when a total of 40 km^3 of water would be stored. At present about 73 km^3 of water flows out of China (Kummu *et al*., 2006).

The steady release of water from the dams is expected to work against the seasonal nature of the river. The effect may be localized, as only 18% of the Mekong's discharge at the mouth comes from Yunnan. The important sources for the Mekong's discharge, the hills of northern Lao PDR and the Annamite Mountains, lie downstream. It is on the sediment where the effect of impoundment will be crucial. About half of Mekong's sediment comes from the narrow northern valley in Yunnan and is generally coarse-grained. The data related to these impoundments are difficult to get and at times become anecdotal, but it has been reported that 30 m of sediment has accumulated in the reservoir behind Manwan in three years. Kummu *et al*. (2006) mention that in Chiang Saen, about 650 km downstream from the Manwan Dam, the measured annual sediment flux has been reduced from about 70×10^9 to 32×10^9 kg. This combination of a small reduction in the peak flow of the wet season and a large reduction in sediment, especially of the coarse variety, may lead to what Kondolf (1997) calls "hungry water". Together, floods, loss of upstream sediment, and loose sand and gravel deposited on rock could lead to stripping of most of the sediment stored in the channel in a few years, transferring the sediment to the downstream alluvial lowland and delta and also via the link river into the Tonlé Sap. The expected changes may be listed as:

(a) channel scour and incision;
(b) bed armouring;
(c) stripping of loose sediment in the rock-cut channel;
(d) conversion of the river to a rock canyon upstream of the alluvial lowland;
(e) erosion at the base of the islands, many of which are farmed and several of which are settled;
(f) accelerated transfer of sediment to the lowlands and the delta on a decadal scale;
(g) accumulation of sediment in the Tonlé Sap Lake leading to its shrinkage;

(h) post-sediment erosion of the delta face;
(i) deterioration of the aquatic life and wetland vegetation.

The depletion of the sediment in the channel would not only alter the morphology and behaviour of the Mekong but also, in several decades, substitute the accelerated passage of sediment to the alluvial lowland and delta with a shortage in downstream sediment flux. Given the timescale, it may be coincident with an increase in storminess in the monsoon tropics associated with climate change and a small rise in sea level resulting in serious consequences. In an ideal scenario this could be modelled with real data. Unfortunately, for the Mekong, the discussion remains speculative at this stage.

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