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CHAPTER

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# Geomorphology and Sedimentology of the Lower Mekong River

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OUTLINE



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## 1. INTRODUCTION

p0090 This chapter provides an introduction to the geomorphology of the Lower Mekong River within a geological and physiographic setting. Although the system is little researched, there is sufficient literature to provide a skeleton overview of the functionality of the River. The regional context of the Mekong River within Southeast Asia is provided by Gupta (2005a). The Mekong River Basin extends from the Tibetan Plateau to the South China Sea,





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strong movements accompanied by extensive lava flows, which also influenced the development of the Mekong drainage network (see Chapter 2).

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## 4. GEOMORPHOLOGICAL ZONATION OF THE MEKONG RIVER

p0150 Adamson, as reported in MRC (2001, p. 91) and MRC (2004, p. 8), recognized six distinct hydromorphological reaches along the Mekong River (Table 5.1). Gupta (2004) proposed an eight-division geomorphological categorization from which Carling (2005) derived a series of seven representative geomorphological reaches for the main stem Lower Mekong River plus the Tonlé Sap system. From this framework, the MRC recognize, for management purposes, six major geomorphological zones along the Mekong River that together with the riverine wetlands, especially the Tonlé Sap, can be regarded as constituting the key fluvial geomorphological attributes of the system (Table 5.1). Zone 1, from the source of the river in China to Chiang Saen in Laos, is a navigable waterway between Cheng Hung in China and Chiang Saen in Laos. Zone 2, from Chiang Saen to Vientiane, is bedrock confined and contains many rapids. Zone 3 extends from Vientiane to Pakse, wherein in the north the river is alluvial, largely single channel and sinuous, being described by Adamson as "broad and stately" but is increasingly bedrock confined towards the south. Zone 4, from Pakse to Kratie is a bedrock-confined multichannel complex with frequent rock shoals and islands and includes major rapids and water falls, notably the Khoné Falls on the Lao PDR-Cambodian border. Zone 5A is from Kratie to Phnom Penh wherein the river is again alluvial, meandering, and an anastomosed complex. Zone 5B is the Tonlé Sap system. Zone 6, from Phnom Penh to the coast is flood-prone fluvial floodplains and the tidally influenced delta. Excluding Zone 1, the Lower Mekong River zones are considered below. At this point, the classification of channel geometry in plan requires some explanation.[1]

### 4.1. Zone 2: Bedrock Single-Thread Channel: Chiang Saen to Vientiane s0030

p0155 From the China border to upstream of Vientiane, the Mekong River is a single-thread channel cut into bedrock and closely confined by mountain slopes. Locally, the river divides around in-channel bedrock outcrops and these are also often the nucleus for deposits of gravel and sand that form in-channel bars and small

[1]Generally the usage here follows convention with some significant variants that help define attributes of the Mekong system clearly. The channel may be relatively straight (sinuosity: 1-1.05), sinuous (sinuosity: 1.06-1.30, i.e., high radius bends), or meandering (sinuosity: 1.31-3.0, low radius bends). The river channel may exhibit a single channel or multiple interconnecting channels. In the case of interconnecting channels, the river might be described as braided, anabranching, or anastomosed. There is no convention on terminology for river reaches exhibiting multiple reaches, although several typologies have been proposed (Bridge, 1993; Nanson and Knighton, 1996). Here, braided river reaches are defined as channels with essentially a single channel at high flow (e.g., bankfull) but multiple channels at low flow. The channels are separated by banks of sand/gravel that are poorly fixed by vegetation, that migrate readily and are submerged by high flows. Divided (or wandering) reaches have up to three channels (Brierley and Fryirs, 2005, p. 119). Anastomosed reaches are defined here as multiple channels (>3) separated by large islands that sustain mature vegetation, that are fixed or migrate slowly by bank erosion and are rarely if ever inundated by high flows (e.g., bankfull). The islands are several hundreds of meters wide and possibly several kilometers long. Anabranch reaches are considered here to be where a channel (usually minor) deviates from the main stem and flows remote from the main river for a downstream distance of many kilometers before joining again with the main channel. Anabranch systems occur in Cambodia where the main channel is anastomosed. This latter planform is similar to that described by Bridge (1993, Fig. 5.4).

t0010 TABLE 5.1 Geomorphological and Hydrological Zonation of the Mekong River

thread

| Adamson | Gupta | Location | Carling (this chapter) | Representative reach characteristics |
|---|---|---|---|---|
| Zone 1 | – | China | Zone 1: China | Not applicable |
| Zone 2 | 1a, 1b, 1c, 1d | 1a: Chinese border to Nam Ou<br>1b: Nam Ou to 30 km upstream of Nam Loei<br>1c: 30 km reach upstream of Nam Loei<br>1d: Nam Loei to 5 km upstream of Vientiane | Zone 2: Bedrock single-thread channel—Chiang Saen to Vientiane: deep pools, bedrock benches | 1. Gradient: 0.0003<br>Channel width: 200-2000 m<br>Reach length: 250 km<br>Low flow depth: ca. 10 m<br>Seasonal stage change: 20 m |
| Zone 3 | 2a, 2b, 3 | 2a: Vientiane to Pakranh<br>2b: Pakranh to Mukdahan<br>3: Mukdahan to Mun confluence near Pakse | Zone 3: Alluvial single tread or divided channel—Vientiane to Pakse | 2. Gradient: 0.0001<br>Channel width: 800-1300 m<br>Reach length: 100 km<br>Low flow depth: ca. 3 m<br>Seasonal stage change: 13 m<br>3. Gradient: 0.00006<br>Channel width: ≤2000<br>Reach length: 400 km<br>Low flow depth: ≤5 m<br>Seasonal stage change: 14 m |
| Zone 4 | 4, 5 | 4: Pakse to Muang Khong<br>5: Muang Kong to Stung Treng | Zone 4: Bedrock anastomosed channels: Pakse to Kratie, that is, Siphandone (4000 islands reach) | 4. Gradient: 0.00006<br>Channel width: 750-5000 m<br>Reach length: 150 km<br>Low flow depth: variable<br>Seasonal stage change: 15 m<br>5. Gradient: 0.0005<br>Channel width: ≤15,000 m<br>Reach length: 200 km<br>Low flow depth: ca. 8 m<br>Seasonal stage change: 9 m |
| Zone 5 | 6, 7 | 6: Stung Treng to Kampong Cham<br>7: Kampong Cham to Phnom Penh | Zone 5A: Alluvial meandering/ anastomosed channels—Kratie to Phnom Penh: scroll bars, backwaters, overbank flooding, that is, upstream of confluence with Tonlé Sap River | 6. Gradient: 0.000005<br>Channel width: ≤4 km<br>Floodplain width: 8-64 km<br>Reach length: 50 km<br>Low flow depth: ca. 5 m |

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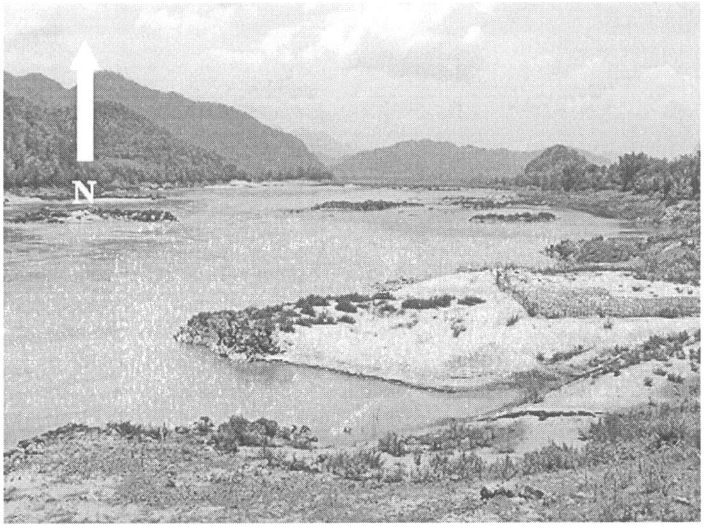


f0020 FIGURE 5.3 View upstream from left bank near Luang Prabang. Width of channel is approximately 500 m.

well-bedded sand including cross bedding that indicates local flow in an upstream direction along the river banks. Thus, these bars are typical of "slack-water" deposits that form in flow separation and slow-flow areas close to the bank line and are best developed in reentrants to the bank line. The size of these sandy bars probably varies annually. These bars may result from anthropogenic disturbance within the system that has led to an increase in the flux of sand through the system in historic and modern times. From inspection of satellite images, much of the course of the Mekong between Nakhon Phanom and Pakse is also a single-thread bedrock channel or, at least, has significant bedrock control alternating with alluvial reaches or exhibiting an alluvial overprint on a bedrock channel.

delete hyphen

(Gupta and Liew, 2007)

p0165 There is a gauging station at Luang Prabang within a bedrock section (Fig. 5.4). The lowest and the highest flow recorded are 485 $m^3$ $s^{-1}$ and 25,200 $m^3$ $s^{-1}$, respectively. At the gauge site, the water depth at which the terraces would flood is 30.2 m which would require an estimated discharge of 44,892 $m^3$ $s^{-1}$. Thus, in the period of record (1960-2006), the benches have not been inundated and a degree of Quaternary and Holocene incision is inferred.

## 4.2. Zone 3: Alluvial Single-Thread or Divided Channel: Vientiane to Mun River Confluence s0035

Between Vientiane and the Mun confluence, much of the river course is alluvial and consists of a fine sand bed with sand and silty sand river banks. However, downstream of Nakhon Phanom, and especially in the downstream reaches, bedrock increases in importance. In the alluvial reaches, the channel is not characterized by tight meanders but rather it is actively migrating laterally via long-radius bends. This process results in steep to vertical cut banks on one side and gentle alluviated banks on the opposing side. The key feature of the alluvial sections of this zone is a tendency for the river course to develop a divided channel (wandering) configuration. Large p0170

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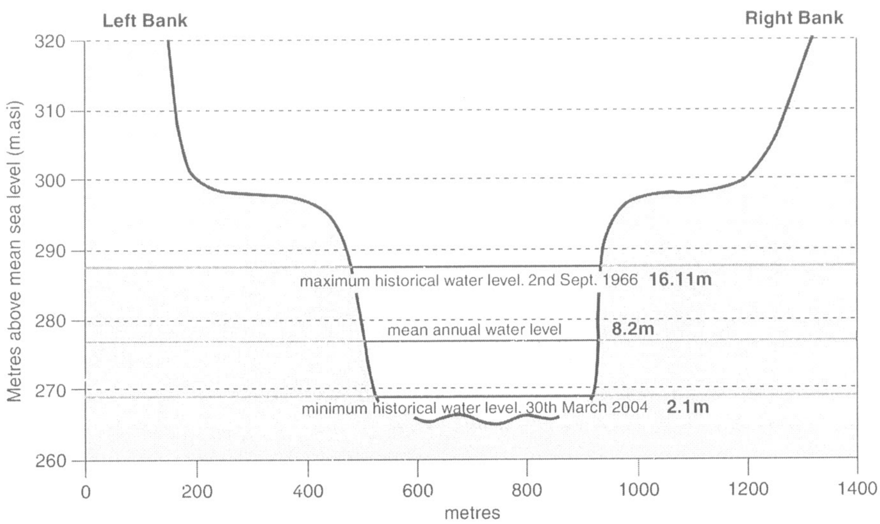


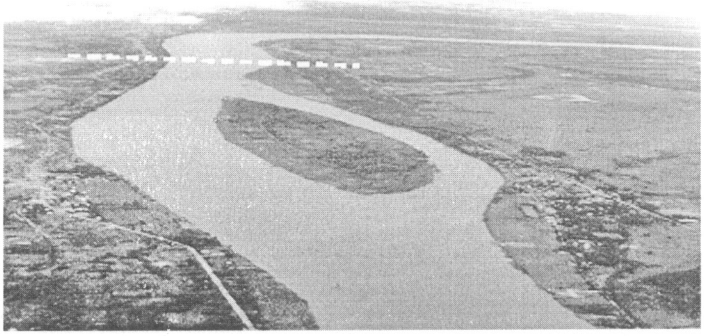

f0025 FIGURE 5.4 Channel cross section at Luang Prabang gauging station.

elongate or lozenge-shaped isolated islands individually known as "ban" occur that appear to be a relict portions of the floodplain rather than having developed by accretion of sand bars in the main channel. Evidence for this assertion is that (i) the top of the islands tend to be flat and at an elevation in accordance with that of the adjacent floodplain; (ii) the island stratigraphy and sedimentology are the same as seen in the floodplain cut banks; (iii) islands often support relict and degraded "primary" forest. A detailed 1:50,000 geomorphological map of the river showing one such island, palaeochannels, and other landscape features in the Vientiane reach was published as annex to books (Ōya, 1979, 1993) and was based on 1967 survey work.

p0175 Through time, islands may become connected to one or other river bank by progressive shoaling of one channel. Islands also extend downstream and upstream by progressive accretion at their extremities. In some examples, such as Ban Don Sang Khi, extension is augmented by aeolian dunes developing on exposed sand flats during the low-water period. At Ban Don Sang Khi, there is a single-channel alluvial reach some 750 m wide and 7-8 m deep at low flows, immediately upstream of the confluence with the Pak Ngum River (Fig. 5.5).

Natural levées occur on both banks which suggest the river used to overtop them, although it does not do so under the modern-flow regimen except in the vicinity of tributary confluences. Beyond the levées are wetlands which have been artificially drained to varying degrees for agriculture. The river bank on the Laotian side is about 8-10 m high and is composed primarily of silt and clay. The ~~backline~~ is in places vertical in the upper half to two-thirds with slumped material along the base or a cut surface inclined to about 45° extends from the low water up to the vertical sections. Most of the bank face is unvegetated but more gentle slopes are patchily covered by annuals, or cultivated for recession agriculture. Bank collapse is by block fall or locally rotational mass failure. Significant basal cutout is not evident and so high flows are responsible for p0180

bankline



f0030 FIGURE 5.5 Oblique aerial view looking downstream during high-stage river discharge at Ban Don Sang Khi. Dashed line indicates gauged section. Width of channel at gauge is 800 m.

recession with negligible retreat during low flows. Although the modern bed is largely composed of fine sand, there are frequent outcrops (< 2 m high) of indurated fluvial pebble beds and black layers, ca. 30-50 cm thick, near the low water mark, which may be organic-rich or black inorganic silts. The outcrops of pebble beds indicate a degree of Holocene incision of the river. The black layers may represent reducing environments associated with back-swamp deposits being exposed as the river migrates laterally. The river is being actively cut back ~~being~~ on the outside of long curving bends with recession rates of 0.1-0.5 m per year. Such recession is compensated by deposition on the other side of the river. Accreting banks are gently inclined and well vegetated with locally intensive recession agriculture.

p0185 The origin of the islands has yet to be confirmed. Some islands may develop by extension and vegetation of sandy bars. However, taking Ban Don Sang Khi as an example, the island appears to have formed by the development of a chute channel across the inside of a long-radius river bend cutting off a portion of floodplain. Such chutes form during very high flows when the river attempts to take a shortcut through the bend rather than follow the longer low-flow course. Ban Don Sang Khi is around 15 m high (Fig. 5.6), the same elevation as the floodplain, and has many large and mature diptocarp trees, which can take a century to grow. The sediments in the banks of the island are not typical of sandy bars but are similar to the floodplain sediments seen in the cut banks of the river. Thus, it is possible that avulsion occurred such that a chute isolated a remnant of floodplain. Further fluvial accretion is occurring at the upstream end of the island which is augmented by the growth of aeolian dunes as wind-blown sand, sourced from exposed parts of the river bed, is trapped by pioneer vegetation.

There is a gauging station at Vientiane and a rated section at Pak Ngum (dotted line on Figs. 5.5 and 5.7). The lowest recorded flow is 1250 $m^3 s^{-1}$, the water depth at bankfull is 19 m, and the highest flow recorded is 25,900 $m^3 s^{-1}$. At Pak Ngum, the river ~~does not seem to have~~ flowed overbank in the period of the gauge record ca. 1960-2000, although back-swamps can become flooded via Mekong water flooding out through tributary junctions. p0190

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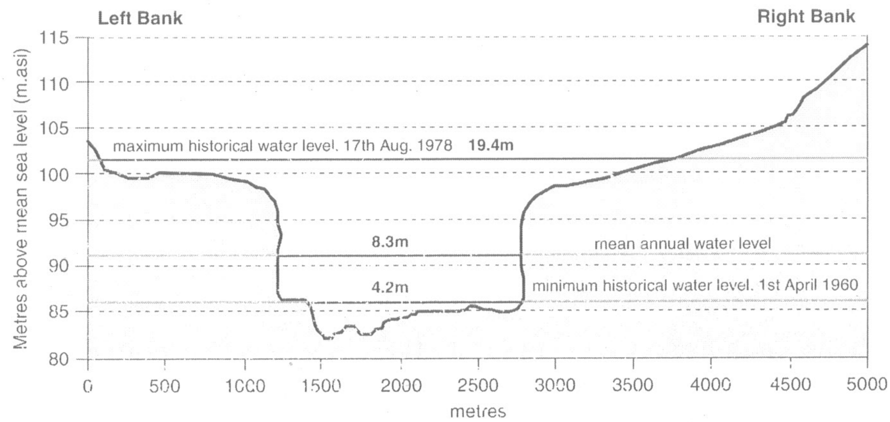


f0055 FIGURE 5.10 Channel cross section at Pakse gauging station.

overbank at Pakse and at Stung Treng in the period of the gauge record ca. 1960-2008: notably in 1978, 1979, and 2000.

## s0045 4.4. Zone 5: Alluvial Meandering/ Anastomosed Channels

p0200 Downstream of Kratie, the river is a floodplain meander complex with anabranch and anastomosed channels connecting in times of high water to Tonlé Sap lake (Fujii *et al.*, 2003). The junction of the Mekong River and the Tonlé Sap River form the two northern arms of a complex channel junction known as Quatre Bras (or Chaktomuk Junction), that in 2002 was recorded as moving downstream by 10 m per year (Anonymous, 2002a). The southern two arms of the Quatre Bras consist of the Mekong River and a major distributary, the Bassac River, which divides from the Mekong River at point. As the monsoon rains commence, the Mekong River starts to rise and floods wetlands adjacent to the river. Local tributary inflow to the Tonlé Sap River and lake also commences. As the level of the Mekong at Phnom Penh continues to rise the flow of the Tonlé Sap reverses and Mekong River water joins local runoff to fill the lake to a depth of around 10 m. As flow in the Mekong falls, the Tonlé Sap flow reverses and the lake is reduced to around 2 m deep.

The main flooding in this zone occurs annually along the Mekong River south of Kratie to the border with Viet Nam and also along the Tonlé Sap River. Much floodplain flow occurs parallel to the main rivers along land depressions and palaeochannels lateral to and between the main rivers. To the south of Kratie, much of the out-of-channel overbank flow is sustained by the guiding control of natural levées (Fig. 5.11) which are well developed, locally prevent return flows into the main rivers and also delay the same during flood recession. Channel migration in this region is extensive and natural but threatens developing infrastructure at some locations, such as at Kampong Cham (Uyen, 1989a,b) where flood revetment that protects large areas of the town from inundation during annual floods is at risk. The Quatre Bras (Chaktomuk) junction is morphologically complex and has been subject to considerable engineering study with a view to management and stabilization (Olesen, 2000). ~~Situated~~ near the town of Kampong Cham, this p0205 Au4

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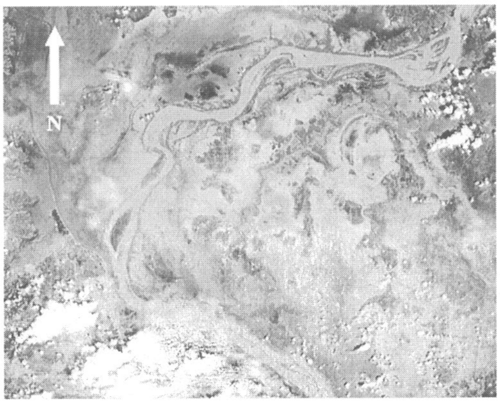


f0060 **FIGURE 5.11** Satellite image of the Mekong River during flood season in vicinity of Kampong Cham. Landsat-7: field of view approximately 45 × 45 km.

is a very complex and dynamic meandering system with anastomosed and anabranch channels. There is an actively meandering main channel developed in very fine sand and silt within an extensive floodplain. The latter is between 8 and 60 km wide. The insides of the meanders are accreting whilst the outsides are eroding rapidly. The sandy accretion areas inside the meanders are called point bars. Here, they are complex, consisting of a multitude of smaller elongate sedimentary bars separated by long wetted small channels that cut across the point bar complex. These small channels are called chute channels. Taken together, the small channel network forms ~~an anastomosed~~ a braided channel network on each point bar complex. The islands are sometimes very large with mature forest but more usually the islands are sandy with rank grasses and sedges. The islands erode readily and are thus individually has transitory features within a relatively stable but dynamic complex of islands and channels. The Tonlé Sap system is described elsewhere in this chapter, but it should be noted that little is known of the geomorphology of the northern Cambodian (Mekong) system and its relationship with the Tonlé Sap lake, Tonlé Sap River, and associated floodplains.

Basalt bedrock outcrops locally and is most evident on the west bank at the town of Kampong Cham. The bedrock outcrops control the overall gradient of the river and also cause "pinch-points" in the river network. It is noted that at Kampong Cham town, the river is reduced to a single channel as it passes the bedrock, but meanders freely and braids somewhat upstream and downstream of this point where it is not constrained. During and since the Quaternary, the river has meandered across much of the floodplain, shifting tens of kilometers. Kilometres The evidence for this is shallow linear or curvilinear pools on the floodplain and long very low-amplitude ridges often occupied by tree lines or picked out by footpaths and field alignments. These ridges are called scroll bars which typically are curvilinear and subparallel with one another. Today, they are actively forming in the point bar complexes. p0210

There is a gauging station at Kratie but the rating is very unstable, varying from year to year. A gauge at Kampong Cham (Fig. 5.12) is more reliable and records the lowest flow as 1880 $m^3$ $s^{-1}$. The highest recorded flow is 69,000 $m^3$ $s^{-1}$ and the channel depth at bankfull is 20 m. Overbank flows occur on an annual basis. p0215

## 4.5. Zone 5: Tonlé Sap Lake and River System s0050

The name Tonlé Sap is applied to the "great lake" that dominates central Cambodia and to the 147 km long river that connects the lake to the Mekong River. The lake has an area of some 3000 $km^2$ during the dry season increasing to 10,000-14,000 $km^2$ during the wet-season floods Au5 (MRCS/UNDP, 1998; MRCS/WUP-FIN, 2003; Tsukawaki *et al.*, 1994) such that the surface area increases fivefold (Puy *et al.*, 1999). Early investigations are reported by Carbonnel and Guiscarfé (1965) and Carbonnel (1972). p0220

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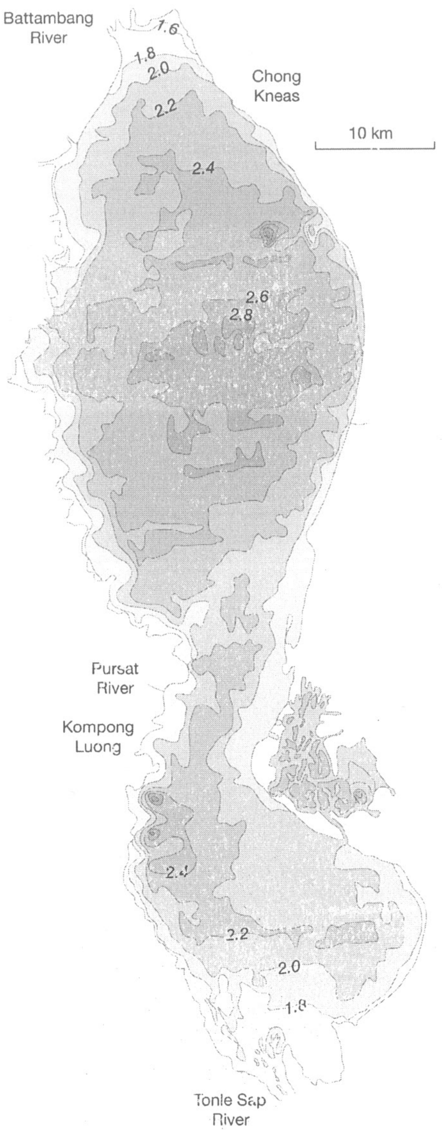


f0070 FIGURE 5.13 Bathymetry of the Tonlé Sap lake. Contours are in meters for dry-season water level.

The original estimates of sedimentation rates were developed by Carbonnel and Guiscarfé (1965) and Carbonnel (1972) from a single radio-carbon date of a single sediment sample obtained at a depth of 1.8 m below the lake bed. Given a date of 5720 ± 300 $^{14}C$ years BP an average sedimentation rate of 0.3 mm per year was determined. A modern sedimentation rate was also determined from estimates of the 1962-1963 sediment load. From this calculation, it was determined that the modern rate of sedimentation was 0.15 mm per year higher than the long-term rate determined from the lake core and consequently it was concluded that the lake was filling more rapidly with silt in modern times (Carbonnel and Guiscarfé, 1965). The suspended sediment data for the Tonlé Sap for the period 1950-1951 and 1955-1956 show around 4.5-6.0 × $10^6$ tonnes per year entering the Tonlé Sap from the Mekong and around 3.0-6.7 × $10^6$ tonnes per year passing into the Mekong from Tonlé Sap. The rate of sedimentation was thus estimated as less than 1 mm per year (Pantulu, 1986). More recently, though still limited, coring studies have determined that sedimentation may have declined through time, interpreted as owing to a lack of additional accommodation space for sedimentation in the northern part of the lake (Tsukawaki, 1997). p0235

## 4.6. Zone 6: Alluvial Deltaic Channels s0055

The Plain of Reeds is a trans-boundary ecosystem of 700,000 ha in Viet Nam and Cambodia lying to the northeast of the Mekong delta but hydrologically interrelated with the deltaic system. A large area of 368,000 ha in the Plain of Viet Nam (Dong Thap Muoi) is composed of acidic sulfate soils (SMEC, 1998). Except for areas of relatively high ground near the Cambodian border and along the river levees, the plain is low lying and is subject to seasonal flooding from the beginning of July until the end of January. Some 60% of flood waters originate from outside of the immediate area. p0240

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f0075 FIGURE 5.14 Satellite image of the Mekong River delta—Landsat-7: 185 × 185 km.

The maximum depth of flooding is around 4 m. In the dry season, the area dries out to leave only scattered ponds and swamps.

p0245 The Mekong delta (Fig. 5.14) can be considered to begin where the Mekong crosses into Viet Nam as two channels: the Bassac River to the west and the Mekong to the east. An 80% of the flow is in the Mekong and 20% in the Bassac. Around 50 km downstream of the Viet Nam border, a major connecting channel—the Van Nao pass—transfers around 40% of the Mekong flow across the Bassac during high-flow conditions. Downstream of this point, the Bassac and Mekong have similar flow volumes during high flows. The delta is highly developed economically but the channels remain largely unengineered such that the various small distributaries still distribute flow from the main rivers through the natural silt levées to flood low-lying interdistributary areas, the latter lying only 2-3 m above sea level. Total delta area is 65,000 km$^2$. In the upper delta, this flooding may reach 10 m in depth but reduces closer to the coast where there are sandy chenier ridges. The degree of saline intrusion is variable but is increasing due to extraction of freshwaters for irrigation; although locally, barrages may reduce salinity values (Campbell, 2007). Estimates of modern sedimentation rates are based on dredging records and indicate an annual accretion rate of around 1 mm (Vongvisessomjai and Phan, 2000). The history of Holocene sedimentation is provided by Nguyen *et al.* (2000), Ta *et al.* (2001, 2002a,b, 2005), Tanabe *et al.* (2003), and Murakami *et al.* (2004) within a regional framework (Sidi *et al.*, 2003; Thanh *et al.*, 2004; Woodroffe, 2000).

A multitude of minor channels drain the floodplain areas between the major distributaries (Fig. 5.15). In addition, there are cross-cutting man-made canals connecting distributaries used for navigation and a variety of managed small channels serving irrigation networks on the floodplains. The bed sediments are silt and very fine sand as are the banks. River banks in this region are densely populated by humans but there is little revetment. Banks are largely stable and vegetated but Viet Nam sees erosion as a major problem because some of the eroding localities are adjacent to important towns. There is little clay and fine organic material and hence very little mud in the system. The Tram Trim (Fig. 5.15) wetland nature reserve represents 1% of the extensive Plain of Reeds. The latter formerly had characteristics similar to the reserve, seasonally flooded grasslands, pools, and minor channels, but today is largely rice monoculture. Satellite images show flood waters progressively crossing from the channels over the floodplain. There is evident strong connectivity between channel and floodplain. Palaeochannels (old channels—fully silted) are evident on the floodplain and will provide microtopographic changes in elevation that the flooding waters will follow. These palaeochannels show that channel migration and avulsion have occurred over geological time but today the channels are relatively stable. p0250

There are rated sections at Tan Chau (Fig. 5.16) on the Mekong River and at Chau Doc on the Bassac River; they are found to be tidal. p0255

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processes and ecological functionality. Some of these wetlands can be regarded as permanently wet whilst others are seasonally dry. Information on Cambodia is contained within the study carried out be Van Oertzen (1999). A detailed inventory exists for Lao PDR for those wetlands that are within 50 km of the river (Claridge, 1996) and although the choice of 50 km is an arbitrary delineation of wetlands connected to the river system it is not unreasonable. The definition of a wetland varies between studies with dramatic differences in the consequent estimates of the natural floodplain wetland. Much former natural wetland is now highly managed floodplain rice paddy (and in Viet Nam—shrimp farms) which may still be classified as wetland areas. Claridge (1996) reports that estimates for Laos have ranged from 560 to 21,800 $km^2$ depending on definition employed. Much rice paddy functionally requires annual flooding from the river but otherwise lacks a natural hydrology and an intact natural ecosystem. Important examples of semi-natural wetlands in Laos include That Luang marsh near Vientiane and within Cambodia, the Stung Treng complex of islands and channels hosts seasonally inundated riverine forest habitat. Stung Treng was declared a Ramsar site in 1999. Within Cambodia, the Tonlé Sap lake, Tonlé Sap River, and associated floodplains are regionally significant and will be described below in more detail. The Plain of Reeds occupying around 13,000 $km^2$, mainly in Viet Nam, is a low-lying depression that floods seasonally, which is now largely devoted to rice cultivation. The 7588 ha Tram Chim National Park in Viet Nam is an exception, constituting a seminatural floodplain area surrounded by rice paddy and which represents around 1% of the Plain of Reeds. The 3280 ha Lang Sen, 23 km northeast of Tram Chim, is the only area within the Plain of Reeds where remnant natural *Melaleuca* forest is found adjacent to a river channel. Other major wetlands in Viet Nam are coastal and brackish, for example, The Ream National Park in Cambodia has extensive areas of mangroves and mud flats.

The MRC have mapped wetland distribution (Fig. 5.17). Wetlands are of several types depending on hydrological function: p0265

- Some wetlands are associated with tributary rivers of the Mekong and as such changes in the tributary river flow regimen and not the changes in the regimen of the main river will moderate their hydrological function. u0010
- Some important wetlands exist at the confluence of major tributaries with the Mekong and are inundated seasonally by the combined flood regimen of the Mekong and the individual tributary (Fig. 5.18). Thus, for these latter systems, the flooding regimen is complex as the timing of high flows within the tributary may be in or out of phase with the timing of the Mekong high flows. u0015
- Other major wetlands, such as downstream of Vientiane and adjacent to Phnom Penh, are some distance from the main river and are flooded via overbank flows and by natural anabranch channels in upstream locations and drain back into the Mekong by similar systems downstream. Today these afflux and efflux channels may be controlled by engineered floodgates. Thus, substantial lengths of these wetland systems may have no direct local connection with the Mekong River. These large wetlands might be back-swamps that have developed behind extensive natural river levées or they might occupy tectonically controlled hollows in the landscape. u0020
- Some smaller wetlands are back-swamps that are inundated directly by flows overtopping the river levées and/or by seepage through the levées. u0025
- Major tracts of floodplain such as downstream of Kratie in Cambodia or in u0030

f0095 FIGURE 5.18 Wetland inundation at tributary confluence with the Mekong River. Flow top to bottom of image. Landsat-7: field of view approximately 30 × 30 km.

the Plain of Reeds in Viet Nam are inundated annually.

u0035 • The Tonlé Sap lake, Tonlé Sap River, and adjacent floodplain complex is possibly unique in as much as the wetland is maintained by an interplay of local drainage systems with the annual reversal of the direction of flow within the Tonlé Sap River induced by high river stage in the Mekong during the wet season (Penny *et al.*, 2005). This system is treated separately ~~below.~~ above (4.5).

u0040 • In-channel wetlands are common but mainly extant only during seasonal low flows. Examples are side channels to the main river that take little flow during the dry season, but which are active river channels during the wet season. A major and important exemplar is the Khoné Falls-Siphandone bedrock river complex that exhibits a complex hydrological and hydraulic regimen and specific globally important ecosystems (Daconto, 2001) that extend downstream to include the Stung Treng Ramsar site noted above.

## 4.8. Soil Erosion and Delivery to the River System s0065

Some sediment within the Lower Mekong system is sourced from within China and Tibet. Within Yunnan province as recently as 1998 as much as 28% of the basin area was classified as "erosion prone" (Puustjarvi, 2000). Throughout the whole basin, forest cover has been steadily decreasing, being replaced by disturbed secondary growth or agricultural systems prone to soil erosion. Vegetation changes in the LMB p0305 (and on similar topography in Thailand) and the impact on sediment erosion from slopes and delivery to the river have been considered using remote-sensing techniques (Chen *et al.*, 2000; Gupta, 1996, 1998; Gupta and Chen, 2001; Gupta and Krishnan, 1994; Gupta *et al.*, 2002), which findings have been summarized by Gupta and Chen (2002) who observed, from satellite images, that bare ground on steep slopes was most prevalent in the first several weeks of the rainy season but soon reduced as vegetation became established. Direct measures of sediment transfer from the slopes to the rivers are lacking, and consequently from the earlier work cited above, Gupta and Chen developed an approximate rule that disturbed vegetated areas generated around 100 tonnes $km^2$ of soil per year whereas bare ground generated around 150 tonnes $km^2$ per year. Field visits demonstrated that this sediment entered first and second order streams via slope wash, gullies, and debris flows. The few available suspended sediment concentration data for the Mekong River (Anonymous, 2002a; Fu *et al.*, 2008; Kummu and Varis, 2006; MRC, unpublished data; Walling, 2005, 2008) tend to show higher concentrations before the end of December each year which tends to confirm that transfer to the main channel network occurs early in the wet season. However, conclusive basin-wide evidence of a significant change in suspended sediment loads and river hydrology owing to land use change is not available (Campbell, 2007; MRC, 2004). Gupta *et al.* (2006) argue that there is little opportunity for storage of sediments in the modern Mekong system for more than 4000 km of the course, with storage potential only available in the last 400 km.

s0070

## 4.9. Planform Adjustments and Bank Stability of the Mekong River

p0310 Although there is evidence for Mekong River channel adjustments in prehistoric and geological time-scales, only changes in modern time-scale are considered here. A series of basin-wide reconnaissance studies has been completed with a view to determining the location and means by which bank protection works (Bergado *et al.*, 1994) should be considered (e.g., Anonymous, 1988; de Vries and Brolsma, 1987a,b; Termes, 1987). These various reports inevitably contain information on channel planform and stability. For example, Rutherfurd and Bishop (1996) noted that the Mekong River planform can simply be classified as straight (rare), meandering, or braided; in addition, the categories of anastomosed and anabranching. Sitthisak (1989), Rutherfurd and Bishop (1996), and Rutherfurd et al. (undated) considered chiefly the reach of the river near Vientiane and noted that this reach lay in a transitional regimen between braided and meandering. Using hydrographic charts and cross sections surveyed at gauging stations, Rutherfurd and colleagues deduced approximate planform adjustments and adjustments in bed level through time and related these to a simple bank stability model. Channel stability has also been considered near Vientiane (Kummu *et al.*, 2007) and Kampong Cham (Uyen, 1989a,b) for various periods between 1961 and 2005 and for the Bassac River (Mansell, 2004). More recently, major studies have been undertaken with regard to the channel stability in the Vientiane (JICA, 2004) and the Phnom Penh areas where, for the latter area, bank recession rates are locally 10 m per year (Anonymous, 2002a).

p0315 Several reports contain information on near-bank velocity field, bed and bank sediment-grain size, stratigraphy, and bank-failure mechanisms. Bank recession through mass collapse occurs mainly during the annual flood recession (JICA, 2004). River banks throughout the system superficially often appear to be homogeneous in vertical section when considering grain size and stratigraphy, but subtle differences do occur and these translate into distinctive differences in bank profile and erosion mechanisms.

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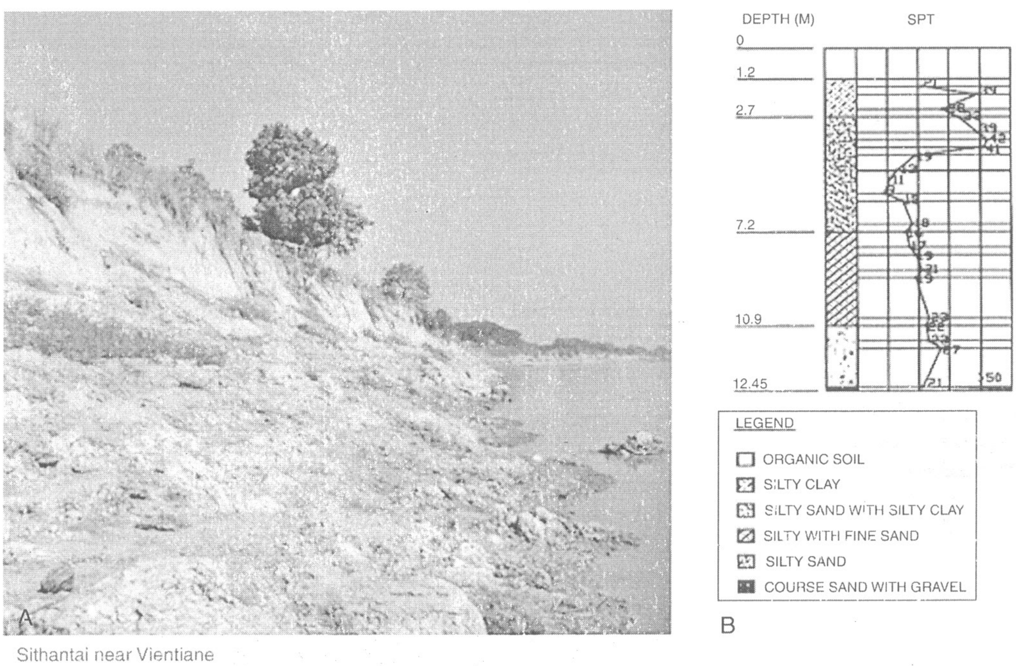
p0320 Bank erosion is locally a social, economic, and political issue along the border between Laos and Thailand. Lateral movement of the river is a completely natural process, which can be understood and predicted to some degree by specialist studies. Erosion on one side of the river is balanced by deposition of sediments against the opposite bank such that the width of the river remains essentially the same although the lateral position of the main channel and the bank lines are changed. The zones of erosion or deposition tend to migrate upstream or downstream through time such that an eroding bank at one time may become a lateral accretion zone at another time and vice versa. Direct human intervention or unintentional activities can affect these processes. Examples are:

- Artificial infilling one side of the channel will accelerate erosion on the opposite side of the river. u0045
- Construction of revetment along one bank alone can cause changes in the flow patterns and the patterns of erosion and deposition such that there are implications for the alignment of the opposing bank line. u0050
- Extraction of aggregates can redirect the direction of the main flow causing changes in the patterns of erosion and deposition. u0055

Figure 5.19A shows a short steep headwall that is largely inactive but subject to localize shear failures and occasional rotational slips. The base of the bank line consists of a complex of slumped units at an overall lower angle. Erosion of the toe of this complex by river p0340




f0100 FIGURE 5.19 Example of bank profile near Sithantai within study reach 2. Redrawn from JICA (2004).

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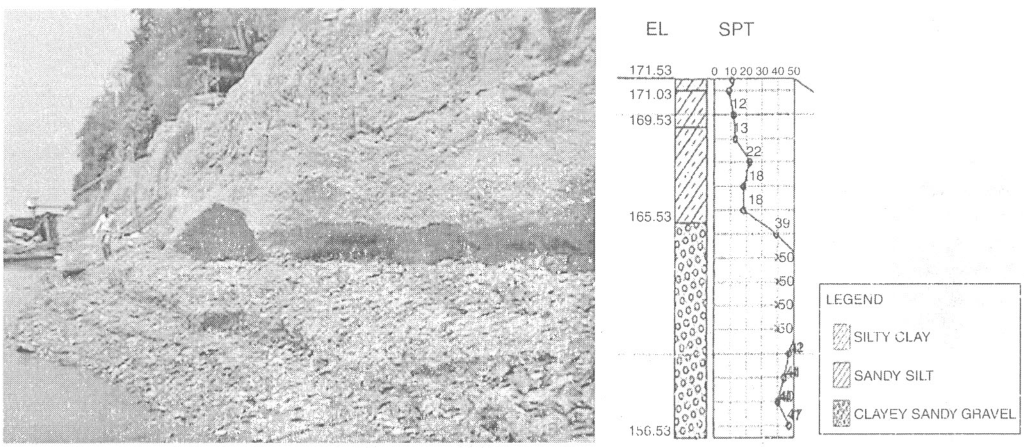
currents results in very slow mass movement away from the bankline toward the river. Much of the material is fine sand and silt, visually little differentiated in the vertical (Fig. 5.19A). However, close inspection reveals quasihorizontal lamination and variation in the character of the sediments (Fig. 5.19B). Often a basal gravel layer underlies sand or silt and sand or a basal sand layer is exposed close to the seasonal low water level. These differences result in composite bank profiles which are subject to different mass movement processes. The difference in failure mechanisms is also dependent on the ground-water conditions as percolation through the sediment mass and more especially along interfaces between sediment units is an important element in bank failure.

p0345 Figure 5.20 shows a near vertical cliff composed in the upper part of silty clay that is quite cohesive and, when dry, resistant to subaerial erosion. The unit is horizontally bedded and this is demonstrated by the slightly eroded horizon at about two-thirds height. The lower third of the cliff consists of stratified gravel close to the angle of repose (32°) but punctuated by small steps indicating the stratigraphic horizons. The deep eroded alcoves are probably the result of seepage, enhanced turbulence along the interface between the underlying gravel, and the superimposed silty clay.

## 4.10. Vertical Bed Level Adjustments and Deep Pools s0075

Vertical scour and fill during the flood season and longer term changes in bed elevations have not been systematically studied, although some limited analysis of repeat cross-section surveys are contained within the literature (Bountieng, 2003). Throughout the Mekong system, both alluvial and bedrock reaches often contain very deep pools, reportedly up to 40-60 m deep (Anonymous, 2002b; Chan *et al.*, 2003; Conlan *et al.*, 2008; Viravong *et al.*, 2006) that seem to be temporally persistent within their spatial locations. These pools are important for fish conservation and as a fisheries resource throughout the system and locally are important for Irrawaddy dolphins (Poulsen *et al.*, 2002). However, although these pools p0350 Au7 Au8

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f0105 FIGURE 5.20 Example of composite gravel and sand bank profile within study reach 2. Redrawn from JICA (2004).

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may constitute important geomorphological features of the Mekong River, the mechanisms by which they are formed and maintained have not been studied within the Mekong. A cursory inspection of air photography, satellite images, and bathymetric maps indicates a possible connection with structurally induced flow constrictions in bedrock reaches and tributary junction scour in alluvial reaches, for example, but the issue is receiving further research.

## s0080 4.11. Floodplain Flooding

p0355 Floodplains can be defined on a practical basis as those areas that are prone to flooding on a regular basis within modern times. The riparian levées may remain exposed whilst the floodplains are submerged (Fig. 5.21). Methods to determine floodplain areas are remote sensing and hydraulic modeling of flood inundation. An example of the former is provided by
1998 Au9 Ratanavong (~~1999~~) for Thabok town in Laos for the 1997 inundation and for the Vientiane plain by Giliespie and Inthiravongsy (1998) using RADARSAT (Hinel, 1998). Hydraulic modeling of flood inundation using the computational fluid dynamics package ISIS has been conducted by the MRC for the Lower Mekong downstream of Kratie (Fig. 5.22).

f0110 FIGURE 5.21 Inundation of floodplain to left of riparian levée.

According to the MRC estimates, 80% of rural flood events and 20% of urban flood events are caused by tributary flows and not main river high flows. The four main flood-prone areas in Laos are situated along the Mekong near large tributaries: (i) Vientiane plain, (ii) Khammoune Province (Thakhek town), (iii) Savannakhet Province, and (iv) Champasak Province (Pakse town). In Thailand, the main flood-prone areas are limited riparian areas along the Mekong and along the tributaries in Nong Khai, Mukdahan, Nakhon Phanom, and Ubon Ratchatanee provinces. p0360

The Mekong River annually floods the floodplain areas downstream of Kratie and the delta area, inundating approximately 1.2-1.8 million ha with flooding in some areas lasting between 2 and 6 months with depths of 0.5-5 m. During the 2000 record flood (1:50 year recurrence), approximately 38,900 km$^2$ were flooded throughout LMB. During 1966, the largest flood on record occurred for the upper and middle reaches of the basin. Impacts vary annually depending on factors such as flood duration, timing in relation to human activities, high water levels, and the significance of regionally or locally generated rainfall. In the case of the 2000 flood, monsoon flood waters were augmented by heavy rainfall especially over the Tonlé Sap and lower reaches of the Mekong. This was followed by intermittent rain showers over the same area. The Tonlé Sap lake was full by late July and thus August floodwaters in the Mekong could not be accommodated and these conjoined factors led to extensive flooding downstream. The flood depth in the delta reached 5.06 m (MRC, 2001). p0365

## 4.12. Sediment Load and Sedimentation s0085

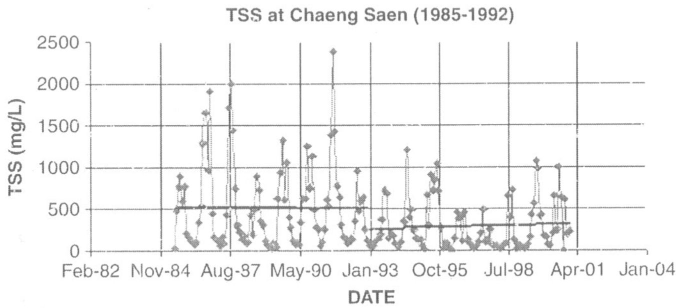
Throughout the LMB, the sediment load is predominately fine sand with local gravel bars mainly evident upstream of Vientiane. There p0370 f0130 


FIGURE 5.25 Suspended solids concentrations in the Mekong River at Chiang Saen, with linear regression lines fitted for the periods before and after Manwan Dam commenced filling in 1992 (source: Mekong River Commision, 2003; The State of the Basin, 2003. Mekong River Commission, Phnom Penh, 300pp).

responsible for trapping suspended sediments (Fu *et al.*, 2008), being some 350 km upstream of Chaeng Saen.

p0390 Walling (2005, 2008) comprehensively reviewed the majority of TSS records until ca. 2002 for the LMB and for the Lancang River in China until 1990. Perhaps the most significant and surprising conclusion that resulted from this work was that more than 50% of the TSS of the LMB was sourced from within China. This result should be treated with caution as it may be an overestimate conditioned by the sampling regimes in both China and the LMB. Nevertheless, it does indicate that a probable major source for TSS in the LMB is the Upper Mekong system. A significant consequence is that changes to the TSS flux should be detectable in Zone 2 during the next several years as river resource development continues within China.

p0395 A major environmental control on TSS is changes in basin-wide land use (Anonymous, 1998). An issue of concern in the LMB is the effect of forest clearance on hydrology and related effects such as flooding, soil erosion, and slope mass movements (Oughton, 1993). Much relevant literature was reviewed by Bruijnzeel (1990). With respect to TSS there are short-term consequences related to the release of solids during clearance and important long-term issues concerning sustained or reduced TSS loads following clearance. The impact will depend largely on the type of land use which influences the degree of runoff (i.e., transport capacity) as well as available soils for erosion. Typical hydrological impacts have been documented for controlled studies in small catchments but attempts to demonstrate the impact on larger systems (such as the Mekong) have not been successful. Such attempts have been made in Thailand, Taiwan, and the Amazon. One possible explanation is that the spatial and temporal variability of rainfall in large tropic catchments is too large and masks any changes in vegetation cover (Bruijnzeel, 1990). A further consideration is that large systems either store sediments "permanently" within the system such as on floodplains, or that there are substantial lag effects for coarser components moving down the system.

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