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The Changing Sediment Load of the Mekong River

The sediment loads of many of the world's major rivers have changed significantly in recent years due to land-use change, reservoir construction, and other human impacts on their drainage basins. For many rivers, the loads have decreased, whereas for others, they have increased. Such changes can have important implications for both the natural functioning of the system as well as for human exploitation of the river system. This paper considers the evidence for recent changes in the sediment load of the Mekong River. The available data have a number of limitations in terms of both sampling frequency and the period of coverage, but they have been processed to provide a basis for considering the changes in the sediment load of the river over the period extending from the early 1960s to 2002. Although there is evidence of increasing loads at some measuring stations, the overall trends show little evidence of major changes, and the system provides evidence of buffering through storage. As of 2002, the construction of major dams on the headwaters in China appears to have had little impact on the sediment load, although as further larger dams are commissioned, the sediment load of the Mekong can be expected to decrease.

INTRODUCTION

The fine sediment load of a river represents an important measure of its hydrology and of the erosion and sediment delivery processes operating within its catchment. Furthermore, the magnitude of the load and the associated suspended sediment concentrations can have important implications for both the natural functioning of the system, for example, through their influence on channel morphology and on the aquatic ecosystems and habitats supported by the river, as well as for human exploitation of the river system.

The fine sediment load of a river is sensitive to both climate change and to a wide range of human activities within its drainage basin that could influence sediment mobilization and transfer, including land clearance, agricultural development, mineral extraction, urbanization and infrastructure development, dam and reservoir construction, and soil conservation and sediment control programs. Recent reports have, for example, highlighted how the annual suspended sediment load of the lower Yellow River in China has progressively decreased over the past few decades from an average of ~1.1 Gt y^{-1} in the period extending from the 1950s to the 1970s, to a value less than 0.2 Gt y^{-1}, in response to lower rainfall, reservoir construction, and increased water use and extensive soil conservation programs (1). Similarly, the present suspended sediment load of the lower Indus River in Pakistan is currently only ~15% of that in the 1930s, primarily as a result of dam construction and water abstraction for irrigation (2, 3). In contrast, the annual sediment load of the Rio Magdalena in Colombia, South America, has increased by ~40% between the 1970s and the late 1990s in response to land clearance, land-use change, and mining activity (1, 4).

Increased sediment loads can bring many problems linked to accelerated loss of reservoir storage capacity through sedimentation and siltation of river channels and water distribution systems, and an associated loss of conveyance capacity and increased turbidity of river water. Although decreasing sediment loads will frequently bring obvious benefits in terms of reduced sedimentation and siltation, it is important to recognize that there can also be negative impacts associated with reduced nutrient inputs to lake, floodplain, delta, and coastal ecosystems and reduced sediment supply to deltas and coastal areas, resulting in delta recession and coastal erosion.

In view of the potential impacts of changing sediment loads on river behavior, river use, and the ecology of the river system, consideration of likely or potential future changes in the sediment load of a river should be seen as an important requirement for sound river basin management. The prediction of future changes should be linked to an assessment and understanding of past changes as a means of evaluating the significance of the predicted changes and their likely impact on the river system. As a large river basin impacted by accelerated development in recent years, including population growth, land clearance, infrastructure development, and water resource and hydropower development, the sediment load of the Mekong River might be expected to have changed over the past few decades, and the ongoing construction of a suite of major dams on the headwaters of the river in China is likely to bring further changes in the future. In this context, the Mekong could be seen as being at a crossroads because of the potential for past changes to be followed by further major changes, depending on the scale and speed of future development. It is important for available information on past, present, and likely future changes in the sediment load of the Mekong River to be evaluated, both to establish the sensitivity of the river system to the drivers of change and to assess their implications for future management strategies.

The Mekong River

The Mekong River is one of the major rivers of the world. It drains a catchment of ~795 000 km^2, and it has been variously ranked as the 12th longest river in the world and as the 8th largest in terms of water discharge (mean discharge = 15 000 m^3 s^{-1}) (5). The Mekong Basin (Fig. 1) embraces considerable physical diversity. The river begins in Tibet, at an altitude of nearly 5000 m, and flows through the mountains of Qinghai and Yunnan Provinces, China, into the deeply dissected terrain of eastern Myanmar, northern Thailand, and Lao People's Democratic Republic (PDR), before entering the extensive alluvial lowlands of Cambodia and discharging to the South China Sea through its delta in Vietnam. This topographic diversity is paralleled by considerable variability in climate, ranging from the cool temperate conditions in the headwaters, where the high mountains experience permanent snow cover, to the tropical conditions over much of the central and southern parts of the basin. Mean annual precipitation ranges from 2000 to 4000 mm over much of the northern and eastern areas of the basin, and values decline toward the west and the lowland areas to the south to a minimum approaching 1000 mm. The

Figure 1. The Mekong River Basin.

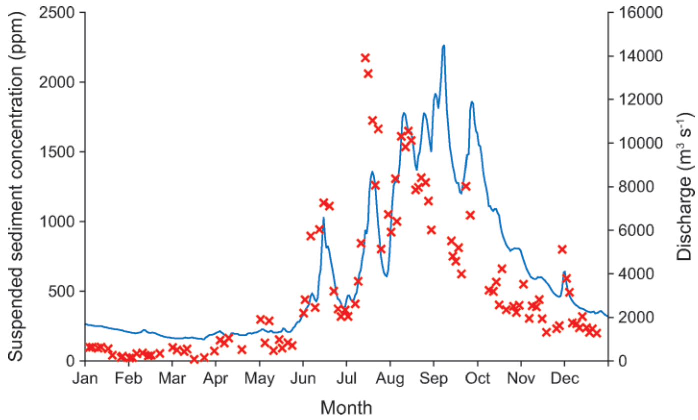

Figure 2. The record of water discharge and the measured suspended sediment concentrations for the Mekong River at Luang Prabang for 1961.

hydrological regime is dominated by the seasonality of the snowmelt runoff from the northern headwaters and the seasonal monsoon over most of the remainder of the basin, which results in up to 90% of the annual rainfall falling between June and October. Over most of the basin, the flow regime is characterized by low flows during the period February to April and a marked peak in August and September. About 80% of the annual runoff occurs between June and November, with as much as 20%–30% occurring in September. The upper basin of the Mekong in China and Myanmar covers an area of ~189 000 km^2 and accounts for 24% of the total area of the basin. However, because of the extensive area of high rainfall within the middle region of the basin and the high amounts of runoff from the northern areas of the Lao PDR and the mountain areas in northern Vietnam, the upper basin contributes only around 18% of the total discharge from the basin.

Most of the land in the Mekong Basin is either farmed or forested. Shifting cultivation is common in the hilly and mountainous areas, and rice is widely grown on the valley flats. The alluvial lowlands in Cambodia and the delta are more extensively cultivated. Much of the forest cover is now degraded as a result of timber exploitation and shifting cultivation. Most of the basin is rural; the population density ranges from ~10 persons km^{-2} in the hill regions to more than 500 persons km^{-2} in the more densely populated delta. Because of the relatively low population density over much of Mekong Basin, the lack of major extractive industries and industrial development, and the limited use of the river as a transport waterway, due to the many rapids, both the basin and the river are relatively unimpacted by human activity, and Kummu and Varis (6) described the Mekong is one of the world's most pristine large rivers.

The existing estimate of the mean annual suspended sediment load of the Mekong reported in the literature (e.g., 7) is ~160 Mt y^{-1}, and Roberts (8) has estimated that about 50% of this load is contributed by the upper part of the basin in China. As indicated already, this portion of the basin accounts for about 24% of the total area of the basin and about 18% of its total discharge, and sediment yields in these mountainous headwaters, which have steep, unstable slopes, are clearly substantially higher than those from the remainder of the basin. Figure 2 provides further information on the suspended sediment transport regime of the river by presenting a plot of the annual discharge hydrograph and the sediment concentrations obtained from a program of frequent sampling for the Mekong at Luang Prabang in 1961. The dominant role of the annual flood in suspended sediment transport is clear, but there is also evidence that sediment concentrations can be greater during the earlier stages of the flood. This could reflect the remobilization of sediment stored within the channel system, a flushing and exhaustion effect associated with sediment mobilization by erosion as the wet season proceeds, and the contribution of sediment from the upper parts of the catchment associated with snowmelt floods. Studies of the sediment deposits in its delta (9) have suggested that the sediment load of the Mekong has remained relatively constant over the past 3000 y. Furthermore, there is currently no evidence of the major reduction in sediment load in recent years reported for other large Asian rivers such, as the Indus, Yellow, and Yangtze Rivers (1, 2). However, as indicated already, population growth, land clearance, land-use change, reservoir construction, and other infrastructure development might be expected to have caused some changes in the sediment load of the Mekong over the past 50 y. For some, if not many, major world rivers, the lack of longer-term sediment measurements precludes meaningful quantitative analysis of recent changes in their sediment loads. In the case of the Mekong, the available data have significant limitations, particularly in terms of the continuity and length of the records, but these data, nevertheless, provide a basis for assessing the likely magnitude and direction of these changes.

AVAILABILITY AND RELIABILITY OF SEDIMENT DATA FOR THE MEKONG

Any attempt to assess changes in the sediment load of a river system is clearly heavily dependent upon the availability of sediment load data. This availability in turn reflects the number and the location of the measuring stations, the amount of data, the reliability, accuracy, and temporal resolution of those data, and the length of the record. In many areas of the world, sediment load data are unavailable. Where sediment data are available, the record length clearly exerts an important constraint on the ability to identify trends, and the reliability of the related analysis will depend heavily upon the nature of the sediment sampling or monitoring program and the accuracy of the resulting load estimates. For most studies aiming to identify trends, emphasis is placed on annual sediment load data. With some measurement programs, sampling frequency is very limited, and the primary aim is to assemble sufficient samples to establish a sediment rating curve that can be used for the overall period. The use of such a rating curve to derive estimates of annual sediment load is unlikely to provide an adequate basis for assessing any trends during that period. Use of all available data to construct the rating curve is likely to obscure the evidence for a changing sediment response and a nonstationary record, and the documented interannual variations in sediment load will primarily reflect trends in the water discharge record over that period. It is important that the available measurements should permit the production of accurate estimates of sediment load for individual years and thus provide a means of identifying any nonstationarity in the record.

The availability of sediment data for the Mekong is limited, and the available data possess a number of deficiencies that prevent a comprehensive analysis of recent trends in the annual sediment load. However, it is important to recognize that the situation for the Mekong is significantly better than that for many other major world rivers because some data are available, and these data relate to a period in excess of 40 y. In this contribution, attention is focused on the records available for the sediment monitoring stations on the middle and lower Mekong at Chiang Saen (Thailand), Luang Prabang (Lao PDR), Nong Khai (Thailand), Mukdahan (Thailand), and Pakse (Laos), although some data for Jinghong on the upper Mekong or Lancang River in China are also considered. One key feature of the sediment measurements undertaken on the Mekong is that such measurements were initiated in the early 1960s at several sites, and although the subsequent records are discontinuous and frequently involve limited numbers of samples, they provide a useful baseline for assessing trends over the ensuing years.

Considering the available data as of 2005 in more detail, information comes from three different measurement programs. The first is the sediment sampling program initiated on the lower Mekong in 1960 within the framework of the Lower Mekong Project, funded by the US Agency for International Development and coordinated by the Harza Engineering Company (10) and continued by national agencies through to the present. This was based on existing US practice and used standard US-designed isokinetic samplers and involved depth-integrated sampling in several vertical profiles in order to derive an estimate of the mean suspended sediment concentration in the cross section. Originally, this network included the measuring stations at Chiang Saen, Luang Prabang, Mukdahan, and Pakse, and in 1972, the station at Nong Khai was also

Table 1. The coverage of the available sediment concentration data for the lower Mekong at the five key sites. The years when sampling was undertaken at the individual sites and the number of samples collected in those years are indicated.

	Location				
Year	Chiang Saen	Luang Prabang	Nong Khai	Mukdahan	Pakse
1960	22	8		9	9
1961	20	105		60	109
1962	5	27		71	44
1963				32	
1964				42	
1965				38	
1966				35	
1967				42	
1968	38			45	
1969	73			66	
1970	83			73	
1971	71			58	
1972	65		58	72	
1973	33		89	74	
1974	33		87	71	
1975	9		33	36	
1976			27	16	
1977			46	26	
1978			47	26	
1979				27	
1980				25	
1981			21	22	
1982			16	19	
1983			18		
1984			16	20	
1985		2	4	1	
1986		22	18	18	
1987		43	15	4	
1988		41	14	6	
1989		44	20	11	
1990		37	22	14	
1991		18	14	19	
1992		37	23	21	
1993				19	
1994	48		24	22	
1995	45		15	18	
1996	32		20	19	
1997	39	12	25	11	11
1998	38	12	26	35	10
1999	40	7	29	43	12
2000	40	9	27	41	14
2001	38	11	30	42	13
2002	38	9	42	38	11
2003	36				

added, using the same basic procedures. The operation of these sampling stations appears to have been somewhat haphazard in terms of both the frequency of sampling and its continuity from year to year. Table 1 indicates the years during which sampling was undertaken and the number of samples collected during those years.

The second data source represents the sediment measurement program undertaken by the Chinese authorities on the upper Mekong or Lancang River at Jinghong. Despite the international status of the Mekong River, access to these data is unfortunately restricted, particularly for recent years. However, annual load data for the years 1963, 1965, 1966, and 1967–1990 were obtained from secondary sources. Full details of the sampling regime at this site are unavailable, but existing information on sampling procedures in China suggests that sampling is likely to be frequent and probably daily.

The third data source is the Water Quality Monitoring Network established by the Mekong River Commission in 1985, which includes three of the sites where sediment monitoring has been undertaken, namely Chiang Saen, Luang Prabang, and Pakse. This is primarily a water quality monitoring program, but the measurements include total suspended solids (TSS). The data from this source have two important potential deficiencies:

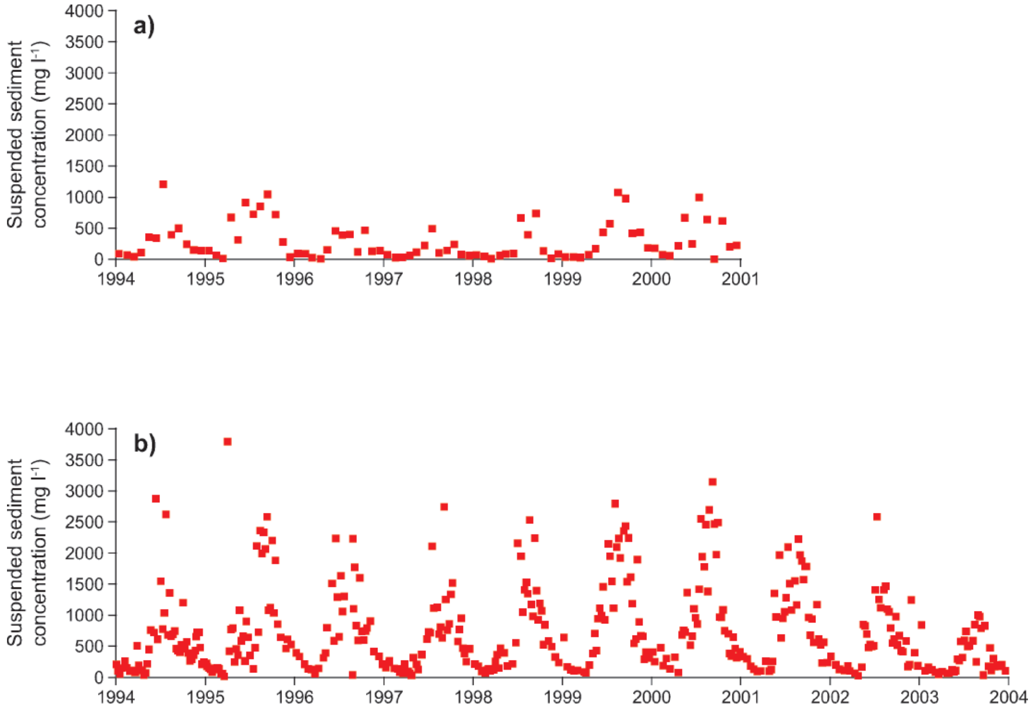

Figure 3. A comparison of the TSS concentrations reported by the Water Quality Monitoring Network program for the sampling station at Chiang Saen (a) and the values of suspended sediment concentration obtained for the same site by the suspended sediment sampling program (b).

i) the sampling frequency is monthly, and *ii)* the samples are collected near the surface (0.3 m depth) of the river using a bottle rather than a true sampler. Because suspended sediment concentrations are known to increase with depth, they are likely to underestimate the true mean concentration in the cross-section.

Since the emphasis of this contribution is on assessing recent trends in the sediment load of the Mekong, based on the information provided by the annual sediment loads, consideration of data reliability focuses on the reliability of the annual load values. In the case of the Lancang River at Jinghong, values of annual load are based on summation of daily loads. Since these data are based on standard Chinese practice, involving frequent sampling using specialized sediment-sampling equipment, they are considered to be reliable.

The data available for the five main measuring stations on the Mekong at Chiang Saen, Luang Prabang, Nong Khai, Mukdahan, and Pakse differ from those for the Lancang River because they represent only values of sediment concentration for the occasions on which sampling was undertaken. Further processing was required to derive estimates of sediment load for individual years. Since trends are being assessed, it is important that the estimates of annual load should reflect any changes in sediment transport taking place within the basin, and, in this study, emphasis was placed on using the data available for individual years to obtain estimates of the annual load for those years, rather than on combining the data for several years to produce a sediment rating curve for that period. In view of the variable sampling frequency from year to year and the relatively small number of samples collected in some years, it was deemed inappropriate to attempt to reconstruct the continuous record of sediment concentration from the infrequent samples or to use interpolation procedures to estimate the load. Emphasis was placed on using rating curves established for individual years (see 11). Detailed scrutiny of the data and comparisons of load estimates derived using rating curves with those obtained by reconstructing the continuous record of suspended sediment concentration for those years where larger numbers of samples were collected demonstrated that a procedure based on a single rating curve of the form $C = aQ^b$ fitted to the sediment concentration (C) and water-discharge (Q) data, using a nonlinear estimation routine, rather than the standard log-log regression technique commonly employed, provided the most reliable estimates of the annual sediment load (see 11). Further analysis of the available data was undertaken to determine the minimum number of samples required to establish a reliable rating curve for a given year and thus to generate a reliable estimate of the sediment load for that year. This analysis suggested that a rating curve based on 25 samples collected at regular intervals throughout the year (e.g., fortnightly) was likely to generate an estimate of the annual load with an accuracy of $\sim\pm10\%$ at the 95% level of confidence (see 11).

Based on this analysis, load estimates were derived for all station years where the number of samples exceeded 20 and these were reasonably uniformly distributed throughout the year. These load estimates were judged to involve an uncertainty associated with the load estimation procedure of $<\pm10\%$–15% at the 95% level of confidence, and it is important to recognize that this level of uncertainty is likely to be of a similar order of magnitude to that associated with the concentration and discharge data. Where the number of samples was <20 but >10 y^{-1}, and the samples were suitably distributed throughout the year, load estimates were obtained by combining the data for two adjacent years in order to establish the rating relationship; in this case, the resulting load estimates were judged to have an equivalent uncertainty of $\sim\pm20\%$.

The data from the Water Quality Monitoring Network also consisted of individual values of TSS for the days on which samples were collected and required further processing to derive estimates of the annual sediment load. However, based on the previous analyses, the monthly sampling frequency was judged to be inadequate to permit the use of rating curves to provide reliable estimates of annual sediment load. The limited sampling frequency is clearly a major and serious limitation of these data, since sampling only once per month is unlikely to provide representative information on sediment concentrations during major floods. In addition, it is also necessary to consider the accuracy of the sediment concentration values, bearing in mind that they were obtained from dip samples collected close to the surface of the river, rather than using specialized sediment-sampling equipment that can collect depth-integrated samples.

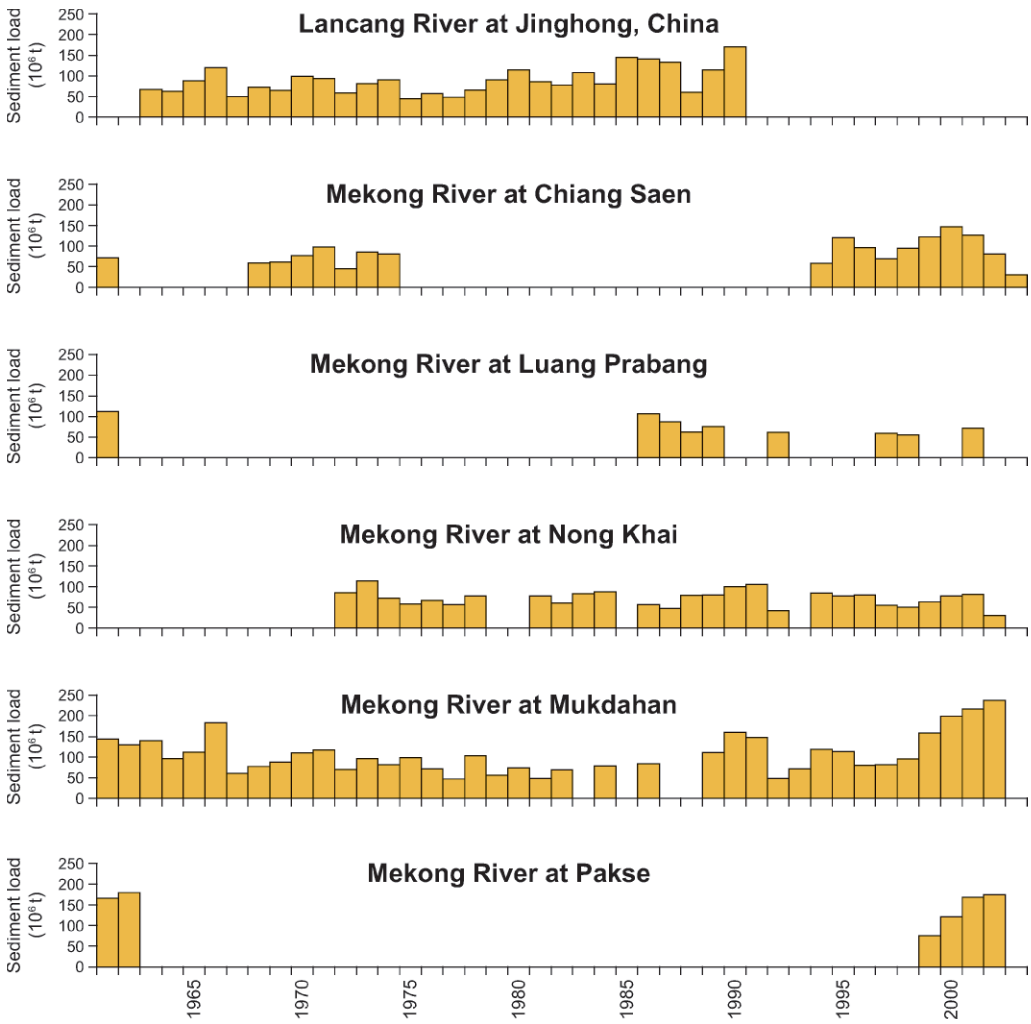

Figure 4. The available estimates of annual sediment load (10^6 t) for the five designated sites on the Mekong River in Thailand and Laos and equivalent data for the period 1983 to 1990 for the upper Mekong or Lancang River at Jinghong, China.

Although it is not possible to make a direct comparison between the concentration values obtained using the two sampling methods, an indication of the potential errors associated with the surface-dip samples is provided by a comparison of the magnitude of the concentration values reported for Chiang Saen for the years 1994 to 2001, for which both data are available (see Fig. 3). During this period, the sediment concentrations reported for the Water Quality Monitoring Network samples rarely exceeded 1000 mg L^{-1} and did not reach 1500 mg L^{-1} (see Fig. 3a). However, the data from the sediment sampling program (see Fig. 3b) indicated that sediment concentrations exceeded 1000 mg L^{-1} for extended periods during the flood season, and, in many years, individual samples exceeded 2500 mg L^{-1}. These findings cast serious doubt on the reliability of the TSS data provided by the Water Quality Monitoring Network for documenting suspended sediment loads, and they were not used in subsequent analysis.

RECENT TRENDS IN THE SEDIMENT LOAD OF THE MEKONG RIVER

The available data on annual suspended sediment loads for the Mekong covering the period from the beginning of measurements in the early 1960s to 2003, assembled in this study and taking account of the issues of reliability outlined here, are presented in Figure 4. Figure 4 emphasizes that any attempt to investigate recent trends in the sediment load of the Mekong River is likely to be compromised by the lack of long time series of annual loads. For the six measuring stations represented in Figure 4, only those at Jinghong, Nong Khai, and Mukdahan have records that span a significant proportion of the past 40 y. The lack of more recent data for the period after 1990 for the station at Jinghong precludes detailed analysis of the impact of the dams constructed on the Lancang River on its sediment to date, and the value of the time series from Nong Khai, whilst continuing to the present, is limited by its more restricted length, having commenced only in 1972. However, notwithstanding these important constraints, the available data provide a basis for assessing and interpreting recent trends in the suspended sediment load of the Mekong River.

It is appropriate to commence with the evidence for changing suspended sediment loads within the Mekong Basin provided by the Lancang Basin, since, as indicated already, previous work has suggested that the portion of the Mekong Basin in China contributes ~50% of the downstream sediment load of the Mekong River. The data presented for the Lancang River at Jinghong in Figure 5 provide clear evidence of an increasing trend for loads in recent years. A simple trend line fitted to the available annual load data in Figure 5a provides evidence of a statistically significant (>99%) increase in sediment load over the period, where average loads have increased from ~60 Mt in the mid-1960s to ~115 Mt in the late 1980s. In contrast, the discharge record for this period shows no evidence of any significant trend. The increasing sediment loads evidenced by the Lancang River have been linked to the marked expansion of population and associated intensification of land use in the middle and lower reaches of this basin in the period commencing in the 1970s. A cumulative double mass plot of the sediment load and discharge data indicates that the impact of these changes on sediment loads was apparent from around 1979, and You (12) suggests that most of this increase was generated within the lower Lancang Basin. The trend line fitted

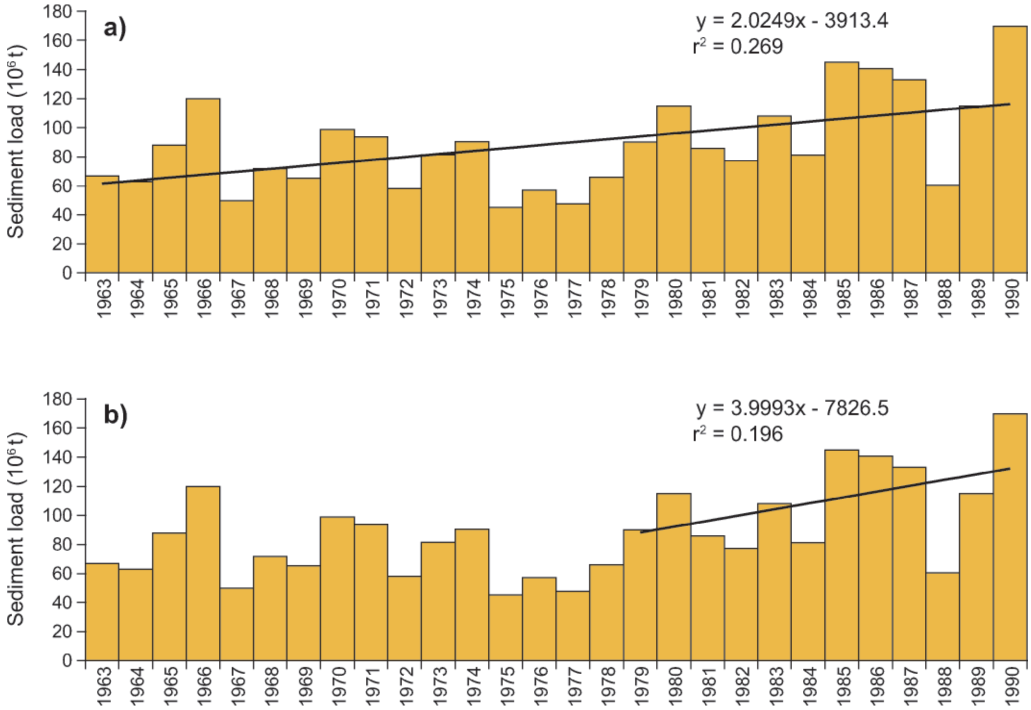

Figure 5. Evidence of an increasing trend in the annual sediment loads of the Lancang River at Jinghong. In (a), the trend line has been fitted to the entire data set, whereas in (b), it has been fitted to the years beginning in 1979.

to Figure 5b assumes that the sediment load of the Lancang River started to increase around 1979 and again provides clear evidence of increasing loads over the period 1979 to 1990.

The construction of dams on the Lancang River in the 1990s can be expected to have caused a decrease in suspended sediment load. The Manwan Dam was constructed during the early 1990s and was fully operational by 1996, and the Dachaoshan Dam was completed in the early 2000s. Although important, both these dams are relatively small by world standards; active capacity/annual inflow ratios are only ~0.007 and 0.006 for the Manwan and Dachaoshan Dams, respectively. Kummu and Varis (6) estimated the trap efficiencies of these dams to be 68% and 66%, respectively, but these values could overestimate the true situation. Furthermore, both dams are located in the middle reaches of the Lancang Basin, and the upstream area contributes only about 50% of the total sediment load generated within the Lancang basin. However, Kummu and Varis (6) cited estimates that suggest that the Manwan Dam could trap as much as ~50–60 Mt of sediment per year, and this would clearly cause a major reduction in the sediment load of the Lancang River. Difficulties in obtaining sediment load data for the period after 1990 unfortunately preclude further analysis of these changes for the Lancang River itself, although any substantial reduction should be detectable further downstream. It is clear that future planned dam construction is likely to have an even more significant impact on the sediment load of the Lancang River, since some of the proposed dams will be larger and some will be located further downstream and therefore control a larger proportion of the basin.

Looking at the stations further downstream in Thailand and Laos, there is less evidence of the increase in sediment load apparent for the Lancang River in the 1980s. A comparison of the annual sediment loads at Chiang Saen for the period 1968 to 1974 (mean annual load = 72.3 Mt) with those for period 1994 to 2000, which were already likely to be impacted (reduced) by the dam construction (mean annual load = 101.4 Mt), provides some evidence of this increase. However, the annual sediment loads for Nong Khai during this period appear to be essentially stationary, and examination of the time-series plot of the relative magnitude of the annual sediment loads at Jinghong and Nong Khai over this period provided in Figure 6 shows that, for half the years shown, the loads at Nong Khai are *less* than those at Jinghong, despite the difference (more than double) in the drainage area and annual discharge between the two sites. This suggests that significant deposition occurs between the two stations and that these conveyance losses have "buffered" the increases in sediment load apparent at Jinghong. Interestingly, Figure 6 suggests that the conveyance losses and associated buffering increased after about 1980, when the annual sediment loads at Jinghong provide clear evidence of an increase (see Fig. 5). In these years, the loads at Nong Khai remained essentially the same as in previous years, causing the loads at Jinghong to exceed those at Nong Khai. The essentially stationary response shown by the time series of annual sediment loads for the Mekong River at Nong Khai, covering the period extending from the early 1970s to the late 1990s, appears to be mirrored by the record for Mukdahan for the 1970s and 1980s, but at this station, the time series suggests that the loads have increased during the 1990s and early 2000s. Since there is no evidence of this increase in the records for Nong Khai, it is likely to reflect increased inputs from tributaries downstream of Nong Khai, increased bank erosion within the reach downstream of Nong Khai, or a significant change (i.e., reduction) in conveyance losses. The first two potential causes would seem to be the most likely.

There has been increasing concern about the potential impact of dam construction on the Lancang River and the sediment load of the middle and lower Mekong River in recent years (6, 13), and it is clearly important to use the available time series to assess the recent and current impact of dam construction. The lack of sediment load data for the Lancang River after 1990 unfortunately precludes analysis of changes in the sediment inputs from the upper Mekong, and emphasis must be placed on the evidence provided by the five designated stations further downstream. This is again limited by the absence of sediment load data for the station at Chiang Saen between 1975 and 1993, the sporadic nature of the data coverage for Luang Prabang in recent years, and the absence of annual load data for Pakse between 1963 and 1998. The lack of sediment load data for Chiang Saen for the early 1990s is particularly unfortunate, since this is when the first impact of the construction of the Manwan Dam might have been evident.

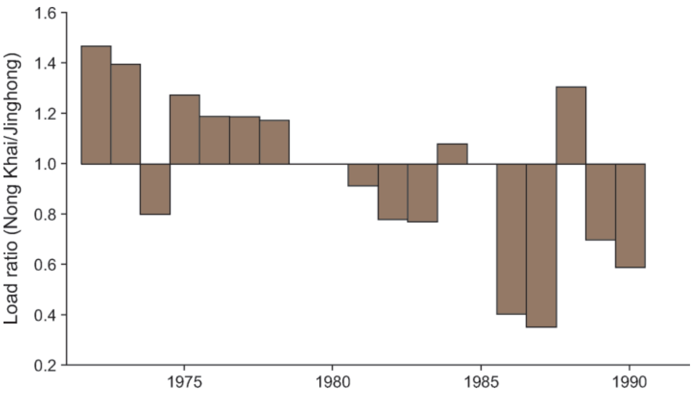

Figure 6. The ratio of the annual suspended sediment loads recorded for the Mekong River at Nong Khai to those measured on the Lancang River at Jinghong and changes in this ratio over the period 1972 to 1990. No ratio value has been plotted for the years 1979, 1980, and 1985 due to the lack of sediment load data for Nong Khai for these years.

Although it is tempting to link the low annual sediment load recorded at Chiang Saen in 2003 to the impact of dam construction and, more particularly, the commissioning of the Dachaoshan Dam, this apparent reduction is more likely to be a reflection of the low water discharge in that year. More data for the early years of the 2000s are needed to assess the impact of the construction of the Dachaoshan Dam during this period. Access to sediment load data for the Lancang River at Jinghong for the period after 1990 would also provide a much clearer and more definitive assessment of the impact of the Manwan and Dachaoshan Dams on sediment inputs from the upper Mekong. The apparent lack of any clear signal of reduced sediment loads at the downstream stations to date could reflect both the location of these dams relative to the main areas of sediment generation within the Lancang Basin and their relatively small capacity/inflow ratios, as well as a degree of buffering by the river system. Construction of larger dams, with a much greater storage capacity, could change this situation.

Although the data presented here provide no definitive evidence of a reduction in the sediment load of the Mekong River in recent years in response to the construction of the Manwan and Dachaoshan Dams on the Lancang River, it is important to note that previous analysis of TSS data obtained from the Water Quality Archive and reported in the Mekong River Commission *State of the Basin Report* for 2003 (5) and by others (6, 13) has suggested that a marked reduction in suspended sediment concentrations could be identified in the data for Chiang Saen after 1992 (the year of commencement of impoundment). Monthly water quality data for this site extended back to 1985, and there is a clear distinction between the pre-1992 and post-1992 data. However, the limitations of the TSS values obtained from the water quality sampling program in representing the true suspended sediment concentrations have already been highlighted (see Fig. 3). Although the sediment measurement program at Chiang Saen only recommenced in 1994 (after having been suspended in 1975), the available data show no clear distinction between the suspended sediment concentrations measured in the late 1960s and early 1970s and those measured after 1994. Lower concentrations were reported by the sediment measurement program for 2003, but these reflected the record low discharge for that year. The clear distinction between the pre- and post-1992 concentrations shown by the water quality data, whilst apparently convincing, might possibly also reflect a change in sampling procedure or sampling location.

DISCUSSION AND CONCLUSIONS

The overriding impression provided by the annual sediment load data presented in Figure 4 is therefore one of relative stability of the sediment loads transported by the Mekong River over the past 40 y. The availability of sediment measurements for four of the measuring stations for 1961 (i.e., Chiang Saen, Luang Prabang, Mukdahan, and Pakse) affords a useful baseline against which to assess the magnitude of any subsequent changes. Any attempt to compare the suspended loads of 1961 with those of more recent years must, however, take into account variations in water discharge between years. In Table 2, the loads for 1961 for a particular station are compared with those for a recent year with similar water discharge. In the case of Luang Prabang and Pakse, there is little difference between the two load values, but in the case of Chiang Saen and Mukdahan, there would appear to be evidence of increases of ~29% and 38%, respectively. Further evidence for increases at Chiang Saen and Mukdahan was presented previously. In both cases, however, the increase is not discernible at the next measuring station downstream (i.e., Luang Prabang and Pakse). The period of record covered by Figure 4 will have coincided with significant land-use change and intensification leading to catchment disturbance as well as the construction of dams in several tributary basins and in the headwaters on the Lancang River. The absence of major changes in sediment loads over the period of record is likely to reflect, to some extent, the balance between increases caused by catchment disturbance and reductions associated with dam construction and associated sediment trapping within the tributary basins. However, as noted already, the Mekong Basin also appears to demonstrate the capacity to "buffer" changes in sediment load occurring in different parts of the basin, a characteristic also highlighted by Ta et al. (9) in their study of sediment supply to the Mekong Delta over the past 3000 y.

The prospect that the major program of dam construction initiated on the Lancang River in China could result in a substantial decrease in the annual suspended sediment load of the middle and lower Mekong nevertheless remains (6, 13). The inability to access recent Chinese data for the Lancang River at Jinghong inevitably reduces the scope for investigating into the current impact of this dam construction. However, two facets of the sediment budget of the middle Mekong Basin add further complexity to any attempt to predict the future sediment response of the river. In the first place, there is, as indicated already, evidence that the annual sediment load of the Lancang River at Jinghong in the late 1990s was of a similar order of magnitude as, and at times possibly greater than, the annual

Table 2. A comparison of the annual suspended sediment load of the Mekong River at Chiang Saen, Luang Prabang, Mukdahan, and Pakse for 1961 with the load for a recent year and similar water discharge.

Station	Sediment load 1961 (10^6 t)	Water discharge 1961 (10^9 m^3)	Recent sediment load (10^6 t)	Recent water discharge (10^9 m^3)
Chiang Saen	71.3	92.0	81.1 (2002)	89.2 (2002)
Luang Prabang	112.4	126.6	118.4 (1997)	118.4 (1997)
Mukdahan	144.5	283.3	199.1 (2000)	296.6 (2000)
Pakse	165.8	384.3	168.0 (2001)	388.0 (2001)

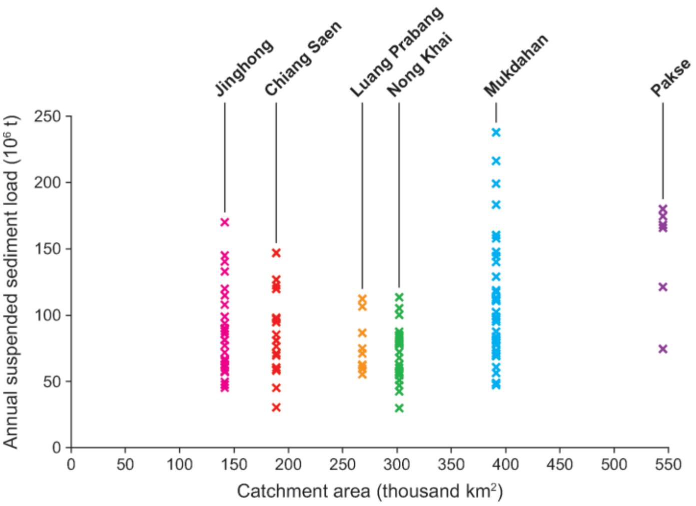

Figure 7. Downstream trends in the annual sediment loads documented for the six measuring stations on the Mekong River in relation to increasing catchment area.

load measured at the downstream stations. This in turn means either that the sediment contribution from the portion of the catchment in Lao PDR and Thailand is negligible, which seems unlikely, or that delivery of sediment through the system involves substantial conveyance losses. These conveyance losses and associated "buffering" are highlighted in Figure 7, which plots the downstream trend in the annual sediment load of the Mekong River, estimated for the different measuring stations, in terms of increasing catchment area. Comparisons of the magnitude of the load between different sites are clearly complicated by the different periods of record involved for the individual sites (see Fig. 4) and should be undertaken with caution. However, the key feature of Figure 7 is the fact there is little evidence of an increase in sediment load between the measuring station at Jinghong and that at Pakse, despite the catchment area having increased nearly fourfold. Existing evidence indicates that this additional contributing area should contribute significant amounts of sediment, but there is little or no increase in the downstream sediment load. In other rivers, similar effects have been attributed to floodplain and channel storage (1), but it has been suggested that there is only limited longer-term storage of fine sediment in the channel of the middle reaches of the Mekong (14). Further analysis is clearly required to resolve the nature of the storage and buffering suggested by Figure 7. If such conveyance losses and associated sediment storage are shown to be important by further analysis of the sediment load data for the main tributaries of the Mekong, they will clearly have important implications for the downstream impact of any reduction in the sediment input from the Lancang River to the Mekong system.

References and Notes

1. Walling, D.E. 2006. Human impact on land-ocean sediment transfer by the world's rivers. *Geomorphology 79*, 192–216.
2. Milliman, J.D., Quraishee, G.S. and Beg, M.A.A. 1984. Sediment discharge from the Indus River to the ocean: past, present and future. In: *Marine Geology and Oceanography of Arabian Sea and Coastal Pakistan*. Haq, B.U. and Milliman, J.D. (eds). Van Nostrand Reinhold, New York, pp. 65–70.
3. Walling, D.E. 2007. Global change and the sediment loads of the world's rivers. In: *Proceedings of the 10th International Symposium on River Sedimentation (August 2007)*. Moscow, pp. 122–130.
4. Restrepo, J.D. and Kjerfve, B. 2000. Magdalena River: interannual variability (1975–1995) and revised water discharge and sediment load estimates. *J. Hydrol. 235*, 37–149.
5. Mekong River Commission. 2003. *State of the Basin Report: 2003*. Mekong River Commission, Phnom Penh.
6. Kummu, M. and Varis, O. 2007. Sediment-related impacts due to upstream reservoir trapping, the lower Mekong River. *Geomorphology 85*, 275–293.
7. Milliman, J.H. and Syvitski, J.P.M. 1992 Geomorphic/tectonic control of sediment discharge to the ocean: the importance of small mountainous rivers. *J. Geol. 100*, 325–344.
8. Roberts, T. 2001. *Downstream Ecological Implications of China's Lancang Hydropower and Mekong Navigational Project*. International Rivers Network (IRN) Report.
9. Ta, K.T.O., Nguyen, V.L., Tateishio, M., Kobayashi, I., Tanabe, S. and Saito, Y. 2002. Holocene delta evolution and sediment discharge of the Mekong River, southern Vietnam. *Quat. Sci. Rev. 21*, 1807–1819.
10. Harza Engineering Company. 1962. *Lower Mekong River Project*. Final Report. Harza Engineering Company.
11. Walling, D.E. 2005. *Evaluation and Analysis of Sediment Data from the Lower Mekong River*. Report. Mekong River Commission, Vientiane, 61 pp.
12. You, L. 1999. A study on temporal changes of river sedimentation in Lancang River basin. *Acta Geograph. Sin. 54*, 93–100.
13. Lu, X.X. and 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. *Hydrol. Earth Syst. Sci. 10*, 181–195.
14. Gupta, A. and Lieuw, S.C. 2007. The Mekong from satellite imagery: a quick look at a large river. *Geomorphology 85*, 259–274.

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