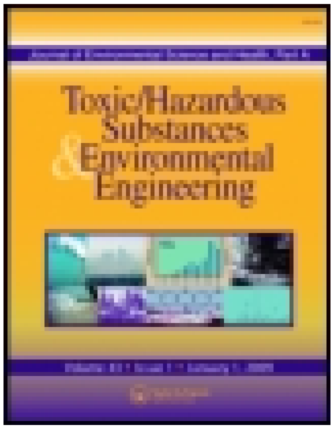


Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering
Publication details, including instructions for authors and subscription information:
http://www.tandfonline.com/loi/lesa20

The ecological complexity of the Thai-Laos Mekong River: I. Geology, seasonal variation and human impact assessment on river quality

Veerasak Udomchoke [a], Patcharee Sunthornranun [a], Apisit Songsasen [a], Kantimanee Phanwichien [a], Pongsakorn Jiwapornkupt [a], Unop Homchan [a], Nitaya Lauhachinda [a], Arthit Sakultantimetha [b], Sornnarin Bangkedphol [b], Keith Torrance [b], Mark D. Gibson [b], Alec F. Gaines [b], Peter H. Booth [b] & Helen E. Keenan [b]

[a] Kasetsart University, Faculty of Science, Chatujak, Bangkok, Thailand

[b] University of Strathclyde, Department of Civil Engineering, David Livingstone Centre for Sustainability, Glasgow, Scotland

Published online: 20 Sep 2010.

Journal of Environmental Science and Health Part A (2010) **45**, 1661–1673

ISSN: 1093-4529 (Print); 1532-4117 (Online)
DOI: 10.1080/10934529.2010.513207

The ecological complexity of the Thai-Laos Mekong River: I. Geology, seasonal variation and human impact assessment on river quality

VEERASAK UDOMCHOKE[1], PATCHAREE SUNTHORNRANUN[1], APISIT SONGSASEN[1], KANTIMANEE PHANWICHIEN[1], PONGSAKORN JIWAPORNKUPT[1], UNOP HOMCHAN[1], NITAYA LAUHACHINDA[1], ARTHIT SAKULTANTIMETHA[2], SORNNARIN BANGKEDPHOL[2], KEITH TORRANCE[2], MARK D. GIBSON[2], ALEC F. GAINES[2], PETER H. BOOTH[2] and HELEN E. KEENAN[2]

[1]*Kasetsart University, Faculty of Science, Chatujak, Bangkok, Thailand.*
[2]*University of Strathclyde, Department of Civil Engineering, David Livingstone Centre for Sustainability, Glasgow, Scotland*

The objective of this study is to assess the variation of pollution in the Thai–Laos Mekong associated with seasonal dynamics concomitant with the natural geological features and human activities that impact on the adverse quality of the river. The complex ecology of the 1500 km stretch of the Thai-Laos Mekong River has been studied in this paper to understand the relationship with the geomorphology, with the sub-tropical monsoonal climate and the impact of human activity. Sub-surface geology controls the nature and extent of the drainage basin and of the river channel. The volume flow of the river varies naturally and dynamically in phase with the rainfall; traditional models based on steady state hydraulics are inappropriate. Continuous erosion of the river banks and bed generates a sediment load of impure silt, mica, quartz and clay minerals that inhibits light penetration and limits the primary productivity of the river. The river separates two countries at different stages of development; it flows through or close to eight non-industrial conurbations (Populations 350,000–2,000,000) but is otherwise sparsely populated. The river is used for subsistence agriculture, village transport, fishing including aquaculture and as a source of domestic water. Hydroelectricity is generated from the Laos tributaries. The river is a depository for partially treated urban waste and untreated village waste, hence populations of *E.coli* bacteria sometimes render the water unsuitable for drinking unless treated with the highest value of 240/100ml found at station 7 during the summer season of 2003. Furthermore the river is polluted by trace metals, notably cadmium and mercury, and by Polycyclic Aromatic Hydrocarbons (PAHs), which are particularly concentrated in the sediments. Previous work has shown that cadmium and mercury exceed the Probable Effect Level (PEL) values of Canadian Environmental Quality Guidelines and that the PAH concentrations were also greater than the Interim Sediment Quality Guidelines (ISQG). Consequently the fish stock, a vital source of protein for the local human population maybe seriously affected. As conflict between the demands of human activities will be exacerbated by the continuing development of the basin; monitoring must be continued and a better model of the river's ecology is needed to predict the impact of development.

Keywords: Mekong River, sub-tropical monsoonal climate, volume flow, water quality, sediment.

Introduction

Previous work on the Mekong by this group of researchers found concentrations of pollutants in the water and sediments at levels that could be harmful to human health and seriously affect the ecosystems of the river. Using Environmental Quality Standards (EQS) as a guideline to assess pollutant parameters, it was found that both metal and organics were present at levels that exceeded the criteria for toxicity.[1] However the Mekong has to be considered in more detail to understand the complexity of the river system and the anthropogenic sources and natural phenomena that influence those findings.

For the rapid development of South East Asia to be sustainable it must be based on sound public understanding of the environment. The human and physical ecology of the Mekong River is experiencing major modification as a result of recent development pressures.[2] Accordingly, the present review provides a case study of the ecological complexity of the important Thai-Laos Mekong River and

Address correspondence to Dr. Helen E Keenan, Graham Hills Building, DLCS, University of Strathclyde, UK; E-mail: h.e.keenan@strath.ac.uk
Received March 10, 2010.

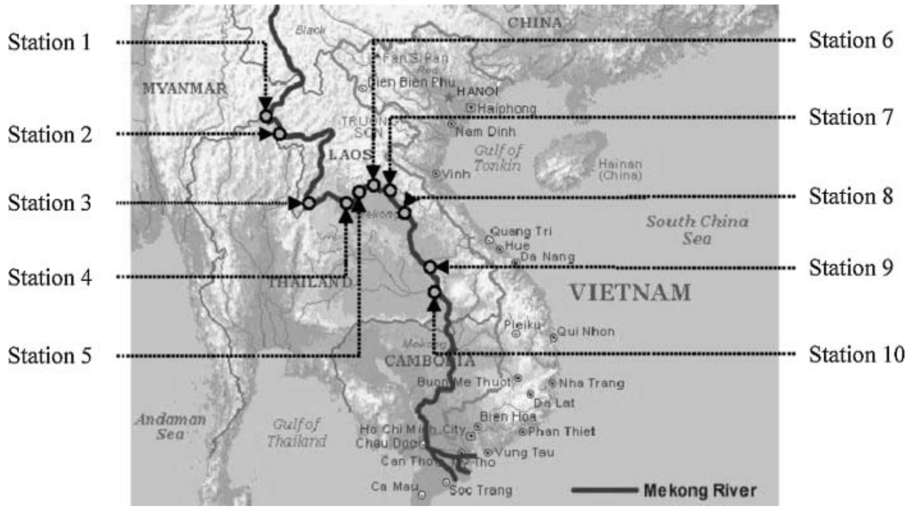
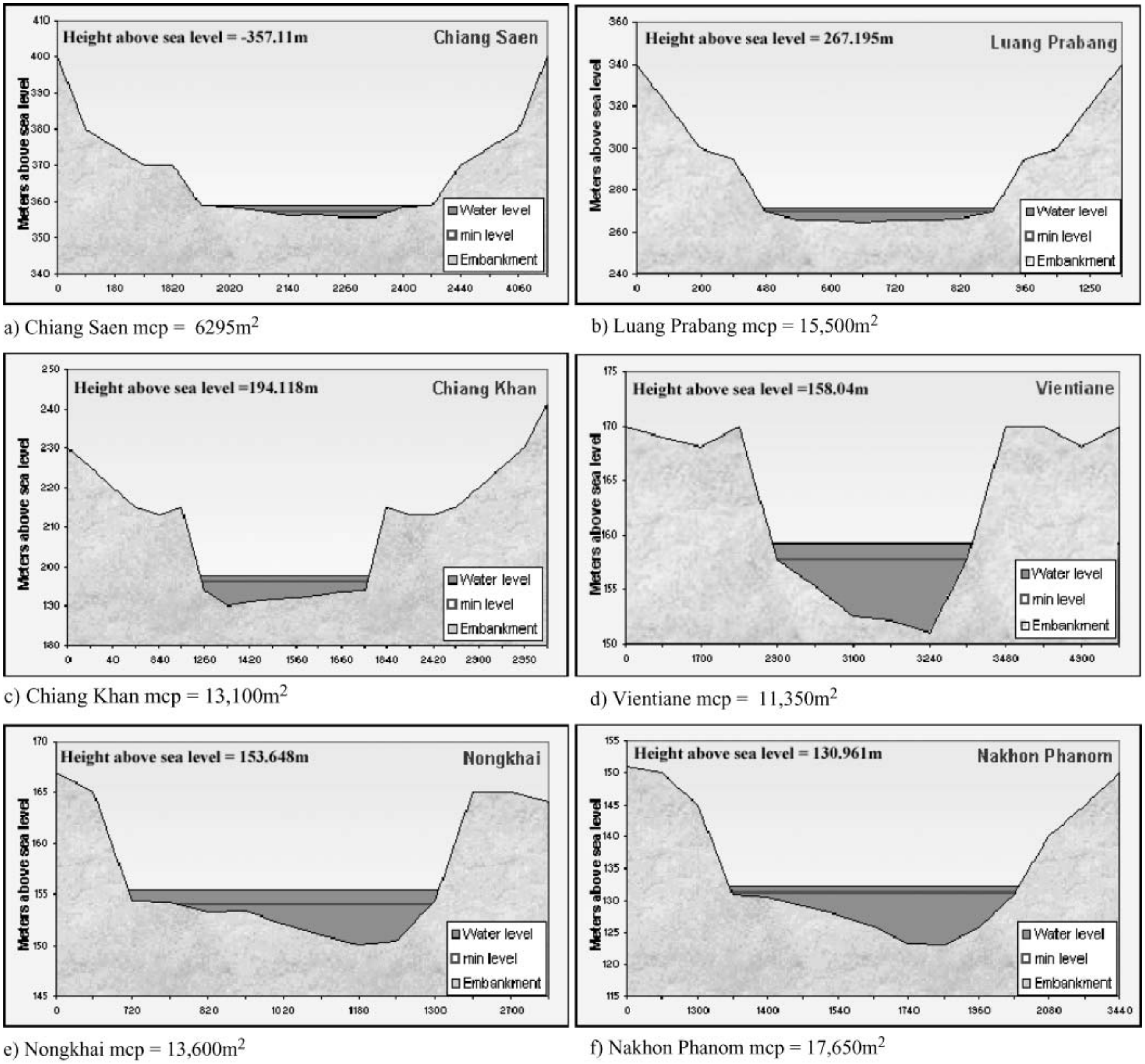


Fig. 1. The Thai-Laos Mekong showing the sampling locations: Station 1: Golden Triangle, Chiang Rai: The Mekong River enters Thailand through Waliang Shan Mountains; Station 2: Wat Jam Pong, Chiang Rai Province: Before the Mekong leaves Thailand for Laos; Station 3: Chiang Khan, Loei Province: The Mekong returns to the Thai-Laos boundary. In Laos, the Nam Ngun tributary enters the Mekong near Vientiane; Station 4: Nong Khai City: The Thai-Laos Friendship Bridge; Station 5: Phonpisai near Nong Khai: Growing urbanisation; Station 6: Wat Ar Hong: A small island precedes the deepest point of the Thai-Laos Mekong; Station 7: Sri Song Kram, Nakorn Phanom Province: The Nam Songkhram tributary enters the Mekong from Thailand; Station 8: Dhat Panom, Nakorn Phanom Province: Busy ferries between Thailand and Laos. The station is placed shortly after the Nam Ngiap, Nam Xan and Theung tributaries enter the Mekong from Laos. A major bridge is under construction between Stations 8 and 9 at Svannakhet. Station 9: Wat Khongchiampurawat, Ubonratchathani Province: After the Xe Nou and Xe Banghiang tributaries enter the Mekong from Laos. Station 10: Khong Chaim, Ubnratchathani Province: Confluence with the Nam Mon and Nam Chi tributaries from Thailand; the last station before the Mekong enters Laos, Cambodia and Vietnam.

discusses the robustness and permanence of the ecology to accommodate such modification. The geomorphology and water flow sections outline the interactions between the geomorphology, water flow and the seasonal variation.[3] The sediment and water quality sections examine the characteristics and importance of sediment and water quality in the light of current urbanisation, sewerage treatment, and agricultural practice. It seems that the tolerance of the physical systems may be compromised. The paper exemplifies the nature of the interconnected and co-evolving causes of environmental problems.[4]

The Mekong River rises in the Tibetan Plateau and travels 4,425 km south-east until it enters the South China Sea through the delta in Vietnam. It is the world's 11th longest river and currently the longest international waterway in Asia. Figure 1 plots the $\sim$1,500 km of the Mekong River that enters Thailand from Myanmar and flows between Thailand and Laos – therefore the term "Thai-Laos Mekong" is used – before it leaves Laos to enter Cambodia. Topographical and land use maps of up to 1 in 50,000 are available through the website of the Mekong River Commission.[5]

Seven towns lie on the river; Chiang Rai (population 1,274,214) in the north, Luang Phrabang (population 367,200), Vientiane (610,000), Nong Khai (905,543), Nakhon Panom (721,540), Svannakhet (850,000) and Pakse (600,000) in the south. In addition Ubonratchathani (1,792,774) is near the river.[5] Elsewhere population densities along the river banks are low, the river flows past villages spaced several kilometers apart. The total population of the Thai-Laos river basin is estimated at >25 million. The towns possess little industry but urbanisation is increasing and each municipality determines its own environmental policy. Future construction may impede and divert the flow of groundwater. Due to domestic wastewater and sewage being piped into the Thai-Laos Mekong (treated in oxidation ponds in Thailand but not yet in Laos) all population centers must be considered present and potential sources of pollution. The river is bridged to carry increasing trade at Vientiane-Nong Khai and a second, recently constructed road bridge links Mukdahan and Svannakhet. The river is currently used for subsistence agriculture, fishing – including a burgeoning aquaculture, transportation – which introduces oil into the river, the deposition of waste and for leisure. The river provides domestic water for the surrounding communities; the fish and seasonal vegetables grown on the river banks and bed are essential sources of food. There is increasing tourism as a result of regional co-operation. In Laos, tributaries of the river are dammed for hydroelectricity. Such dams may disrupt the natural ecology.[6] As the basin is developed, the conflicting demands on the resources of the basin will increase and



a) Chiang Saen mcp = 6295m^2

b) Luang Prabang mcp = 15,500m^2

c) Chiang Khan mcp = 13,100m^2

d) Vientiane mcp = 11,350m^2

e) Nongkhai mcp = 13,600m^2

f) Nakhon Phanom mcp = 17,650m^2

Fig. 2. Cross-sections of the Thai-Laos Mekong basin showing their height above sea level, and the maximum channel capacities without flooding, mcp.

this emphasises the importance of an assessment of the ecological capacities to inform future planning decisions.

Water flow in the Thai-Laos Mekong River

Geomorphology

As with most rivers, the major characteristics of the Thai-Laos Mekong are controlled by its geology. The river, up to 600 m wide and ~10m deep in places, carves through the granite Waliang Shan mountains in the north over 350m above sea-level. Evidence of a fold structure along the mountain chain can be seen at sampling Stations 1 and 2 along the La-Am fault where some andesite and rhyolite can be observed. The river flows through volcanic belts at Stations 3 and 4. Mesozoic rocks of the Khorat group can be seen by the river banks at Stations 6 and 9 and at Station 7 the river flows through a strike/slip fault that forms a particularly straight south-east channel. From Stations 4 to10 the river flows through Mesozoic, interbedded siltstone, sandstone and shale. Tributaries entering the Mekong from Laos at Stations 4–6 will have flowed through granite and Palaeozoic rock at the upper part of the sub-watershed on the left bank. Tributaries entering the east bank at Station 7

Table 1. Stratigraphy of the Thai-Laos Mekong basin.[7,8]

Depth (m)	*Description*
0–6	Mainly load deposits and alluvium
6–9	Wind blown sand
9–11	Swamp and lake deposits
11–14	Red and yellow loess
14–15	Sand with organic matter
15–16	Ferricrete
16–∼30	Younger gravel beds with tektites
∼30–47	Older gravel beds
47–49	Bedded iron oxides and goethitic clay
49–50	Volcanic basalt
50 and deeper	Residual soil, saprolites and rocks of the Khorat Plateau including weathered, friable Mesozoic sandstone

will have risen in the limestone mountains roughly parallel to the Thai-Laos Mekong. Figure 2 shows cross-sections of the Thai-Laos basin.

Generally the narrow flood plains on the right, Thai, bank of the river extend into the infertile, sandstone Khorat Plateau consisting of two basins separated by a mountain range and drained principally by the Songkhram (northern basin) and the Mun and Nam Chi (southern basin) rivers. The left, Laos, bank[7] extends into a 100 km wide strip of fertile land rising into limestone mountains sufficiently steep that the Mekong tributaries are being dammed for hydroelectricity.[8] As the Thai-Laos Mekong travels south-east the ratio of width to depth increases irregularly (Fig. 2). When the river leaves Laos for Cambodia, it can be 1 km wide and 25,000 m^2 in cross-section; it has become estuarine though it has 400 km to travel to its delta in Vietnam. Table 1 summarizes the stratigraphy of the river.

Climate and water flow

Seasons and temperature

Whereas the extent of the river basin and channel is determined by geology, the flow of the river and the surrounding agriculture is naturally controlled by the sub-tropical, monsoonal climate, even in the northern mountains. Consequently, as the Thai-Laos Mekong flows south its volume increases about five-fold from the rain collected in the 600,000 km^2 drainage basin. Maximum channel capacities are given in Figure 2. There are three seasons; cool during the northeast monsoon around November to February, hot and dry from March to June and wet from July to October initiated by the arrival of the southern monsoon. Daily surface temperatures in the river vary between about 18°C (∼ December) and 26°C (∼ April) in the north and between about 23°C (∼ December) and 32°C (∼ April) in the south (Table 2).

The annual cycle of water flow

The flow of the Thai-Laos Mekong varies in phase with the rainfall (Fig. 3), the annual cycle being similar to that of the lower Irrawaddy.[9] In the hot, dry season around April the river, only 1–2 m deep, trickles between fertile, cultivated, braided mud-flats. With the advent of rain, the river rapidly increases in volume becoming a maximum between July and October, usually in August–September, when it may flood. Such flooding is essential for wet-rice-growing in the fertile, left plain but is undesirable on the less fertile, right, sandstone Khorat Plateau and in the towns. Weather being erratic, flooding varies from year to year; being particularly severe in 1995, 1996 and 2000.[5] Comparison of the maximum channel capacities (Fig. 2) with the maximum volume flows measured by the Mekong River Commission[5] indicates the average current in August/September to be about 1–2 ms^{-1}, suggesting a maximum current in the center of the river of 3–4 ms^{-1}. Despite patches of white water, the August–September river is observed to be tranquil, consistent with its Froude number of less than unity and to be curved rather than meandering. The flow is turbulent, however, the Reynolds number being large.

After August/September rainfall diminishes, the level of the river decreases and by the cool season around December sand bars appear, particularly near the entrances of tributaries. Vegetables are cultivated on the river-banks and the sand bars as they become revealed. Evaporation reduces the level of the river further as the hot season approaches. Thus, the flow exhibits a natural, dramatic seasonal variation not present in traditional formulations relevant to rivers in temperate climates.[10] From Figure 3 the volume of the water flow at time t is $(A[1+\sin(\omega t+\varepsilon)] + A_O)$, where A_O is the minimum volume flow (in the hot season) and $(2A+A_O)$ is the maximum volume flow (in the rainy season). A and A_O vary with location. If the time t is expressed as a fraction of a year, ω gives the period of the annual cycle – roughly 2π - and ε is a phase angle ensuring that maximum flow occurs in August/September. A and A_O depend on rainfall and on such factors as the coverage of the basin by vegetation. Hydraulic conductivities through the basin may be expected to vary dramatically with season and with the geology of the basin but, as yet few measurements have been made. Comparison of the flow through the aquifers with the much better understood flow through aquifers having similar geology in temperate regions would be of great interest.

Understanding of the flow of rivers in temperate climates is founded on the existence of steady states and equilibrium.[11] The rapid variation in flow illustrated in Figure 3 indicates that future work should determine the extent to which such steady states are relevant to the flows of sub-tropical rivers. Later sections suggest that a similar problem may exist in considering the distribution of pollutants in the sub-tropical ecosystem.

Table 2. Seasonal analyses of water quality at the surface of the Thai-Laos Mekong (2001–2003).

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
Dec 2001										
Temperature (°C)	18	19.5	21.6	21.7	21.3	21.7	22	22.2	21. 6	22.6
TSS (mg/L)	188	186	174	154	179	182	132	195	219	181
Transparency (m)	0.2	0.2	0.2	0.2	0.1	0.2	0.2	0.2	0.1	0.15
DO (mg/L)	9.4	9.11	8.55	8.39	8.61	8.45	8.52	8.67	8.61	8.52
DO(% saturation)	102	102	99	98	100	98	100	102	100	99
BOD (mg/L)	0.74	1.52	0.31	0.14	0.66	0.28	0.10	0.65	0.48	1.01
BOD/DO (%)	7.8	16.7	3.6	1.7	7.7	3.3	1.2	7.5	5.6	11.9
Nitrate (mg/L)	2.8	nd	nd	1.9	1.1	nd	nd	nd	nd	nd
Conductivity (μS/cm)	236	243	241	256	249	228	226	219	202	205
TDS (mg/L)	126	120	132	140	135	122	120	124	110	80
pH	8.5	8.2	8.4	8.3	8.4	8.3	8.4	8.25	8.5	8.4
Coliform (MPN/100mL)	920	350	94	70	350	91	33	94	49	9
Faecal coliform (MPN/100 mL)	26	33	8	11	27	21	8	8	8	2
Apr 2002										
Temperature (°C)	26.2	26.1	29.7	28.4	29.9	30.4	31.6	31.5	31.2	32.3
TSS (mg/L)	696	835	487	813	1,187	488	649	442	817	1,066
Transparency (m)	0.3	0.3	0.5	0.5	0.45	0.6	0.35	0.5	0.38	0.65
DO (mg/L)	7.52	7.31	7.84	7.11	7.63	8.18	8.10	7.36	6.28	7.00
DO (% saturation)	94	92	104	92	104	109	110	100	85	96
BOD (mg/L)	1.24	0.80	0.29	0.14	1.05	0.64	1.24	0.36	0.10	0.22
BOD/DO (%)	16.5	10.9	3.7	2.0	13.8	7.8	15.3	4.9	1.6	3.1
Nitrate (mg/L)	nd	nd	nd	nd	nd	nd	nd	nd	nd	nd
Conductivity (μS/cm)	385	358	172	309	310	272	260	262	253	246
TDS (mg/L)	120	131	125	134	140	133	128	126	110	115
pH	8.4	8.3	8.7	8.1	8.8	8.9	8.1	8.5	8.6	8.5
Coliform (MPN/100mL)	240	46	920	350	1,600	49	540	350	240	340
Faecal coliform (MPN/100 mL)	22	14	34	13	130	0	79	17	27	34
Aug 2002										
Temperature (°C)	24.7	24.2	26.0	26.2	26.2	26.3	26.3	26.8	26.7	26.6
TSS (mg/L)	1,007	859	815	781	436	713	518	478	434	461
Transparency (m)	0.05	0.05	0.05	0.05	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
DO (mg/L)	7.5	7.8	7.3	7.0	6.6	6.7	6.7	6.5	6.6	7.0
DO (% saturation)	92	95	91	88	83	84	85	82	84	88
BOD (mg/L)	4.9	2.9	0.6	0.7	0.7	0.8	0.9	1.1	1.1	0.5
BOD/DO (%)	65.5	37.0	8.5	10.1	10.3	11.3	14.4	16.3	17.0	7.8
Nitrate (mg/L)	nd	nd	nd	nd	nd	nd	nd	nd	nd	Nd
Conductivity (μS/cm)	200	211	192	193	191	184	172	157	148	141
TDS (mg/L)	100	130	120	115	120	110	100	90	90	80
pH	7.9	7.8	8.4	8.0	7.9	8.1	8.0	8.1	7.9	7.9
Coliform (MPN/100 mL)	270	0	460	220	220	230	170	260	1,300	490
Faecal coliform (MPN/100 mL)	2.2	0	9.2	5.4	1.4	3.5	1.1	1.4	3.5	2.8
Dec 2002										
Temperature (°C)	21.1	21.2	23.5	25.5	24.3	25	25.7	26.7	26.3	26.5
Transparency (m)	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.15	0.15	0.15
DO (mg/L)	8.53	8.32	8.1	8.08	7.83	7.75	7.68	7.63	7.63	7.64
DO (% saturation)	99	97	98	100	95	96	96	97	96	96
BOD (mg/L)	0.97	1.63	0.99	0.66	0.73	0.50	0.35	0.64	0.33	0.86
BOD/DO (%)	11.4	19.6	12.2	8.2	9.3	6.5	4.6	8.4	4.3	11.3
TDS (mg/L)	93	100	111	108	105	91	88	90	93	80
pH	8.5	8.5	8.7	8.6	8.6	8.5	8.6	8.5	8.7	8.6
Apr 2003										
Temperature (°C)	21.8	23.7	26	27.9	26.3	27.2	27	25.8	28.7	28
Transparency (m)	0.35	0.35	0.35	0.3	0.35	0.3	0.3	0.25	0.4	0.6
DO (mg/L)	8.18	7.84	8.2	8.68	7.7	7.98	7.8	7.57	7.87	7.64
DO (% saturation)	96	95	103	112	97	101	99	94	103	99

(Continue on next page)

Table 2. Seasonal analyses of water quality at the surface of the Thai-Laos Mekong (2001–2003). *(Continued)*

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
BOD (mg/L)	0.55	0.16	0.82	0.65	0.25	0.15	0.40	0.12	0.24	0.17
BOD/DO (%)	6.7	2.0	10	7.5	3.0	1.9	5.1	1.6	3.0	2.2
Nitrate (mg/L)	nd	0.6	0.1	nd	nd	nd	0.2	2.1	2.0	0.6
Conductivity (μS/cm)	281	260	278	212	280	245	240	245	252	231
TDS (mg/L)	142	130	128	131	143	122	123	125	120	118
pH	8.7	8.6	8.8	8.8	8.7	8.7	8.8	8.7	8.8	8.9
Faecal coliform (MPN/100 mL)	33	5	5	170	48	22	240	7	5	22
Aug 2003										
Temperature (°C)	18.1	19.4	21.9	21.4	22.2	22.9	23.4	21.8	22.2	21.9
TSS (mg/L)	128	133	125	121	117	139	112	106	91	76
Transparency (m)	0.3	0.2	0.2	0.25	0.2	0.25	0.25	0.25	0.3	0.35
DO (mg/L)	8.7	9.0	8.89	7.83	8.57	8.39	8.8	8.81	8.49	8.6
DO (% saturation)	95	101	104	91	101	100	106	103	100	101
BOD (mg/L)	1.32	0.61	0.28	1.06	0.1	0.08	0.28	0.36	0.15	0.21
BOD/DO (%)	15.2	6.8	3.1	13.5	1.2	1.0	3.2	4.1	1.8	2.4
Nitrate (mg/L)	nd	nd	nd	nd	0.9	1.1	0.9	2.4	0.9	1.8
Conductivity (μS/cm)	232	210	128	148	152	130	123	111	102	108

nd = not detected.
DO (% saturation) has been calculated from the solubility of oxygen in pure water at the relevant temperature. No correction has been made for variations in atmospheric pressure.

Sediment

Many properties of the Thai-Laos Mekong River are determined by the cocoa-coloured sediment it carries. The presence of these sediments:

1. Visually displays continual and marked erosion of the river channel.
2. Limits the primary productivity of the river by inhibiting the penetration of light to not more than 0.6m below the river's surface (Table 2).
3. Scrubs the river water relatively clean by adsorbing pollutants.
4. Pollutes organisms, notably fish that assimilate sediment.
5. Facilitates the cultivation of the river bed and banks in the cool and hot seasons.

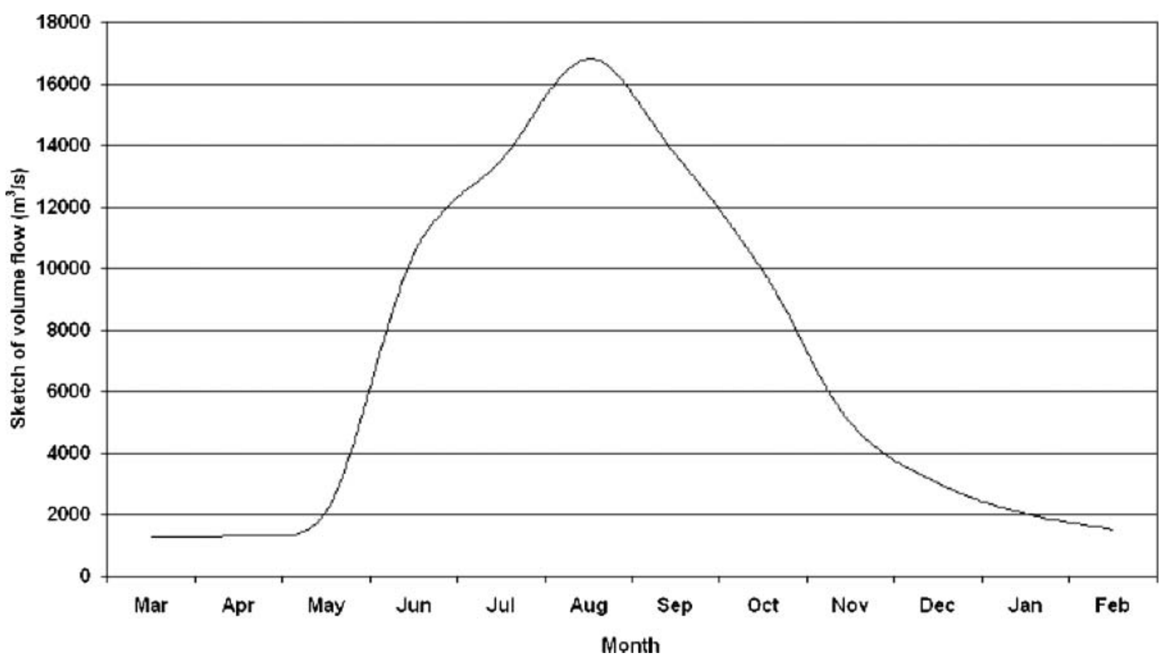


Fig. 3. Sketch illustrating the typical annual flow of the Thai-Laos Mekong at all stations. The volume flow is greater in the south than in the north. (Assessed from monthly measurements The Mekong River Commission, 2005).

Formation and behavior

Although sediment is introduced by the tributaries and sand bars have formed where the tributaries enter the river, observations indicate sediment to be continually generated all along the river by the erosion of the banks and bed by the impact of turbulent water in the same way that sediment is formed and carried by American rivers.[10] The banks of the Thai-Laos Mekong have often to be protected. Surface values of the Total Suspended Solids (TSS) included in Table 2, show marked seasonal variation. Table 2 indicates that during the rainy and cool seasons TSS values are proportional to the flow. The variations in TSS from one location to another can be attributed to variations in the friability of the banks, to the slope of the bed and the curvature of the river – that is on the stress of the flowing water on the river banks. There is a tendency for TSS values to be higher at the two most northerly sampling locations than in the southern plains. The rather high TSS values generated in August-September are consistent with the lack of vegetation binding the river banks. As yet there are no measurements of depth profiles but the small size of the particles suggests there will be little variation of TSS with depth during the wet and cool seasons.[10] In the hot season, April, although the river is shallow and flowing but slowly, the observed TSS values are much higher than those observed in the cool season, December.

During the hot season surface sediment arises from the bed of the river, the bed-load, and is transported differently from the suspended sediment derived from the river-banks in the wet and cool seasons.[11] Sediment particles being small and the river turbulent, the particles settle slowly. In the wet season it is predicted that many sediment particles will be carried the length of the Thai-Laos Mekong before settlement. From Table 2 and Figure 2 it is suggested that when, in August/September, the Thai-Laos Mekong is full but not flooding, an average current of 1 ms^{-1} bears a load of 4–5 tons of sediment per second in from the north and removes 20–25 tons of sediment per second from the south. The flow and the total sediment load are greatly depleted outside the rainy season.

Sediment loads in December are but one twenty-fifth of those carried in August/September. Sand-bars near the mouths of tributaries indicate that when the Mekong is slowed by interaction with its tributaries suspended particles have sufficient time to sediment. Most load will be transported to the delta during the wet season. Continual erosion slowly changes the path of the river.[11] Any change in the flow of water through the basins into the river will produce changes in erosion and in the formation of sediment. Development of the agriculture in the basins could cause changes in the river felt as far as the delta.

Composition

Microscopic inspection indicates ~80% of the sediment particles to range from very fine sand to silt, most particles being less than 1 micron in diameter. Their pigmentation is ad/absorbed on their surface. Some 80% of the sediment consists of quartz sand, much of it, at least from locations 3 to location 9 deriving from the friable and porous sandstone of the Mesozoic Khorat rocks. There are occasional flakes of mica, especially near Station 4. The major cations present (Fig. 4) comprise a rather small proportion of the

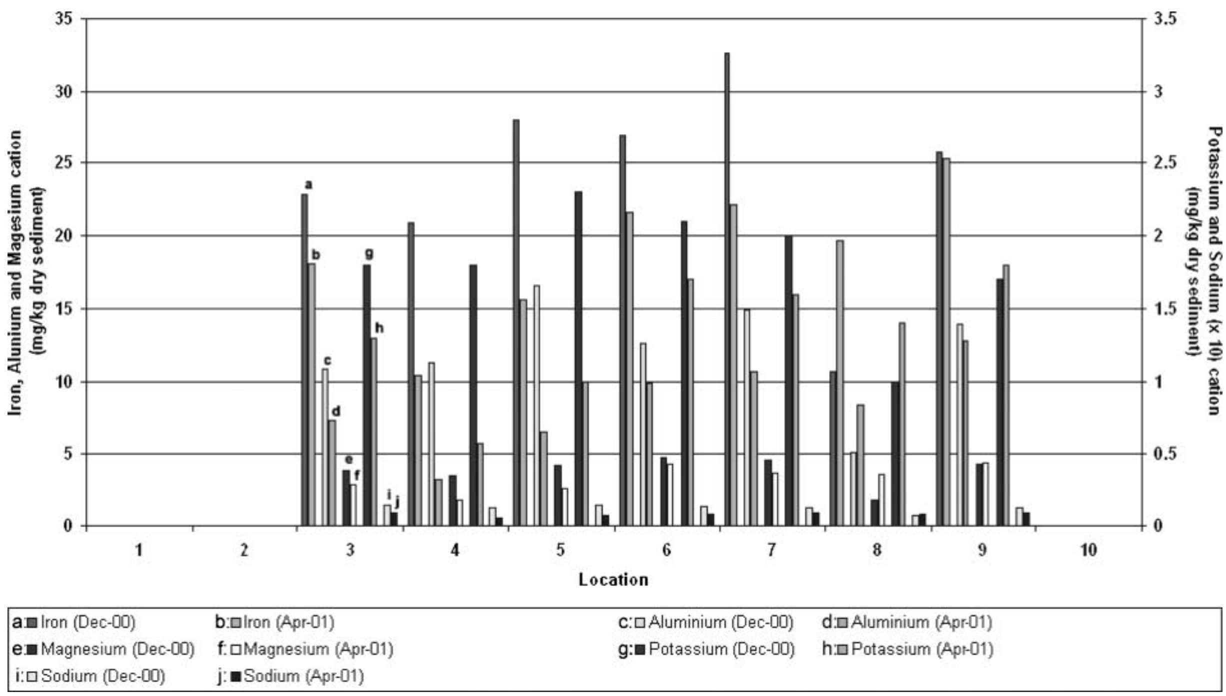


Fig. 4. Histograms of the concentrations of the major cations in sediments (mg/kg).

sediment. Though the drainage basin contains montmorillonite and kaolinite[12] magnesium and aluminium analyses (Fig. 4) indicate no sediments to have contained more than 5% of montmorillonite and 7% of kaolinite. The atomic aluminium to iron ratio in many of these sediments was close to unity (Table 3), however, suggesting a less conventional description of the basin geology.

Experimental methodology

Sampling

Sampling locations are indicated on Figure 1. Water and sediments were sampled from within the top metre of the River and stored cool in clean containers until analysis. Phytoplankton was filtered from 20 L of surface water through a plankton net of 40 micron diameter mesh. The cells were preserved in 10% alcohol for identification.[13]

Waters

All water quality analyses were performed according to conventional standard methods.[14,15]

Sediments

Sediments were examined on glass slides through a 1000x magnification, oil immersion microscope whose field of vision was observed on an electronic monitoring screen. To determine their metal content atomic ratio (Table 3), 2 g of air dried sediment were digested with 5 mL of nitric acid (Aristar, Merck) at 40°C for 2 hours, followed by 1 hour at 90°C and 2 hours at 140°C. After cooling, 4 drops of perchloric acid were added and the sample was digested until almost dry. Then, 2 mL of nitric acid was added and then diluted to 5mL with nanopure water (Barnstead NANOpure). Finally the digested sample was passed through an acid-washed, 1 mm pore size, 25mm diameter, PTFE syringe filter (Merck) to remove any particulates. Metal standards were passed through the PTFE filter to check for any retention, none was found. Acid blanks were extracted and prepared in the same manner as the samples. Metal analyses used a Jobin-Yvon JY-24 inductively coupled plasma optical emission spectrometer.[16]

Metal contents were recalculated to a dry basis from the measured moisture content of the samples by drying at 105°C. The combustible content of the sediment was determined by using ~0.5 g of dried sediment accurately weighed into a loosely covered crucible and heated in air in a muffle furnace to 900°C (a similar temperature to that used in assays of the volatile contents of kerogen) maintained at 900°C for 1 h, cooled then weighed at room temperature. The percentage of organic carbon in the sediments was determined by the Soil Survey Standard Test Method C6A/2.[17]

Trace metals

A known weight, ~0.5 g, of sample was digested with 5ml of concentrated perchloric acid and 20 mL of concentrated hydrofluoric acid in a MARS55-CEM digester for 1 h. The resulting solution was evaporated to ~3 mL in a fume cupboard and then further digested with concentrated nitric acid until the resulting solution was clear. The concentrations of trace metals were determined by Atomic Absorption Spectrophotometry using a Perkin Elmer Analyst 800.[16] Metal analyses were validated by carrying out the procedures on appropriate certified standards (Table 6).

Polycyclic aromatic hydrocarbons

A known weight of dried sample, ~0.2 g, was hydrolysed by gentle reflux with ~20 mL of ethanol and ~0.75 g of sodium hydroxide for ~90 min. After cooling, 20 mL of *n*-hexane was added and the whole was shaken. Sufficient nanopure water was added to form two phases. The hexane phase was removed and the residue was extracted with 2 further 20 mL volumes of *n*-hexane. The three hexane extracts were bulked. Their total volume was recorded and their fluorescence at 360 nm (310 nm excitation) was compared with the fluorescence of standard concentrations of chrysene in *n*-hexane and with appropriate blanks.[18,19] All chemicals were of HPLC purity.

Results

The observed concentrations of major cations varied slightly with both season and location (Fig. 4). Occasional significant changes in the concentrations of major cations — i.e., in the clay mineral content — suggest that, consistent with the observation of sand bars, the sediment particles in the cool and hot seasons are partially localised. Further work should elucidate how the detailed variation in clay mineral content depends on local variations in the geology and dynamics of the river.

Table 3 compares the ratios of the concentrations of cations, averaged over all locations, with those of aluminium and potassium, cations known to be part of the clay mineral lattice. The average ratios of Fe/Al, K/Al and Na/K were the same in December (cool season, suspended sediment) and April (hot season, bed-load). Though the proportion of the clay minerals in the sediments sometimes changes, the composition of the clay minerals appears constant all along the Thai-Laos Mekong.

Table 4, compiled by averaging over all sampling locations, provides the average seasonal concentrations of material lost on combustion of the sediments (i.e., from organic matter, from crystalline water in clay minerals and from carbonates, nitrates and sulphates). The concentration of combustible material was less than 10% throughout the year and varied with season. The suspended sediment in

Table 3. Atomic ratios of the concentrations of the cations in sediments (averaged over all locations).

	Fe/Al	*Mg/Al*	*K/Al*	*Na/K*	*Mn/K*
Dec 2000	0.96 ± 0.04	0.37 ± 0.02	0.11 ± 0.03	0.11 ± 0.005	0.15 ± 0.01
Apr 2001	1.1 ± 0.04	0.44 ± 0.02	0.11 ± 0.005	0.11 ± 0.01	0.19 ± 0.01
	Ti/K	*Cr/K*	*Cu/K*	*Zn/K*	*Pb/K*
Dec 2000	0.078 ± 0.005	0.019 ± 0.001	0.024 ± 0.001	0.056 ± 0.003	0.005 ± 0.001
Apr 2001	0.12 ± 0.076	0.016 ± 0.001	0.008 ± 0.002	0.031 ± 0.002	0.003 ± 0.003
	Cd/K				
Dec 2000	0.005 ± 0.001				
Apr 2001	0.002 ± 0.001				

August, when the river is in full flow, appears to contain a rather larger proportion of combustible material than the bed-load in the hot season (April). Determinations indicate that less than 2% of the dried sediment was composed of organic carbon (Table 4) and thus probably less than half of the combustible material consisted of organic material.

Water quality

As yet, local administrations conduct little regular testing of water quality or of pollution. Tables 2 and 5 present the results of seasonal monitoring of the surface of the Thai-Laos Mekong during 2001–2004.

The river is always slightly basic; the pH being 8.35 ± 0.1 suggests the basicity is maintained by the weathering of the clay minerals in the sediment in the presence of dissolved carbonate.[20] The total concentration of dissolved solids is also rather constant. It is hypothesised that the dissolved solids are leached from the ground by the water passing through the drainage basins, the concentration of material becoming dissolved in the river being determined by its concentration in the soil.

The surface water is almost always fully oxygenated; the lower dissolved oxygen contents observed in August-September (rainy season) may be due to the increased BOD from run-off into the river from surrounding areas. Although the biological oxygen demand (BOD) was usually less than 10% of the dissolved oxygen, testifying to the normal paucity of organic chemicals in the water, the demand was observed to be high during the rainy season (e.g., August 2002) and also on several occasions at the two most northerly sampling stations. Depth profiles have yet to be measured but the behavior of bottom-dwelling fish indicates oxygen persists to the river-bed.

The river is infertile in terms of phytoplankton and zooplankton (Table 5). Although no overhead vegetation impedes illumination of the surface, the depth of the euphotic zone is limited by the sediment to a thin surface layer and populations of plankton are correspondingly patchy, diverse and low (Table 5).[10,13]

From the cool season until the following hot, dry season nitrate concentrations in the euphotic zone of the Thai-Laos Mekong are frequently undetectable especially in the rainy season (Tables 2 and 5), the concentrations appear to peak in those months when the basin land is fertilized.[5] Vegetables cultivated on the river-bed and banks in the cool and hot seasons sometimes require nitrate fertiliser. It is hypothesized that nitrate flowing into the river from its basins is utilized by the phytoplankton in the euphotic zone as fast as it enters the river.

Whereas the river water is of Thai classification II or III,[21] Table 2 shows only 2 out of 50 water samples to be free of faecal Coliform. Generally, the MPN of total Coliform bacteria per 100 mL of water exceeded 50. In 14 water samples there were more than 500 Coliform bacteria per 100 mL. Most high values occurred in August when the surface water of the Thai-Laos Mekong was unfit for drinking and care should be taken in using it for washing. The Coliform bacteria arise from piped sewerage from towns — though in Thailand this passes through oxidation ponds —, village waste, which is generally untreated, and the leaching of pollutants from the land. The last would peak during the rainy season. There should be continual monitoring of total Coliform, and especially of Faecal Coliform, both in river water and in filtered river water and the implications of the results should be promulgated. Effective treatment of sewerage should be encouraged.

Figure 3 emphasises the marked seasonal variation in water flow within the Thai-Laos-Mekong basin. Not only

Table 4. Weight loss of sediments on combustion to 900°C (% of dry weight).

Dec 2000	*Apr 2002*	*Aug 2002*	*Apr 2003*	*Aug 2003*	*Dec 2003*	*Mar 2004*
5.9 ± 0.3% (By seasonal)	2.9 ± 0.4%	9.0 ± 0.6%	3.2 ± 0.4%	6.1 ± 0.5%	2.35 ± 0.3%	1.8 ± 0.3%

Sites	*S1*	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
(By location)	0.69%	0.67%	0.80%	0.69%	1.00%	1.10%	1.78%	1.29%	0.81%	1.10%

Table 5. Plankton populations ($10^5/m^3$).

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
Dec 2001										
Phytoplankton										
Bacillariophyta (9sp)	1.2	0.6	0.4	0.4	0.5	0.2	0.4	1.4	29.5	0.2
Chlorophyta (2sp)	0	0	0.02	0	0	0	0	0	0	0.04
Cyanophyta (4sp)	0.3	0.2	0.05	0.1	0.1	0.05	0.06	0.1	0.2	0.05
Total phytoplankton (Wrongrat, 1996)	1.5	0.8	0.5	0.5	0.6	0.25	0.5	1.5	29.7	0.3
Total zooplankton (Wrongrat, 1995)	0.05	0.05	0.05	0	0	0	0.03	0	0	0.02
Apr 2002										
Phytoplankton										
Bacillariophyta (15sp)	10.3	8.2	8.7	2.6	4.8	0	4.9	5.9	0.9	3.3
Chlorophyta (12sp)	1.8	2.6	5.6	5.1	3.2	1.4	0	1.1	3.3	1.3
Cyanophyta (4 sp)	0.1	0	0.4	0	0.2	0.05	0	0.05	0.06	0.07
Euglenophyta (1sp)	0	0.02	0	0	0	0	0	0.03	0	0
Pyrrophyta (2 sp)	0.02	0	0.06	0	0.03	0.2	0	0.05	0.02	0
Total phytoplankton (Wrongrat,[13])	12.2	10.8	14.8	7.7	8.2	1.7	4.9	7.1	4.3	4.7
Total zooplankton (Wrongrat,[13])	0.02	0	0.3	0.8	0.05	0.4	0.4	0.15	0.05	0

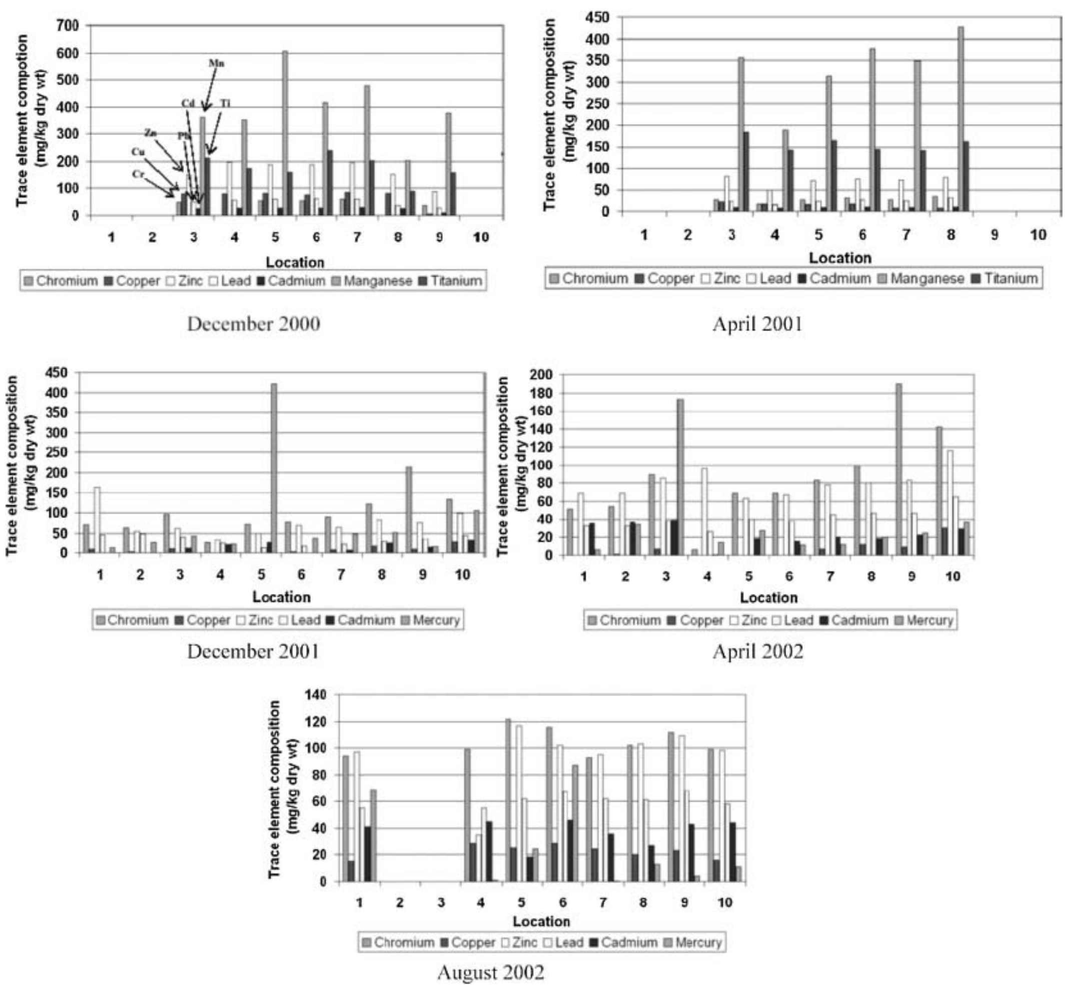


Fig. 5. Trace element composition of sediments (mg/kg dry weight; Hg in μg/kg dry weight).

Table 6A. Experimental ratios of concentrations of trace metals in the sediments and water of the Thai-Laos Mekong River.

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
Cu, Dec 2001	100	25	180	—	—	100	200	170	290	1250
Cu, Apr 2002	13	100	670	—	11	—	1000	1100	770	670
Cu, Aug 2002	500	—	—	1250	1500	1250	1200	1250	1400	1300
Zn, Dec 2001	5000	1000	170	140	50	500	250	123	170	1250
Zn, Apr 2002	170	1250	435	2500	1400	2000	1700	1400	2000	1700
Zn, Aug 2002	1000	—	—	670	1500	1800	1700	1300	1700	1250
Hg, Apr 2002	6700	—	—	12500	33000	12500	12500	15000	20000	29000
Hg, Aug 2002	—	—	—	1300	—	—	1000	15000	11000	—

will hydraulic conductivities through the basin vary significantly with season, the TSS values in the river itself indicate that in August/September some 20 tons of fresh sediment are formed every second and flow through the river. Accordingly, monitoring of trace metals and PAHs has paid particular attention to the temporal and spatial variation of pollutant concentrations.

Trace metals

Most metals other than the alkalis being rather insoluble in the slightly basic river water, one expects that trace metals entering the river will be removed by adsorption onto the sediment. Indeed, all coloured cations can be seen to have become ab/adsorbed on the surface of the sediments from those metals analysed only copper, zinc and mercury were the only metals detected in the river water. The concentrations of copper and zinc, being at the ppb level, were significantly lower than those deemed to be unsafe.[22,23] However, most water samples contained 0.5–1 ppb of mercury, approaching levels considered unsafe.[22,23] To some extent the mercury may have an agricultural source (pesticides and anti-fungal agents) and concentrations could vary with the agricultural cycle,[24] this could be confirmed by more frequent sampling at appropriate times.

Figure 5 shows the seasonal concentrations of the trace metals cadmium, chromium, copper, lead, manganese, mercury, titanium and zinc in Thai-Laos Mekong sediments. The concentrations of cadmium, lead and mercury approach or exceed those considered hazardous when compared to EQS values (Table 6B).[22,25] Table 6A shows the ratios of the concentrations of copper, zinc and mercury in the sediments to those in the river water. Table 3 indicates that the concentrations of copper and zinc in the river sediments are derived from sources other than the geology. Occasional low values of the sediment/water concentration ratios for copper and zinc (Table 6A) may be attributed to localised inputs of metal salts into the river water. The constancy of the values of the observed ratios of the concentrations of zinc–and to a lesser extent of copper–throughout the southern sampling locations rather irrespective of season is possible evidence (Table 6A) that this region of the river may be considered to be in a steady state.

Although from the results in Table 6A it may be concluded that mercury is more strongly adsorbed to the sediments from the water phase than the other metals, this may

Table 6B. The ChrV/LC50 of PAHs and EQS values of metals.

PAHs	*ChrV(mg/L)/LC50(mg/L) (Fish)*	*Metals*	*EQS limit (mg/kg): LEL/SEL**
Fluorene	0.280/3.880	Cd	0.6/10
Phenanthrene	0.160/2.150	Mn	460/1,110
Anthracene	0.160/2.150	Pb	31/250
Fluoranthene	0.055/0.760		
Pyrene	0.055 /0.760		
Benzo(a)anthracene	0.019/0.263		
Chrysene	0.019/0.263		
Benzo(b)fluoranthene	0.006/0.089		
Benzo(k)fluoranthene	0.006/0.089		
Benzo(a)pyrene	0.006/0.089		
Dibenzo(a,h)anthracene	0.002/0.030		
Benzo(g,h,i)perylene	0.002/0.030		
Indeno(1,2,3-cd)pyrene	0.002/0.030		

*LEL: Lowest Effect Level (A *Lowest Effect Level* is a level of sediment contamination that can be tolerated by the majority of benthic organisms). SEL: Severe Effect Level (*Severe Effect Level* indicates a level at which pronounced effects are shown).

Table 7. Total extractable polycyclic aromatic hydrocarbons (chrysene equivalents).

	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
(a) Surface concentrations in river water (μg/L) LOD = 0.2										
Aug 2002	2.25	—	1.3	1.75	—	2.8	1.06	1.9	1.45	—
Apr 2003	1.5	1.6	1.3	1.2	1.3	1.3	1.6	1.3	1.1	1.1
	S1	*S2*	*S3*	*S4*	*S5*	*S6*	*S7*	*S8*	*S9*	*S10*
(b) Concentrations in dry sediments (μg/g) LOD = 0.02										
Nov 2000	—	—	1.2	0.58	1.15	1.9	1.0	2.8	1.0	—
Apr–May 2001	—	—	0.2	0.75	1.6	3.0	1.0	2.7	—	—
Dec 2001	0.1	0.06	1.1	0.45	0.48	0.27	0.12	0.8	0.3	0.80
Apr 2002	0.06	0.06	0.041	0.02	0.04	0.02	0.04	0.06	0.03	0.06
Aug 2002	0.10	—	—	0.11	0.21	0.15	0.15	0.27	0.10	0.13
Apr 2003	0.24	0.23	0.25	0.55	0.16	0.17	0.28	0.13	0.17	0.21
Aug 2003	0.33	0.08	0.85	0.44	0.23	0.34	0.39	0.20	0.23	0.28
Dec 2003	0.35	0.15	0.32	0.43	0.50	0.15	0.40	2.8	0.24	0.05
Mar 2004	0.05	0.09	0.01	0.06	0.14	0.07	0.18	0.45	0.04	0.14

be misleading as often the concentration in water is below the detection limits.

Polycyclic aromatic hydrocarbons (PAHs)

Table 7 records seasonal surface water and sediment concentrations of PAHs in the Thai-Laos Mekong. This fluorescence is due not only to the individual PAHs but also to those PAHs that have become metabolised and excreted by living organisms such as fish. Synchronous spectra indicate the presence of a range of PAHs including mono-, bi-, tri-and tetracyclic aromatics. PAHs may have originated from domestic waste, atmospheric precipitation and motor engines. Concentrations of PAHs exceeding 1 μg/L observed in water samples in 2002 and 2003 indicated the water to be slightly polluted - similarly polluted to the eastern Mediterranean, for example.[26] Further monitoring is necessary to establish the significance of seasonal variations. From Table 7 it is seen that concentrations of PAHs in river sediments have diminished since 2001. River sediments, with occasional exceptions, now appear unpolluted by PAHs, concentrations generally being around 0.25 μg of chrysene equivalent per g of dry sediment, a value that appears less than the Canadian sediment quality guidelines (table 6B).[22,27]

However, had the observed PAHs been accruing in the organic fraction of the sediment, Tables 4 and 7 would show many of the organic fractions to have been polluted and to have formed a significant hazard to health. Accordingly the PAH concentrations throughout the soil and vegetation of the Thai-Laos Mekong basin, including vegetables cultivated on the river-banks, should be monitored. The ratios of the PAH concentrations in the sediment and the surface water were of the same order of magnitude at all locations in both August 2002 and April 2003, suggesting the concentrations to have been in a steady state. Further monitoring is needed to confirm this and obviously there is always the possibility of a localised spillage of PAHs. The average values of the ratios, 78 ± 15 and 152 ± 10, for August 2002 and April 2003, respectively, testify to the effectiveness of the sediment in scrubbing the river water.

Cadmium, mercury and the PAHs in the Thai-Laos Mekong pose hazards to public health. Further work by this group of researchers indicates that the fish are seriously unhealthy which may result in reduced stocks and increased poverty for those reliant on this major river.

Conclusions

Rock paintings along the south west bank of the Thai-Laos- Mekong testify to the existence of human civilization for at least 4 millenia, the current ecology of the 1500 km stretch of the river is considerably more complex. The present study, based on both seasonal monitoring of the river since 2000 and access to 20 years of monitoring by the Mekong River Commission, has revealed the linkages between physical variables, human activity and the consequent widespread, longer-term changes. The geomorphology and the monsoonal climate interact with urbanisation, large-scale agriculture and the development of hydroelectricity to generate phenomena that may be disturbing.

The river is often contaminated, particularly in the rainy season; it is polluted and the fish stock, a major source of protein for the local human population, is most probably seriously unhealthy. The sustainability of practices along the Thai-Laos stretch of the Mekong River is uncertain. The consequences of the interactions between increasing urbanization and agriculture within the drainage basin have yet to be modelled. There is a need to analyse the potential inputs arising from the multi various policies of the several countries through which the Mekong flows and to seek consensual decisions about resource use. In this way ecological complexity becomes rooted in the social and ethical systems which are the key to sustainable development.[28] Scientific monitoring provides precise data that may be used to regulate human activity, however monitoring needs to continue for a full assessment to be made of the pollution status and future impacts of anthropogenic activity and factors such as climate change.

Acknowledgments

We are grateful to the Mekong River Commission for courteously permitting us to use their data. This work was financed by the National Research Council of Thailand, by Kasetsart University, and by the University of Strathclyde. Collaboration was generously funded by the British Council.

References

[1] Keenan, H.E.; Sentenac, P.; Songsasen, A.; Sakultantimetha, A.; Bangkedphol, S. Monitoring and modeling of metals and PAH contaminants in Thai:Laos Mekong River, Lect. ser. Comp. Computt. Sci. **2006**, 682–689.

[2] Lauhachinda, N.; Udomchoke, V.; Songsasean, A.; Homchan, U.; Piwapornkupt, P.; Suntharnranun, P.; McGilligan, J.F.; Keenan, H.E.; Gibson, M.D.; Gibson, G.; Gaines, A.F. The environment of Thai-Laos Mekong river (2001–2004), Mekong Research for the People of Mekong **2006**, *10*, 18–21.

[3] Mainuddin, M.; Kirby, M. Spatial and temporal trends of water productivity in the lower Mekong river basin. Agr. Water Manage. **2009**, *96*, 1,567–1,578.

[4] Glasser, H. On the evaluation of wicked problems, In Lichfield N; Angela, B.D.; Abdul, K.; Anna, P., Eds.; Evaluation in planning, facing the challenge of complexity, Kluwer, Amsterdam, 1998.

[5] The Mekong River Commission; 2005; http://www.mrcmekong.org/info-resources/ffw//stations.css.htm.

[6] Hungspreugs, M.; Utoomprurkporn,W.; Sompongchaiyakul, P.; Heungraksa, W. Possible impact of dams and river diversions on material fluxes to the Gulf of Thailand, Mar. Chem. **2002**, *79*, 185–191.

[7] Nutalaya, P.; Soxlsxi, S. Seismotectonic map of Thailand, US Geological Survey, Asian Institute of Technology, 1985.

[8] NAMTHEUN; http://www.namtheun2.com/.2005.

[9] Beckinsale, R.P. River regimes. In Chorley, R.J., Eds.; Water, Earth and Man. Methuen, London, 1969, 455–471.

[10] Patrick, R. Rivers of the United States, Wiley, New York, USA; 1995.

[11] Simons, D.B.; Senturk, F. Sediment Transport Technology, Water Resources Publications Washington, DC, USA, 1976.

[12] Udomchoke, V. Origin and Engineering Characteristics of the problem soils in the Khorat Basin, Northeastern Thailand. PhD Thesis, Asian Institute of Technology. Bangkok, Thailand, 1991.

[13] Wongrat, L.; Phytoplankton, Faculty of Fisheries, Kasetsart University, Bangkok, Thailand, 1996.

[14] American Public Health Association (APHA), Methods for the Examination of Water and Wastewater 20th Ed.; APHA, Washington DC, 1995.

[15] Eaton, A.D.; Clesceri, L.S.; Greenberg, A.E. Standard Methods for the Examination of Water and Wastewater, United Book Press Inc., Baltimore, 1995.

[16] Standard Methods 3120, Determination of metals by ICP. Standard Methods for the Examination of Water and Waste Water, 19th Ed.; ISBN 0-87553-223, 1995.

[17] Rayment, G.E.; Higginson, F.R. Soil survey standard test method, organic carbon Australian Laboratory Handbook of Soil and Water Chemical Methods, Australian Soil and Land Survey Handbook, Inkata Press, Melbourne and Sydney, Australia; 1992.

[18] UNEP. Determination of petroleum hydrocarbons in sediments, Reference methods for marine pollution studies, No. 20, 1992, 36–49.

[19] UNEP. Monitoring programme for the eastern Adriatic coastal area, Map Technology Report Series, No. 86, 1994.

[20] Stumm, W.; Morgan, J.J. Aquatic Chemistry, Eds.; Wiley, New York, USA, 1970.

[21] Department of Pollution Control, Thailand, Water Quality Standards and Criteria in Thailand. Kurusapa Publishing, Bangkok, 2004.

[22] Canadian Environmental Quality Guidelines, Summary Table, 2003; www.ccme.ca/publications/ceqg_rcqe.html?category_id=124.

[23] WHO Guidelines for Drinking Water Quality, 3rd Eds.; USA, 2004.

[24] Graslund, S.; Holmstrom, K.; Wahlstrom, A. A field survey of chemicals and biological products used in shrimps farming, Marine Pol. Bull, Geneva, Switzerland. **2003**, *6*, 81–90.

[25] ANZECC, Aquatic ecosystems-rationale and background information. In: Australian and New Zealand guidelines for fresh and marine water quality, 2000, 4–16.

[26] Yilmaz, K. Polycyclic aromatic hydrocarbons in the eastern Mediterranean Sea, Marine Pol. Bull. **1998**, *36*, 922–925.

[27] Canadian Sediment Quality Guidelines for the Protection of Aquatic Life, 2001; www.elaw.org/assets/pdf/sediment+summary_table.pdf.

[28] Selman, P. Environmental Planning: The Conservation and Development of Biophysical Resources, SAGE Publications, London, Thousand Oaks, New Delhi, 2000.