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The ecological complexity of the Thai-Laos Mekong River: II. Metals and polyaromatic hydrocarbons (PAHs) monitoring, modelling and environmental fate

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The Mekong is an essential source of water and protein for the denizens of Thai Laos countries. It is hypothesized that pollution may be adversely affecting the water and sediment quality, which threatens the short and long-term use of this major river system. This directly impacts on the health and population of the aquatic life and ultimately human health and the economy for both countries is affected.

The quality of the river can be assessed from various chemical and physical parameters, such as PAHs and metals content of both the water and the sediment. The introduction of Environmental Quality Standards (EQS) allows comparison of the values obtained with the guidelines. Furthermore the modelling program EPISUITE was used to determine the environmental partitioning of pollutants within the different environmental compartments. Using the data produced for PAHs and metals the experimental model was compared to the default model. This involved experimentally measuring the log K_{oc} for Mekong sediments and from this determining the log K_{ow}. High availability in sediment of pollutants may lead to greater biomagnification in bethnic fish, which may then be hazardous for human consumption even if it is safe for the species that is accumulating pollutants. The potential for this is shown by the calculated accumulation in biota C_{bio} values exceeding both the Chronic value (ChrV) and Lethal Concentration 50 (LC_{50}) for fish in the Mekong River. When compared to the EQS guidelines the amount of some PAHs, cadmium and lead in sediment were above the lowest effect level but below the severe effect level.

Keywords: PAHs, metal, biomagnifications, sediment-water partition coefficient, organic carbon partition coefficient, octanol-water partition coefficient, bioconcentration factor, chronic value, lethal concentration 50.

Introduction

The Mekong River (known in Tibet as *Dza-chu*, China as *Lancang Jiang* and Thailand as *Mae Nam Khong*), is a major river in southeastern Asia. It is the longest river in the region. From its source in China's Qinghai Province near the border with Tibet, the Mekong flows generally southeast to the South China Sea, a distance of 4,200 km. The Mekong crosses Yunnan Province, China, and forms the border between Myanmar (Burma) and Laos and most of the border between Laos and Thailand. It then flows across Cambodia and southern Vietnam into a rich delta before emptying into the South China Sea. In the upper course are steep descents and swift rapids, but the river is navigable south of Luangphrabang in Laos.

The natural resource management issues and priorities vary significantly depending on the level of development and populations in each country. In northeastern Thailand, with over 20 million people, the water resources are virtually fully developed. In Laos, with 5 million people and a much poorer country from a GDP perspective, the water resources are largely underdeveloped. Cambodia, with 10 million people, is recovering from decades of war, and in the Mekong delta some 20 million Vietnamese live on some of the most highly productive agricultural land in the world.[1] Utilization of water and soil in these regions of the Mekong River by those populations can cause serious environmental problems. Recalcitrant pollutants introduced by upstream activities may have little impact on local populations but impact adversely on those downstream.

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Pollution of both the water and sediments may adversely impact on wildlife and human health. Heavy metals are of great ecological importance as pollutants to the river system. PAHs are known persistent organic pollutants (POPs) characterized by their hydrophobicity with a capacity to persist in the environment. Water and sediments act as reservoirs for heavy metals and PAHs that may lead to greater bioavailability, bioaccumulation and biomagnification through the food chain. In particular the solubility and the soil/sediment-water distribution coefficient (K_d) of heavy metals and PAHs are of paramount importance in order to predict the behavior and mobility of pollutants within the environment.[2–3]

K_d is determined as:

$$K_d = \frac{\mu\text{gs chemical/g solids}}{\mu\text{gw chemical/g } H_2O} \quad (1)$$

The partitioning of heavy metals and PAHs between sediment-water is dependent on both the physical and chemical properties of each metal. The proportion of organic carbon in the sediment is relevant to this study for 2 reasons.

1. The organic content of the sediment may form chelates or ligands with the metals and thus show greater partitioning to the organic (sediment) phase than would be expected. Moreover, organic content of sediment also relate to its adsorption potential for PAHs.
2. EPISUITE uses the organic carbon content in calculating the percentage in each environmental media.

$$K_{oc} = \frac{K_d}{\%OC} \times 100 \quad (2)$$

High concentrations of pollutants in the environment directly affect the potential for bioaccumulation. To predict the amount of pollutants that contaminate organisms, the dimensionless octanol-water partition coefficient (K_{ow}) is used. K_{ow} is one of the most important descriptors of chemical behavior in the environment, whereby octanol is selected to be representative of lipids in organisms because of the similar carbon to oxygen ratio.[4] Karickhoff (1981) showed that organic carbon was responsible for the adsorption capacity of sediments and that the partition coefficient between sediment and water expressed in term of an organic carbon partition coefficient (K_{oc}) was closely related to the K_{ow}.[5] One proposed correlation from Karickhoff is:

$$K_{oc} = 0.41 K_{ow} \quad (3)$$

Cadmium, manganese and lead were studied as they are representative of the three classes of heavy metals. Cadmium and manganese are d-block metals, Mn^{2+} is regarded as a hard acid, while Cd^{2+} is regarded as a soft acid. Lead is a p-block metal and Pb^{2+} is regarded as a borderline acid.

Samples were taken in 2003 from 10 stations as shown in Figure 1 and analyzed for TOC, PAHs, Cd, Pb and Mn.[6] The objective of this study was not just to analyze the pollutants but also to model partitioning in various medium (sediment, water and organisms in term of K_{ow}) from the measured sediment values.

The values obtained were used in EPISUITE to compare the experimental values with the default. Moreover, the experimental data was compared to the standard limits set for environmental quality and impact assessment. Using an Estimation Program Interface (EPI) suite, several parameters for each of the heavy metals were obtained.[8] These included the percentage of the compound expected in each environmental compartment, which calculated from the chemical and physical properties of the compound, and the Bioconcentration Factor (BCF). Using ECOSAR, the fish Chronic Value (ChrV) and the predicted 14 days Lethal Concentration 50 (LC_{50}) for fish were also obtained.[9] Finally, in the absence of local or regional EQS guidelines, the amounts of metals were assessed in terms of sediment quality guidelines and severe effect level as pollution indicators with Australian and New Zealand Guidelines for Fresh and Marine Water Quality.[10] For PAHs in fresh water sediment were compared with Canadian environmental quality guidelines.[11]

Material and methods

Chemical

All reagents used were of analytical reagent grade. Lead nitrate was purchased from Merck (Darmstadt, Germany). Manganese chloride was purchased from Carlo Erba (Milan, Italy). Cadmium nitrate was purchased from APS Ajax Finechem (Auburn, Australia). All standard PAHs were purchased from Fluka (Steinheim, Switzerland). All solvents for HPLC were of HPLC grade from Fluka (Steinheim, Switzerland).

Apparatus

The MARS-X (CEM Corporation, USA), pressurised microwave-assisted digester was used to digest the sediments. The Analyst 800 (Perkin Elmer, USA) atomic absorption spectrophotometer was used to analyse each metal in the sample. The high performance liquid chromatographic system, Agilent (1100 series) with ChromSpher PAHs column from Varian (250 × 4.6 mm I.D) was used to analyse each PAHs in the samples.

Determination of partition coefficient (K_d) in sediment from Mekong River

Standard test method for determining a sorption constant for an organic chemical in soil and sediments (E1195-01) was used for the determination of K_d in sediment.[3]

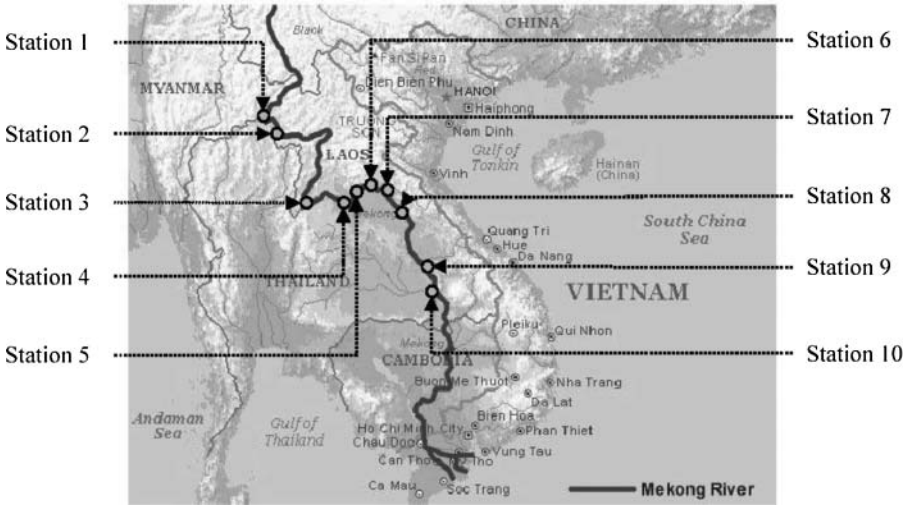

Fig. 1. Map shows the area of sampling sediment from Mekong River.[7] Station 1: Golden Triangle, Chiang Rai: The Mekong River enters Thailand through Waliang Shan Mountains. Station 2: Wat Jam Pong, Chiang Rai Province: Before the Mekong leaves Thailand for Laos. Station 3: Chiang Khan, Loei Province: 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 urbanization. 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.

Determination of organic carbon in sediment of Mekong River

Soil survey standard test methods (C6A/2) was used for the determination of organic carbon in sediments.[12]

Determination of cadmium, manganese and lead in sediment of Mekong River

Microwave sample preparation note (5OS-15) was used for the digestion step.[13]

Determination of PAHs in sediment of mekong river

Analysis was carried out as developed by the authors.[14]

Modeling

Estimation Program Interface (EPI) suite is the calculation model that was considered in this work to describe the behavior of heavy metals and PAHs in the environment. The EPI was used to estimate Bio-concentration Factor (BCF) and the percentage of the compound expected in each environmental compartment. ECOSAR was used to calculate Chronic Values (ChrV) and Lethal Concentration 50 (LC_{50}).[9]

Results and discussion

The soil-water distribution coefficient (K_d) of heavy metals and PAHs is related to various environmental indexes. The higher K_d value, the greater percentage of partitioning to solids. This also affects the aquatic concentration for the Chronic Value (ChrV) and LC_{50} values. From Table 1, it was found that the percent organic carbon in sediments of every station is low (less than 2 percent).

Table 1. Amount of organic carbon in 10 stations of sediment from Mekong River.

Station No.	*% Organic carbon*
1	0.69
2	0.67
3	0.80
4	0.69
5	1.00
6	1.10
7	1.78
8	1.29
9	0.81
10	1.10
$\bar{x}$	0.99 ± 0.33

Table 2. The partition coefficient (K_d) of metals in 10 stations of sediment from Mekong River.

	K_d		
Station No.	*Cd*	*Mn*	*Pb*
1	22.39	72.11	31.62
2	81.28	34.04	85.11
3	56.23	70.15	30.2
4	26.92	26.73	56.23
5	38.9	33.11	38.02
6	22.39	35.81	52.48
7	13.18	30.06	21.38
8	16.6	26.73	26.3
9	13.18	30.55	43.65
10	41.69	37.07	52.48
$\bar{x}$	33.28 ± 21.85	39.64 ± 16.96	43.75 ± 18.82

Table 3. $\log K_{oc}$ and $\log K_{ow}$ that were calculated from experimental data.

Metal	K_d	$logK_{oc}$	$logK_{ow}$
Cd	33.28 ± 21.85	3.47 ± 0.36	3.86 ± 0.36
Mn	39.64 ± 16.96	3.59 ± 0.25	3.98 ± 0.25
Pb	43.75 ± 18.82	3.63 ± 0.28	4.02 ± 0.28

Table 4. Comparison of $\log K_{oc}$ and $\log K_{ow}$ values between default and experimental data of metals from Mekong River sediment.

Metal		$logK_{oc}$	$logK_{ow}$
Cd	*Default	1.16	0.07
	Experimental ($\bar{x}$)	3.47 ± 0.36	3.86 ± 0.36
Mn	*Default	1.16	0.23
	Experimental ($\bar{x}$)	3.59 ± 0.25	3.98 ± 0.25
Pb	*Default	1.16	0.73
	Experimental ($\bar{x}$)	3.63 ± 0.28	4.02 ± 0.28

*Default from EPISUITE.

Table 6. Relationship between C_{aq} and C_{bio} compared with the ChrV and LC_{50} values for 10 stations of metals.

Metals		C_{aq} *(mg/L)*	C_{bio} *(mg/L)*	*ChrV (mg/L)*	LC_{50} *fish (mg/L)*
Cd	*Default	–	0.70	↓	↓
	Experimental ($\bar{x}$)	0.22	41.51	↓	↓
Mn	*Default	–	13.16	↓	↓
	Experimental ($\bar{x}$)	4.16	963.14	↑	↓
Pb	*Default	–	4.96	↓	↓
	Experimental ($\bar{x}$)	1.57	390.05	↑	↓

*Default C_{bio} was calculated from BCF: $C_{aq} = C_{sed}/K_d$, $C_{bio} = C_{aq}$ x BCF.
↑:C_{bio} values above threshold for water, ↓: C_{bio} values below threshold for water.

Cadmium, lead and manganese

The K_d of sediments for Cd, Pb and Mn from station 1-3 are relatively higher than other stations, which may be due to the presence of high montmorironite content in the sediment.[6] Moreover, K_d was related to the percentage of organic carbon which may be important, as absorbed metals can form organometallic compounds.[15] From Table 1, the relative K_{oc}, K_{ow} and aqueous concentration (C_{aq}) for Cd, Pb and Mn were calculated as shown in Table 2 to Table 6.

Although default models are useful, experimental values differ greatly from those predicted as seen in Table 4. The fugacity model shows that most of Cd, Pb and Mn partitions into the sediment (Table 5). With each metal showing greater percent partitioning to solids, therefore, bioaccumulation is greater in mud dwelling bottom feeding fish. Higher bioaccumulation may occur for all fish as suspended solids would also be heavily contaminated.

The ChrV and LC_{50} values indicate toxic concentrations in water that can be used comparatively with the potentially accumulated concentrations. Toxicity tests for accumulation of heavy metals are difficult to assess due to variation in BCFs for each heavy metal and each species of fish. Phanwichien et al. demonstrated the correlation between

Table 5. Bio-concentration factors, percentage of metals in each environmental compartment, ChrV and LC_{50} values (from EPI suite) compared between default and experimental data.

			Partitioning				
Metals		*BCF*	*%Solid*	*%Air*	*%Water*	*ChrV (mg/L)*	LC_{50} *fish (mg/L)*
Cd	*Default	3.16	6.23	38.10	55.70	678.75	2567.69
	Experimental ($\bar{x}$)	187.20	83.78	4.19	12.00	—	—
Mn	*Default	3.16	6.32	38.10	55.60	9589.12	251.94
	Experimental ($\bar{x}$)	231.50	84.53	3.87	11.60	—	—
Pb	*Default	3.16	6.00	34.10	59.90	181.88	3552.71
	Experimental ($\bar{x}$)	248.50	89.00	2.90	8.11	—	—

*Default: BCF and partitioning from EPISUITE, ChrV and LC_{50} from ECOSAR.
Experimental: BCF from $\log K_{ow}$ value, calculated from experimental K_d, modeled in EPISUITE.

Table 7. Comparison of quality standards for 10 sampling stations of metals with sediment quality standards (Australian and New Zealand guidelines for fresh and marine water quality, 2000).

Station	C_{sed} *(mg/kg)*		
*EQS limit (mg/kg): LEL/SEL**	*Cd 0.6/10*	*Mn 460/1,110*	*Pb 31/250*
1	9.34	179.12	54.22
2	7.43	139.65	56.62
3	5.78	147.4	61.04
4	6.76	123.02	62.26
5	8.42	136.35	74.93
6	9.38	137.69	67.72
7	10.5	207.73	70.67
8	5.92	205.65	72.54
9	3.24	128.27	76.96
10	7.06	244.36	89.72

***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).

Cd, Cu and Zn accumulations in liver, kidney and muscle of the Mekong Catfish and concomitant adverse physiological effects.[16] In this investigation, the potential accumulative values for Cd, Pb and Mn are under the ChrV and LC_{50} values except the experimental Mn and Pb that exceed the ChrV. But this does not account for biomagnifications through the food chain. The presence of aquatic metals particularly Cd and Hg adversely affects fish health, particularly those mechanisms that protect against diseases.[17] This results in depletion of fish stocks and would be devastating for the 60 million inhabitants of the Mekong as fish is the major source of protein. Biomagnifications that occurs through the food chain may attain levels dangerous for the consumer, although the animal exposed may not exhibit adverse physiological effects. The most documented evidence for biomagnifications comes from two episodes of mercury poisoning in Japan that resulted in many human fatalities.[18] Such levels as found in the Mekong may result in similar scenarios.

The C_{sed} of Cd, Mn and Pb in sediments of the Mekong River are in the range of 3.24–10.50 ppm, 123.02–244.36 ppm and 54.22–89.72 ppm, respectively. Therefore the C_{bio} value of Mn is high compared with Cd and Pb. The calculated Cbio values for Mn and Pb exceeded the ChrV and LC_{50} values.

Table 7 shows the comparison between the mean value of C_{sed} of Cd, Mn and Pb with the LEL (lowest effect level) and SEL (severe effect level).[19] The C_{sed}values of Cd and Pb are higher than LEL values for all stations but only one station for cadmium exceeds the SEL values (Station 7).

PAHs

As expected the more hydrophobic the PAH the greater the BCF and persistence as presented in Table 8 and the greater the % partitioning to sediment, this is associated with lower concentrations for ChrV and LC_{50} values. Higher BCF values will increase the biomagnification, thus very low levels of PAHs in water and sediment may exert adverse physiological effects through the food chain. It was also noted that the potential accumulative values for PAHs almost always exceed the ChrV and LC_{50} values for water. The fugacity model in Table 8 shows that most of the PAHs partition into sediment.[4] However this is based on a default model where the values are obtained from chemical and physical properties and not experimental data. Work on this project has shown that the Mekong sediments are low in Total Organic Carbon (TOC) with all stations having values of <2%, this

Table 8. Bio-concentration factors, % PAH predicted in each environmental compartment and ChrV and LC_{50} values (from EPI suite and ECOSAR).

PAHs	*BCF*	*Partitioning (scenario 6*)*			*ChrV(mg/L)/ LC_{50}(mg/L) (Fish)*
		% Solid	*%Air*	*% Liquid*	
Fluorene	82	82	2	16	0.280/3.880
Phenanthrene	47	47	0	53	0.160/2.150
Anthracene	47	47	0	53	0.160/2.150
Fluoranthene	81	81	0	19	0.055/0.760
Pyrene	1 100	70	0	30	0.055 /0.760
Benzo(a)anthracene	5 400	93	0	7	0.019/0.263
Chrysene	5 900	94	0	6	0.019/0.263
Benzo(b)fluoranthene	5 600	94	0	7	0.006/0.089
Benzo(k)fluoranthene	10 000	96	0	4	0.006/0.089
Benzo(a)pyrene	10 000	96	0	4	0.006/0.089
Dibenzo(a,h)anthracene	22 000	97	0	3	0.002/0.030
Benzo(g,h,i)perylene	25 000	97	0	3	0.002/0.030
Indeno(1,2,3-cd)pyrene	29 000	97	0	3	0.002/0.030

Table 9. Relationship between $C_{aq}$and C_{bio} compared with the ChrV and LC_{50} values for average results from each sampling station (N = 10) of PAHs (April 2003, dry season).

PAHs	*C_{aq} (mean ppb)*	*C_{bio} (mean ppm)*	*ChrV / LC_{50} (ppm fish)*
Pyrene	1.35	1.49	↑ / ↑
Benzo(a)anthracene	5.60	30.24	↑ / ↑
Chrysene	2.69	15.87	↑ / ↑
Benzo(b)fluoranthene	1.22	6.83	↑ / ↑
Benzo(k)fluoranthene	1.23	12.30	↑ / ↑
Benzo(a)pyrene	2.10	21.00	↑ / ↑
Dibenzo(a,h)anthracene	1.54	33.88	↑ / ↑
Benzo(g,h,i)perylene	1.06	26.50	↑ / ↑
Indeno(1,2,3-cd)pyrene	1.18	34.22	↑ / ↑

$C_{aq} \times$ BCF = C_{bio} (potential bioaccumulation).
ChrV : chronic value, LC_{50} lethal concentration 50 (14 days).
↑:C_{bio} values above threshold for water. ↓: C_{bio} values below threshold for water.

may lead to elevated concentrations in water concomitant with greater bioaccumulation.

Measurable quantities of PAHs were detected in both water (Tables 9 and 10) and sediments (Tables 11 and 12) at most stations. Due to dilution by a greater volume of water in the wet season, the PAHs concentration was lower in the wet season than the dry season.

The concentration of most PAHs in sediment exceeds the ISQG (Tables 11 and 12) regardless of the season. Although the concentrations were not greater than the PEL value, partitioning shown in Table 8 is mainly to sediments. Therefore accumulative values may increase. This must impact directly on mud dwelling and bottom feeder fish.

Table 10. Relationship between $C_{aq}$and C_{bio}compared with the ChrV and LC_{50} values for average results from each sampling station (N = 10) of PAHs (August 2003, wet season).

PAHs	*C_{aq} (mean ppb)*	*C_{bio} (mean ppm)*	*ChrV / LC_{50} (ppm fish)*
Pyrene	0.58	0.64	↑ / ↓
Benzo(a)anthracene	<dl	....	....
Chrysene	<dl	....	....
Benzo(b)fluoranthene	0.18	1.01	↑ / ↑
Benzo(k)fluoranthene	0.14	1.4	↑ / ↑
Benzo(a)pyrene	<dl	....	....
Dibenzo(a,h)anthracene	<dl	....	....
Benzo(g,h,i)perylene	0.27	6.75	↑ / ↑
Indeno(1,2,3-cd)pyrene	0.15	4.35	↑ / ↑

$C_{aq} \times$ BCF = C_{bio} (potential bioaccumulation).
ChrV : chronic value, LC_{50} lethal concentration 50 (14 days).
<dl : lower than detection limit.
↑:C_{bio} values above threshold for water. ↓: C_{bio} values below threshold for water.

Table 11. Comparison of C_{sed} and quality standards of PAHs average values (N = 10) (April 2003 dry season).

PAHs	*C_{sed} actual (μg/kg dry wt)*	*STANDARDS (μg/kg dry wt)*	
		ISQG	*PEL*
Fluorene	52.85	21.2 ↑	144
Phenanthrene	153.35	41.9 ↑	515
Anthracene	82.78	46.9 ↑	245
Fluoranthene	180.67	111 ↑	2 355
Pyrene	79.30	53 ↑	875
Benzo(a)anthracene	32.77	31.7 ↑	385
Chrysene	13.98	57.1	862
Benzo(b)fluoranthene	34.60	nv	nv
Benzo(k)fluoranthene	79.26	nv	nv
Benzo(a)pyrene	30.34	31.9	782
Dibenzo(a,h)anthracene	55.08	6.22 ↑	135
Benzo(g,h,i)perylene	101.30	nv	nv
Indeno(1,2,3-cd)pyrene	7.66	nv	nv

ISQG : Interim Sediment Quality Guideline. PEL: Probable Effect Level Canadian Environmental Quality Guidelines (freshwater sediment).

$$C_{sed}\ \text{actual} = \text{Result} \times \left(\frac{\text{Extraction efficiency}}{100}\right).$$

PAHs are only one group of a range of POPs present in the river system. Adverse physiological effects from exposure to these chemicals may include: mutagenic, carcinogenic and endocrine disrupting processes.[20] The additive

Table 12. Comparison of C_{sed} and quality standards of PAHs average values (N = 10) (August 2003 wet season).

PAHs	*C_{sed} actual (μg/kg dry wt)*	*STANDARDS (μg/kg dry wt)*	
		ISQG	*PEL*
Fluorene	70.72	21.2 ↑	144
Phenanthrene	377.11	41.9 ↑	515
Anthracene	209.53	46.9 ↑	245
Fluoranthene	290.57	111 ↑	2 355
Pyrene	85.84	53 ↑	875
Benzo(a)anthracene	35.16	31.7 ↑	385
Chrysene	18.38	57.1	862
Benzo(b)fluoranthene	16.11	nv	nv
Benzo(k)fluoranthene	85.05	nv	nv
Benzo(a)pyrene	28.03	31.9	782
Dibenzo(a,h)anthracene	61.62	6.22 ↑	135
Benzo(g,h,i)perylene	88.55	nv	nv
Indeno(1,2,3-cd)pyrene	12.25	nv	nv

ISQG : Interim Sediment Quality Guideline. PEL: Probable Effect Level Canadian Environmental Quality Guidelines (freshwater sediment).

$$C_{sed}\ \text{actual} = \text{Result} \times \left(\frac{\text{Extraction efficiency}}{100}\right).$$

and synergistic effects of groups of chemicals may also have to be considered.

Conclusion

This study predicts the partitioning concentration of Cd, Pb, Mn and PAHs in each environmental compartment of the Mekong River. The comparison between the results and the guideline used indicated that the Mekong River may be considered polluted by Cd and Pb especially at the first part of the river entering Thailand from upriver. However, Mn should also be considered as a pollutant because the potential bioconcentration in biota C_{bio} is greater than ChrV. However, C_{sed} value of Mn was still within the PEL and LEL range.

Although the sources of these pollutants are difficult to assess, there is little industry along Thai:Laos Mekong River. For example, the previous study showed that the ratio of Cd:Zn is approximately 10:1, which was greater than naturally occurring volcanic rock sources at a ratio of greater > 50:1.[18,21–23] This indicates an anthropogenic source, therefore, this is most probably inherited pollution from upstream industry.

From the results of this study and by comparison to the guideline used it is clear that the Thai:Laos Mekong may be considered polluted by some PAHs, Cd and Pb. However, the Australian, New Zealand and Canadian guidelines for fresh and marine water quality should be used with caution because the guidelines are developed specifically for those countries. Climatic conditions and species used in deriving the guidelines may be different to those in the Mekong River.

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