Intercompartment (Editor-in-Chief: Wim Salomons)

Research Article

Partitioning Characteristics of PAHs Between Sediment and Water in a Shallow Lake*

Min Qiao, Shengbiao Huang and Zijian Wang**

State Key Laboratory of Environmental Aquatic Chemistry, Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, P.O. Box 2871, Beijing 100085, P. R. China

** Corresponding author (wangzj@rcees.ac.cn)

DOI: <http://dx.doi.org/10.1065/jss2008.03.279>

Please cite this paper as: Qiao M, Huang S, Wang Z (2008): Partitioning Characteristics of PAHs Between Sediment and Water in a Shallow Lake. J Soils Sediments 8 (2) 69–73

Abstract

Goal, Scope and Background. Distribution of hydrophobic organic contaminants in abiotic compartments is essential for describing their transfer and fate in aquatic ecosystems. Taihu Lake is the third largest freshwater lake in China. Water quality of Taihu Lake has deteriorated greatly during the last decades and has threatened the water supply. The aim of the present study was to investigate the partitioning of polycyclic aromatic hydrocarbons (PAHs) among overlying water, suspended particulate matter (SPM), sediments, and pore water in Meiliang Bay, Taihu Lake and to provide useful information for the ecological engineering in this area.

Materials and Methods. Overlying water and surface sediment were sampled from six sites in Meiliang Bay, Taihu Lake, China. Within 72 h of sampling, sediments were centrifuged to obtain the pore water. Overlying water samples were filtered to separate dissolved and SPM samples. After extraction, samples were purified following a clean-up procedure. PAH fraction was obtained by elution with a mixture of hexane: DCM (7:3, V/V) and analyzed by GC/MS.

Results. PAHs concentrations in overlying water varied from 37.5 ng/L to 183.5 ng/L. Concentrations of PAHs in pore water were higher than those in overlying water. The total concentrations of 16 priority PAHs in sediments ranged from 2091.8 ng/g-dw to 4094.4 ng/g-dw. PAHs concentrations on SPM were decreased with suspended solid concentrations (SSC). Total PAHs concentrations on SPM varied in the range of 3369.6 ng/g-dw to 7531.1 ng/g-dw. The partition coefficients between sediment and overlying water ($\log K_{oc}$) for PAHs with $\log K_{ow} < 5$ were positively correlated with their octanol-water partition coefficients ($\log K_{ow}$) ($n=39$, $r=0.79$, $p<0.0001$). Partition coefficients between sediment and pore water ($\log K_{oc}'$) for all PAHs were also significantly correlated with their $\log K_{ow}$ values ($n=48$, $r=0.82$, $p<0.0001$).

Discussion. In general, PAHs derived from combustion sources tend to bind strongly to soot particles in natural sediment. Consequently, K_{oc} values observed in the natural environment could be orders of magnitude higher than those predicted by linear correlation relationships under laboratory conditions. In the present study, the ratio of $\log K_{oc}$ values to $\log K_{ow}$ values falls consistently above 1, indicating that the sediment soot carbon in the bay was more attractive for PAHs than *n*-octanol. The $\log K_{oc}'$ was also higher than that predicted under labora-

tory conditions, suggesting that the measured pore water PAH concentrations were lower than those predicted. That is to say, not all the sediment PAHs can be available to partition rapidly into sediment pore waters. A variation in soot content is a possible reason. Furthermore, concentrations of PAHs on SPM were higher than those in sediments. The compositions of PAHs on SPM and in sediments were similar, indicating the importance of re-suspension process of sediments in the partitioning process of the shallow lake.

Conclusions. The results indicated the equilibrium partitioning model could be used to predict PAHs distribution in various phases of a shallow lake in the stagnation period, but re-suspension processes should be considered to modify the relationship between $\log K_{oc}$ s and $\log K_{ow}$ s.

Recommendations and Perspectives. Concentration, particle size and composition of resuspended particles could affect the relationship between $\log K_{oc}$ s and $\log K_{ow}$ s. Further work should be done under field conditions, especially where a steady thermodynamic equilibrium state could be assumed.

Keywords: Aquatic ecosystems; China; freshwater lake; K_{ow} ; PAHs; partitioning; polycyclic aromatic hydrocarbons; shallow lake; SPM; surface sediments; suspended particulate matter; Taihu Lake; water quality

Introduction

Contaminants in aquatic environments may exist in different forms, including dissolved forms, those bound to dissolved organic matter, adsorbed to suspended particulate matter (SPM) and associated with surface sediments (Readman et al. 1984). Polycyclic aromatic hydrocarbons (PAHs) are one of the most widespread organic chemicals originating mainly from incomplete combustion of organic materials and accidental spillage of fossil fuels (Li & Chen 2003). Most of these chemicals are of great environmental concern due to the known or potential genotoxicity and carcinogenicity, such as benzo[a]pyrene. Numerous studies have focused on the fate and transport of these chemicals (Moon et al. 2003, Palm et al. 2004) and application of remedial technologies to manage those (Iturbe et al. 2004, Chaudhry et al. 2005, Trably & Patureau 2006). Due to the different intrinsic physicochemical properties of individual PAHs, such as solubility, vapor pressure and lipophilicity, they tend to interact to different extents with sediments, SPM, and biota (Broman et al. 1996, Zhou & Rowland

* ESS-Submission Editor: Prof. Dr. Ulrich Förstner (u.foerstner@tu-harburg.de)

1997, Zhou & Maskaoui 2003), and are subject to various transformation processes including chemical transformation, biodegradation and photochemical degradation. The partitioning of PAHs between sediment and water at equilibrium has been widely considered as a partitioning process (Karickhoff et al. 1979, Means et al. 1980), where dissolved organic carbon (DOC) and particulate organic carbon (POC) have also been suggested to play an important role in controlling the fate of the hydrophobic compounds in aquatic systems (Mittra & Dickhut 1999). DOC and POC would suppress the bioavailability, alternate distribution patterns and mobility of PAHs and, therefore, reduce their risk to aquatic organisms (Viguri et al. 2002, Hellou et al. 2005). In general, the characterization of a contaminant release involves acquisition of aqueous samples from the water column, which may in turn be separated into filterable and non-filterable fractions and sediment samples, which may in turn be fractionated into solids and pore waters, as well as biota living in the water column or sediments (Mott 2002). Many studies have investigated the partitioning of PAHs; however, most of them were conducted in laboratory or estuarine waters. Few phases were examined in shallow lakes, where there are strong interfacial exchange and re-suspension processes. The steady-state equilibrium may be established in the stagnation period, which facilitates the research on partitioning processes under field conditions. In our previous work (Qiao et al. 2006a,b), we investigated the level of PAHs in sediment from a shallow lake in China. However, with the rapid economic development and population rise, the water quality in this area has deteriorated and the water contamination has threatened the water supply. To improve the water quality, ecological engineering was implemented during the last several years. The objective of this work is to study comprehensively the behavior of PAHs in water, suspended particulate matter, sediment, and sediment pore water phases in the lake and provide information for the ecological remediation engineering in this area.

1 Materials and Methods

1.1 Sampling sites

The study area, Taihu Lake, is the third largest freshwater lake in China. Meiliang Bay (water surface area: 135 km²) lies on its northern shore and serves as the municipal water source for Wuxi City, an industrial city with a population of

1 million. Overlying water and surface sediment were sampled from six sites (Fig. 1) in Meiliang Bay, Taihu Lake in July 2003 with the aid of a global positioning system (GPS). The sediments were scooped with a stainless steel grab sampler and placed into aluminum jars, which had been pre-washed with dichloromethane (DCM). Deionized water was prepared as field blank and preserved and handled in the same manner as regular samples. One duplicate was collected from one of the sampling sites. Samples were stored in ice chests and the sediment sections were centrifuged at 3000 g for 20 min to obtain the pore water within 72 h of sampling. The pore water was then decanted and vacuum filtered through 0.7 µm glass fiber filters (APFF, Millipore, USA). Overlying water samples (about 40 L) were collected in pre-cleaned 10-L amber glass bottles and filtered to separate dissolved and SPM samples. SPM samples were freeze-dried and stored in pre-cleaned aluminum foil at -20°C until extraction. The centrifuged sediments were also freeze-dried then ground with a mortar and pestle and kept at -20°C until further analyses. Organic carbon content was analyzed with Apollo 9000 (Tekar-Dohrmann USA).

1.2 Sample extract and materials

Overlying water and pore water samples were extracted using a solid-phase extraction (SPE) system from Supelco. The Oasis HLB cartridge (Waters USA) was first washed with 5 mL of DCM (HPLC Grade, Fisher, USA), followed by 5 mL of methanol (HPLC Grade, Fisher, USA) and 5 mL of distilled water. The cartridge was eluted with 15 mL of DCM. Sediment and particulate matter samples were extracted for 72 h with 1:1 acetone-DCM (V/V) using a Soxhlet extractor. Acid-activated copper slices were used to remove sulfur. All of the extracts were evaporated under a gentle flow of nitrogen gas and solvent-exchanged into hexane. The final extracts were purified following a clean-up procedure on a 2:1 silica gel/aluminum oxide column (1 mm i.d. × 60 mm). PAH fraction was obtained by elution with 70 ml of a mixture of hexane: DCM (7:3, V/V). The eluates were also evaporated and changed into solvent hexane. Internal standard was added before GC/MS analysis.

Standards of 16 US EPA priority PAHs [naphthalene (Naph), acenaphthylene (Aceph), acenaphthene (Ace), fluorene (Fl), phenanthrene (Phe), anthracene (An), fluoranthene (Flu),

Fig. 1: Map of study area and sampling sites

pyrene (Pyr), benzo[*a*]anthracene (BaA), chrysene (Chr), benzo[*b*]fluoranthene (BbF), benzo[*k*]fluoranthene (BkF), benzo[*a*]pyrene (BaP), indeno[1,2,3-*cd*]pyrene (Inp), dibenzo[*a,h*]anthracene (DBA), benzo[*ghi*]perylene (BgP)] in a mixture solution of 2000 µg/ml were purchased from Supelco (USA). Neutral silica gel (60–200 mesh) and alumina (50–200 mesh) were purchased from Acros Organics (USA).

1.3 Instrumental analysis and quality assurance

Concentrations of PAHs in the extracts were determined using an Agilent 6890 gas chromatograph equipped with a split / splitless injector, a 7673 autosampler and a 5973 mass selective detector (MSD) under the selected ion monitoring mode (SIM). All results for sediment samples were reported on a dry-weight basis. Detailed instrumental conditions were described previously (Qiao et al. 2006a). All data were subject to strict quality control procedures. Recoveries were monitored by adding surrogate standard compounds to each sample prior to extraction and procedural blanks were analyzed with each set of samples. Satisfactory analytical quality control was achieved. The recoveries of individual PAHs for sediment fell between 58.7% and 96.3% and ranged from 62.1% to 106.5% for overlying water and 60.4% to 98.2% for SPM. Analytical results were not corrected for recovery.

2 Results

2.1 PAHs concentrations

PAHs concentrations in overlying water varied from 37.5 ng/L to 183.5 ng/L, which were lower compared with those reported in other areas in China (Zhou & Maskouli 2003, Zhang et al. 2004). PAHs in overlying water were mainly dominated by less hydrophobic ones such as phenanthrene, naphthalene and fluorene, while those with high molecular weight or more hydrophobic ones were not detected. Concentrations of PAHs in pore water were higher than those in overlying water (Table 1). The concentration gradient between pore water and overlying water suggests the possible dynamic diffusion of hydrophobic PAHs from pore water to overlying water.

The total concentrations of 16 priority PAHs in sediments ranged from 2091.8 ng/g-dw to 4094.4 ng/g-dw. As has been described in our previous work (Qiao et al. 2006a), highest concentrations of PAHs were found in sediments collected from the northern part of the bay and PAHs were mainly derived from pyrolytic origin. Total PAHs concentrations on SPM varied in the range of 3369.6 ng/g-dw to 7531.1 ng/g-dw, which were obviously higher than their corresponding concentra-

Table 1: Concentrations of total PAHs in overlying water (W), pore water (PW), sediment (SED), and suspended particulate matter (SPM) from Meiliang Bay, Taihu Lake

Sampling sites	W (ng/L)	PW (ng/L)	SED (ng/g-dw)	SPM (ng/g-dw)
M1	183.5	325.0	2981.6	3369.6
M2	177.1	346.2	3787.1	4297.6
M3	37.5	507.4	3632.1	5671.9
M4	120.6	1686.4	4094.4	5766.5
M5	166.7	1224.6	2349.5	7008.8
M6	121.3	981.4	2091.8	7531.1

Fig. 2: Composition of PAHs on suspended particulate matter (SPM) and sediment (SED) in Meiliang Bay, Taihu Lake

tions in sediments (see Table 1). In addition, the composition of PAHs for SPM and sediments was similar (Fig. 2), indicating the possible re-suspension of sediments.

2.2 Partitioning between sediment and overlying water

The organic carbon normalized partition coefficients ($\log K_{oc}$) for different PAHs were positively correlated with the $\log K_{ow}$ data (Martinez et al. 2004) ($r=0.79$ $p<0.0001$) obtained using the linear free energy model, and the relationship between $\log K_{oc}$ and $\log K_{ow}$ gives $\log K_{oc}=0.8406\log K_{ow}+1.339$ (Fig. 3). However, the quantitative relationship between $\log K_{oc}$ and $\log K_{ow}$ derived in the present work was different from that observed under laboratory conditions using a spiking approach, for Karickhoff et al. (1979) and Means et al. (1980) giving the correlation of $\log K_{oc}=\log K_{ow}-0.21$ and $\log K_{oc}=\log K_{ow}-0.317$, respectively.

2.3 Partitioning between sediment and pore water

The relationship between organic carbon normalized partition coefficients for pore water ($\log K_{oc}'$) and $\log K_{ow}$ values

Fig. 3: Relationship between $\log K_{oc}$ and $\log K_{ow}$ for PAHs detectable in overlying water in Meiliang Bay, Taihu Lake. Solid line represents the relationship derived from field measured data and dotted line represents the 1:1 relationship

Fig. 4: Relationship between organic carbon normalized partition coefficients for pore water ($\log K_{oc}'$) and $\log K_{ow}$ for PAHs detectable in pore water in Meiliang Bay, Taihu Lake

is shown in Fig. 4. Contaminant concentrations in pore water and sediment were in thermodynamic equilibrium and, therefore, PAH concentration in pore water was controlled by its hydrophobic property and its concentration in sediment organic carbon. The quantitative relationship between $\log K_{oc}'$ values and $\log K_{ow}$ values gives $\log K_{oc}' = 0.9052 \log K_{ow} + 0.4167$. ($r = 0.82$, $p < 0.0001$)

2.4 Partitioning between suspended particulate matter and overlying water

The individual PAH concentrations on SPM were decreased with suspended solid concentrations (SSC) (Fig. 5), which is consistent with the results by Zhou et al. (1998) that maximum PAH contents on SPM tended to occur in low turbidity zones. No correlations were found between the concentrations of individual PAHs on the SPM and particulate organic carbon (POC). This is probably due to the presence of a particulate phase like soot, to which PAHs are significantly more strongly associated with than natural organic matter (Gustafsson et al. 1997).

Fig. 5: Variation of PAHs concentrations on SPM with suspended solids (SS) concentration

3 Discussion

Partitioning of PAH between overlying water and sediment is not only related to their solubility, but also depends on structural and physicochemical properties, such as molecular weight, molecular area, octanol/water partitioning coefficient (Narbonne et al. 1999). There were many observations, such as those by Karickhoff et al. (1979) and Means et al. (1980), indicated that sediment organic matter was an important phase for the accumulation of PAHs. Many laboratory-derived studies showed that the partition coefficient for hydrophobic contaminants tends to be closely correlated to their octanol/water partition coefficients (K_{ow}) (Baker et al. 2000, Chiou et al. 1998). In general, there is a reversible adsorption/desorption process for fresh spiked PAHs, while PAHs derived from combustion sources tend to bind strongly to soot particles in natural sediment (Readman et al. 1987, Zhou et al. 1999). Consequentially, K_{oc} values observed in the natural environment could be orders of magnitude higher than those predicted by linear correlation relationships under laboratory conditions. In the present study, the ratio of $\log K_{oc}$ values to $\log K_{ow}$ values falls consistently above 1 (see Fig. 3), indicating that the soot particles in sediment of Meiliang Bay was more attractive for PAHs than *n*-octanol (Accardi-Dey & Gschwend 2003, Gustafsson et al. 1997, Mitra & Dickhut 1999).

Contaminant in pore water is usually considered to be the most bioavailable (Forbes et al. 1998). The resulting partition coefficient in this study was also higher than that predicted by Karickhoff et al. (1979) and Means et al. (1980), suggesting that the measured pore water PAH concentrations were lower than those predicted. That is to say, not all the sediment PAHs can be available to partition rapidly into sediment pore waters. Maruya et al. (1996) had reported a similar result in a field study in San Francisco Bay. They thought a variation in soot content is a possible reason for the observed trends since the activity coefficient of a highly aromatic PAH solute in the organic carbon matrix of the sediments would be lower in sediments with higher soot content, resulting in higher values of K_{oc}' and PAHs concentrations lower than that expected in the pore water.

As PAHs are relatively hydrophobic there is a strong potential that these chemicals will interact with SPM at the particle/water interface leading to their removal from the water column and accumulation on SPM (Weber et al. 2006). In natural waters, the sorption and binding of contaminants to SPM have an impact on their toxicity, bioavailability, and general fate (Liu & Amy 1993, Tremblaya et al. 2005), which had been identified as the dominant mechanism for the subsequent trapping of PAHs in estuarine sediments. Numerous studies have shown a hydrophobic-dependent particulate partitioning of PAHs between the dissolved and particulate phases in different marine environments (Readman et al. 1984, Broman et al. 1991). Particle/water interactions are very complex and temperature, salinity, or DOM concentrations were suspected to influence the sorption of hydrophobic contaminants to SPM (Zhou & Rowland 1997, Zhou et al. 1998). In this study, it is suggested that the decrease of PAHs concentrations in SPM with increased SSC is partly due to increased DOM concentrations at higher SSC, with the effect of increasing the solubility of PAHs. Furthermore, the

mixing of resuspended sediment particles with relatively low concentrations of PAHs with soot-like particles of high PAH levels can also result in decreased PAHs concentrations in SPM. The results indicated the importance of re-suspension of sediments in partitioning processes in the shallow lake. More work still needs to be done to investigate contaminant distributions on particles in field conditions.

4 Conclusions

The interfacial partitioning of PAHs have been studied in the abiotic phases of Meiliang Bay, Taihu Lake, China. Results suggested that the distribution between different compartments appears to be accordant with the hydrophobic partition theory. The partition coefficients logarithm of sediment-water ($\log K_{oc}$) and sediment-pore water ($\log K_{oc}'$) were significantly correlated with $\log K_{ow}$ values. The PAHs concentrations on SPM were decreased with SSC and were higher than the levels in sediment. Furthermore, the compositions of PAHs on SPM and in sediments were similar, thus indicating the re-suspension of sediments. The results qualified the utility of equilibrium partitioning models to predict PAHs distribution in various phases of a shallow lake in the stagnation period.

5 Recommendations and Perspectives

The influence of suspended solids on the partitioning process of PAHs is not yet fully examined in this paper. Concentration, particle size and composition of re-suspended particles could affect the relationship between $\log K_{oc}$ s and $\log K_{ow}$ s. While there is much work being carried out in laboratory in this respect, further work should be done under field conditions.

Acknowledgements: We gratefully acknowledge the support of National Natural Science Foundation of China (40590390, 20507019) and Chinese Academy of science (KZCX3-SW-431) for conducting this research.

References

- Accardi-Dey A, Gschwend PM (2003): Reinterpreting literature sorption data considering both absorption into organic carbon and adsorption onto black carbon. *Environ Sci Technol* 37, 99–106
- Baker JR, Mihelcic JR, Shea E (2000): Estimating K_{oc} for persistent organic pollutants, limitations of correlations with K_{ow} . *Chemosphere* 41, 813–817
- Broman D, Näf C, Rolff C, Zebühr Y (1991): Occurrence and dynamics of polychlorinated dibenzo-p-dioxins and dibenzofurans and polycyclic aromatic hydrocarbons in the mixed surface layer of remote coastal and offshore waters of the Baltic. *Environ Sci Technol* 25, 1850–1864
- Broman D, Näf C, Axelman J, Bandh C, Pettersen H, Johnstone R, Wallberg P (1996): Significance of bacteria in marine waters for the distribution of hydrophobic organic contaminants. *Environ Sci Technol* 30, 1238–1241
- Chaudhry Q, Blom-Zandstra M, Gupta SK, Joner E (2005): Utilising the synergy between plants and rhizosphere microorganisms to enhance breakdown of organic pollutants in the environment. *Env Sci Pollut Res* 12, 34–48
- Chiou CT, McGroddy SE, Kile DE (1998): Partition characteristics of polycyclic aromatic hydrocarbons on soils and sediments. *Environ Sci Technol* 32, 264–269
- Forbes TL, Forbes VE, Giessing A, Hansen R, Kure LK (1998): Relative role of pore water versus ingested sediment in bioavailability of organic contaminants in marine sediments. *Environ Toxicol Chem* 17, 2453–2462
- Gustafsson Ö, Haghseta F, Chan C, Macfarlane J, Gschwend PM (1997): Quantification of the dilute sedimentary soot phase: implications for PAH speciation and bioavailability. *Environ Sci Technol* 31, 203–209
- Hellou J, Steller S, Leonard J, Langille MA, Tremblay D (2005): Partitioning of polycyclic aromatic hydrocarbons between water and particles compared to bioaccumulation in mussels, a harbour case. *Mar Environ Res* 59, 101–117
- Iturbe R, Flores C, Chavez C, Bautista G, Torres L (2004): Remediation of contaminated soil using soil washing and biopile methodologies at a field level. *J Soils Sediments* 4, 115–122
- Karickhoff SW, Brown DS, Scott TA (1979): Sorption of hydrophobic pollutants on natural sediments. *Water Res* 13, 241–248
- Li JL, Chen BH (2003): Equilibrium partition of polycyclic aromatic hydrocarbons in a cloud-point extraction process. *J Colloid Interf Sci* 263, 625–632
- Liu H, Amy G (1993): Modeling partitioning and transport interactions between natural organic matter and polynuclear aromatic hydrocarbons in groundwater. *Environ Sci Technol* 27, 1553–1562
- Martinez E, Gros M, Lacorte S, Barceló D (2004): Simplified procedures for the analysis of polycyclic aromatic hydrocarbons in water, sediments and mussels. *J Chromatogr A* 1047, 181–188
- Maruya KA, Risebrough RW, Horne AJ (1996): Partitioning of polynuclear aromatic hydrocarbons between sediments from San Francisco Bay and their porewaters. *Environ Sci Technol* 30, 2942–2947
- Means JC, Wood SG, Hassett JJ, Banwart WL (1980): Sorption of polynuclear aromatic hydrocarbons by sediments and soils. *Environ Sci Technol* 14, 1524–1528
- Mitra S, Dickhut RM (1999): Three-phase modeling of polycyclic aromatic hydrocarbon association with pore-water-dissolved organic carbon. *Environ Toxicol Chem* 18, 1144–1148
- Moon JW, Goltz MN, Ahn KH, Park JW (2003): Dissolved organic matter effects on the performance of a barrier to polycyclic aromatic hydrocarbon transport by groundwater. *J Contam Hydrol* 60, 307–326
- Mott HV (2002): Association of hydrophobic organic contaminants with soluble organic matter, evaluation of the database of K_{oc} values. *Adv Environ Res* 6, 577–593
- Narbonne JF, Djomo JE, Ribera D, Ferrier V, Garrigues P (1999): Accumulation kinetics of polycyclic aromatic hydrocarbons adsorbed to sediment by the Mollusk *Corbicula fluminea*. *Ecotox Environ Safe* 42, 1–8
- Palm A, Cousins I, Gustafsson Ö, Axelman J, Grunder K, Broman D, Brorstrom-Lunden E (2004): Evaluation of sequentially-coupled POP fluxes estimated from simultaneous measurements in multiple compartments of an air–water–sediment system. *Environ Pollut* 128, 85–97
- Qiao M, Wang CX, Huang SB, Wang DH, Wang ZJ (2006a): Composition, sources and potential toxicological significance of PAHs in the surface sediments of the Meiliang Bay, Taihu Lake, China. *Environ Int* 32, 28–33
- Qiao M, Chen YY, Zhang QH, Huang SB, Ma M, Wang CX, Wang ZJ (2006b): Identification of Ah receptor agonists in sediment of Meiliang Bay, Taihu Lake, China. *Environ Sci Technol* 40, 1415–1419
- Readman JW, Mantoura RFC, Rhead MM (1984): The physico-chemical speciation of polycyclic aromatic hydrocarbons (PAH) in aquatic systems. *Fresenius Z Anal Chem* 319, 126–131
- Readman JW, Mantoura RFC, Rhead MM (1987): A record of polycyclic aromatic hydrocarbon (PAH) pollution obtained from accreting sediments of the Tamar estuary, UK, evidence for nonequilibrium behaviour of PAH. *Sci Total Environ* 66, 73–94
- Trably E, Patureau D (2006): Successful treatment of low PAH-contaminated sewage sludge in aerobic bioreactors. *Env Sci Pollut Res* 13, 170–176
- Tremblay L, Kohl SD, Rice JA, Gagné JP (2005): Effects of temperature, salinity, and dissolved humic substances on the sorption of polycyclic aromatic hydrocarbons to estuarine particles. *Mar Chem* 96, 21–34
- Viguri J, Verde J, Irabien A (2002): Environmental assessment of polycyclic aromatic hydrocarbons (PAHs) in surface sediments of the Santander Bay, Northern Spain. *Chemosphere* 48, 157–165
- Weber J, Kreutzmann J, Plantikow A, Pfützner S, Claus E, Manz W, Heininger P (2006): A novel particle contact assay with the Yeast *Saccharomyces cerevisiae* for ecotoxicological assessment of freshwater sediments. *J Soils Sediments* 6, 84–91
- Zhang ZL, Hong HS, Zhou JL, Yu G (2004): Phase association of polycyclic aromatic hydrocarbons in the Minjiang River Estuary, China. *Sci Total Environ* 323, 71–86
- Zhou JL, Rowland SJ (1997): Evaluation of the interactions between hydrophobic organic pollutants and suspended particles in estuarine waters. *Water Res* 31, 1708–1718
- Zhou JL, Fileman TW, Evans S, Donkin P, Llewellyn C, Readman JW, Mantoura RFC, Rowland SJ (1998): Fluoranthene and pyrene in the suspended particulate matter and surface sediments of the Humber Estuary, UK. *Mar Pollut Bull* 36, 587–597
- Zhou JL, Fileman TW, Evans S, Donkin P, Readman JW, Mantoura RFC, Rowland S (1999): The partition of fluoranthene and pyrene between suspended particles and dissolved phase in the Humber Estuary, a study of the controlling factors. *Sci Total Environ* 243/244, 305–321
- Zhou JL, Maskaoui K (2003): Distribution of polycyclic aromatic hydrocarbons in water and surface sediments from Daya Bay, China. *Environ Pollut* 121, 269–281

Received: October 24th, 2006
Accepted: April 17th, 2007
OnlineFirst: April 18th, 2007