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Occurrence, sources, and ecological risks of PBDEs, PCBs, OCPs, and PAHs in surface sediments of the Yangtze River Delta city cluster, China

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Abstract Polybrominated diphenyl ethers (PBDEs), organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), and polycyclic aromatic hydrocarbons (PAHs) in 25 surface sediments in three cities (Nantong, Wuxi, and Suzhou) in the Yangtze River Delta, eastern China were measured. The mean concentrations were 378, 45.8, 1.98, 4,002 ng/g for PBDEs, OCPs, PCBs, and PAHs, respectively. Their levels in the sediments in the three cities were generally consistent with the city industrialization. PBDEs and OCPs were markedly dominated by deca-BDE (>90 %) and DDTs (>70 %). A principle component analysis of the analytes identified three major factors suggesting different sources of the contaminants in the sediments. PBDEs and the organic carbon in the sediments have common sources from industrial activities; whereas OCPs and PCBs, correlated with the second factor, were mainly from historical sources. The third factor with loadings of PAHs is indicative of various combustion sources. Ecological risk assessment indicated that the potential highest risk is from DDTs, for which 22 sites exceed the effects range low (ERL) values and three sites exceed the effects range median (ERM) value.

Keywords PBDEs · PCBs · OCPs · PAHs · Sources · Ecological risk

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Introduction

Persistent organic pollutants (POPs) are toxic chemicals that adversely affect human health and the environment around the world (USEPA 2009). Organochlorine pesticides (OCPs), polychlorinated biphenyls (PCBs), and polybrominated diphenyl ethers (PBDEs) represent the three well-known classes of manmade POPs that are widespread in the environment and living organisms (Hu et al. 2008). Some POPs such as dioxins and polycyclic aromatic hydrocarbons (PAHs) are accidentally formed as a byproduct from industrial or combustion processes. Many of these hazardous chemicals have been included in the Stockholm Convention on POPs.

PBDEs are widely used in textiles, furniture, electronics, and automotive interiors, and have attracted considerable interest in recent years. Considering the rapid economic growth and prosperous manufacturing

industries, China has been a large manufacturer and consumer of flame retardants (Zhou 2006). The estimated domestic production volume of technical deca-BDE around 2006 was 20,000 t (Xiao 2006). Recent investigations from China have raised concerns about the extensive presence of PBDEs in the environment and humans (Zhu et al. 2009; Ma et al. 2012; Shi et al. 2013).

The production of certain OCPs has been banned for decades in most countries in the world, however, they are still frequently detected in the environment due to their substantial use in the past and global movement (Szlinder-Richert et al. 2008). The total production amounts of HCHs and DDTs in China were approximately 4.5×10^6 t and 0.44×10^6 t between the 1950s and 1980s, respectively (Zhang et al. 2009). Agricultural use of most OCPs in China has been banned since the early 1980s, whereas small-scale use (e.g., on forest lands) is still permitted (Wang et al. 2007).

PCBs, which were formerly used in a variety of industrial and commercial appliances such as transformers, capacitors, and plasticizers, have been banned for many years. Recent research indicated that urban regions (such as buildings, paints, and old appliances) are still significant sources of PCBs to the environment in Europe and North America (Diamond et al. 2010). PCBs have not been widely used in many developing countries including China, whereas primitive dismantling of electronic waste has become a substantial emission source of PCBs (Wang et al. 2011c). Consequently, elevated levels in the environment and humans of PCBs have been reported in parts of Africa and Asia in recent years (Breivik et al. 2011).

The metropolitan area of the Yangtze River Delta (YRD) has long been an industrial heartland and a prime economic mover in China. Previous investigations on the POP contamination have been conducted in sediments in the Yangtze River Estuary, adjacent sea, and Taihu Lake (Chen et al. 2006; Zhao et al. 2010b; Wang et al. 2011b; Gao et al. 2013), whereas few efforts have been made to examine the occurrence of POPs in urban background sediments. There have been few studies to measure these pollutants concurrently in the sediments in this region. An investigation on the correlations among these historically or currently used organic compounds in the environment will give insights into their sources.

In the present study, the concentrations of PBDEs, PCBs, OCPs, and PAHs were measured in surface sediments from the cities of Suzhou, Wuxi, and Nantong in the YRD. Their contamination levels in the cities were compared to evaluate the impact of urban development on the aquatic environment. The compositions of and correlations among these organic contaminants were examined to understand their sources and environmental processes. The ecological risks of some selected POPs in the sediment were also evaluated.

Materials and methods

Sampling locations

The YRD is located on the eastern coast of China consisting of 16 cities. It covers approximately 109 km^2 and is home to more than 100 million residents. The YRD city cluster accounts for over 17 % of the total economy in China in 2012. Twenty-five surface sediment samples were collected in the rivers (including the Beijing-Hangzhou Grand Canal, Yangtze River, and the branches) running through Suzhou, Wuxi, and Nantong in October and November 2009, respectively (Fig. 1). A grab sampler was used to collect the surface sediments (top 5 cm). The samples were placed in a prewashed stainless steel container using a clean steel spoon, then they were transferred to the laboratory on ice and kept in a freezer (−20 °C) before analysis.

Sample preparation and analysis

The sample preparation procedures and instrumental analysis have been reported elsewhere (Zhang et al. 2012a) and were descried briefly here. The samples were thoroughly dried at room temperature, grounded, and sieved through a sieve (1 mm in pore size). Accelerated solvent extractor (ASE-300, Dionex Corp., USA) was used to extract the samples with a mixture of dichloromethane and hexane (1:1, *v*/*v*) in two cycles and 5-min static time. Each sample was spiked with ^{13}C-substituted surrogates prior to extraction, which included ^{13}C-BDE28, ^{13}C-BDE47, ^{13}C-BDE153, ^{13}C-BDE183, and ^{13}C-BDE209 for PBDEs, ^{13}C-CB28, ^{13}C-CB47, ^{13}C-CB153, ^{13}C-CB183, and ^{13}C-CB209 for PCBs, ^{13}C-p,p′-DDT for OCPs, and ^{13}C-benzo(a)pyrene for PAHs. The ^{13}C-substituted standards were all purchased from Wellington Lab, Canada, except for ^{13}C-BDE209 that was from Cambridge Isotope Lab, USA. Activated copper powder was added to remove sulfur in the samples. The extracts were

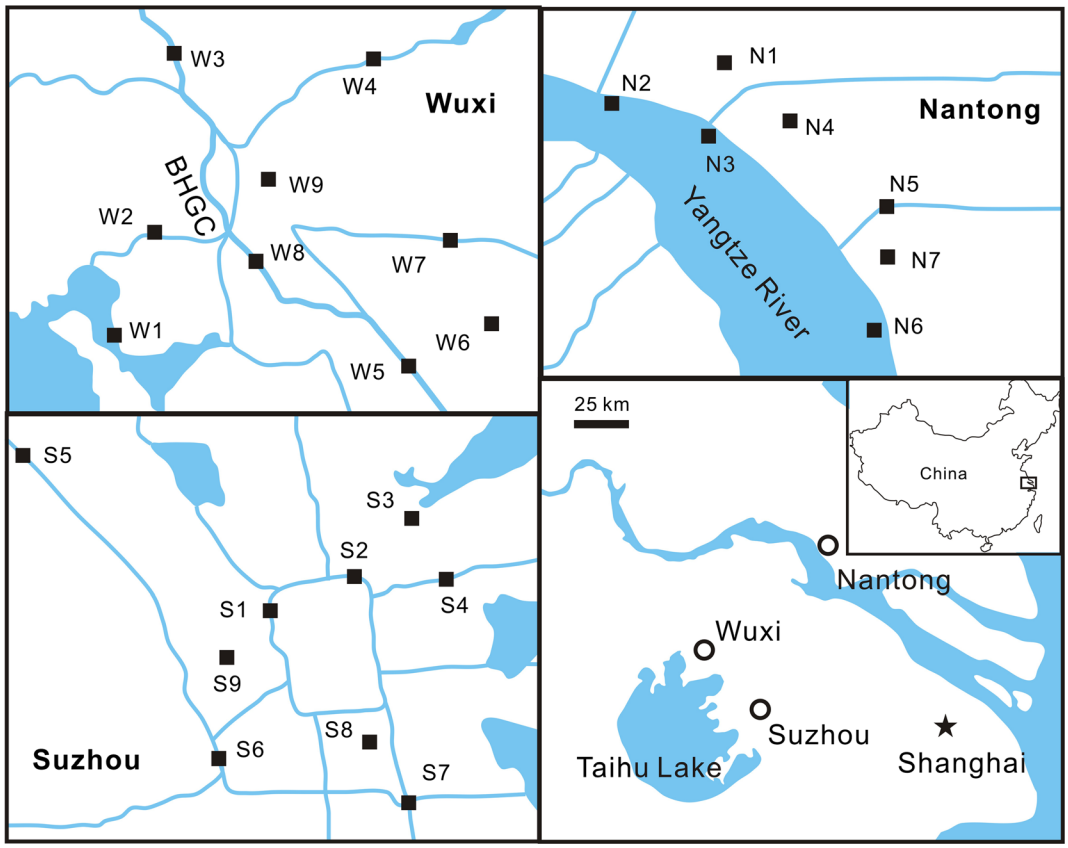

Fig. 1 Sediment sampling sites in Wuxi, Nantong, and Suzhou in the YRD, eastern China

concentrated and solvent-changed to hexane. The clean-up for PCBs and PBDEs are performed by combining sulfuric acid treatment and a multilayer silica gel column, packed with sulfuric acid, alkali, and neutral silica gel. A 6-mL Florisil Cartridge (Supelco Corp., USA) was used for OCPs and PAHs cleanup. The analytes were all eluted with 25 % dichloromethane in hexane.

PBDEs, including 39 mono- to hepta-BDEs (BDE1, BDE2, BDE3, BDE7, BDE8, BDE10, BDE11, BDE12, BDE13 BDE15, BDE17, BDE25, BDE28, BDE30, BDE32, BDE33, BDE35, BDE37, BDE47, BDE49, BDE66, BDE71, BDE75, BDE77, BDE85, BDE99, BDE100, BDE116, BDE118, BDE119, BDE126, BDE138, BDE153, BDE154, BDE155, BDE166, BDE181, BDE183, and BDE190), PCBs (including 32 di- to hepta-CBs), OCPs (DDTs, HCHs, HCB, heptachlor, aldrin, oxy-chlordane, heptachlor epoxide A, heptachlor, epoxide B, chlordanes, dieldrin, endrin, alpha-endosulfan, methoxychlor, and mirex), and 16 priority PAHs listed by the US Environmental Protection Agency were determined by Agilent 7890-5975 high-resolution gas chromatography coupled to mass spectrometry (GC-MS; Agilent Technologies, USA) in electron impact mode. A Shimaszu 2010 GC-MS (Shimaszu Corp., Japan) was applied for analyzing BDE209 in negative chemical ionization mode.

Quality control

A procedural blank and a matrix spiked sample were run with each batch of samples. Only BDE209 was detected in the procedural blanks at an average concentration of 8.5 ng/extract, which were at least ten times lower than those in the sample extracts. The recoveries of target compounds in the matrix spiked samples were 70–130 %, except that a few analytes with higher vapor pressures (such as CB8, BDE1, 2, 3, and 10 and naphthalene) showed lower recoveries. The method detection limits based on the average sample mass are 0.03−0.10 ng/g for PCBs, 0.02−0.08 ng/g for DDTs, 0.05 ng/g for Chlordanes, 0.03 ng/g for HCB, 0.10−5.70 ng/g for PBDEs, and 0.05−0.1 ng/g for PAHs.

Organic carbon determination

The organic carbon (OC) contents in the sediments were determined by a CHN Elemental Analyzer (MT-5, Yanaco, Japan). Sediment samples (20–30 mg) were accurately weighed for combustion at 450 °C in a platinum boat for 5 min, under 8 % oxygen in helium.

Results and discussion

Concentrations and spatial variations

The total concentrations of PBDEs in the sediments ranged from 57.1 to 2,061 ng/g dry weight with a median of 305 ng/g (Table 1). It is expected that BDE209 was the dominant congener with a median concentration of 303 ng/g. The result was in agreement with the prevalence of technical deca-BDE mixtures in China compared with penta- and octa-BDE mixtures. The mean concentrations BDE209 in sediments in the three cities decreased in an order of Nantong (598 ng/g)>Suzhou (327 ng/g)>Wuxi (249 ng/g). The two highest concentrations of BDE209 were found in Nantong sediments (sites N7 and N1 with concentrations of 2,059 and 1,077 ng/g, respectively) (Fig. 2). The N7 site is close to a flame-retardant manufacturing plant, demonstrating that flame-retardant manufacturing plant is a significant source of flame retardants into the environment. The PBDE source at N1 site (in a discarded logistical waterway) was not clear, but the high OC content (2.04 %) suggests it was likely also subject to point sources. The BDE209 concentrations at other sites showed relative small variation from 56.6 to 624 ng/g.

The concentrations of lower brominated BDEs (L-PBDEs; including BDE28, BDE47, BDE99, BDE153, and BDE183) in the sediments has a median concentration of 1.89 ng/g ranging from 0.33 to 16.0 ng/g. Their mean concentrations ranked in the order of Suzhou (4.09 ng/g)>Wuxi (2.41 ng/g)>Nantong (1.69 ng/g). The top four L-PBDE concentrations were all observed in the sediments from Suzhou, which is more industrialized than Wuxi and Nantong.

The L-PBDE levels were comparable to those (averaged 5.21 ng/g) in the Taihu Lake nearby Suzhou and Wuxi (Zhou et al. 2012). The BDE209 levels were obviously higher than those (averaged 37.5 ng/g) in the Taihu Lake and those (<94.6 ng/g) in the Qiantang River in the YRD reported previously (Chen et al. 2006; Zhou et al. 2012). Our results were close to the PBDE levels in urban riverine sediments from another industrialized region in southern China (Chen et al. 2013; Sun et al. 2013) but higher than those from less industrialized urban regions (0.13−30.5 ng/g) (Chen et al. 2009; Zhao et al. 2011; Li et al. 2012a). The concentrations of L-PBDEs (<8 ng/g) in the riverine and coastal sediments from Indonesia were comparable to our results, while the concentrations of BDE209 (<27 ng/g) were substantially lower than our values (Ilyas et al. 2011). High sediment concentrations of PBDEs (up to 18,700 ng/g) were reported in a Korea lake (Moon et al. 2012).

The total concentrations of PCBs ranged from nondetectable (nd) to 8.28 ng/g, with median of 1.62 ng/g. Average PCB concentrations of 14.1−24.9 ng/g in sediments of the Yangtze River Estuary

Table 1 Summary of the POP concentrations (ng/g dw) in the surface sediments from the cities of Wuxi, Nantong, and Suzhou in the YRD, eastern China

Analyte	Suzhou			Wuxi			Nantong		
	Range	Median	Mean	Range	Median	Mean	Range	Median	Mean
PAHs	772–15,907	2,977	5,495	611–8,969	2,483	3,738	735–8,452	1,383	2,423
PCBs	0.77–8.28	1.97	2.61	0.19–4.08	1.48	1.66	0.10–4.23	1.07	1.29
DDTs	4.03–243	24.9	50.5	6.85–34.6	11.6	16.4	nd–55.0	18.1	20.3
Chlordane	nd–3.28	0.78	1.42	nd–1.57	0.79	0.81	nd–0.95	0.09	0.30
HCB	0.37–229	2.74	37.2	0.45–18.2	1.45	3.30	nd–12.1	1.73	3.33
L-PBDEs	0.43–16.0	4.09	5.94	0.44–6.99	1.69	2.41	0.33–2.95	1.84	1.69
BDE209	101–535	349	327	56.6–340	233	249	68.0–2,059	310	598
OC	0.40–2.39	0.84	1.04	0.36–1.64	0.67	0.80	0.31–2.04	0.95	1.12

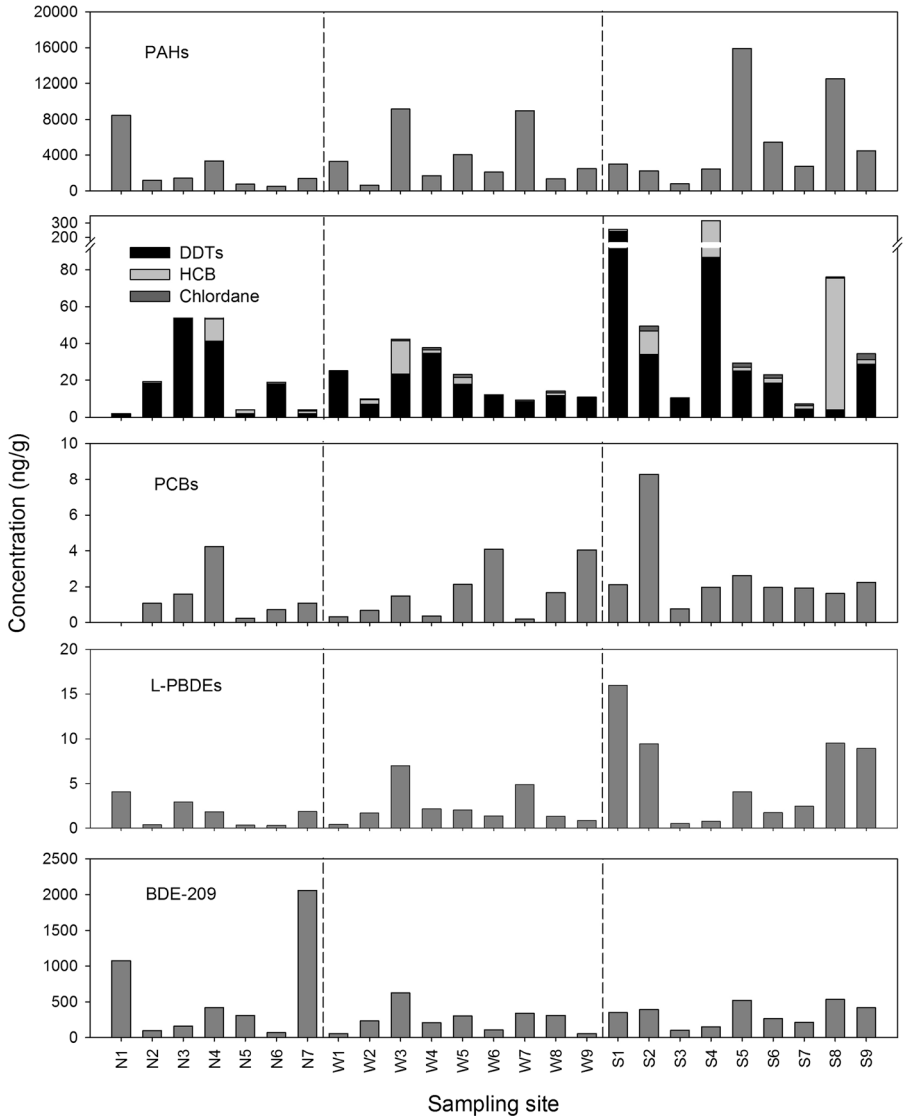

Fig. 2 Spatial variations of the POP concentrations in the surface sediments in Suzhou, Wuxi, and Nantong

have been observed by Gao et al. (2013), which were higher than the levels in the present study. Our result was also significantly lower than the average PCB levels (ranging from 9.20 to 233 ng/g) in the urban sediments recently reported in China (Liu et al. 2007; Yang et al. 2009; Zhang et al. 2010; Zhao et al. 2010a) as well as in many riverine, estuarial, and lake sediments at other locations in the world (Vane et al. 2007; Shen et al. 2009; Hoai et al. 2010; Martinez et al. 2010; Ilyas et al. 2011). The likely explanation is that the three cities in the present study are all emerging cities where commercial PCBs products were not used in large quantities in the past. The differences in the mean PCB concentrations in the three regions (Suzhou, 2.61 ng/g; Wuxi, 1.66 ng/g; and Nantong, 1.29 ng/g) were relatively small.

The total concentrations of OCPs ranged from nd to 316 ng/g, with median of 230 ng/g. DDT and its metabolites (with a median of 18.1 ng/g) accounted for more than 70 % of the OCPs. The highest mean OCP levels were still observed in Suzhou (34.3 ng/g). The DDT concentrations in this region were higher than many of the concentrations (with average values of <12.6 ng/g) recently reported in China (Tan et al. 2009; Zhong et al. 2011; Yang et al. 2013). Our DDT levels were within the range recently reported in riverine sediments in the USA

(averaged 0.04 ng/g), Ghana (1.1 ng/g), Korea (3.64 ng/g), Spain (113 ng/g), and Vietnam (135 ng/g) (Kumar et al. 2008; Kim et al. 2009; Hoai et al. 2010; Navarro-Ortega et al. 2010; Kuranchie-Mensah et al. 2012; Alonso-Hernandez et al. 2014). HCB and chlordane were detected but HCHs and other OCPs were not detected in any samples. The highest OCP concentration was observed at site S4 (316 ng/g) close to an industrial drainage point, followed by S1 (256 ng/g) in the downtown area in Suzhou. This finding indicated that the pollution of OCPs at the two sites was not probably derived from agricultural applications.

The concentrations of 15 PAHs (except for naphthalene) ranging from 493 to 15,907 ng/g had a median of 2,483 ng/g. A previous study showed that vehicular emission, coal combustion, and wood combustion contributed more than 90 % of the PAHs in Taihu Lake sediments (near the study region) (Zhang et al. 2012b). The means of the sediment PAH concentrations in Suzhou, Wuxi, and Nantong were 5,495, 3,738, and 2,423 ng/g, consistent more with the industrialization of the cities. Among the five sites with the highest PAHs concentrations, three (S5, S8, and W3) are located in the Beijing-Hangzhou Grand Canal, one (N1) is located in an unused transport waterway, and one (W7) is in a river near residential zone. This implied that emissions from ship engines may be an important source of PAHs in the sediments.

Compositions and source identification

The congener pattern of the L-PBDEs in the sediment (Fig. 3) showed that BDE47 was the most abundant congener, followed by BDE183. The contributions of BDE47 was clearly higher than BDE99, with a mean BDE47/(BDE47+BDE99) ratio of 0.89 (varied from 0.43 to 1) that was much larger than those in the technical mixtures (0.42 and 0.50) (La Guardia et al. 2006). We also observed a higher contribution of BDE28. This pattern differed from those in the technical penta-BDE mixtures, in which the contributions of BDE183 and 28 are lower and contributions of BDE99 are higher. BDE183 is considered to be an indicator of technical octa-BDE mixture. Its elevated contributions may be due to the decline of PBDEs from penta-BDE mixture, which has been banned in most countries by Stockholm Convention. Nevertheless, a more likely explanation is that BDE183 in the sediments was formed from microbial or photolytic debromination of highly brominated BDEs (Bezares-Cruz et al. 2004; He et al. 2006). Elevated contributions of BDE183 and 28 have also been found in riverine (but not in the estuarine) sediments in the Pearl River Delta (Chen et al. 2013) but not in marine sediments from the East China Sea and Bohai Sea (Wang et al. 2009; Li et al. 2012b). Overall, the altered PBDE profiles in the sediments in the present study suggest that some congeners may have encountered degradation due to the reduced fresh inputs, especially in riverine buried sediments.

The average PCB congener profile in the sediments (hexa->penta->tetra->tri->hepta-CBs) (Fig. 3) was similar to those observed in sediments in the Pearl River Delta and Korea (Lee et al. 2001; Wang et al. 2011a) but different from those in the Yangtze River Estuary and East China Sea (Yang et al. 2012). The ratio of (DDD+DDE)/DDT is commonly used as an indicator of the resident time and degree of degradation of DDT in the environment. In the present study the (DDD+DDE)/DDT ratios were between 0.14 and 1 (0.61 on average) and at 17 sites near or larger than 0.5, indicating DDTs mainly originated from historic use in this region and underwent long-term weathering in the environment. The two sites in Suzhou (S1 near an industrial drainage point and S4 at the downtown) with the highest DDT levels had ratios below 0.5 suggesting fresh inputs. One possible current source is boat painting additive, in which DDT was used to prevent aquatic biota (Edge et al. 2001). Dicofol containing 15 % DDTs is a pesticide being used in China (Qiu et al. 2005). However, the ratios of *o*,*p*′-DDT/*p*,*p*′-DDT in the sediments (0 to 0.34) were much closer to that in technical DDT (0.2) than in dicofol (~7) (Qiu et al. 2005), indicating that dicofol contributes a small proportion of the DDT contamination in the sediments in this region.

The composition of PAHs were substantially constant in the sediments (Fig. 3), which were dominated by high molecular weight (HMW) PAHs (4, 5 and 6 rings) contributing 82 % of the 15 PAHs relative to low molecular weight homologues (2 and 3 rings). This indicated the PAHs in the sediments have similar sources and originated mainly from the combustion processes. Principal component analysis (PCA) was performed to identify the sources of PAHs. The factor loadings of PCA were listed in Table 2. The 15 PAHs in the sediments were clearly clustered into LMW and HMW groups. Phe, Fl, Py, and An are indicators of coal combustion, whereas HMW PAHs such as IP, BP, and BkF are highly associated with vehicular emissions, i.e.,

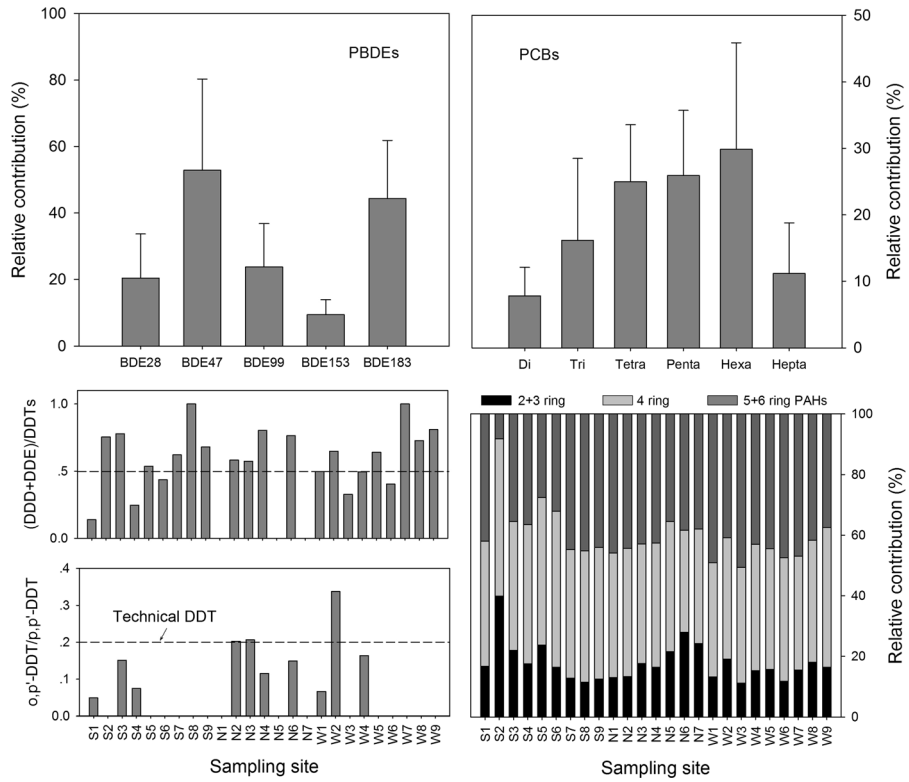

Fig. 3 The congener pattern of PBDEs, homologue composition of PCBs, ratios of (DDD+DDE)/DDTs, and *o,p'*-DDT/*p,p'*-DDT, and compositions of PAHs in the surface sediments in Suzhou, Wuxi, and Nantong

Table 2 Factor loadings of PCA for PAHs in the sediments from the three cities of Wuxi, Nantong, and Suzhou (important loading values of each variable are italicized)

PAHs	Component 1	Component 2
Acenaphthene (Ace)	0.414	*0.858*
Acethene (Ac)	0.398	*0.880*
Fluorene (Flu)	0.345	*0.920*
Phenanthrene (Phe)	0.466	*0.854*
Anthracene (An)	0.518	*0.827*
Fluoranthracene (Fl)	0.556	*0.811*
Pyrene(Pyr)	0.582	*0.792*
Benzo(a)anthracene (BaA)	*0.762*	0.629
Chrysene (Chr)	*0.842*	0.511
Benzo(b)fluoanthracene (BbF)	*0.871*	0.484
Benzo(k)fluoanthracene (BkF)	*0.873*	0.478
Benzo(a)pyrene (BaP)	*0.873*	0.473
Indo(1,2,3 cd)pyrene (IP)	*0.912*	0.392
Dibenzo(ah)anthracene (DBA)	*0.900*	0.410
Benzo(ghi)perlyrene (BghiP)	*0.905*	0.404

a combination of diesel and gasoline combustion (Sofowote et al. 2008). Thus, coal combustion and vehicle exhaust represent the primary emission sources of PAHs in the sediments in this region. Further multiple linear regression analysis showed that the two sources contributed approximately 49 and 51 % of the PAH burden in the sediments, respectively. It should be noted that there certainly are other sources (such as wood combustion and unburned fossil fuel) of PAHs to the sediments, which the PCA was unable to differentiate. This result was consistent with that observed by Zhang et al. in the Taihu Lake (Zhang et al. 2012b).

To demonstrate the relationships among the variables and the similarities and differences in their origins and behaviors, PCA were also performed for all the eight classes of POPs (LMW and HMW PAHs, PCBs, DDTs, chlordane, HCB, L-PBDEs, and BDE209) and OC in the sediments (Table 3). Three components were extracted and rotated, which accounted for 79 % in total of the variance in the data set. The first rotated component showed high loadings for PBDEs and OC. This component is indicative of industrial sources for PBDEs in the sediments, especially the electronics industry that

Table 3 Factor loadings of PCA for the POPs and OC in the sediments from Wuxi, Nantong, and Suzhou (important loading values of each variable are italicized)

Compounds	Component 1	Component 2	Component 3
OC	*0.878*	−0.072	−0.209
LMW PAHs	−0.012	−0.068	*0.964*
HMW PAHs	−0.038	−0.022	*0.966*
PCBs	0.016	*0.827*	0.062
DDTs	−0.189	*0.801*	−0.136
Chlordane	0.520	*0.600*	0.212
HCB	0.351	*0.642*	−0.359
L-PBDEs	*0.811*	0.363	0.064
BDE209	*0.931*	−0.122	0.014

is prevalent in YRD. The result also showed that L-PBDEs and BDE209 in the sediments probably had a similar source, although penta- and octa-BDE mixtures have been phased out in China since 2007. The second component is highly loaded in PCBs, DDTs, chlordane, and HCB which are related mainly to historical sources. Although fresh inputs could not be excluded as mentioned above, this component can be identified tentatively as a source from soil erosion loss. OCPs in the soils were due to agricultural applications, and PCBs in the soils were presumably attributed to atmospheric deposition. The third component displayed good correlations with PAHs that were predominantly from various combustion sources. It was found that the OC loadings in the latter two components are very low, suggesting that the organic matter in the sediments is largely determined by inputs from industries rather than soil erosion loss and combustion of coal and fossil fuel. It should be noted that the loadings of the variables in the three factors of the PCA may also be a reflection of differences in their environmental behaviors of these contaminants due to their diverse physicochemical properties.

Ecological risk assessment

The effects range low (ERL) and the effects range median (ERM) values established by the US National Oceanic and Atmospheric Administration (NOAA) were used to assess the aquatic sediment quality (Long et al. 1995). The ERL represents the chemical concentration blow which an adverse effect would rarely be observed, while the ERM represents the concentration above which adverse effects would frequently occur. Comparison with the ERL and ERM values is shown in Fig. 4. The PCB concentrations at all sites were much lower than ERL value, indicating that the ecological risk of PCBs in the sediments was

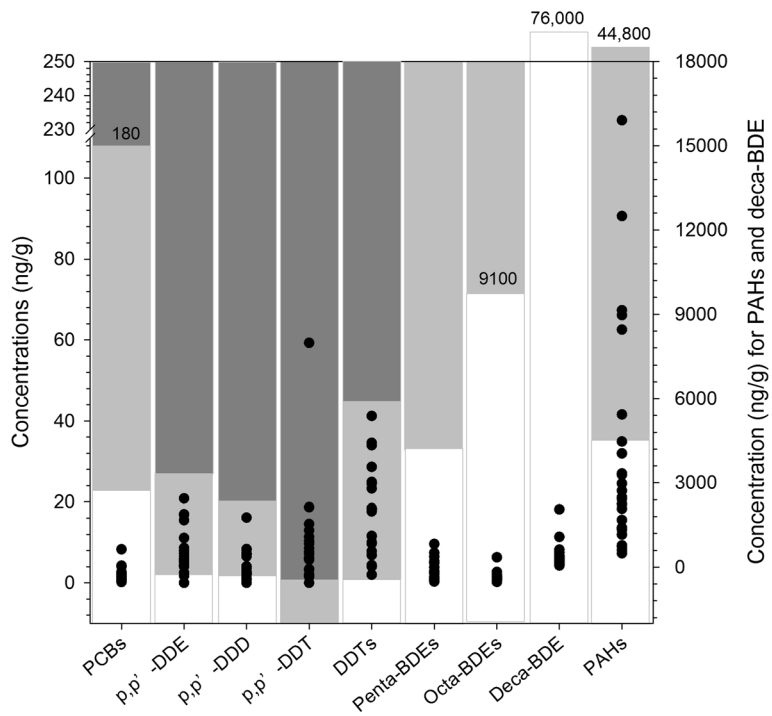

Fig. 4 Sediment quality assessment of selected POPs in the sediments. The *white*, *gray*, and *dark gray bars* represent below ERLs, ERLs−ERMs, and above ERMs for PCBs, DDTs, and PAHs, respectively. For PBDEs, the *white and gray bars* represent below- and above-risk quotients, respectively

considerably low. For PAHs, at 8 of 25 sites the concentrations exceed the ERL and 1 site (4 %) exceed ERM suggesting potential ecological risk. Based on this sediment quality guideline, the highest potential ecological risk was observed for DDTs, for which, 22 sites exceed ERL value and 3 sites exceed ERM value. In the sediments, *p,p′*-DDT was responsible for the most risks from DDTs, with 20 sites above the ERL and 11 sites above the ERM. The BaP equivalent (BaP_{eq}) is also a useful index to assess the potential risk of PAHs. The BaP_{eq} concentrations of PAHs ranged from 49.5 to 1,280 ng/g with a median of 226 ng/g, much higher than those in the Taihu Lake (10.5−92.2 ng/g) (Zhang et al. 2012b). Environment (2006) recommended risk quotients of 31, 9,100, and 76,000 ng/g dw in sediment for penta-, octa-, and deca-BDEs, respectively. The PBDE concentrations in the sediments in the present study were all below the risk quotients suggesting a minimal potential risk to benthic organisms from PBDE exposure.

Conclusions

Historically or currently used organic compounds (OCPs, PCBs, and PBDEs) and PAHs were widely present in the sediments in the study region. PBDEs and DDTs showed high levels in the present study compared with many values recently found in other sediments in the world, while the PCB levels in the present study were substantially low. The sediment levels of these POPs in the three cities were generally consistent with the city industrialization levels indicating a significant influence of economic development on the POPs contamination. PCA indicated that industrial sources, historical sources (presumable soil erosion loss), and combustion sources (in particular coal, diesel, and gasoline combustion) are responsible primarily for the occurrence of PBDEs and organic matter, OCP and PCB, and PAHs in the sediments, respectively. The PCA loadings may also be due to the differences in their environmental behaviors. Sediment quality assessment indicated that DDTs could pose the highest risk for benthic organisms followed by PAHs, whereas ecological risks from PCBs and PBDEs were potentially low.

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