2016 年 第 11 卷
第 2 期,421-435

生 态 毒 理 学 报
Asian Journal of Ecotoxicology

Vol. 11, 2016
No.2, 421-435

DOI:10.7524/AJE.1673-5897.20150714001
张璐璐, 刘静玲, 何建宗, 等. 中国典型城市水环境中邻苯二甲酸酯类污染水平与生态风险评价[J]. 生态毒理学报,2016, 11(2): 421-435
Zhang L L, Liu J L, He K C, et al.The occurrence and ecological risk assessment of phthalate esters (PAEs) in urban aquatic environments of China [J]. Asian Journal of Ecotoxicology, 2016, 11(2): 421-435 (in Chinese)

中国典型城市水环境中邻苯二甲酸酯类污染水平与生态风险评价

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收稿日期:2015-07-14 **录用日期:**2015-10-15

摘要: 邻苯二甲酸酯类(PAEs)作为一类重要的环境激素类化学物质,被广泛应用于塑料的增塑剂中。随着工业的发展,中国 PAEs 的需求量迅速增加,PAEs 已成为中国城市水环境的重要风险因子,因此需要对其进行生态风险评价。本研究首先针对我国典型城市水环境中 PAEs 的污染现状进行文献综述,总结归纳得到我国典型城市水环境中 PAEs 的污染分布特征;其次运用熵值法计算了我国典型水环境中 PAEs 对于藻类、水蚤和鱼类种群的生态风险,并依据生态风险等级划分标准将 PAEs 生态风险划分为 4 个水平。文献综述结果表明我国城市水环境中的 PAEs 浓度多数都高于 8.00 μg·L^{-1},超过了我国地表水环境质量标准(PRC-NS 2002)和饮用水质量标准(PRC-NS 2006)中的规定限值,且在大城市或 PAEs 工业区周围的污染水平要显著高于其他区域。将我国与国外典型城市水环境中 PAEs 的污染水平进行比较,结果表明我国水环境中的 PAEs 污染水平明显高于其他国家。此外,我国城市水环境中 PAEs 的污染不仅出现在地表水环境中,而且在广东东莞等地的地下水环境中也出现了 PAEs 污染,PAEs 浓度范围为 0.0~6.7 μg·L^{-1}。生态风险评价的结果表明,邻苯二甲酸二丁酯(DBP)、邻苯二甲酸二异辛酯(DEHP)和邻苯二甲酸丁苄酯(BBP)是我国城市水环境中最主要的风险因子。PAEs 污染分布特征和生态风险评价的结果表明我国城市水环境中的 PAEs 生态风险值总体处于 10 ≤ 风险熵(RQ) <100 到 RQ ≥ 100 水平,尤其是在大城市或者 PAEs 工业密集区域,因此,亟需对我国城市水环境中 PAEs 的生态风险进行早期预警和风险管理。

关键词: 邻苯二甲酸酯类(PAEs);城市水环境;污染分布特征;生态风险评价
文章编号: 1673-5897(2016)2-421-15 **中图分类号:** X171.5 **文献标识码:** A

The Occurrence and Ecological Risk Assessment of Phthalate Esters (PAEs) in Urban Aquatic Environments of China

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Received 14 July 2015 **accepted** 15 October 2015

基金项目:国家重点基础研究发展计划(2015CB458900);河北科技大学博士启动基金(1181200)
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Abstract: Phthalate esters (PAEs) are endocrine disruptors and have been used as plasticizing agents in cellulosics and elastomers. The demand for PAEs has grown rapidly, especially in China. It will lead to much more environmental PAE contamination. PAEs are listed as the chemical that poses significant ecological risk. This paper reviews the literature concerning the pollution status of PAEs, summarizes the main characteristics of PAEs in typical aquatic environment in China, assesses the ecological risk of PAEs to alage, daphnia, and fish by risk quotient (RQ) approach which is based on the predicted no effect concentration (PNEC) and PAE concentrations in aquatic environments. The results showed that PAEs concentrations in most of river and lake waters were higher than 8.00 $\mu g \cdot L^{-1}$, which are higher than the concentrations of PAEs in the Environmental Quality Standards for Surface Water (PRCNS 2002) (DEHP, 8.00 $\mu g \cdot L^{-1}$ and DBP, 3.00 $\mu g \cdot L^{-1}$) and Standards for Drinking Water Quality (PRCNS 2006) (DEHP, 8.00 $\mu g \cdot L^{-1}$, DBP, 3.00 $\mu g \cdot L^{-1}$ and DEP, 3.00 $\mu g \cdot L^{-1}$), respectively. With the increasing consumption of PAEs in metropolitan areas, the concentrations of PAEs detected in urban water bodies were obviously higher than those in other areas of China. Compared with other countries, the PAE concentrations in the waters of China are higher than global PAE levels. Furthermore, PAE pollution of water bodies was found not only in surface waters but also in underground waters; for instance, PAE concentrations in the range of 0.00-6.70 $\mu g \cdot L^{-1}$ were detected in underground waters in Dongguan, Guangdong Province, China. The results of RQs showed that significant ($10 \leqslant RQ < 100$) or very significant ($RQ \geqslant 100$) potential adverse effects for algae, daphnia, and fish in aquatic environments near PAE-based industrial and urban areas, and DBP, DEHP and BBP contributed the most. Thus, the ecological risk of PAEs in Chinese aquatic environments should be considered, especially in areas where commercial plastics are produced.

Keywords: phthalate esters (PAEs); urban aquatic environment; pollution level; ecological risk; China

邻苯二甲酸酯类,又称酞酸酯,缩写 PAEs,是邻苯二甲酸形成的酯的统称。PAEs 一般为无色液体,具有低挥发性、难溶于水和易溶于有机溶液等特点[1]。它是一类重要的环境激素类物质,主要用于塑料的增塑剂,也广泛应用于日常生活用品中,例如玩具、食品包装材料、医用血袋和胶管、乙烯地板、壁纸、清洁剂、润滑油和个人护理用品等[2]。因此,PAEs 作为普遍存在的污染物广泛存在于水体、土壤和大气环境中[3-4]。例如,根据美国有毒物质释放数据库(Toxics Release Inventory (TRI) database)计算,2012 年美国 PAEs 的释放量为 1 492 674 kg,其中释放到大气环境中的 PAEs 有 1 354 968 kg,释放到水环境中的 PAEs 有 237 kg[5]。

由于 PAEs 可能具有致癌性、致畸性和致突变性[6-9],美国和其他很多国家把 PAEs 列为优先控制污染物[10-11]。虽然在某些区域和国家已经采取了很多控制措施来限制和降低 PAEs 的生产与使用[12],但在亚洲 PAEs 的生产、使用并未得到有效控制。随着工业的发展,我国 PAEs 的用量迅速增加,在 2010 年我国 PAEs 用量高达 1.36×10^{6} t[13];在 2010—2015 期间,我国年均 PAEs 的用量增幅约为 7.7% [14];此外,我国还是 PAEs 最大的进口国。由于 PAEs 在环境中具有难降解、生物富集和内分泌干扰效应,因此 PAEs 已成为我国城市水环境的重要风险因子。

对 PAEs 有效的环境管理取决于准确评价其生态风险水平,因此越来越多的研究对环境中 PAEs 的潜在生态风险进行评价[15-16]。PAEs 对于水生生物的有害影响一般会随着烷基链长度的增加而加大,但由于酯类较低的水溶性特点,该趋势会在烷基链长度达到生物机体耐受量限值时发生改变[17]。根据大量的研究结果,烷基链大于 6 个的 PAEs 在溶解限值时,对于很多水生生物的急性和慢性毒性测试结果表明无毒[18]。因此,本研究主要关注低分子量的 PAEs,如邻苯二甲酸二甲酯(DMP)、邻苯二甲酸二乙酯(DEP)、邻苯二甲酸二丁酯(DBP)、邻苯二甲酸丁苄酯(BBP)、邻苯二甲酸二己酯(DHP)和邻苯二甲酸二异辛酯(DEHP)。虽然我国的环境科学工作者已经意识到 PAEs 在水环境中的生态风险,但多数研究仅集中于单一水环境中 PAEs 的污染现状与生态风险评价,对我国典型城市水环境中 PAEs 的生态风险管理存在不确定性。因此,本研究首先对我国典型城市水环境中 PAEs 的污染现状的文献进行综述,总结归纳得到我国典型城市水环境中 PAEs 的污染分布特征;其次运用熵值法计算了我国典型水环

境中 PAEs 对于藻类、水蚤和鱼类种群的生态风险,对于我国城市水环境安全具有重要的现实意义。

1　材料与方法(Materials and methods)

1.1　数据收集方法

为了准确掌握我国典型城市水环境中 PAEs 的污染分布特征,本研究首先运用文献综述法对中国知网、万方、Elsevier、Springer、Google Scholar 和 PubMed 数据库中关于我国典型城市水环境中 PAEs 的污染现状的文章和硕、博士论文等进行文献综述,由于通过 PAEs、污染现状和分布特征等关键词收索到的文献数量较多,因此本研究主要分析有关我国典型城市水环境中 PAEs 污染分布特征的文章。有关 PAEs 对目标生物的毒理数据主要从 USEPA 的 ECOTOXicology 数据库[5]和相关文献中获得[19]。

1.2　环境介质中 PAEs 的分析方法

PAEs 的分析步骤主要可以分为:样品前处理、萃取、清洗、分离和检测。萃取和清洗是 PAEs 分析中最具挑战和关键的步骤,直接关系到整个分析方法能否确定检出限。萃取方法可以分为溶剂萃取或液-液萃取[20]和固相微萃取(SPME)[21];对于分离和检测步骤,研究主要关注分析技术如液相色谱-质谱(LC-MS)[22],气相色谱-质谱(GC-MS)[23]以及其他技术[24-25]。Cai 等[26]开发了一种新分析方法来检测水体中 PAEs 浓度,主要包括固相萃取、用乙腈定量解吸和高效液相色谱(HPLC)的分析方法。虽然不同研究中采用的分析方法会影响到 PAEs 数据的结果,但由于本研究旨在掌握我国城市典型水环境中 PAEs 的整体污染水平,因此分析方法的差异不会影响到本文的结论。

1.3　PAEs 生态风险评价方法

PAEs 的生态风险评价方法依据欧盟技术指导性文件[27]和先前的研究[15],主要采用熵值法来评价水体中 PAEs 的潜在生态风险[28-29]。在本研究中,风险熵(RQ)被用来评估目标生物的生态风险,它主要是根据环境中 PAEs 的测量浓度(MEC)与预测的无效应浓度(PNEC)之间的比值。PNEC 的估算是根据毒理学的相关浓度(LC_{50}或 EC_{50})与安全系数(f)的比值。因此,鱼类、水蚤和藻类对 DMP、DEP、DnBP 和 BBP 的 LC_{50} 或 EC_{50} 被应用于生态风险值的计算。PAEs 的风险熵计算公式为:

$$RQ = \frac{MEC}{PNEC} = \frac{MEC}{\frac{L(E)C_{50}}{f}}$$

根据相关的文献,我们把生态风险分为下面 4 个水平[30]:

当 $RQ < 1.00$ 时,表示无显著风险;当 $1.00 \leqslant RQ < 10.0$ 时,表示存在较小的潜在负效应;当 $10.0 \leqslant RQ < 100$ 时,表示存在显著的潜在负效应;当 $RQ \geqslant 100$ 时,表示存在预期的潜在负效应。

2　研究结果(Results)

2.1　我国 PAEs 的生产和消费

表 1 列出了我国大陆地区 2000—2010 年 PAEs 的供应和需求量,在 2000—2010 期间 PAEs 的表观消费量显著增加,其中 2010 年比 2000 年的产量增加了 183.54%,表观消费量增加了 79.18%。表 2 列出了我国 PAEs 的主要生产企业及其产量,其中齐鲁增塑剂有限公司作为内地最大的 PAEs 制造商,其年产量高达 40.00×10^4 t,主要生产邻苯二甲酸二辛酯(DOP)、DBP、邻苯二甲酸二异壬酯(DiNP)和邻苯二甲酸二异癸酯(DiDP);PAEs 生产企业集中分布在山东、广东、浙江和江苏省。

2.2　水环境中的 PAEs 污染水平

根据我国典型水环境中 PAEs 的污染分布特征,除广州(城市湖泊)、北京(城市湖泊)和长江江苏段外,我国典型河流和湖泊水体中 PAEs 浓度多数均高于 8.00 $\mu g\cdot L^{-1}$,而根据我国地表水环境质量标准[32]和饮用水环境质量标准[33],DEHP 的浓度限值

表 1　我国大陆地区 2000—2010 年 PAEs 的供应和需求量(10^4t)

Table 1　The supply-demand situation of PAEs in the mainland in China during the period of 2000-2010 (10^4 tons)

年份 Year	产量(10^4 t) Output (10^4 ton)	净进口量(10^4 t) Net import volume (10^4 ton)	表观消费量(10^4 t) Apparment consumption (10^4 ton)
2000	39.50	36.40	75.90
2001	46.40	36.70	83.10
2002	53.70	43.60	97.20
2003	54.00	51.00	105.00
2004	55.00	50.00	105.00
2005	50.50	45.80	96.30
2006	67.30	48.70	116.00
2007	66.60	46.90	113.00
2008	90.00	35.00	128.00
2009	104.00	32.00	136.00
2010	112.00	21.60	136.00

为 8.00 μg·L-1 或 DBP 的浓度限值为 3.00 μg·L-1 和 DEHP 的浓度限值为 8.00 μg·L-1 、DBP 的浓度限值为 3.00 μg·L-1 或 DEP 的浓度限值为 3.00 μg·L-1。因此,我国水环境中 PAEs 的潜在生态风险不容忽视[34-35]。将我国典型水环境中 PAEs 的污染水平与其他国家相比,结果表明整体上我国水环境中的 PAEs 污染水平较高,但在尼日利亚西南部的 Ogun 河 PAEs 的污染水平较高,达到 395.00～4 775.00 μg·L-1,它的最大值要高于我国地表水环境质量标准的 597 倍(表 3)。

随着城市 PAEs 消费量的日益增加,导致城市水环境中 PAEs 污染水平显著高于农村地区。这主要是因为城市水环境会接收大量未经有效处理的工业废水,如德国柏林市污水处理厂所排放的废水中 PAEs 浓度较高(高达 182.00 μg·L-1)。此外,PAEs 的污染不仅发生在地表水环境中,也会污染地下水环境,如广东省东莞市地下水的 PAEs 浓度范围为 0.00～6.70 μg·L-1。尽管如此,PAEs 在地表水环境中(河流、湖泊和水库)的污染水平要显著高于地下水环境[36]。

表 2　2006 年我国 PAEs 的主要生产企业及其产量[31]

Table 2　Main production and types of PAEs in China (in 2006)[31]

生产企业 Manufacturer	PAEs 种类 PAEs types	省份 Location	产量(10^4 t) Production capacity (10^4 ton)
大陆地区 Mainland			
齐鲁增塑剂有限公司 Qilu Plasticizers co., LTD	DOP、DBP、DiNP、DiDP	山东 Shandong	40.00
镇江连城化工有限公司 Zhenjiang Liancheng Chemical Industry co., LTD	DOP、DiNP、DOA、DiDP	江苏 Jiangsu	26.00
金陵石化有限公司 Jinling Petrochemical co., LTD	DOP、DBP	江苏 Jiangsu	20.00
宏鑫化工有限公司 Hongxin Chemical co., LTD	DOP、DBP、DiBP	山东 Shandong	20.00
河南安庆化工有限公司 Henan Anqing Chemical co., LTD	DOP、DBP、DiDP、DiNP、DOTP、DOA、DOS	河南 Henan	15.00
基华集团安利化工有限公司(苏州) Jihua Group Amway Chemical co., LTD (Suzhou)	DOP	江苏 Jiangsu	12.00
埃克森美孚化工有限公司(番禺) Exxon Chemical co., LTD (Panyu)	DiNP	广东 Guangdong	11.00
浙江华泰化工有限公司 Zhejiang Huatai Chemical co., LTD	DOP、DOTP、DiNP、DOA、DOS	浙江 Zhejiang	10.00
上海连城化工有限公司 Shanghai Liancheng Chemical co., LTD	DiNP、DOA、DiDP	上海 Shanghai	10.00
东莞市宝田化工有限公司 Dongguan Baotian Chemical co., LTD	DOP、DiNP	广东 Guangdong	9.00
东莞星宝塑胶制品有限公司 Dongguan Xingbao Chemical co., LTD	DOP、DiNP	广东 Guangdong	9.00
石家庄白龙有限公司 Shijiazhuang Bailong co., LTD	DOP、DBP、DiBP	河北 Hebei	6.00
北京华英化学有限公司 Beijing Huaying Chemical co., LTD	DOP	北京 Beijing	4.30
杭州大自然有机化工有限公司 Hangzhou Nature Organic Chemical co., LTD	DOP、DBP、DiBP、DOA、DBS、DOS	浙江 Zhejiang	3.60
天津溶剂厂 Tianjin Solvent Factory	DOP、DBP、DiBP、DHP	天津 Tianjin	3.00
香港 Hongkong			
南亚塑胶工业有限公司 South Asia Plastic Industry co., LTD	DOP	浙江 Zhejiang	15.00
台湾 Taiwan			
联成集团 UPC Group	DOS、DiNA、DiDA、DBS	广东 Guangdong	11.50

表 3　我国与其他国家水环境中 PAEs 的污染水平

Table 3　Concentrations of PAEs in aquatic environment in China, compared with other countries

地点 Location	PAEs 浓度/(ng·L^{-1}) PAEs levels/(ng·L^{-1})	水环境 Media	参考文献 References
中国 China			
湖泊或水库 Lake and reservoir water			
北京-公园湖泊 Beijing-Park Lakes	6 400.00～138 100.00	湖泊水 Park lake water	[37]
苏州-太湖 Suzhou-Taihu Lake	1 888.00～126 100.00	湖泊水 Urban lake water	[38]
太原-汾河水库 Taiyuan-Fenhe Reservoir	37 490.00	水库水 Reservoir water	[39]
广州-城市湖泊 Guangzhou-Urban Lakes	1 690.00～4 720.00	湖泊水 Urban lake water	[40]
北京-城市湖泊 Beijing-Urban Lakes	386.00～3 184.00	湖泊水 Urban lake water	[41]
河水 River			
海河 Haihe River	3 890.00～141 780.00	河水 Urban river waters	[42]
长江-武汉段 Yangtze River-Wuhan	34.00～91 220.00	河水 Urban river waters	[14]
黄河-太原 Yellow River-Taiyuan	87 230.00	河水 Urban river waters	[39]
松花江-吉林段 Songhua River-Jilin	2 500.00～68 960.00	河水 Urban river waters	[43]
黄河 Yellow River	3 990.00～45 450.00	河水 Middle and lower reaches	[44]
长江三角洲 Yangtze River Delta	61.00～28 550.00	河水 River waters	[45]
湘江-株洲 Xiangjiang River-Zhuzhou	22 390.00～27 400.00	河水 River waters	[46]
钱塘江-浙江 Qiantangjiang River-Zhejiang	4 150.00～15 380.00	河水 River waters	[47]
长江-江苏 Yangtze River-Jiangsu	178.00～1 474.00	河水 River waters	[48]
地表水 Surface water			
上海 Shanghai	0.00～13 530.00	地表水 Surface water	[47]
扬州 Yangzhou	0.00～10 430.00	地表水 Surface water	[47]
河口/港口/海湾水 Estuary/Port/Harbor water			
长江河口 Yangtze Estuary area	3 380.00	海水 Marine water	[49]
地下水 Ground water			
广州-东莞 Guangzhou-Dongguan	0.00～6 700.00	地下水 Groundwater	[50]
湖北-江汉平原 Hubei-Jianghan Plain	80.10～1 882.00	地下水 Groundwater	[51]
饮用水源 Drinking water source			
长江三角洲-苏州 Yangtze River Delta -Suzhou	5 700.00～14 000.00	饮用水 Drinking water source	[52]
长江三角洲-无锡 Yangtze River Delta -Wuxi	6 300.00～12 000.00	饮用水 Drinking water source	[52]
长江三角洲-常州 Yangtze River Delta -Changzhou	3 500.00～8 300.00	饮用水 Drinking water source	[52]
长江三角洲-盐城 Yangtze River Delta -Yancheng	3 000.00～3 800.00	饮用水 Drinking water source	[52]
长江三角洲-徐州 Yangtze River Delta -Xuzhou	40.00	饮用水 Drinking water source	[52]
污水处理厂 Wastewater treatment plants			
北京 Beijing-Wastewater treatment plants	41 440.00～69 880.00	污水处理厂进水 Wastewater treatment plants influents	[53]
哈尔滨 Harbin	21 010.00	城市废水 Municipal wastewater	[54]
北京 Beijing-Wastewater treatment plants	720.00～4 240.00	污水处理厂出水 Wastewater treatment plants effluents	[53]
其他国家 Other countries			
湖泊水 Lake water			
美国- Pontchartrain 湖 USA-Lake Pontchartrain	0.00～20 000.00	湖泊水 Lake water	[55]
河水 River water			

续表3

地点 Location	PAEs 浓度/(ng·L^{-1}) PAEs levels/(ng·L^{-1})	水环境 Media	参考文献 References
尼日利亚-Ogun 河 Nigeria-Ogun River	3 950 000.00~4 775 000.00	河水 River water	[56]
马来西亚-Klang 河 Malaysia-Klang River	5 000.00~69 200.00	河水 River water	[57]
意大利-Rieti 河 Italy-Rieti River	0.00~45 900.00	河水 River water	[58]
瑞士-Svartan 河 Sweden-Svartan River	320.00~3 100.00	河水 River water	[59]
英国-Trent 河 UK-Trent River	740.00 ~1 800.00	河水 River water	[60]
法国-Seine 河 France-Seine River	464.00~771.00	河水 River water	[61]
西班牙-Embo 河 Spain-Embo River	0.00~700.00	河水 River water	[62]
西班牙-Galicia 河 Spain-Galicia River	69.00	河水 River water	[63]
地表水 Surface water			
德国-柏林 Germany-Berlin	330.00~97 800.00	地表水 Surface water	[64]
新西兰 New zealand	540.00~26 200.00	淡水 Freshwater	[3]
意大利- Rieti 雨水 Italy- Rieti Rain Water	3 700.00~11 400.00	居民区雨水 Residental center rain water	[65]
意大利- Rieti 雨水 Italy- Rieti Rain Water	3 200.00~8 300.00	市中心雨水 City center rain water	[65]
意大利- Rieti 雨水 Italy- Rieti Rain Water	7 100.00~7 800.00	工业区雨水 Industrial center rain water	[65]
河口/港口/海湾水 Estuary/Port/Harbor water			
泰国 Thailand	8 640.00	海水 Gulf water	[66]
加拿大-False Creek 海港 Canada-False Creek Harbor	3.30~1 060.00	海水 Marine water	[67]
西班牙-工业港口 Spain-Industrial Port	0.00~2 120.00	海水 Marine water	[62]
饮用水源 Drinking water source			
日本-东京 Japan-Tokyo	210.00~5 700.00	地表水 Surface water	[68]
德国 Germany	1 010.00	自来水 Tap water	[69]
德国 Germany	740.00	瓶装水 Bottled mineral water	[69]
污水处理厂 Wastewater treatment plants			
德国-柏林 Germany-Berlin	1 740.00~1 82 000.00	废水 Sewage effluents	[64]
西班牙-加利西亚 Spain-Galicia wastewater treatment plants	6 623.00	污水处理厂进水 Wastewater treatment plants influent	[63]
法国 France	2 819.00~4 682.00	污水处理厂出水 Wastewater treatment plants effluents	[61]
西班牙-加利西亚 Spain-Galicia wastewater treatment plants	1 278.00	污水处理厂出水 Wastewater treatment plants effluent	[63]

表4 生态风险评价中鱼类、水蚤和藻类的急性毒性数据(LC_{50}或EC_{50})

Table 4 Acute toxicity (LC_{50} or EC_{50}) used for the risk assessment for fish, daphnia, and algae

PAEs 种类 Compound	鱼类(*Lepomis macrochirus*) Fish (*Lepomis macrochirus*)			无脊椎动物(*Daphnia magna*) Invertebrate (*Daphnia magna*)			藻类(*Selenastrum capricornutum*) Algae(*Selenastrum capricornutum*)		
	$L(E)C_{50}$ /(mg·L^{-1})	NOEC /(mg·L^{-1})	参考文献 References	$L(E)C_{50}$ /(mg·L^{-1})	NOEC /(mg·L^{-1})	参考文献 References	$L(E)C_{50}$ /(mg·L^{-1})	NOEC /(mg·L^{-1})	参考文献 References
DMP	50.00	15.30	[17]	33.00	< 1.70	[74]	142.00	< 64.70	[17]
DEP	16.70	1.65	[17]	86.00	37.50	[17]	16.00	3.65	[17]
DBP	0.48	0.42	[17]	3.00	1.70	[17]	0.40	0.21	[17]
BBP	1.70	0.36	[17]	3.70	1.00	[75]	0.21	< 0.10	[17]
DHP	> 0.11	0.11	[17]	> 0.18	0.03	[17]	> 0.33	0.18	[17]
DEHP	> 0.20	0.20	[17]	> 1.00	1.00	[76]	> 0.10	0.10	[17]

表 5　我国典型水环境中 DMP、DEP、DBP、BBP、DHP 和 DEHP 对鱼类种群的 RQ 以及总生态风险(μg·L^{-1})

Table 5　Fish RQ results for DMP, DEP, DBP, BBP, DHP, and DEHP and the sum of RQs for each location in China (μg·L^{-1})

区域 Location	DMP	DEP	DBP	BBP	DHP	DEHP	合计 Sum	参考文献 References
湖泊或水库 Lake and reservoir water								
北京-窑洼湖公园湖泊 Beijing-Yaowahu Park Lake	1.22	12.70	61.00	49.40	ND	160.00	284.00	[37]
北京-朝阳公园湖泊 Beijing-Chaoyang Park Lake	0.14	1.64	12.60	136.00	ND	27.50	178.00	[37]
北京-颐和园湖泊 Beijing-Lake in Summer Palace	0.06	0.67	7.38	15.00	ND	46.70	69.80	[37]
北京-红领巾公园湖泊 Beijing-Honglingjin Park Lake	0.23	2.97	16.20	15.30	ND	31.00	65.70	[37]
北京-人定湖公园湖泊 Beijing-Rendinghu Park Lake	ND	ND	4.00	14.50	ND	45.30	63.80	[37]
北京-莲花池公园湖泊 Beijing-Lianhuachi Park Lake	0.02	0.29	10.40	13.10	ND	34.50	58.20	[37]
北京-龙潭湖公园湖泊 Beijing-Longtanhu Park Lake	ND	ND	5.86	15.60	ND	32.20	53.60	[37]
北京-玉渊潭公园湖泊 Beijing-Yuyuantan Park Lake	ND	ND	12.60	13.30	ND	25.70	51.60	[37]
苏州-太湖 Suzhou-Taihu Lake	2.78	4.23	20.90	11.70	ND	ND	39.70	[38]
北京-北海 Beijing-Beihai Lake	0.02	1.23	6.31	ND	ND	26.80	34.40	[37]
北京-什刹海 Beijing-Shichahai Lake	ND	ND	8.50	13.30	ND	ND	21.80	[37]
太原-汾河水库 Taiyuan-Fenhe Reservoir	-	-	17.21	-	-	4.15	21.40	[39]
北京-陶然亭公园湖泊 Beijing-Taoranting Park Lake	0.05	0.61	ND	13.10	ND	ND	13.70	[37]
广州-城市湖泊 Guangzhou-Urban Lakes	0.00	0.01	5.76	ND	ND	0.85	6.62	[40]
北京-官厅水库 Beijing-Guanting Reservoir	0.00	ND	0.73	1.32	ND	0.44	2.49	[41]
北京-颐和园湖泊 Beijing-Lakes in Summer Palace	0.00	0.04	0.63	0.02	ND	1.31	1.99	[41]
北京-什刹海 Beijing-Shichahai	0.01	0.01	0.16	0.51	ND	1.20	1.87	[41]
河水 River water								
长江-江苏 Yangtze River-Jiangsu	1.63	175.00	1 161.00	58.30	ND	10.30	1 407.00	[48]
长江-武汉枯水期 Yangtze River Low water period-Wuhan	0.01	ND	84.90	ND	ND	273.00	359.00	[14]
黄河-伊洛河 Yellow River Tributary-Yiluo	0.02	0.14	35.70	ND	ND	159.00	195.00	[44]
黄河-蟒沁河 Yellow River Tributary-Mangqin	ND	0.21	61.90	ND	ND	115.00	177.00	[44]
黄河-小浪底 Yellow River Main River-Xiaolangdi	ND	0.10	50.00	ND	ND	120.00	170.00	[44]
松花江-吉林 Songhua River-Jilin	0.04	1.02	163.00	ND	ND	ND	164.00	[43]
长江三角洲 Yangtze River Delta	0.01	0.05	17.10	0.2	ND	142.00	159.00	[45]
黄河-洛阳 Yellow River Tributary-Luoyang	ND	0.06	50.00	ND	ND	101.00	151.00	[44]
海河-城市段 Haihe River-Urban Area	-	-	17.40	-	-	109.00	126.00	[42]
黄河-开封 Yellow River Main River-Kaifeng	0.02	0.27	ND	ND	ND	80.00	80.30	[44]
黄河-郑州 Yellow River Main River-Zhengzhou	0.01	0.19	ND	ND	ND	15.00	75.00	[44]
黄河-东明 Yellow River Main River-Dongming	0.01	0.23	ND	ND	ND	70.00	70.20	[44]
台湾河流 Taiwan Rivers	ND	0.30	11.70	ND	ND	46.50	58.50	[77]
黄河-新蟒河 Yellow River Tributary-Xinmang	ND	0.18	22.00	ND	ND	29.30	51.50	[44]
黄河-孟州 Yellow River Tributary-Mengzhou	0.037	0.01	31.00	ND	ND	19.60	50.60	[44]
钱塘江-浙江 Qiantangjiang River-Zhejiang	ND	5.19	17.00	ND	ND	10.00	32.20	[47]
黄河-太原 Yellow River-Taiyuan	ND	ND	18.10	ND	ND	3.95	22.00	[39]
湘江-株洲 Xiangjiang River-Zhuzhou	1.29	2.15	8.12	10.10	ND	ND	21.60	[46]
黄河-胶东 Yellow River Main River-Jiaodong	0.02	0.26	ND	ND	ND	16.20	16.50	[44]
黄河-孟津 Yellow River Main River-Mengjin	0.02	0.10	10.20	ND	ND	1.74	12.00	[44]
长江-武汉段丰水期 Yangtze River High water period-Wuhan	0.02	0.22	0.32	ND	ND	0.14	0.70	[14]
地表水 Surface water								
扬州 Yangzhou	ND	1.07	3.79	ND	ND	14.90	19.80	[47]

续表5

区域 Location	DMP	DEP	DBP	BBP	DHP	DEHP	合计 Sum	参考文献 References
上海 Shanghai	ND	1.47	3.60	ND	ND	12.70	17.70	[47]
河口/港口/海湾 Estuary/Port/Harbor water								
长江口 Yangtze Estuary area	ND	0.59	2.62	ND	ND	6.50	9.71	[49]
地下水 Ground water								
广州-东莞 Guangzhou-Dongguan	0.00	0.03	0.93	0.03	ND	2.35	3.34	[50]
饮用水 Drinking water source								
长江三角洲 -苏州 Yangtze River Delta -Suzhou	0.00	0.05	22.10	0.81	ND	4.90	27.90	[52]
长江三角洲 -无锡 Yangtze River Delta -Wuxi	0.00	0.04	18.90	0.07	ND	2.80	21.80	[52]
长江三角洲 -常州 Yangtze River Delta -Changzhou	0.00	0.02	12.90	0.97	ND	4.80	18.70	[52]
长江三角洲 -盐城 Yangtze River Delta -Yancheng	0.00	0.04	7.86	0.11	ND	0.70	8.71	[52]
长江三角洲 -徐州 Yangtze River Delta -Xuzhou	ND	ND	0.10	ND	ND	0.06	0.16	[52]
污水处理厂 Wastewater treatment plants								
北京-进水 Beijing-Influents	ND	35.90	11.40	32.40	ND	38.00	118.00	[53]
北京-出水 Beijing-Effluents	ND	ND	ND	9.75	ND	12.50	22.30	[53]

2.3 我国典型水环境中的 PAEs 的生态风险评价

在我国 PAEs 对水环境造成的生态风险仍处于未知状态。PAEs 对水生生态系统的影响主要取决于 PAEs 的输入量和其毒性参数。本研究中 PAEs 的生态风险评价方法以欧盟技术指导性文件为基础[27],该文件要求至少同时考虑鱼类、水蚤和藻类的 LC_{50} 或 EC_{50}。PAEs 的毒性数据主要来源于 Staples 的综述“Aquatic Toxicity of Eighteen Phthalate Esters”[28]。RQ 值是根据最大无影响效应浓度(NOEC)、最低的 LC_{50}或 EC_{50}以及安全系数(1 000)进行计算[27]。表 4 列出了 RQ 计算过程中 3 个种群对 PAEs 的 LC_{50}、EC_{50}和 NOEC。表 5~7 列出了我国典型城市水环境中典型 PAEs 对鱼类、水蚤和藻类的 RQ 值,3 个种群的 RQ 值呈现明显差异。在我们计算的 6 种 PAEs 中,DBP、DEHP 和 BBP 为最主要的风险物质。DMP 对 *Lepomis macrochirus* 的 RQ 变化范围为 0.00~2.78,对 *Daphnia magna* 的 RQ 变化范围为 0.00~25.10,对 *Selenastrum capricornutum* 的 RQ 变化范围为 0.00~0.66。相比而言,DEP、DBP、BBP 和 DEHP 在长江-江苏段、松花江-吉林段对 *Lepomis macrochirus* 种群、在北京-朝阳公园湖泊对 *Selenastrum capricornutum* 种群的 RQ 达到预期的潜在负效应水平,即 RQ > 100。一般来说,藻类对于 PAEs 极其敏感,而 *Daphnia magna* 的 RQs 相对较小。除了 DMP、DEP 和 DHP 以外,多数 PAEs 的 RQs 变化范围都在 10.0~100.00,这表明我国水环境中的 PAEs 存在显著的潜在负效应,研究发现 DMP、DEP 和 DHP 主要通过生长限制对鱼类、水蚤和藻类产生生态风险[15, 28]。

为了计算 PAEs 在我国水环境中的联合效应,本研究将各个点位中各种 PAEs 的 RQ 进行加和计算,得到 PAEs 的总生态风险。结果表明,在长江三角洲-徐州段鱼类、水蚤和藻类种群的总生态风险处于无显著风险水平,即 RQ < 1.00,鱼类种群总的风险值变化范围为 0.16 (长江三角洲-徐州段)~1 407.00 (长江-江苏段),水蚤种群总生态风险变化范围为 0.04 (长江三角洲-徐州段)~333.00 (长江-江苏段),藻类种群总生态风险变化范围为 0.31 (长江三角洲-徐州段)~2 634.00 (长江-江苏段)。总生态风险的结果表明在长江-江苏段 PAEs 对鱼类、水蚤和藻类种群均存在显著的潜在负效应,即 RQ > 100。

对于城市湖泊来说,除北京什刹海外,颐和园和官厅水库中 PAEs 的生态风险处于无显著风险或较小的潜在负效应水平,大部分城市湖泊的 PAEs 生态风险处于存在显著的潜在负效应或预期的潜在负效应水平。对于城市河流来说,除长江-武汉段丰水期外,大部分河流的 PAEs 生态风险处于存在显著的潜在负效应或预期的潜在负效应水平。对于其他水环境来说,如北京污水处理厂进水的 PAEs 生态风险处于存在预期的潜在负效应水平,而其他水环境多数处于存在较小的潜在负效应或显著的潜在负效应水平。因此,需要对我国城市水环境中 PAEs 的生态风险进行研究,可以通过长期或短期的毒理学数据,表征 PAEs 混合物在水环境中的综合效应,建立

水环境中可靠的 PAEs 生态风险评价方法。

此外,大量研究结果表明 PAEs 可以在生物体内产生生物富集效应[70-72]。Cheng 等[71]检测了香港市场上 20 多种鱼类体内 PAEs 浓度,结果表明在淡水鱼类体内 ΣPAEs 浓度范围为 1.66～3.14 μg·g^{-1}(湿重),在海洋鱼类体内 ΣPAEs 浓度范围为 1.57～7.10 μg·g^{-1}(湿重);其中在淡水鱼类和海洋鱼类中,DEHP 和 DBP 均为主要的 PAEs 风险物质。Mo 等[73]检测了珠江三角洲 9 个种植园中 11 种蔬菜的 PAEs 浓度,结果表明 ΣPAEs 浓度范围为 0.07～11.20 μg·g^{-1}(干重),PAEs 浓度均值为 3.20 μg·g^{-1}(干重),其中 *Brassica parachinensis* 体内 PAEs 浓度最高,这些结果表明 PAEs 可以通过胃肠消化系统在生物体内富集,而 PAEs 的生物富集系数变化范围为 0.0001～0.61。

表 6　我国典型水环境中 DMP、DEP、DBP、BBP、DHP 和 DEHP 对水蚤种群的 RQ 以及总生态风险(μg·L^{-1})

Table 6　*Daphnia magna* RQ results for DMP, DEP, DBP, BBP, DHP, and DEHP and the sum of RQs for each location in China (μg·L^{-1})

区域 Locations	DMP	DEP	DBP	BBP	DHP	DEHP	合计 Sum	参考文献 References
湖泊或水库 Lake and reservoir water								
北京-窑洼湖公园湖泊 Beijing-Yaowahu Park Lake	10.90	0.56	15.10	17.80	ND	32.00	76.40	[37]
北京-朝阳公园湖泊 Beijing-Chaoyang Park Lake	1.29	0.07	3.12	49.00	ND	5.50	59.00	[37]
北京-颐和园湖泊 Beijing-Lake in Summer Palace	25.10	0.19	5.17	4.22	ND	ND	34.60	[37]
北京-红领巾公园湖泊 Beijing-Honglingjin Park Lake	0.05	0.00	25.80	0.18	ND	0.24	26.20	[37]
北京-人定湖公园湖泊 Beijing-Rendinghu Park Lake	2.06	0.13	4.00	5.50	ND	6.20	17.90	[37]
北京-莲花池公园湖泊 Beijing-Lianhuachi Park Lake	0.52	0.03	1.82	5.40	ND	9.33	17.10	[37]
北京-龙潭湖公园湖泊 Beijing-Longtanhu Park Lake	ND	ND	0.99	5.22	ND	9.06	15.30	[37]
北京-玉渊潭公园湖泊 Beijing-Yuyuantan Park Lake	0.17	0.01	2.57	4.71	ND	6.89	14.30	[37]
苏州-太湖 Suzhou-Taihu Lake	ND	ND	1.45	5.60	ND	6.43	13.50	[38]
北京-北海 Beijing-Beihai Lake	ND	ND	3.12	4.80	ND	5.13	13.00	[37]
北京-什刹海 Beijing-Shichahai Lake	0.15	0.01	1.56	ND	ND	5.36	7.08	[37]
太原-汾河水库 Taiyuan-Fenhe Reservoir	ND	ND	2.10	4.79	ND	ND	6.89	[39]
北京-陶然亭公园湖泊 Beijing-Taoranting Park Lake	0.41	0.03	ND	4.70	ND	ND	5.14	[37]
广州-城市湖泊 Guangzhou-Urban Lakes	-	-	4.25	-	-	0.83	5.08	[40]
北京-官厅水库 Beijing-Guanting Reservoir	0.01	0.00	1.42	ND	ND	0.17	3.02	[41]
北京-颐和园湖泊 Beijing-Lakes in Summer Palace	0.03	ND	0.18	0.48	ND	0.09	0.78	[41]
北京-什刹海 Beijing-Shichahai	0.04	0.00	0.16	0.01	ND	0.26	0.46	[41]
河水 River water								
长江-江苏 Yangtze River-Jiangsu	14.70	7.68	287.00	21.00	ND	2.05	332.00	[48]
长江-武汉枯水期 Yangtze River Low water period-Wuhan	0.06	ND	21.00	ND	ND	54.70	75.80	[14]
黄河-伊洛河 Yellow River Tributary-Yiluo	0.16	0.01	8.82	ND	ND	31.80	40.80	[44]
黄河-蟒沁河 Yellow River Tributary-Mangqin	0.36	0.04	40.40	ND	ND	ND	40.80	[44]
黄河-小浪底 Yellow River Main River-Xiaolangdi	ND	0.01	15.30	ND	ND	23.00	38.30	[44]
松花江-吉林 Songhua River-Jilin	ND	0.00	12.40	ND	ND	24.00	36.40	[43]
长江三角洲 Yangtze River Delta	0.08	0.00	4.23	0.07	ND	28.40	32.80	[45]
黄河-洛阳 Yellow River Tributary-Luoyang	ND	0.00	12.40	ND	ND	20.30	32.70	[44]
海河-城市段 Haihe River-Urban Area	-	-	4.31	-	-	21.70	26.00	[42]
黄河-开封 Yellow River Main River-Kaifeng	0.15	0.01	ND	ND	ND	16.00	16.20	[44]
黄河-郑州 Yellow River Main River-Zhengzhou	0.06	0.01	ND	ND	ND	15.00	15.10	[44]
黄河-东明 Yellow River Main River-Dongming	0.10	0.01	ND	ND	ND	14.00	14.10	[44]
台湾河流 Taiwan Rivers	ND	0.01	2.88	ND	ND	9.30	12.20	[77]
黄河-新蟒河 Yellow River Tributary-Xinmang	0.34	0.00	7.65	ND	ND	3.91	11.90	[44]

续表6

区域 Locations	DMP	DEP	DBP	BBP	DHP	DEHP	合计 Sum	参考文献 References
黄河-孟州 Yellow River Tributary-Mengzhou	ND	0.01	5.44	ND	ND	5.86	11.30	[44]
钱塘江-浙江 Qiantangjiang River-Zhejiang	11.60	0.10	2.01	3.63	ND	ND	11.30	[47]
黄河-太原 Yellow River-Taiyuan	ND	0.23	4.19	ND	ND	2.00	6.42	[39]
湘江-株洲 Xiangjiang River-Zhuzhou	ND	ND	4.47	ND	ND	0.79	5.26	[46]
黄河-胶东 Yellow River Main River-Jiaodong	0.15	0.01	ND	ND	ND	3.24	3.40	[44]
黄河-孟津 Yellow River Main River-Mengjin	0.15	0.00	2.52	ND	ND	0.35	3.01	[44]
长江-武汉段丰水期 Yangtze River High water period-Wuhan	0.17	0.01	0.08	ND	ND	0.03	0.29	[14]
地表水 Surface water								
扬州 Yangzhou	ND	0.05	0.94	ND	ND	2.98	3.96	[47]
上海 Shanghai	ND	0.07	0.89	ND	ND	2.53	3.48	[47]
河口/港口/海湾 Estuary/Port/Harbor water								
长江口 Yangtze Estuary area	ND	0.03	0.65	ND	ND	1.30	1.97	[49]
地下水 Ground water								
广州-东莞 Guangzhou-Dongguan	0.06	0.00	0.23	0.01	ND	0.47	0.72	[50]
饮用水 Drinking water source								
长江三角洲 -苏州 Yangtze River Delta -Suzhou	0.03	0.00	5.47	0.29	ND	0.98	6.78	[52]
长江三角洲 -无锡 Yangtze River Delta -Wuxi	0.02	0.00	4.66	0.02	ND	0.56	5.26	[52]
长江三角洲 -常州 Yangtze River Delta -Changzhou	0.03	0.00	3.18	0.35	ND	0.96	4.52	[52]
长江三角洲 -盐城 Yangtze River Delta -Yancheng	0.04	0.00	1.94	0.04	ND	0.14	2.16	[52]
长江三角洲 -徐州 Yangtze River Delta -Xuzhou	ND	ND	0.02	ND	ND	0.01	0.04	[52]
污水处理厂 Wastewater treatment plants								
北京-进水 Beijing-Influents	ND	1.58	2.81	11.70	ND	7.60	26.50	[53]
北京-出水 Beijing-Effluents	ND	ND	ND	3.51	ND	2.50	6.01	[53]

表 7 我国典型水环境中 DMP、DEP、DBP、BBP、DHP 和 DEHP 对藻类种群的 RQ 以及总生态风险($\mu g \cdot L^{-1}$)

Table 7 *Selenastrum capricornutum* RQ results for DMP, DEP, DBP, BBP, DHP, and DEHP and the sum of RQs for each location in China ($\mu g \cdot L^{-1}$)

区域 Locations	DMP	DEP	DBP	BBP	DHP	DEHP	合计 Sum	参考文献 References
湖泊或水库 Lake and reservoir water								
北京-窑洼湖公园湖泊 Beijing-Yaowahu Park Lake	0.29	5.75	122.00	178.00	ND	320.00	626.00	[37]
北京-朝阳公园湖泊 Beijing-Chaoyang Park Lake	0.03	0.74	25.20	490.00	ND	55.00	571.00	[37]
北京-颐和园湖泊 Beijing- Lake in Summer Palace	0.01	0.30	14.80	54.00	ND	93.30	162.00	[37]
北京-红领巾公园湖泊 Beijing-Honglingjin Park Lake	ND	ND	8.00	52.20	ND	90.60	151.00	[37]
北京-人定湖公园湖泊 Beijing-Rendinghu Park Lake	0.05	1.34	32.40	55.00	ND	62.00	151.00	[37]
北京-莲花池公园湖泊 Beijing-Lianhuachi Park Lake	0.00	0.13	20.80	47.10	ND	68.90	137.00	[37]
北京-龙潭湖公园湖泊 Beijing-Longtanhu Park Lake	ND	ND	11.70	56.00	ND	64.30	132.00	[37]
北京-玉渊潭公园湖泊 Beijing-Yuyuantan Park Lake	ND	ND	25.20	48.00	ND	51.30	125.00	[37]
苏州-太湖 Suzhou-Taihu Lake	0.66	1.91	41.90	42.20	ND	ND	86.60	[38]
北京-北海 Beijing-Beihai Lake	0.00	0.10	12.60	ND	ND	53.60	66.30	[37]
北京-什刹海 Beijing-Shichahai Lake	ND	ND	17.00	47.90	ND	ND	64.90	[37]
太原-汾河水库 Taiyuan-Fenhe Reservoir	0.01	0.27	ND	47.00	ND	ND	47.30	[39]
北京-陶然亭公园湖泊 Beijing-Taoranting Park Lake	-	-	34.40	-	-	8.30	42.70	[37]

续表7

区域 Locations	DMP	DEP	DBP	BBP	DHP	DEHP	合计 Sum	参考文献 References
广州-城市湖泊 Guangzhou-Urban Lakes	0.00	0.00	11.50	ND	ND	1.70	13.20	[40]
北京-官厅水库 Guanting Reservoir	0.00	ND	1.45	4.76	ND	0.87	7.08	[41]
北京-颐和园湖泊 Beijing-Lakes in Summer Palace	0.00	0.00	0.31	1.83	ND	2.39	4.54	[41]
北京-什刹海 Beijing-Shichahai	0.00	0.00	1.26	0.06	ND	2.61	3.93	[41]
河水 Riverwater								
长江-江苏 Yangtze River-Jiangsu	0.39	78.90	2 323.00	210.00	ND	20.50	2 633.00	[48]
长江-武汉枯水期 Yangtze River Low water period-Wuhan	0.00	ND	170.00	ND	ND	547.00	717.00	[14]
黄河-伊洛河 Yellow River Tributary-Yiluo	0.00	0.06	71.40	ND	ND	318.00	389.00	[44]
黄河-蟒沁河 Yellow River Tributary-Mangqin	ND	0.09	124.00	ND	ND	230.00	354.00	[44]
黄河-小浪底 Yellow River Main River-Xiaolangdi	ND	0.04	100.00	ND	ND	240.00	340.00	[44]
松花江-吉林 Songhua River-Jilin	0.01	0.46	327.00	ND	ND	ND	327.00	[43]
长江三角洲 Yangtze River Delta	0.00	0.02	34.20	0.72	ND	284.00	319.00	[45]
黄河-洛阳 Yellow River Tributary-Luoyang	ND	0.03	100.00	ND	ND	203.00	303.00	[44]
海河-城市段 Haihe River-Urban Area	-	-	34.90	-	-	217.00	252.00	[42]
黄河-开封 Yellow River Main River-Kaifeng	0.00	0.12	ND	ND	ND	160.00	160.00	[44]
黄河-郑州 Yellow River Main River-Zhengzhou	0.00	0.08	ND	ND	ND	150.00	150.00	[44]
黄河-东明 Yellow River Main River-Dongming	0.00	0.11	ND	ND	ND	140.00	140.00	[44]
台湾河流 Taiwan Rivers	ND	0.14	23.30	ND	ND	93.00	116.00	[77]
黄河-新蟒河 Yellow River Tributary-Xinmang	ND	0.08	44.00	ND	ND	58.60	103.00	[44]
黄河-孟州 Yellow River Tributary-Mengzhou	0.01	0.00	61.90	ND	ND	39.10	101.00	[44]
钱塘江-浙江 Qiantangjiang River-Zhejiang	ND	2.35	34.00	ND	ND	20.00	56.30	[47]
黄河-太原 Yellow River-Taiyuan	0.30	0.97	16.20	36.30	ND	ND	53.80	[39]
湘江-株洲 Xiangjiang River-Zhuzhou	ND	ND	36.20	ND	ND	7.90	44.10	[46]
黄河-胶东 Yellow River Main River-Jiaodong	0.01	0.12	ND	ND	ND	32.40	32.50	[44]
黄河-孟津 Yellow River Main River-Mengjin	0.01	0.04	20.40	ND	ND	3.47	23.90	[44]
长江-武汉段丰水期 Yangtze River High water period-Wuhan	0.01	0.10	0.64	ND	ND	0.28	1.02	[14]
地表水 Surface water								
扬州 Yangzhou	ND	0.48	7.57	ND	ND	29.80	37.90	[47]
上海 Shanghai	ND	0.67	7.19	ND	ND	25.30	33.20	[47]
河口/港口/海湾 Estuary/Port/Harbor water								
长江口 Yangtze Estuary area	ND	0.27	5.24	ND	ND	13.00	18.50	[49]
地下水 Ground water								
广州-东莞 Guangzhou-Dongguan	0.00	0.01	1.86	0.10	ND	4.70	6.67	[50]
饮用水 Drinking water source								
长江三角洲 -苏州 Yangtze River Delta -Suzhou	0.00	0.02	44.30	2.90	ND	9.80	57.00	[52]
长江三角洲 -无锡 Yangtze River Delta -Wuxi	0.00	0.02	37.60	0.24	ND	5.60	43.50	[52]
长江三角洲 -常州 Yangtze River Delta -Changzhou	0.00	0.01	25.70	3.50	ND	9.60	38.80	[52]
长江三角洲 -盐城 Yangtze River Delta -Yancheng	0.00	0.02	15.70	0.38	ND	1.40	17.50	[52]
长江三角洲 -徐州 Yangtze River Delta -Xuzhou	ND	ND	0.20	ND	ND	0.11	0.31	[52]
污水处理厂 Wastewater treatment plants								
北京-进水 Beijing-Influents	ND	16.20	22.70	117.00	ND	76.00	232.00	[53]
北京-出水 Beijing-Effluents	ND	ND	ND	35.10	ND	25.00	60.10	[53]

我国作为全球范围内最大的 PAEs 生产国和消费国,PAEs 应用广泛,它已经严重威胁到我国水环境生态安全。总体而言,我国 PAEs 的主要来源为塑料业和增塑剂相关的产业。由于我国对 PAEs 和以 PAEs 为原料产品的需求日益增加,因此我国未来 PAEs 的污染水平将日益严峻。PAEs 的生态风险评价主要是基于准确检测环境介质中 PAEs 的浓度和相关的毒理学参数。需要通过 PAEs 在水环境中长期的生物暴露研究才能确定自然条件下 PAEs 对水环境造成的生态影响。目前,亟需掌握我国不同环境介质中 PAEs 的来源、污染分布特征、毒性参数和生态风险水平,尤其是在高度城市化的地区和 PAEs 工业密集区域。

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