

目次

持久性、迁移性和潜在毒性化学品环境健康风险与控制研究现状及趋势分析 张少轩, 陈安娜, 陈成康, 景侨楠, 刘建国 (3017)

我国厨余垃圾资源化技术的多维绩效评价 杨光, 史波芬, 周传斌 (3024)

基于 MSPA 和电路理论的京津冀城市群热环境空间网络 乔治, 陈嘉悦, 王楠, 卢应爽, 贺瞳, 孙宗耀, 徐新良, 杨浩, 李莹, 王方 (3034)

城市空间格局与热环境响应关系:以合肥市区为例 陈媛媛, 姚侠妹, 偶春, 张清怡, 姚晓洁 (3043)

天津市“十三五”期间 PM_{2.5} 减排效果评估 肖致美, 徐虹, 蔡子颖, 张裕芬, 刘茂辉, 孙猛, 李鹏, 杨宁, 戴运峰 (3054)

清洁取暖对保定市采暖期 PM_{2.5} 中碳质气溶胶的影响 罗宇睿, 张凯, 赵好希, 任家豪, 段菁春, 李欢欢, 关健, 郭志强, 李博文 (3063)

南京地区细颗粒物污染输送影响及潜在源区 谢放尖, 郑新梅, 窦焱焱, 杨峰, 刘春蕾, 李洁, 谢轶嵩, 王艳, 胡建林, 陈长虹 (3071)

大气环流型对珠三角 2015~2020 年臭氧变化的影响 汪瑶, 刘润, 辛繁 (3080)

热带气旋对海南岛臭氧污染的影响分析 符传博, 丹利, 佟金鹤, 徐文帅 (3089)

基于 CMAQ 和 HYSPLIT 模式的日照市夏季臭氧污染成因和来源分析 林鑫, 全纪龙, 王伊凡, 陈羽翔, 刘永乐, 张鑫, 敖丛杰, 刘浩天 (3098)

2016~2020 年成都市控制 PM_{2.5} 和 O₃ 污染的健康效益评价 张莹, 田琪琪, 魏晓钰, 张少波, 胡文东, 李明刚 (3108)

深圳市 2022 年春季新冠疫情管控期间空气质量分析 刘婵芳, 张傲星, 房庆, 叶毓婧, 杨红龙, 陈炯恺, 吴雯潞, 侯岳, 莫佳佳, 傅宗攻 (3117)

贵州省生物质燃烧源大气污染物排放清单 王艳妮, 杨敬婷, 黄贤峰, 程燕, 陆标, 顾兆林 (3130)

西安市大气降水的主要化学组分及其来源 周东, 黄智浦, 李思敏, 王森, 牛振川, 熊晓虎, 冯雪 (3142)

宜昌市大气微塑料的分布、呼吸暴露及溯源 刘立明, 王超, 巩文雯, 陆安祥, 任东, 涂清, 贾漫珂 (3152)

雅鲁藏布江水化学演变规律 江平, 张全发, 李思悦 (3165)

无定河流域地表水硝酸盐浓度的时空分布特征及来源解析 徐奇峰, 夏云, 李书鉴, 王万洲, 李志 (3174)

太浦河水体与沉积物中重金属的季节变化特征与污染评价 罗鹏程, 涂耀仁, 孙婷婷, 刘生辉, 高佳欣, 寇佳怡, 顾心彤, 段艳平 (3184)

北京市北运河水体中抗生素污染特征及风险评估 蒋宝, 隋珊珊, 孙成一, 王亚玲, 荆降龙, 凌文翠, 李珊珊, 李国傲 (3198)

氮和氧同位素示踪伊洛河河水硝酸盐来源及转化过程 郭文静, 张东, 蒋浩, 吴洋洋, 张郭妙, 段慧真, 许梦军, 麻冰涓, 陈昊, 黄兴宇 (3206)

淮河下游湖泊表层水和沉积物中 PPCPs 分布特征及风险评估 武宇圣, 黄天寅, 张家根, 田永静, 庞燕, 许秋瑾 (3217)

西宁市浅层地下水化学特征及形成机制 刘春燕, 于开宁, 张英, 荆继红, 刘景涛 (3228)

叶尔羌河流域平原区地下水污染风险评价 闫志云, 曾妍妍, 周金龙, 孙英, 马常莲 (3237)

密云水库细菌群落组成结构及影响因素 陈颖, 王佳文, 梁恩航, 陈倩 (3247)

可见光激发下模拟海水中四环素光降解的机制和路径 许恒韬, 付小航, 丰卫华, 王挺 (3260)

纳米零价铁改性生物炭对水中氨氮的吸附特性及机制 陈文静, 石峻岭, 李雪婷, 张李金, 刘富强, 陈正祝, 庞维海, 杨殿海 (3270)

高锰酸钾改性椰壳生物炭对水中 Cd(II) 和 Ni(II) 的去除性能及机制 张凤智, 王敦球, 曹星洋, 刘桥京, 岳甜甜, 刘立恒 (3278)

铜改性净水污泥水热炭对水体中磷的吸附特性及底泥内源磷的固定 何李文泽, 陈钰, 孙飞, 李艳君, 杨顺生, 张志鹏 (3288)

城镇生活污水处理厂出水硝酸盐浓度及同位素组成的影响因素 张东, 葛文彪, 赵爱萍, 高振朋, 陈昊, 张琮, 蒋浩, 吴文阳, 廖琪, 李成杰, 黄兴宇, 麻冰涓 (3301)

基于 Meta 分析的污水处理工艺对微塑料去除效果影响 符立松, 侯磊, 王艳霞, 李晓琳, 王万宾, 梁启斌 (3309)

我国自然生态系统氮沉降临界负荷评估 黄静文, 刘磊, 顾晓元, 凌超普 (3321)

气候变化和人类活动对东部沿海地区 NDVI 变化的影响分析 金岩松, 金凯, 王飞, 刘春霞, 秦鹏, 宗全利, 刘佩茹, 陈明利 (3329)

基于 InVEST 模型和 PLUS 模型的环杭州湾生态系统碳储量 丁岳, 王柳柱, 桂峰, 赵晨, 朱望远 (3343)

河西走廊中段荒漠绿洲土壤生态学计量特征 孙雪, 龙永丽, 刘乐, 刘继亮, 金丽琼, 杜海峰, 陈凌云 (3353)

乌梁素海东部流域非生长季草地土壤细菌群落结构的垂向差异 李文宝, 张博尧, 史玉娇, 郭鑫, 李兴月 (3364)

芦芽山华北落叶松林土壤剖面细菌群落分布格局 毛晓雅, 刘晋仙, 贾彤, 吴铁航, 柴宝峰 (3376)

植被类型对黄土高原露天采区复垦土壤碳循环功能基因的影响 赵蛟, 马静, 朱燕峰, 于昊辰, 张琦, 陈浮 (3386)

施用生物炭对麦田土壤细菌群落多样性和冬小麦生长的影响 姚丽茹, 李伟, 朱良正, 曹布仓, 韩娟 (3396)

甜龙竹不同种植年限对土壤真菌群落的影响 朱书红, 辉朝茂, 赵秀婷, 刘蔚漪, 张仲富, 刘会会, 张文君, 朱礼月, 涂丹丹 (3408)

生物炭对热带地区辣椒种植土壤 N₂O 排放及其功能基因的影响 陈琦琦, 王紫君, 陈云忠, 王誉琴, 朱启林, 胡天怡, 胡煜杰, 伍延正, 孟磊, 汤水荣 (3418)

覆膜和有机无机配施对夏玉米农田温室气体排放及水氮利用的影响 蒋洪雨, 雷琪, 张彪, 吴淑芳 (3426)

不同类型地膜覆盖对土壤质量、根系生长和产量的影响 穆晓国, 高虎, 李梅花, 赵欣茹, 郭宁, 靳磊, 李建设, 叶林 (3439)

基于 PMF 模型的某铅锌冶炼城市降尘重金属污染评价及来源解析 陈明, 王琳玲, 曹柳, 李名闯, 申哲民 (3450)

云南 5 城市道路扬尘 PM_{2.5} 中重金属含量表征及健康风险 韩新宇, 郭晋源, 史建武, 李定霜, 王怡明, 宁平 (3463)

兰州市黄河风情线地表积尘及周边绿地土壤重金属污染特征及风险评价 李军, 李开明, 王晓槐, 焦亮, 臧飞, 毛潇萱, 杨云钦, 台喜生 (3475)

PMF 和 RF 模型联用的土壤重金属污染来源解析与污染评价:以西北某典型工业园区为例 高越, 吕童, 张鑫凯, 张博哈, 毕思琪, 周旭, 张炜, 曹红斌, 韩增玉 (3488)

基于 APCS-MLR 受体模型和地统计法的矿区周边农用地土壤重金属来源解析 张传华, 王钟书, 刘力, 刘燕 (3500)

PCA-APCS-MLR 和地统计学的典型农田土壤重金属来源解析 王美华 (3509)

三峡库区稻田土壤重金属污染特征及风险评价 刘娅君, 李彩霞, 梅楠, 张美平, 张成, 王定勇 (3520)

皖江经济带耕地重金属健康风险评价及环境基准 刘海, 魏伟, 潘海, 宋阳, 靳磊, 李建设, 叶林, 黄健敏 (3531)

张家口市万全区某种植区土壤重金属污染评价与来源分析 安永龙, 殷秀兰, 李文娟, 金爱芳, 鲁青原 (3544)

滁州市表层土壤重金属含量特征、源解析及污染评价 汤金来, 赵宽, 胡睿鑫, 徐涛, 王宜萱, 杨扬, 周葆华 (3562)

矿业废弃地重金属形态分布特征与迁移转化影响机制分析 魏洪斌, 罗明, 向奎, 查理思, 杨慧丽 (3573)

基于成土母质的矿产资源基地土壤重金属生态风险评价与来源解析 卫晓峰, 孙紫坚, 陈自然, 魏浩, 孙厚云, 刘卫, 傅大庆 (3585)

不同种类蔬菜重金属富集特征及健康风险 祁浩, 庄坚, 庄重, 王琪, 万亚男, 李花粉 (3600)

山东省典型灌溉区土壤-小麦重金属健康风险评估 王菲, 费敏, 韩冬锐, 李春芳, 曹文涛, 姚磊, 曹见飞, 吴泉源 (3609)

基于机器学习方法的小麦镉富集因子预测 牛硕, 李艳玲, 杨阳, 商艳萍, 王天齐, 陈卫平 (3619)

《环境科学》征订启事(3062) 《环境科学》征稿简则(3116) 信息(3164, 3259, 3572)

淮河下游湖泊表层水和沉积物中 PPCPs 分布特征及风险评估

武宇圣^{1,2,3}, 黄天寅³, 张家根^{1,2,3}, 田永静³, 庞燕^{1,2*}, 许秋瑾^{1,2*}

(1. 中国环境科学研究院湖泊水污染治理与生态修复技术国家工程实验室, 北京 100012; 2. 中国环境科学研究院国家环境保护湖泊污染控制重点实验室, 北京 100012; 3. 苏州科技大学环境科学与工程学院, 苏州 215009)

摘要: 为了解淮河下游湖泊(洪泽湖和高邮湖)表层水和沉积物中药品及个人护理品(PPCPs)的赋存特征及生态风险,采集了23个采样点的43个表层水和沉积物样品,检测了样品中的61种PPCPs,分析了洪泽湖和高邮湖PPCPs的浓度水平空间分布,计算了典型PPCPs在研究区水/沉积物系统的分配系数,并利用商值法对目标PPCPs的生态风险进行评价.结果表明,洪泽湖和高邮湖表层水中 \sum PPCPs浓度分别是 $1.56 \sim 2534.44 \text{ ng}\cdot\text{L}^{-1}$ 和 $3.32 \sim 1027.47 \text{ ng}\cdot\text{L}^{-1}$,沉积物中 \sum PPCPs含量分别是 $1.7 \sim 926.7 \text{ ng}\cdot\text{g}^{-1}$ 和 $1.02 \sim 289.37 \text{ ng}\cdot\text{g}^{-1}$,其中表层水中林可霉素(LIN)浓度最高,沉积物中强力霉素(DOX)含量最高,都以抗生素类药物为主要组分;PPCPs空间分布呈现洪泽湖高、高邮湖低的特征;分配特征表明研究区域典型PPCPs更倾向停留在水相, $\lg K_{oc}$ 和 $\lg K_d$ 之间具有显著相关性,表明沉积物中总有机碳(TOC)对典型PPCPs在水/沉积物系统的分配起重要作用;生态风险评估结果显示PPCPs对表层水和沉积物中藻类的生态风险显著高于蚤类和鱼类,表层水中PPCPs的生态风险高于沉积物,洪泽湖的生态风险高于高邮湖.

关键词: 淮河下游湖泊; 药品与个人护理品(PPCPs); 分布特征; 分配系数; 生态风险评估

中图分类号: X524 文献标识码: A 文章编号: 0250-3301(2023)06-3217-11 DOI: 10.13227/j.hjks.202207169

Distribution Characteristics and Risk Assessment of PPCPs in Surface Water and Sediments of Lakes in the Lower Reaches of the Huaihe River

WU Yu-sheng^{1,2,3}, HUANG Tian-yin³, ZHANG Jia-gen^{1,2,3}, TIAN Yong-jing³, PANG Yan^{1,2*}, XU Qiu-jin^{1,2*}

(1. National Engineering Laboratory for Lake Pollution Control and Ecological Restoration, Chinese Research Academy of Environmental Sciences, Beijing 100012, China; 2. State Environmental Protection Key Laboratory for Lake Pollution Control, Chinese Research Academy of Environmental Sciences, Beijing 100012, China; 3. School of Environmental Science and Engineering, Suzhou University of Science and Technology, Suzhou 215009, China)

Abstract: In order to understand the occurrence characteristics and ecological risks of pharmaceuticals and personal care products (PPCPs) in surface water and sediments of Hongze Lake and Gaoyou Lake in the lower reaches of the Huaihe River, 43 surface water and sediment samples from 23 sampling sites were collected, and 61 PPCPs were detected in the samples. The concentration level and spatial distribution of target PPCPs in Hongze Lake and Gaoyou Lake were analyzed, the distribution coefficient of typical PPCPs in the water/sediment system in the study area was calculated, and the ecological risk of target PPCPs was evaluated using the entropy method. The results showed that the PPCPs in surface water of Hongze Lake and Gaoyou Lake were $1.56\text{-}2534.44 \text{ ng}\cdot\text{L}^{-1}$ and $3.32\text{-}1027.47 \text{ ng}\cdot\text{L}^{-1}$, respectively, and those in sediment were $1.7\text{-}926.7 \text{ ng}\cdot\text{g}^{-1}$ and $1.02\text{-}289.37 \text{ ng}\cdot\text{g}^{-1}$, respectively. The concentrations of lincomycin (LIN) in surface water and doxycycline (DOX) in sediment were the highest, and antibiotics were the main components. The spatial distribution of PPCPs was higher in Hongze Lake and lower in Gaoyou Lake. The distribution characteristics of typical PPCPs in the study area showed that typical PPCPs tended to stay in the water phase, and there was a significant correlation between $\lg K_{oc}$ and $\lg K_d$, indicating that total organic carbon (TOC) played an important role in the distribution of typical PPCPs in the water/sediment system. The ecological risk assessment results showed that the ecological risk of PPCPs to algae in surface water and sediment was significantly higher than that of fleas and fish, the ecological risk value of PPCPs in surface water was higher than that in sediment, and the ecological risk of Hongze Lake was higher than that of Gaoyou Lake.

Key words: lakes in the lower reaches of the Huaihe River; pharmaceuticals and personal care products (PPCPs); distribution characteristics; distribution coefficient; ecological risk assessment

药品与个人护理品(pharmaceuticals and personal care products, PPCPs)作为一类典型的新型污染物在世界范围内广泛使用,主要由抗生素类药物、非抗生素类药物和个人护理品这3部分组成,其中抗生素类药物主要包括磺胺类、四环素类、喹诺酮类和大环内酯类等;非抗生素类药物主要包括非甾体抗炎药、血脂调节剂、内分泌药物、 β -受体阻滞药和精神刺激药物等;个人护理品主要包括杀菌剂、驱虫剂、人造麝香、杀虫剂和防晒剂等^[1].

PPCPs在提高人类生活质量,促进养殖业发展等方面有很好的应用,但是由于人类的广泛使用和持续排放,导致PPCPs在水环境中呈现假持久性现象,随着食物链和食物网的传递,对生态系统和人体健康

收稿日期: 2022-07-16; 修订日期: 2022-09-05

基金项目: 国家水体污染控制与治理科技重大专项(2017ZX07301006-006)

作者简介: 武宇圣(1997~),男,硕士研究生,主要研究方向为新型污染物的环境风险与控制, E-mail: 2922355861@qq.com

* 通信作者, E-mail: 190068749@qq.com; xuqj@caes.org.cn

康均会造成潜在危害^[2]. 近年来,我国水环境中 PPCPs 污染的相关报道日渐增多,众多研究者在松花江^[3]、白洋淀^[4]、汾河^[5]、骆马湖^[6]、太湖^[7]、洞庭湖^[8]、三亚市^[9]、九龙江^[10]、钦州湾^[11]和宁夏第三排水沟^[12]等天然水体和饮用水源地中的多种环境介质中检测出不同浓度水平的 PPCPs,因此 PPCPs 对水环境的影响亟待关注.

洪泽湖与高邮湖位于淮河下游地区,是我国南水北调东线工程重要的枢纽湖泊^[13]. 这两座湖泊分别是我国第四和第六大淡水湖泊,均属于大型过水性湖泊^[14]. 淮河主干来水汇入洪泽湖后,又经淮河水道进入高邮湖,最终排入长江入海^[15]. 两座湖泊作为淮河流域经济带重要的农业、渔业和生活用水来源,对区域内经济社会的可持续发展和南水北调东线的供水水质安全发挥着重要作用^[16]. 当前对两座湖泊的污染报道多集中在氮磷和重金属等常规污染物方面,有关 PPCPs 这一类新型污染物的研究较少^[17,18]. 因此,本研究在系统分析洪泽湖、高邮湖表层水和沉积物中 PPCPs 浓度特征的基础上,探讨了典型 PPCPs 在水/沉积物系统的分布及分配特征,并进行了生态风险评价,以期为淮河流域湖泊中新型污染物的赋存现状与污染防控提供数据支撑和科学依据.

1 材料与方法

1.1 仪器与试剂

仪器设备:超高效液相色谱-串联三重四级杆质谱仪(Agilent LC 1260-MS 6470,美国)、Oasis HLB 固相萃取小柱(Waters,美国)、12位固相萃取装置(Supelco Visiprep,美国)、氮吹仪(N-EVAP-111,南京)、涡旋混合器(QL-901,海门)和纯水机(EPED-20TF,南京).

标准样品:磺胺甲噁唑(SMX)、磺胺甲噁二唑(SMT)、磺胺间甲氧嘧啶(SMM)、磺胺氯吡啶(SCP)、甲氧苄啶(TMP)、磺胺塞唑(STZ)、磺胺甲基嘧啶(SMR)、磺胺异噁唑(SIX)、磺胺二甲基异噁唑(SIM)、磺胺甲氧吡啶(SMP)、磺胺喹噁啉(SQX)、磺胺二甲嘧啶(SMZ)、磺胺二甲氧嘧(SDM)、磺胺嘧啶(SDZ)、诺氟沙星(NOR)、氧氟沙星(OFL)、环丙沙星(CIP)、恩诺沙星(ENR)、达氟沙星(DAN)、马波沙星(MAR)、沙氟沙星(SAR)、洛美沙星(LOM)、司氟沙星(SPA)、培氟沙星(PEF)、双氟沙星(DIF)、氟甲喹(FLU)、噁喹酸(OA)、萘啶酸(NA)、四环素(TC)、土霉素(OTC)、金霉素(CTC)、强力霉素(DOX)、美他环素(MTC)、红霉素(ETM)、罗红霉素(ROX)、泰乐

菌素(TYL)、替米考星(TMC)、克拉霉素(CLA)、氯霉素(Chl)、氟苯尼考(FLO)、克林霉素(CLD)、林可霉素(LIN)、莫能菌素(MON)、青霉素(PCG)、泰妙菌素(TIM)、甲砒霉素(THI)、舒必利(SP)、双氯芬酸(DIC)、酮洛芬(KPF)、布洛芬(ibu)、对乙酰氨基酚(ATP)、吲哚美辛(IND)、扑湿痛(MEF)、普萘洛尔(PRO)、美托洛尔(MTP)、苯扎贝特(BEZ)、氯贝酸(CLO)、吉非罗齐(GEM)、咖啡因(CAF)、卡马西平(CBZ)和避蚊胺(DEET)共61种;内标物为磺胺甲噁唑-¹³C₆、盐酸环丙沙星-D8、红霉素-C2、避蚊胺-S14和吉非罗齐-D6. 以上标准品和内标物均购于美国Sigma公司,纯度均大于98%.

主要试剂:甲醇、甲酸和乙腈购自美国Fisher公司.

1.2 样品采集与前处理

于2021年11月在洪泽湖和高邮湖进行表层水样品和沉积物样品采集,具体采样点见图1. 采样点位包括洪泽湖与高邮湖出入湖河口、中心湖区及湖湾等区域,总计点位23个,其中H1~H14号位于洪泽湖,G1~G9号位于高邮湖.

野外采样前,用甲醇和去离子水润洗采样相关设备. 表层水样由有机玻璃采水器采集(水面以下0.5 m),密闭保存于1 L的棕色玻璃瓶中,在0~4℃冷藏保存;沉积物样品由彼得逊采泥器采集(表面0~5 cm),混合均匀后用锡纸包裹放入塑料袋中,冷藏条件下运往实验室.

水样前处理:将1 L水样过滤,加入25 ng提取内标液、500 mg Na₂EDTA和25 mg抗坏血酸,混合均匀并老化30 min. 活化和平衡HLB固相萃取柱,水样过柱. 高纯水淋洗小柱,抽真空下干燥0.5 h,甲醇洗脱萃取柱. 在水浴中以高纯氮气吹干. 最后用含0.025%甲酸的甲醇水定容,加入25 ng进样内标液,涡旋混合. 过膜移入自动进样样品瓶中,4℃下冷藏待分析.

沉积物前处理:将沉积物样品进行冷冻干燥,研磨过100目筛. 取1 g样品放入离心管中,加提取内标并老化30 min. 加入15 mL磷酸盐缓冲液,涡旋混合,加入20 mL乙腈,涡旋超声. 离心并转移上层清液至锥形瓶中,重复提取3次(第3次不加缓冲液),旋蒸至20~30 mL. 加入超纯水稀释,加入500 mg Na₂EDTA、抗坏血酸,混匀后抽滤. 后面处理步骤与水样一致.

1.3 样品测定条件

采用UPLC-MS/MS系统测定PPCPs浓度,色谱柱为Agilent eclipse plus-C18液相色谱柱(3.5 μm ×

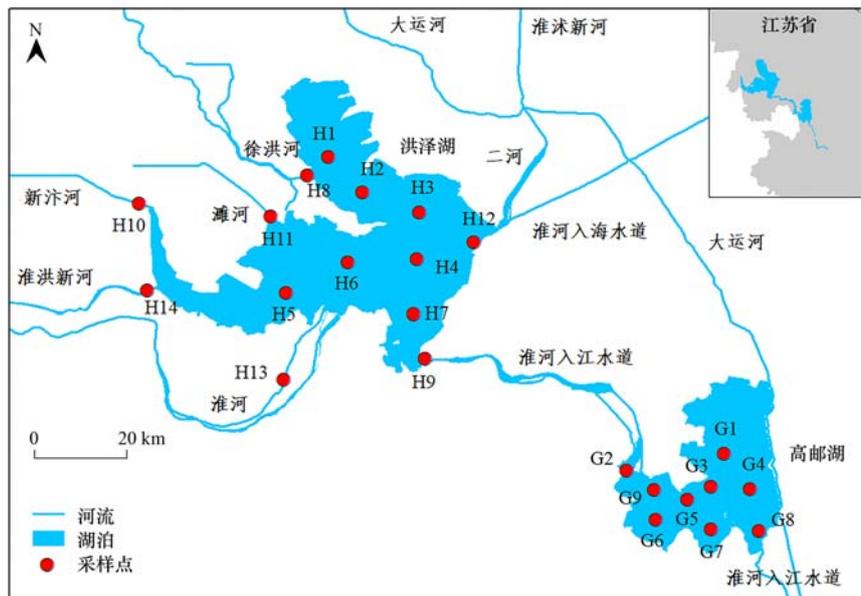


图1 洪泽湖和高邮湖采样点分布示意

Fig. 1 Sampling sites distribution in Hongze Lake and Gaoyou Lake

150 × 2.1 mm). 流动相 A 为含 0.05% 甲酸的高纯水, 流动相 B 为甲醇. 进行梯度洗脱, 洗脱程序为: 0 ~ 15 min, 5% B 线性增加至 95% B, 保留 4 min, 然后瞬间降至 5% B, 平衡 11 min. 流速为 0.4 mL · min⁻¹, 柱温为 20℃, 进样体积为 5 μL. 采用喷雾电离源 (ESI), 多反应监测 (MRM) 模式检测, 鞘气温度为 350℃, 鞘气流量为 7 L · min⁻¹, 干燥气温度为 300℃, 干燥气流量为 7 L · min⁻¹, 高纯氮气压力位 0.15 ~ 0.20 MPa.

1.4 质量保证与控制

采用内标法对样品进行定量分析, 10 个样品为一批, 每批样品中设置空白和空白加标样, 所有样品均加入内标物以控制前处理过程中的损失. 各目标 PPCPs 的线性相关系数均大于 0.99. 内标回收率为 72.13% ~ 125.16%, 水和沉积物中 61 种 PPCPs 的加标回收率范围为 82.75% ~ 115.52% 和 72.52% ~ 135.21%. 检出限与定量限分别为 3 倍信噪比和 10 倍信噪比, 水和沉积物样品中 61 种 PPCPs 的检出限范围为 0.03 ~ 0.56 ng · L⁻¹ 和 0.02 ~ 0.45 ng · g⁻¹, 定量限范围为 0.05 ~ 1.86 ng · L⁻¹ 和 0.09 ~ 1.68 ng · g⁻¹, 相对偏差均小于 10%, 空白样品中未检出这 61 种 PPCPs 符合质量控制要求.

1.5 生态风险评估方法

采用风险商 (RQ) 对水体中 PPCPs 的生态风险进行评价^[19], 分为 4 级: RQ < 0.01 为无风险, 0.01 ≤ RQ < 0.1 为低风险, 0.1 ≤ RQ < 1 为中风险, RQ ≥ 1 为高风险, 具体计算公式为:

$$RQ = MEC/PNEC$$

式中, MEC 为环境实测浓度, ng · L⁻¹; PNEC 为预测

无效应浓度, ng · L⁻¹.

将沉积物 PPCPs 含量转换为间隙水中 PPCPs 的浓度, 然后通过水生生物毒性效应数据对沉积物进行生态风险评估^[20], 其计算公式为:

$$RQ = \frac{MEC}{PNEC_{water} \times K_{oc} \times F_{oc}}$$

式中, MEC 为环境实测含量, ng · g⁻¹; PNEC_{water} 为水体中预测无效应浓度, ng · L⁻¹; K_{oc} 为有机碳化合物含量, L · kg⁻¹; F_{oc} 为有机碳在沉积物中的含量 (经实验测定, 取值为 0.01 g · g⁻¹).

采用联合风险商 (RQ_{sum}) 来表征 PPCPs 对水生生态系统的生态风险^[21], 计算公式为:

$$RQ_{sum} = \sum RQ$$

2 结果与讨论

2.1 洪泽湖和高邮湖表层水中 PPCPs 浓度分布

洪泽湖和高邮湖表层水 PPCPs 检出结果如图 2 所示. 其中洪泽湖表层水 61 种 PPCPs 共检出 21 种, 高邮湖检出 19 种. 从浓度水平来看, 洪泽湖表层水 ∑ PPCPs 浓度范围在 1.56 ~ 2534.44 ng · L⁻¹ 之间, 平均值为 204.19 ng · L⁻¹, 检出浓度最高的物质为林可霉素和舒必利, 林可霉素和舒必利最高值分别为 551.26 ng · L⁻¹ 和 63.26 ng · L⁻¹; 高邮湖表层水 ∑ PPCPs 浓度范围在 3.32 ~ 1027.47 ng · L⁻¹ 之间, 平均值为 98.28 ng · L⁻¹, 检出浓度最高的物质也是林可霉素和舒必利, 最高值分别为 223.04 ng · L⁻¹ 和 38.72 ng · L⁻¹. 从检出率方面来看, 洪泽湖表层水中检出率达到 100% 的 PPCPs 共有 16 种, 其余

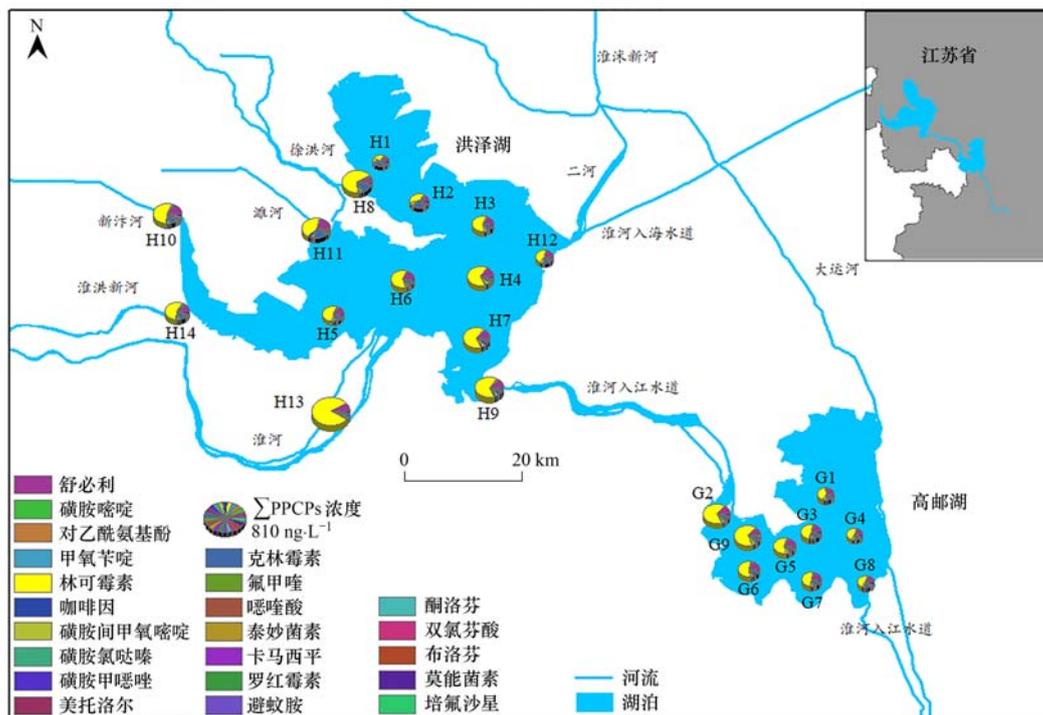


图2 洪泽湖和高邮湖表层水中 PPCPs 浓度分布

Fig. 2 Distribution of PPCPs content in surface water of Hongze Lake and Gaoyou Lake

PPCPs 的检出率在 7.14%~92.86% 之间;高邮湖表层水中检出率为 100% 的 PPCPs 共有 15 种,其余 PPCPs 的检出率在 11.11%~88.89% 之间。

从主要检出物质来看,林可霉素、舒必利和克林霉素都是两座湖泊表层水的主要检出物质,且与同是淮河流域的骆马湖检出结果相似^[22],但是同其他河流湖泊相比,咖啡因和避蚊胺在两座湖泊检出浓度则较低,不是主要污染物。从浓度范围来看,洪泽湖 \sum PPCPs 浓度范围 ($1.56 \sim 2534.44 \text{ ng}\cdot\text{L}^{-1}$) 整体高于高邮湖 ($3.32 \sim 1027.47 \text{ ng}\cdot\text{L}^{-1}$),可能与洪泽湖作为淮河流域中游大型的过水性湖泊,既是上游地区污染的“汇”,也是下游地区和南水北调污染的“源”有关^[23]。洪泽湖和高邮湖 \sum PPCPs 浓度范围明显低于北运河 ($132 \sim 25474 \text{ ng}\cdot\text{L}^{-1}$)^[24]、白洋淀 ($42.3 \sim 7710 \text{ ng}\cdot\text{L}^{-1}$)^[25] 和骆马湖 ($2.67 \sim 6514.91 \text{ ng}\cdot\text{L}^{-1}$)^[22],而高于长江南京段 ($2.25 \sim 739.40 \text{ ng}\cdot\text{L}^{-1}$)^[26]、长江中游 ($35.40 \sim 704.57 \text{ ng}\cdot\text{L}^{-1}$)^[27]、洞庭湖 ($3.03 \sim 695.7 \text{ ng}\cdot\text{L}^{-1}$)^[8]、金沙江 ($1.26 \sim 525.8 \text{ ng}\cdot\text{L}^{-1}$)^[28]、河南省水源地 ($24.2 \sim 317.6 \text{ ng}\cdot\text{L}^{-1}$)^[29] 和汉江 ($37.47 \sim 292.96 \text{ ng}\cdot\text{L}^{-1}$)^[30]。总体来说,洪泽湖和高邮湖表层水中 PPCPs 浓度处于中低水平。

从空间分布来看,洪泽湖 H13 和 H8 点位的 \sum PPCPs 浓度最高,分别为 $706.84 \text{ ng}\cdot\text{L}^{-1}$ 和 $434.57 \text{ ng}\cdot\text{L}^{-1}$ 。H13 点位于淮河干流,H8 点位于徐

洪河,这两条河均为洪泽湖的主要入湖河流,尤其淮河干流更是占到洪泽湖 70% 以上入湖水量,入湖河流接纳的生活污水和工业废水汇入可能造成了高浓度的检出^[31]。高邮湖 G2 和 G9 点位的 \sum PPCPs 浓度高,分别为 $331.53 \text{ ng}\cdot\text{L}^{-1}$ 和 $339.05 \text{ ng}\cdot\text{L}^{-1}$ 。G2 点位位于淮河入江水道,G9 点位位于金湖县禽畜养殖区,淮河入江水道是连接洪泽湖与高邮湖的重要河道,因而淮河经洪泽湖来水对高邮湖北部湖区 PPCPs 有一定影响,而金湖县养殖区污水的外源输入可能是 G9 点位浓度高的主要原因^[32]。

洪泽湖和高邮湖表层水 PPCPs 组分特征如图 3 所示。根据检出情况,洪泽湖和高邮湖表层水中抗生素类药物的占比明显高于非抗生素类药物和个人护理品的占比。洪泽湖和高邮湖表层水抗生素类药物占比分别为 81.7% 和 79.3%,平均值分别为 $250.19 \text{ ng}\cdot\text{L}^{-1}$ 和 $164.49 \text{ ng}\cdot\text{L}^{-1}$;非抗生素类药物占比分别为 16.4% 和 18.7%,平均值分别为 $50.29 \text{ ng}\cdot\text{L}^{-1}$ 和 $38.74 \text{ ng}\cdot\text{L}^{-1}$;个人护理品占比分别为 1.9% 和 2.0%,平均值分别为 $5.84 \text{ ng}\cdot\text{L}^{-1}$ 和 $4.25 \text{ ng}\cdot\text{L}^{-1}$ 。造成这种现象的原因可能是养殖业是研究区周边几个县市的主要产业(盱眙的龙虾、高邮的麻鸭和洪泽的螃蟹),大量养殖废水的排放造成了表层水中抗生素类药物的高浓度检出^[33]。

2.2 洪泽湖和高邮湖沉积物中 PPCPs 含量分布

洪泽湖和高邮湖沉积物中 PPCPs 检出结果如图 4 所示。其中洪泽湖沉积物 61 种 PPCPs 共检出

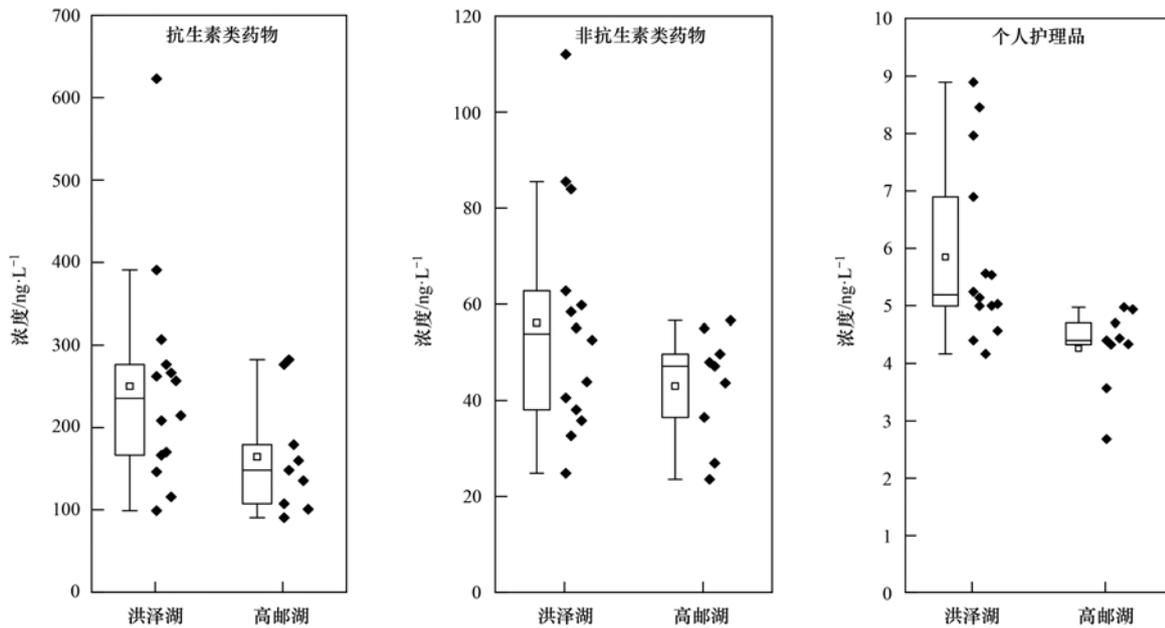


图3 洪泽湖和高邮湖表层水中 PPCPs 组分对比

Fig. 3 Comparison of PPCPs components in surface water of Hongze Lake and Gaoyou Lake

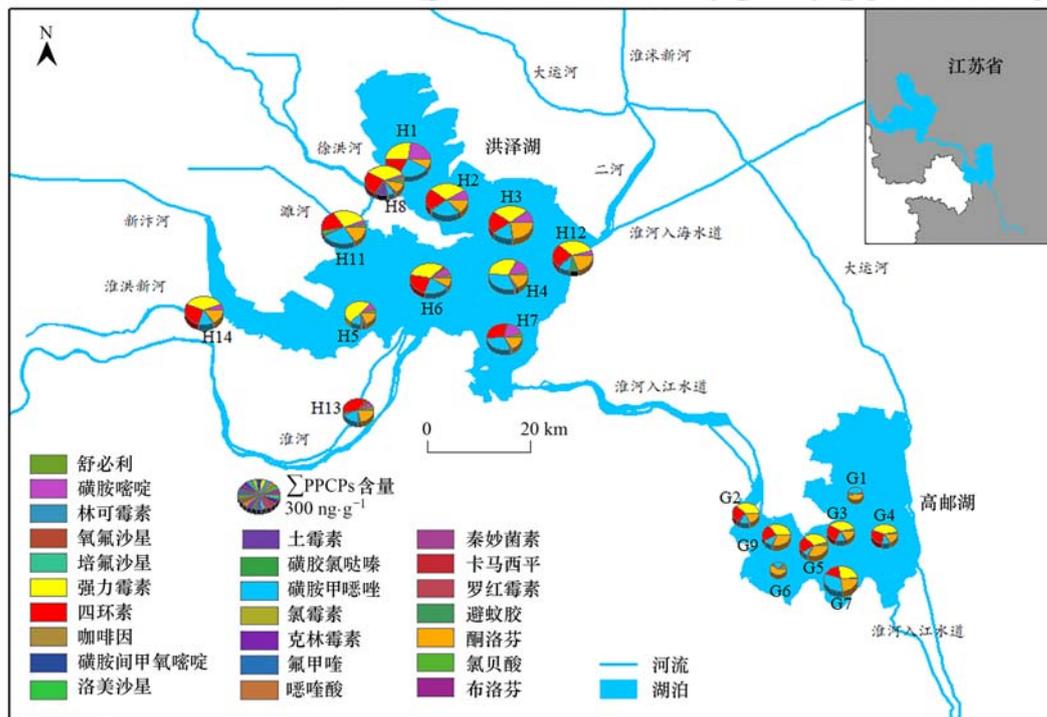


图4 洪泽湖和高邮湖沉积物中 PPCPs 含量分布

Fig. 4 Distribution of PPCPs content in sediments of Hongze Lake and Gaoyou Lake

24 种,高邮湖检出 16 种.从含量水平来看,洪泽湖沉积物 \sum PPCPs 含量范围在 $1.7 \sim 926.7 \text{ ng}\cdot\text{g}^{-1}$ 之间,平均值为 $134.74 \text{ ng}\cdot\text{g}^{-1}$,检出含量最高的物质为强力霉素和四环素,最高值分别为 $97.23 \text{ ng}\cdot\text{g}^{-1}$ 和 $63.61 \text{ ng}\cdot\text{g}^{-1}$;高邮湖沉积物 \sum PPCPs 含量范围在 $1.02 \sim 289.37 \text{ ng}\cdot\text{g}^{-1}$ 之间,平均值为 $49.64 \text{ ng}\cdot\text{g}^{-1}$,检出含量最高的物质为强力霉素和酮洛芬,最高值分别为 $36.17 \text{ ng}\cdot\text{g}^{-1}$ 和 29.91

$\text{ng}\cdot\text{g}^{-1}$.从检出率方面来看,洪泽湖沉积物中检率达到 100% 的 PPCPs 共有 9 种,其余 PPCPs 的检出率在 $8.3\% \sim 75\%$ 之间;高邮湖沉积物中检出率为 100% 的 PPCPs 共有 9 种,其余 PPCPs 的检出率在 $12.5\% \sim 75\%$ 之间.

从主要检出物质来看,强力霉素、酮洛芬和四环素均为两座湖泊沉积物中的主要检出物质,且主要以四环素类抗生素(TCs)为主.从含量范围来看,洪泽湖 \sum PPCPs 含量范围($1.7 \sim 926.7 \text{ ng}\cdot\text{g}^{-1}$)显

著低于珠江口 ($152 \sim 1\,483 \text{ ng}\cdot\text{g}^{-1}$)^[34], 高于骆马湖 ($0.25 \sim 330.02 \text{ ng}\cdot\text{g}^{-1}$)^[35]、上海青浦区水体 ($0.07 \sim 688.59 \text{ ng}\cdot\text{g}^{-1}$)^[36] 和太湖 ($1.60 \sim 129 \text{ ng}\cdot\text{g}^{-1}$)^[37]; 高邮湖 \sum PPCPs 含量范围 ($1.02 \sim 289.37 \text{ ng}\cdot\text{g}^{-1}$) 低于白洋淀 ($131.65 \sim 750.27 \text{ ng}\cdot\text{g}^{-1}$)^[38], 高于黄河三角洲 ($40.97 \sim 207.44 \text{ ng}\cdot\text{g}^{-1}$)^[39]、汉江 ($3.35 \sim 171.84 \text{ ng}\cdot\text{g}^{-1}$)^[30] 和西藏申扎镇水体 ($0.96 \sim 56.38 \text{ ng}\cdot\text{g}^{-1}$)^[40]. 洪泽湖沉积物中 PPCPs 污染水平整体高于高邮湖, 且同国内其他河湖相比处于中高水平, 这可能与其检出种类主要以 TCs 为主有关, TCs 本身官能团较多, 容易吸附到沉积物上, 而高邮湖水量比洪泽湖小, 因而处于中低水平^[41].

从空间分布来看, 洪泽湖 H1 和 H3 点位的 \sum PPCPs 含量最高, 分别为 $353.63 \text{ ng}\cdot\text{g}^{-1}$ 和 $336.52 \text{ ng}\cdot\text{g}^{-1}$. H1 和 H3 点位于洪泽湖中北部的非

过水区, 水力交互较小, 污染物更易沉积, 周边养殖废水的排入都可能导致该点位 PPCPs 含量高于其他点位. 高邮湖 G7 点位的 \sum PPCPs 含量最高, 为 $196.48 \text{ ng}\cdot\text{g}^{-1}$. G7 点位于南部郭集镇水产养殖区, 该养殖区拥有 2 km^2 的罗氏沼虾养殖面积, TCs 的大量使用可能造成了该点位的高含量^[42].

洪泽湖和高邮湖沉积物 PPCPs 组分特征如图 5 所示. 洪泽湖和高邮湖沉积物中抗生素类药物的占比明显高于非抗生素类药物和个人护理品的占比. 洪泽湖和高邮湖沉积物抗生素类药物占比分别为 80.7% 和 69.7%, 含量平均值分别为 $220.12 \text{ ng}\cdot\text{g}^{-1}$ 和 $83.45 \text{ ng}\cdot\text{g}^{-1}$; 非抗生素类药物占比分别为 18.1% 和 28.8%, 含量平均值分别为 $49.48 \text{ ng}\cdot\text{g}^{-1}$ 和 $34.46 \text{ ng}\cdot\text{g}^{-1}$; 个人护理品占比分别为 1.2% 和 1.5%, 含量平均值分别为 $3.18 \text{ ng}\cdot\text{g}^{-1}$ 和 $1.84 \text{ ng}\cdot\text{g}^{-1}$.

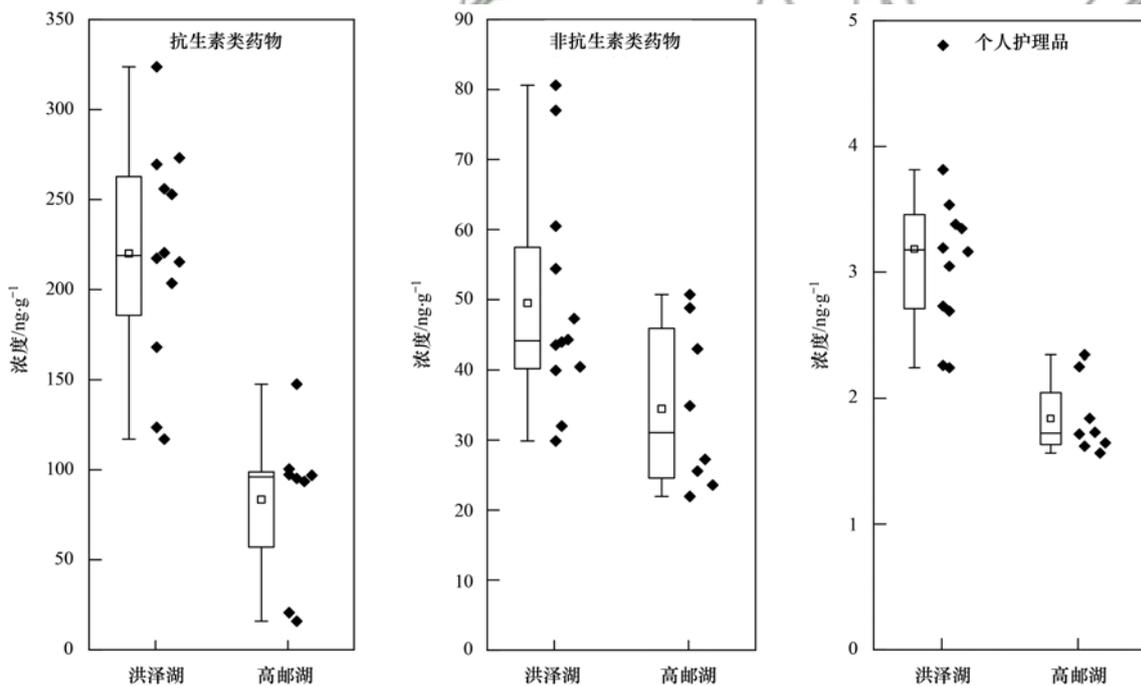


图 5 洪泽湖和高邮湖沉积物中 PPCPs 组分对比

Fig. 5 Comparison of PPCPs components in sediments of Hongze Lake and Gaoyou Lake

2.3 洪泽湖和高邮湖水/沉积物系统 PPCPs 的分配特征

当环境条件发生变化时, 沉积物可作为 PPCPs 的二次污染源, 将 PPCPs 重新释放到水体中, 因此 PPCPs 在水/沉积物系统的分配行为日益引发关注. 有机污染物在水/沉积物系统的分配系数 K_d 值 (沉积物与水中污染物含量比值) 是用来研究其在水环境中分配行为的重要参数^[43]. 考虑到研究区水和沉积物之间检测频率的差异, 仅选择表层水和沉积物中检测频率较高的 PPCPs 进行分析.

由图 6(a) 和图 6(b) 可以看出, 洪泽湖与高邮湖典型 PPCPs 的 $\lg K_d$ 值介于 $-3.88 \sim 1.97 \text{ L}\cdot\text{kg}^{-1}$ 和 $-3.19 \sim 2.53 \text{ L}\cdot\text{kg}^{-1}$ 之间, 同上海市青浦区水体 ($\lg K_d$ 值范围为 $2.86 \sim 5.61 \text{ L}\cdot\text{kg}^{-1}$)^[36] 和黄河三角洲 ($\lg K_d$ 值范围为 $1.55 \sim 4.06 \text{ L}\cdot\text{kg}^{-1}$)^[39] 相比较, 表明研究区内检出率较高的 PPCPs 更倾向于停留在水中. 其中, 酮洛芬 (KPF) 是研究区内的 $\lg K_d$ 值范围最高的 PPCPs (洪泽湖 $0.83 \sim 1.97 \text{ L}\cdot\text{kg}^{-1}$, 均值 $1.32 \text{ L}\cdot\text{kg}^{-1}$; 高邮湖 $1.26 \sim 2.53 \text{ L}\cdot\text{kg}^{-1}$, 均值 $1.78 \text{ L}\cdot\text{kg}^{-1}$), 这表明 KPF 更倾向于吸附到沉积

物上,这可能与 KPF 的辛醇-水分配系数 ($\lg K_{ow}$ 为 3.12) 较高有关. 此外,研究区内不同采样点和不同种类 PPCPs 的 $\lg K_d$ 值变化较大,这表明 PPCPs 自身性质、沉积物特性及采样点环境因素都是影响 PPCPs 在水/沉积物系统分配的重要因素^[44]. 如图 6 (c) 和图 6 (d) 所示,将 K_d 值除以对应沉积物 TOC 值计算有机碳归一化分配系数 (K_{oc}),来进一步探究 TOC 对 PPCPs 的分配影响作用,洪泽湖与高邮湖

$\lg K_{oc}$ 值范围分布为 $-0.8 \sim 5.09 \text{ L} \cdot \text{kg}^{-1}$ 和 $0.03 \sim 5.38 \text{ L} \cdot \text{kg}^{-1}$ ^[45]. 如图 6 (e) 和图 6 (f) 所示,将目标 PPCPs 的 $\lg K_d$ 值和 $\lg K_{oc}$ 值进行相关性分析发现 PPCPs 的 $\lg K_d$ 和 $\lg K_{oc}$ 之间存在显著线性关系,表明沉积物 TOC 值能够影响沉积物和水间 PPCPs 分配特征,这与刷泽佳等^[46]在石家庄地表水得出的抗生素 K_d 值同沉积物 TOC 之间呈显著相关的研究结论相似.

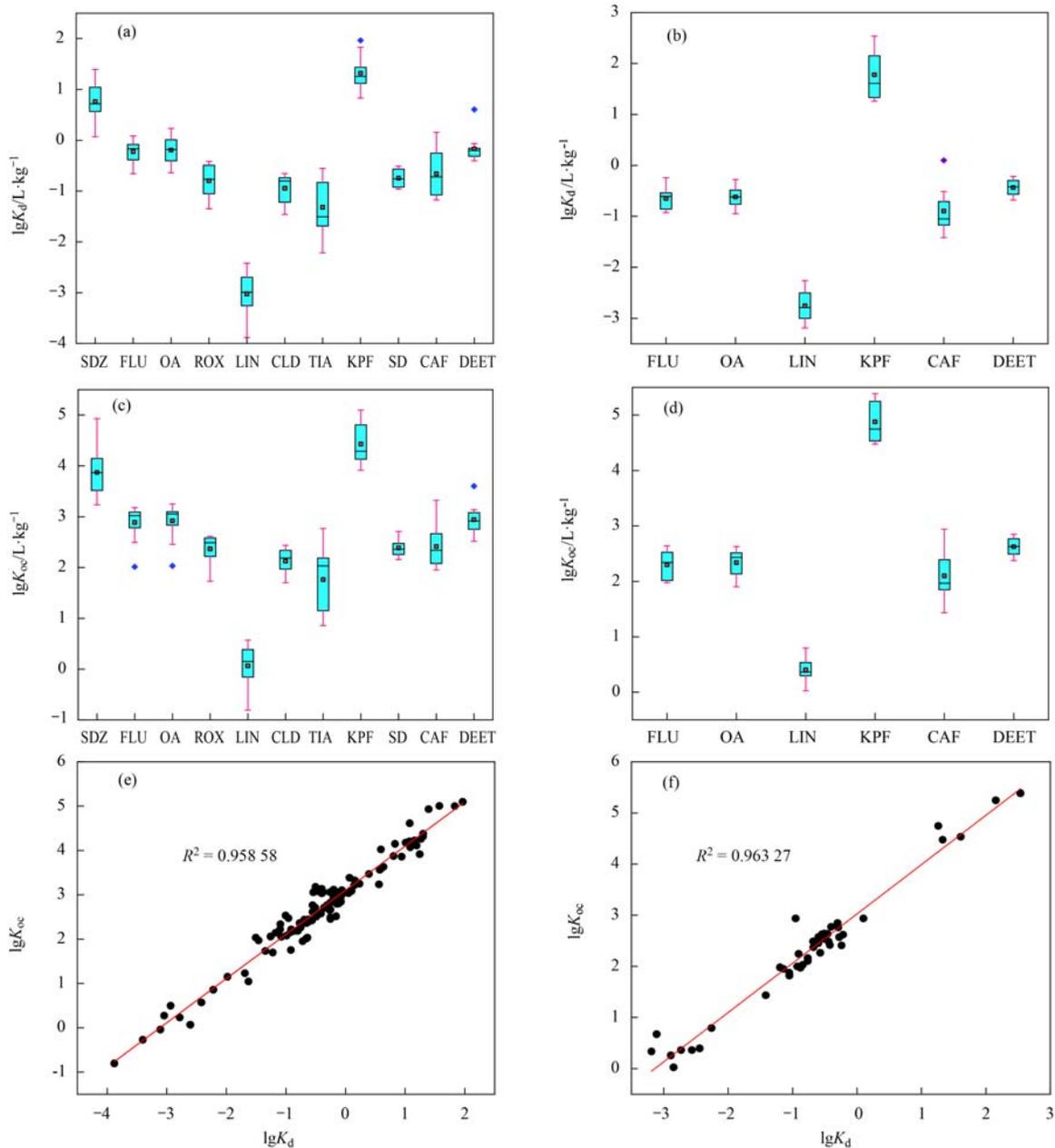


图 6 洪泽湖和高邮湖典型 PPCPs 的分配特征

Fig. 6 Distribution characteristics of typical PPCPs in Hongze Lake and Gaoyou Lake

2.4 生态风险评价

根据检测的 PPCPs 数据,运用商值法计算 PPCPs 的 RQ 值,研究区表层水和沉积物 PPCPs 对藻类、蚤类和鱼类的生态风险评价结果如图 7 所

示.不同营养级生物对 PPCPs 的敏感程度存在差异,藻类和蚤类的敏感程度明显高于鱼类,尤其 PPCPs 对藻类的风险最高.以藻类为保护对象,研究区表层水中 LIN 的风险等级最高,达到了中风险

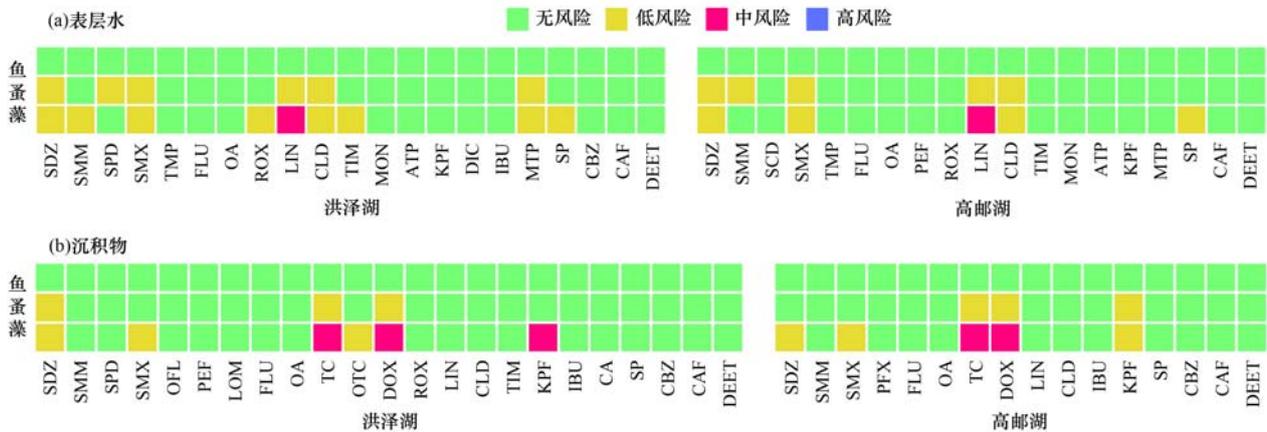


图 7 表层水和沉积物中目标 PPCPs 生态风险评价

Fig. 7 Ecological risk assessment of the target PPCPs in the surface water and sediments

($0.1 \leq RQ < 1$), 沉积物中 DOX、TC 和 KPF 的 RQ 均大于 0.1, 处于中风险; 以蚤类为保护对象, 研究区表层水中 SDZ、SMM、SPD、SMX、LIN、CLD、MTP 和 SP 的 RQ 处于低风险($0.01 \leq RQ < 0.1$), 沉积物中 SDZ、DOX、TC 和 KPF 为低风险; 以鱼类为保护对象, 研究区表层水和沉积物 PPCPs 污染物均

无明显风险 ($RQ < 0.01$).

从空间分布来看, 研究区各采样点的 RQ_{sum} 如图 8 所示. 表层水中 H8、H11、H13 点位的藻类风险水平达到中风险($0.1 \leq RQ_{sum} < 1$), 这 3 个点位均位于洪泽湖, 其他点位的藻类为低风险水平($0.01 \leq RQ_{sum} < 0.1$), 蚤类所有点位均为低风险, 鱼类为

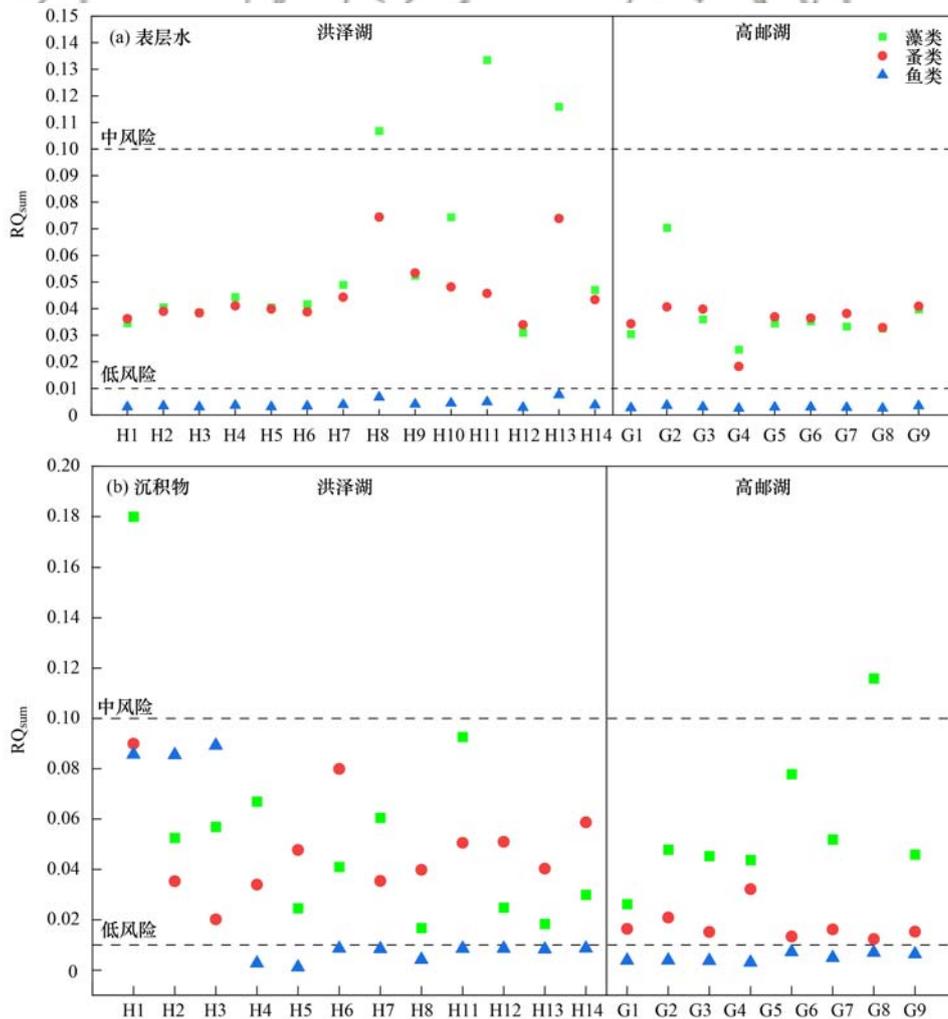


图 8 各采样点 PPCPs 生态风险

Fig. 8 Ecological risk of PPCPs at each sampling site

无风险($RQ_{sum} < 0.01$); 沉积物中 H1 和 G7 点位的藻类风险水平为中风险, H1 位于洪泽湖, G7 位于高邮湖, 藻类在其他点位均为低风险, 鱼类在洪泽湖 H1、H2 和 H3 点位达到低风险, 其余点位均为无风险, 蚤类在所有点位均为低风险. 总体而言, 研究区所有点位表层水和沉积物的藻类风险高于蚤类和鱼类, 表层水和沉积物中 PPCPs 对于洪泽湖的总体风险大于高邮湖.

3 结论

(1) 洪泽湖和高邮湖表层水中 \sum PPCPs 浓度分别为 $1.56 \sim 2\,534.44 \text{ ng}\cdot\text{L}^{-1}$ 和 $3.32 \sim 1\,027.47 \text{ ng}\cdot\text{L}^{-1}$, 沉积物中 \sum PPCPs 含量分别为 $1.7 \sim 926.7 \text{ ng}\cdot\text{g}^{-1}$ 和 $1.02 \sim 289.37 \text{ ng}\cdot\text{g}^{-1}$. 表层水中林可霉素、舒必利检出浓度较高, 沉积物中强力霉素、四环素检出浓度较高, 都以抗生素类 PPCPs 为主要组分. PPCPs 含量的空间分布受入湖河流和周边养殖影响较大, 整体呈现洪泽湖高、高邮湖低的特征.

(2) PPCPs 水/沉积物系统分配特征变化较大, 洪泽湖与高邮湖典型 PPCPs 的 $\lg K_d$ 值介于 $-3.88 \sim 1.97 \text{ L}\cdot\text{kg}^{-1}$ 和 $-3.19 \sim 2.53 \text{ L}\cdot\text{kg}^{-1}$ 之间, PPCPs 整体倾向停留在水相, TOC 对 PPCPs 在水/沉积物系统的分配行为影响显著.

(3) 生态风险评估结果显示, 表层水和沉积物中 PPCPs 对藻类的生态风险明显高于蚤类和鱼类, 表层水中林可霉素对藻类均处于中风险, 沉积物中四环素、强力霉素和酮洛芬对藻类均处于中风险. 各点位空间风险评估结果显示, 表层水中洪泽湖 H8、H11 和 H13 点位藻类为中风险, 沉积物中洪泽湖 H1 点位、高邮湖 G7 点位藻类为中风险. 沉积物中 PPCPs 的生态风险值低于表层水体, 洪泽湖的生态风险高于高邮湖.

参考文献:

- [1] Wang H, Xi H, Xu L L, *et al.* Ecotoxicological effects, environmental fate and risks of pharmaceutical and personal care products in the water environment: a review[J]. *Science of the Total Environment*, 2021, **788**, doi: 10.1016/j.scitotenv.2021.147819.
- [2] Su C, Cui Y, Liu D, *et al.* Endocrine disrupting compounds, pharmaceuticals and personal care products in the aquatic environment of China: which chemicals are the prioritized ones? [J]. *Science of the Total Environment*, 2020, **720**, doi: 10.1016/j.scitotenv.2020.137652.
- [3] He S N, Dong D M, Zhang X, *et al.* Occurrence and ecological risk assessment of 22 emerging contaminants in the Jilin Songhua River (Northeast China) [J]. *Environmental Science and Pollution Research*, 2018, **25**(24): 24003-24012.
- [4] Zhang P W, Zhou H D, Li K, *et al.* Occurrence of pharmaceuticals and personal care products, and their associated environmental risks in a large shallow lake in North China[J]. *Environmental Geochemistry and Health*, 2018, **40**(4): 1525-1539.
- [5] Wang L F, Li H, Dang J H, *et al.* Occurrence, distribution, and partitioning of antibiotics in surface water and sediment in a typical tributary of Yellow River, China [J]. *Environmental Science and Pollution Research*, 2021, **28**(22): 28207-28221.
- [6] Kong M, Bu Y Q, Zhang Q, *et al.* Distribution, abundance, and risk assessment of selected antibiotics in a shallow freshwater body used for drinking water, China [J]. *Journal of Environmental Management*, 2021, **280**, doi: 10.1016/j.jenvman.2020.111738.
- [7] Kong M, Xing L Q, Yan R M, *et al.* Spatiotemporal variations and ecological risks of typical antibiotics in rivers inflowing into Taihu Lake, China[J]. *Journal of Environmental Management*, 2022, **309**, doi: 10.1016/j.jenvman.2022.114699.
- [8] Xu X M, Xu Y R, Xu N, *et al.* Pharmaceuticals and personal care products (PPCPs) in water, sediment and freshwater mollusks of the Dongting Lake downstream the Three Gorges Dam [J]. *Chemosphere*, 2022, **301**, doi: 10.1016/j.chemosphere.2022.134721.
- [9] 任丙南, 耿静. 三亚市水体中 PPCPs 的污染水平、分布特征及生态风险评估[J]. *环境科学*, 2021, **42**(10): 4717-4726.
- [9] Ren B N, Geng J. Occurrence, distribution, and ecological risk assessment of pharmaceutical and personal care products in the aquatic environment of Sanya City, China [J]. *Environmental Science*, 2021, **42**(10): 4717-4726.
- [10] Hong B, Lin Q Y, Yu S, *et al.* Urbanization gradient of selected pharmaceuticals in surface water at a watershed scale [J]. *Science of the Total Environment*, 2018, **634**: 448-458.
- [11] Cui Y F, Wang Y H, Pan C G, *et al.* Spatiotemporal distributions, source apportionment and potential risks of 15 pharmaceuticals and personal care products (PPCPs) in Qinzhou Bay, South China [J]. *Marine Pollution Bulletin*, 2019, **141**: 104-111.
- [12] 李富娟, 高礼, 李凌云, 等. 宁夏第三排水沟中药物和个人护理品 (PPCPs) 的污染特征与生态风险评估[J]. *环境科学*, 2022, **43**(8): 4087-4096.
- [12] Li F J, Gao L, Li L Y, *et al.* Contamination characteristics and ecological risk assessment of pharmaceuticals and personal care products (PPCPs) in the Third Drain of Ningxia [J]. *Environmental Science*, 2022, **43**(8): 4087-4096.
- [13] Zhang X J, Wang G Q, Tan Z X, *et al.* Effects of ecological protection and restoration on phytoplankton diversity in impounded lakes along the eastern route of China's South-to-North Water Diversion Project [J]. *Science of the Total Environment*, 2021, **795**, doi: 10.1016/j.scitotenv.2021.148870.
- [14] 卞宇峥, 薛滨, 张风菊. 近三百年来洪泽湖演变过程及其原因分析[J]. *湖泊科学*, 2021, **33**(6): 1844-1856.
- [14] Bian Y Z, Xue B, Zhang F J. The changes of Lake Hongze and its driving forces over the past three hundred years [J]. *Journal of Lake Science*, 2021, **33**(6): 1844-1856.
- [15] 杨霄, 韩昭庆. 1717-2011 年高宝诸湖的演变过程及其原因分析[J]. *地理学报*, 2018, **73**(1): 129-137.
- [15] Yang X, Han Z Q. The change of the Gaobao lakes and its driving forces (1717-2011) [J]. *Acta Geographica Sinica*, 2018, **73**(1): 129-137.
- [16] 邓恒. 洪泽湖与淮河流域关系及其调蓄能力研究[D]. 天津: 天津大学, 2018.
- [16] Deng H. Study on the relationship between Hongze Lake and Huaihe River and its storage capacity [D]. Tianjin: Tianjin

- University, 2018.
- [17] 韩年, 袁旭音, 周慧华, 等. 洪泽湖入湖河流沉积物有机磷分布特征及外源输入对其形态转化的影响[J]. 湖泊科学, 2020, **32**(3): 665-675.
Han N, Yuan X Y, Zhou H H, *et al.* Distribution characteristics of organic phosphorus in the sediments of rivers entering the Lake Hongze and the effects of exogenous substances on their fraction transformation[J]. *Journal of Lake Science*, 2020, **32**(3): 665-675.
- [18] 胡斌, 王沛芳, 张楠楠, 等. 洪泽湖溶解态有机质与重金属汞的结合特性[J]. 环境科学, 2022, **43**(5): 2510-2517.
Hu B, Wang P F, Zhang N N, *et al.* Binding affinity between heavy metal hg and dissolved organic matter in Hongze Lake[J]. *Environmental Science*, 2022, **43**(5): 2510-2517.
- [19] Verlicchi P, Al Aukidy M, Galletti A, *et al.* Hospital effluent; Investigation of the concentrations and distribution of pharmaceuticals and environmental risk assessment[J]. *Science of the Total Environment*, 2012, **430**: 109-118.
- [20] Hu Y, Yan X, Shen Y, *et al.* Antibiotics in surface water and sediments from Hanjiang River, Central China; occurrence, behavior and risk assessment [J]. *Ecotoxicology and Environmental Safety*, 2018, **157**: 150-158.
- [21] Cleuvers M. Aquatic ecotoxicity of pharmaceuticals including the assessment of combination effects[J]. *Toxicology Letters*, 2003, **142**(3): 185-194.
- [22] 陈宇, 王涌涛, 黄天寅, 等. 骆马湖水体中药品及个人护理用品的污染特征及风险评估[J]. 环境科学研究, 2021, **34**(4): 902-909.
Chen Y, Wang Y T, Huang T Y, *et al.* Pollution characteristics and risk assessment of pharmaceuticals and personal care products (PPCPs) in Luoma Lake [J]. *Research of Environmental Sciences*, 2021, **34**(4): 902-909.
- [23] 刘超, 胡智华, 姚天启, 等. 洪泽湖入湖河流对湖区水质的响应关系[J]. 江苏水利, 2022, (1): 40-46, 50.
Liu C, Hu Z H, Yao T Q, *et al.* Response of inflow river to the water quality of Hongze Lake [J]. *Jiangsu Water Resources*, 2022, (1): 40-46, 50.
- [24] Meng Y, Zhang J L, Fiedler H, *et al.* Influence of land use type and urbanization level on the distribution of pharmaceuticals and personal care products and risk assessment in Beiyun River, China [J]. *Chemosphere*, 2022, **287**, doi: 10.1016/j.chemosphere.2021.132075.
- [25] Yang L, Wang T Y, Zhou Y Q, *et al.* Contamination, source and potential risks of pharmaceuticals and personal products (PPCPs) in Baiyangdian Basin, an intensive human intervention area, China[J]. *Science of the Total Environment*, 2021, **760**, doi: 10.1016/j.scitotenv.2020.144080.
- [26] Yang H H, Lu G H, Yan Z H, *et al.* Occurrence, spatial-temporal distribution and ecological risks of pharmaceuticals and personal care products response to water diversion across the rivers in Nanjing, China [J]. *Environmental Pollution*, 2019, **255**, doi: 10.1016/j.envpol.2019.113132.
- [27] He P, Wu J M, Peng J Q, *et al.* Pharmaceuticals in drinking water sources and tap water in a city in the middle reaches of the Yangtze River; occurrence, spatiotemporal distribution, and risk assessment [J]. *Environmental Science and Pollution Research International*, 2022, **29**(2): 2365-2374.
- [28] Liu S, Wang C, Wang P F, *et al.* Anthropogenic disturbances on distribution and sources of pharmaceuticals and personal care products throughout the Jinsha River Basin, China [J]. *Environmental Research*, 2021, **198**, doi: 10.1016/j.envres.2020.110449.
- [29] 周颖, 吴东海, 陆光华, 等. 河南省地表水源中 PPCPs 分布及生态风险评估[J]. 环境科学, 2021, **42**(1): 159-165.
Zhou Y, Wu D H, Lu G H, *et al.* Distribution and ecological risk assessment of PPCPs in drinking water sources of Henan Province [J]. *Environmental Science*, 2021, **42**(1): 159-165.
- [30] 高月, 李杰, 许楠, 等. 汉江水相和沉积物中药品和个人护理用品 (PPCPs) 的污染水平与生态风险[J]. 环境化学, 2018, **37**(8): 1706-1719.
Gao Y, Li J, Xu N, *et al.* Pollution levels and ecological risks of PPCPs in water and sediment samples of Hanjiang River [J]. *Environmental Chemistry*, 2018, **37**(8): 1706-1719.
- [31] 万杰, 袁旭音, 叶宏萌, 等. 洪泽湖不同入湖河流沉积物磷形态特征及生物有效性[J]. 中国环境科学, 2020, **40**(10): 4568-4579.
Wan J, Yuan X Y, Ye H M, *et al.* Characteristics and bioavailability of different forms of phosphorus in sediments of rivers flowing into Hongze Lake [J]. *China Environmental Science*, 2020, **40**(10): 4568-4579.
- [32] 翁郁馨, 杨慧婷, 陈辉辉, 等. 江苏高宝邵伯湖表层水体典型精神类药物及其代谢产物的污染水平、分布特征及风险评估[J]. 湖泊科学, 2022, **34**(6): 1993-2007.
Weng Y X, Yang H T, Chen H H, *et al.* Pollution level, distribution characteristics and risk assessment of psychotropic substances and their metabolites in surface water of Lakes Gaoyou, Shaobo and Baoying, Jiangsu Province [J]. *Journal of Lake Science*, 2022, **34**(6): 1993-2007.
- [33] Divya K R, Zhao S S, Chen Y S, *et al.* A comparison of zooplankton assemblages in Nansi Lake and Hongze Lake, potential influences of the East Route of the South-to-North Water Transfer Project, China [J]. *Journal of Oceanology and Limnology*, 2021, **39**(2): 623-636.
- [34] Li S, Shi W Z, Li H M, *et al.* Antibiotics in water and sediments of rivers and coastal area of Zhuhai City, Pearl River estuary, South China [J]. *Science of the Total Environment*, 2018, **636**: 1009-1019.
- [35] 陈宇, 许亚南, 项颂, 等. 骆马湖表层沉积物中 PPCPs 的赋存特征及生态风险评估[J]. 环境科学研究, 2021, **34**(8): 1835-1843.
Chen Y, Xu Y N, Xiang S, *et al.* Characteristics and ecological risk assessment of PPCPs in surface sediments of Luoma Lake [J]. *Research of Environmental Sciences*, 2021, **34**(8): 1835-1843.
- [36] 张智博, 段艳平, 沈嘉豪, 等. 长三角一体化示范区青浦区水环境中 22 种 PPCPs 的多介质分布特征及风险评估[J]. 环境科学, 2022, **43**(1): 349-362.
Zhang Z B, Duan Y P, Shen J H, *et al.* Multimedia distribution characteristics and risk assessment of 22 PPCPs in the water environment of Qingpu District, Yangtze River Delta demonstration area [J]. *Environmental Science*, 2022, **43**(1): 349-362.
- [37] 张盼伟, 周怀东, 赵高峰, 等. 太湖表层沉积物中 PPCPs 的时空分布特征及潜在风险[J]. 环境科学, 2016, **37**(9): 3348-3355.
Zhang P W, Zhou H D, Zhao G F, *et al.* Spatial, temporal distribution characteristics and potential risk of PPCPs in surface sediments from Taihu Lake [J]. *Environmental Science*, 2016, **37**(9): 3348-3355.
- [38] 王同飞, 张伟军, 李立青, 等. 白洋淀清淤示范区沉积物中抗生素和多环芳烃的分布特征与风险评估[J]. 环境科学, 2021, **42**(11): 5303-5311.

- Wang T F, Zhang W J, Li L Q, *et al.* Distribution characteristics and risk assessment of antibiotics and polycyclic aromatic hydrocarbons in the sediments of desilting demonstration area in Baiyangdian Lake[J]. *Environmental Science*, 2021, **42** (11): 5303-5311.
- [39] Zhao S N, Liu X H, Cheng D M, *et al.* Temporal-spatial variation and partitioning prediction of antibiotics in surface water and sediments from the intertidal zones of the Yellow River Delta, China[J]. *Science of the Total Environment*, 2016, **569-570**: 1350-1358.
- [40] 侯先宇, 高俊敏, 王德睿, 等. 西藏申扎镇水土环境中抗生素的残留水平与分布特征[J]. *中国环境科学*, 2021, **41** (12): 5849-5856.
- Hou X Y, Gao J M, Wang D R, *et al.* Residue levels and distribution characteristics of antibiotics in the soil and water environment of Shenzha Town, Tibet[J]. *China Environmental Science*, 2021, **41**(12): 5849-5856.
- [41] Zhang J Q, Dong Y H. Effect of low-molecular-weight organic acids on the adsorption of norfloxacin in typical variable charge soils of China[J]. *Journal of Hazardous Materials*, 2008, **151** (2-3): 833-839.
- [42] 孙文祥, 许飞, 魏文志. 高邮湖生态修复区渔业资源恢复效果评价[J]. *水产养殖*, 2020, **41**(1): 64-67, 70.
- [43] Cheng D M, Xie Y J, Yu Y J, *et al.* Occurrence and partitioning of antibiotics in the water column and bottom sediments from the intertidal zone in the Bohai Bay, China[J]. *Wetlands*, 2016, **36** (1): 167-179.
- [44] Li S, Huang Z, Wang Y, *et al.* Migration of two antibiotics during resuspension under simulated wind-wave disturbances in a water-sediment system[J]. *Chemosphere*, 2018, **192**: 234-243.
- [45] Cao S S, Duan Y P, Tu Y J, *et al.* Pharmaceuticals and personal care products in a drinking water resource of Yangtze River Delta Ecology and Greenery Integration Development Demonstration Zone in China: occurrence and human health risk assessment [J]. *Science of the Total Environment*, 2020, **721**, doi: 10.1016/j.scitotenv.2020.137624.
- [46] 刷泽佳, 付雨, 赵鑫宇, 等. 喹诺酮类抗生素在城市典型水环境中的分配系数及其主要环境影响因子[J]. *环境科学*, 2022, **43**(9): 4543-4555.
- Ju Z J, Fu Y, Zhao X Y, *et al.* Distribution coefficient of QNs in urban typical water and its main environmental influencing factors [J]. *Environmental Science*, 2022, **43**(9): 4543-4555.



CONTENTS

Research Status and Trend Analysis of Environmental and Health Risk and Control of Persistent, Mobile, and Toxic Chemicals	ZHANG Shao-xuan, CHEN An-na, CHEN Cheng-kang, <i>et al.</i> (3017)
Assessment of the Multidimensional Performances of Food Waste Utilization Technologies in China	YANG Guang, SHI Bo-fen, ZHOU Chuan-bin (3024)
Spatial Network of Urban Heat Environment in Beijing-Tianjin-Hebei Urban Agglomeration Based on MSPA and Circuit Theory	QIAO Zhi, CHEN Jia-yue, WANG Nan, <i>et al.</i> (3034)
Relationship Between Urban Spatial Pattern and Thermal Environment Response in Summer: A Case Study of Hefei City	CHEN Yuan-yuan, YAO Xia-mei, OU Chun, <i>et al.</i> (3043)
Assessment of Emission Reduction Effect of Major Air Pollution Control Measures on PM _{2.5} Concentrations During 13th Five-Year Period in Tianjin	XIAO Zhi-mei, XU Hong, CAI Zi-ying, <i>et al.</i> (3054)
Effect of Clean Heating on Carbonaceous Aerosols in PM _{2.5} During the Heating Period in Baoding	LUO Yu-qian, ZHANG Kai, ZHAO Yu-xi, <i>et al.</i> (3063)
Transport Influence and Potential Sources of PM _{2.5} Pollution for Nanjing	XIE Fang-jian, ZHENG Xin-mei, DOU Tao-tao, <i>et al.</i> (3071)
Impact of Atmospheric Circulation Patterns on Ozone Changes in the Pearl River Delta from 2015 to 2020	WANG Yao, LIU Run, XIN Fan (3080)
Effects of Tropical Cyclones on Ozone Pollution in Hainan Island	FU Chuan-bo, DAN Li, TONG Jin-he, <i>et al.</i> (3089)
Analysis of Causes and Sources of Summer Ozone Pollution in Rizhao Based on CMAQ and HYSPLIT Models	LIN Xin, TONG Ji-long, WANG Yi-fan, <i>et al.</i> (3098)
Health Benefit Evaluation for PM _{2.5} as Well as O ₃ _{8h} Pollution Control in Chengdu, China from 2016 to 2020	ZHANG Ying, TIAN Qi-qi, WEI Xiao-yu, <i>et al.</i> (3108)
Impacts of COVID-19 Lockdown on Air Quality in Shenzhen in Spring 2022	LIU Chan-fang, ZHANG Ao-xing, FANG Qing, <i>et al.</i> (3117)
Emission Inventory of Airborne Pollutants from Biomass Combustion in Guizhou Province	WANG Yan-ni, YANG Jing-ting, HUANG Xian-feng, <i>et al.</i> (3130)
Main Chemical Components in Atmospheric Precipitation and Their Sources in Xi'an	ZHOU Dong, HUANG Zhi-pu, LI Si-min, <i>et al.</i> (3142)
Distribution, Respiratory Exposure, and Traceability of Atmospheric Microplastics in Yichang City	LIU Li-ming, WANG Chao, GONG Wen-wen, <i>et al.</i> (3152)
Hydrochemical Evolution in the Yarlung Zangbo River Basin	JIANG Ping, ZHANG Quan-fa, LI Si-yue (3165)
Temporal and Spatial Distribution Characteristics and Source Analysis of Nitrate in Surface Water of Wuding River Basin	XU Qi-feng, XIA Yun, LI Shu-jian, <i>et al.</i> (3174)
Seasonal Variation Characteristics and Pollution Assessment of Heavy Metals in Water and Sediment of Taipu River	LUO Peng-cheng, TU Yao-jen, SUN Ting-ting, <i>et al.</i> (3184)
Pollution Characteristics and Risk Assessment of Antibiotics in Beiyun River Basin in Beijing	JIANG Bao, SUI Shan-shan, SUN Cheng-yi, <i>et al.</i> (3198)
Tracking Riverine Nitrate Sources and Transformations in the Yiluo River Basin by Nitrogen and Oxygen Isotopes	GUO Wen-jing, ZHANG Dong, JIANG Hao, <i>et al.</i> (3206)
Distribution Characteristics and Risk Assessment of PPCPs in Surface Water and Sediments of Lakes in the Lower Reaches of the Huaihe River	WU Yu-sheng, HUANG Tian-yin, ZHANG Jia-gen, <i>et al.</i> (3217)
Characteristics and Driving Mechanisms of Shallow Groundwater Chemistry in Xining City	LIU Chun-yan, YU Kai-ning, ZHANG Ying, <i>et al.</i> (3228)
Groundwater Pollution Risk Assessment in Plain Area of the Yarkant River Basin	YAN Zhi-yun, ZENG Yan-yan, ZHOU Jin-long, <i>et al.</i> (3237)
Composition Structure and Influence Factors of Bacterial Communities in the Miyun Reservoir	CHEN Ying, WANG Jia-wen, LIANG En-hang, <i>et al.</i> (3247)
Photo-Degradation Mechanism and Pathway for Tetracycline in Simulated Seawater Under Irradiation of Visible Light	XU Heng-tao, FU Xiao-hang, FENG Wei-hua, <i>et al.</i> (3260)
Adsorption Characteristics and Mechanism of Ammonia Nitrogen in Water by Nano Zero-valent Iron-modified Biochar	CHEN Wen-jing, SHI Jun-ling, LI Xue-ting, <i>et al.</i> (3270)
Removal Performance and Mechanism of Potassium Permanganate Modified Coconut Shell Biochar for Cd(II) and Ni(II) in Aquatic Environment	ZHANG Feng-zhi, WANG Dun-qiu, CAO Xing-feng, <i>et al.</i> (3278)
Phosphorus Adsorption in Water and Immobilization in Sediments by Lanthanum-modified Water Treatment Sludge Hydrochar	HE Li-wenze, CHEN Yu, SUN Fei, <i>et al.</i> (3288)
Factors Affecting Nitrate Concentrations and Nitrogen and Oxygen Isotope Values of Effluents from Waste Water Treatment Plant	ZHANG Dong, GE Wen-biao, ZHAO Ai-ping, <i>et al.</i> (3301)
Effects of Wastewater Treatment Processes on the Removal Efficiency of Microplastics Based on Meta-analysis	FU Li-song, HOU Lei, WANG Yan-xia, <i>et al.</i> (3309)
Assessment of Critical Loads of Nitrogen Deposition in Natural Ecosystems of China	HUANG Jing-wen, LIU Lei, YAN Xiao-yuan, <i>et al.</i> (3321)
Impacts of Climate Change and Human Activities on NDVI Change in Eastern Coastal Areas of China	JIN Yan-song, JIN Kai, WANG Fei, <i>et al.</i> (3329)
Ecosystem Carbon Storage in Hangzhou Bay Area Based on InVEST and PLUS Models	DING Yue, WANG Liu-zhu, GUI Feng, <i>et al.</i> (3343)
Soil Stoichiometry Characterization in the Oasis-desert Transition Zone of Linze, Zhangye	SUN Xue, LONG Yong-li, LIU Le, <i>et al.</i> (3353)
Vertical Differences in Grassland Bacterial Community Structure During Non-Growing Season in Eastern Ulansuhai Basin	LI Wen-bao, ZHANG Bo-yao, SHI Yu-jiao, <i>et al.</i> (3364)
Distribution Pattern of Bacterial Community in Soil Profile of <i>Larix principis-rupprechtii</i> Forest in Luya Mountain	MAO Xiao-ya, LIU Jin-xian, JIA Tong, <i>et al.</i> (3376)
Effects of Vegetation Types on Carbon Cycle Functional Genes in Reclaimed Soil from Open Pit Mines in the Loess Plateau	ZHAO Jiao, MA Jing, ZHU Yan-feng, <i>et al.</i> (3386)
Effects of Biochar Application on Soil Bacterial Community Diversity and Winter Wheat Growth in Wheat Fields	YAO Li-ru, LI Wei, ZHU Yuan-zheng, <i>et al.</i> (3396)
Effects of Different Planting Years of <i>Dendrocalamus brandisii</i> on Soil Fungal Community	ZHU Shu-hong, HUI Chao-mao, ZHAO Xiu-ting, <i>et al.</i> (3408)
Effects of Biochar Amendment on N ₂ O Emission and Its Functional Genes in Pepper Growing Soil in Tropical Areas	CHEN Qi-qi, WANG Zi-jun, CHEN Yun-zhong, <i>et al.</i> (3418)
Effects of Mulching and Application of Organic and Chemical Fertilizer on Greenhouse Gas Emission and Water and Nitrogen Use in Summer Maize Farmland	JIANG Hong-li, LEI Qi, ZHANG Biao, <i>et al.</i> (3426)
Effects of Different Types of Plastic Film Mulching on Soil Quality, Root Growth, and Yield	MU Xiao-guo, GAO Hu, LI Mei-hua, <i>et al.</i> (3439)
Pollution Assessment and Source Analysis of Heavy Metals in Atmospheric Deposition in a Lead-zinc Smelting City Based on PMF Model	CHEN Ming, WANG Lin-ling, CAO Liu, <i>et al.</i> (3450)
Characterization and Health Risk of Heavy Metals in PM _{2.5} from Road Fugitive Dust in Five Cities of Yunnan Province	HAN Xin-yu, GUO Jin-yuan, SHI Jian-wu, <i>et al.</i> (3463)
Pollution Characteristics and Risk Assessment of Heavy Metals in Surface Dusts and Surrounding Green Land Soils from Yellow River Custom Tourist Line in Lanzhou	LI Jun, LI Kai-ming, WANG Xiao-huai, <i>et al.</i> (3475)
Source Apportionment and Pollution Assessment of Soil Heavy Metal Pollution Using PMF and RF Model: A Case Study of a Typical Industrial Park in Northwest China	GAO Yue, LÜ Tong, ZHANG Yun-kai, <i>et al.</i> (3488)
Source Analysis of Soil Heavy Metals in Agricultural Land Around the Mining Area Based on APCS-MLR Receptor Model and Geostatistical Method	ZHANG Chuan-hua, WANG Zhong-shu, LIU Li, <i>et al.</i> (3500)
Source Analysis of Heavy Metals in Typical Farmland Soils Based on PCA-APCS-MLR and Geostatistics	WANG Mei-hua (3509)
Characteristics and Risk Evaluation of Heavy Metal Contamination in Paddy Soils in the Three Gorges Reservoir Area	LIU Ya-jun, LI Cai-xia, MEI Nan, <i>et al.</i> (3520)
Health Risk Assessment and Environmental Benchmark of Heavy Metals in Cultivated Land in Wanjiang Economic Zone	LIU Hai, WEI Wei, SONG Yang, <i>et al.</i> (3531)
Evaluation and Source Analysis of Soil Heavy Metal Pollution in a Planting Area in Wanquan District, Zhangjiakou City	AN Yong-long, YIN Xiu-lan, LI Wen-juan, <i>et al.</i> (3544)
Heavy Metal Concentration, Source, and Pollution Assessment in Topsoil of Chuzhou City	TANG Jin-lai, ZHAO Kuan, HU Rui-xin, <i>et al.</i> (3562)
Analysis on the Distribution Characteristics and Influence Mechanism of Migration and Transformation of Heavy Metals in Mining Wasteland	WEI Hong-bin, LUO Ming, XIANG Lei, <i>et al.</i> (3573)
Ecological Risk Assessment and Source Apportionment of Heavy Metals in Mineral Resource Base Based on Soil Parent Materials	WEI Xiao-feng, SUN Zi-jian, CHEN Zi-ran, <i>et al.</i> (3585)
Enrichment Characteristics of Heavy Metals and Health Risk in Different Vegetables	QI Hao, ZHUANG Jian, ZHUANG Zhong, <i>et al.</i> (3600)
Health Risk Assessment of Heavy Metals in Soil and Wheat Grain in the Typical Sewage Irrigated Area of Shandong Province	WANG Fei, FEI Min, HAN Dong-nui, <i>et al.</i> (3609)
Prediction of Cadmium Uptake Factor in Wheat Based on Machine Learning	NIU Shuo, LI Yan-ling, YANG Yang, <i>et al.</i> (3619)