

目次

河北南部城市臭氧和 VOCs 的污染特征及传输贡献 赵江伟, 聂赛赛, 于玉洁, 王帅, 崔建升, 王玮, 任晓伟, 朱烁 (4775)

基于卫星和地面监测的河西走廊 O₃ 浓度时空分布及潜在源区分析 李锦超, 曹春, 方锋, 唐千惠, 梁朕月 (4785)

海南岛臭氧污染时空变化及敏感性特征 符传博, 丹利, 佟金鹤, 徐文帅 (4799)

华东地区对流层 O₃ 和前体物 HCHO 及 NO₂ 的时空特征 王晓雯, 刘昊霞, 王扬, 宋宜凯 (4809)

2006 ~ 2020 年广东省大气甲醛排放演变特征 明桂英, 朱曼妮, 沙青娥, 张雪驰, 饶思杰, 陈诚, 刘慧琳, 郑君瑜 (4819)

淄博市涂装行业 VOCs 排放水平及减排潜力 黄玥润, 杨文, 王秀艳, 王雨燕, 程颖, 王帅 (4832)

西安市城市降尘和土壤尘 PM₁₀ 和 PM_{2.5} 中碳组分特征 沈利娟, 王红磊, 孙杰娟, 刘诗云, 刘焕武, 赵天良 (4843)

长江流域径流模拟及其对极端降雨的响应 高爽, 凌超普, 汤水荣, 王心亮, 王慧勇, 孟磊, 颜晓元 (4853)

黄河流域内蒙古段水化学同位素特征及水体转化关系 裴森森, 段利民, 苗平, 潘浩, 崔彩琪, 张波, 籍健勋, 罗艳云, 刘廷玺 (4863)

古堆泉域岩溶地下水水化学特征及成因 唐春雷, 申豪勇, 赵春红, 王志恒, 谢浩, 赵一, 梁永平 (4874)

华北平原典型城市(石家庄)地下水重金属污染源解析与健康风险评价 陈慧, 赵鑫宇, 常帅, 宋圆梦, 卢梦淇, 赵波, 陈昊达, 高赛, 王琳静, 崔建升, 张璐璐 (4884)

湖南东江湖表层沉积物重金属的空间分布、形态及生态风险 张同亮, 衣丽霞, 黎常成, 袁首枢, 豆奕轩, 田胜艳, 林尚璇 (4896)

太湖水华前表层水 CDOM 的光谱特征与来源解析 王永强, 卢少勇, 黄蔚, 韩镇阳, 国晓春 (4906)

白洋淀典型水域 COD 的组成及各组分贡献 李琦, 张超, 张文强, 温胜芳, 单保庆, 季恺悦 (4915)

白洋淀典型抗生素的源解析及其特定源风险评估 宋圆梦, 赵波, 卢梦淇, 赵鑫宇, 陈慧, 陈昊达, 高赛, 王琳静, 崔建升, 张璐璐 (4927)

雅鲁藏布江中游河流生态系统健康状态对水环境因子的响应 李晓东, 杨清, 刘惠秋, 巢欣, 杨胜烟, 巴桑 (4941)

鄱阳湖典型河湖交汇区浮游植物现状分析 于新平, 陈宇炜, 刘金福, 王俊颖, 徐光锋, 邹浩月, 陈楠, 夏雨 (4954)

不同臭臭程度下城市河道浮游植物群落结构、多样性和功能群 张琪琪, 曾劼, 尹卓, 冯杰, 刘静, 修宇鑫, 刘国, 许春阳 (4965)

反硝化脱氮对太湖蓝藻水华态势的影响 李昌杰, 许海, 詹旭, 张铮惠, 朱梦圆, 邹伟, 肖曼, 倪子怡, 朱慧 (4977)

密云水库入库河流微生物群落演替对氮素形态转化的影响 辛苑, 张耀方, 李添雨, 叶芝茵, 申佩弘, 魏源送, 高超龙, 宋舒兴, 张俊亚 (4985)

城市尾水氮代谢过程中芽孢杆菌对微藻作用机制 赵志瑞, 马超, 颜嘉晨, 李书缘, 李晴, 胡紫如, 呼庆, 刘硕, 万敬敏 (4996)

高效异养硝化-好氧反硝化菌 *Glutamicibacter* sp. WS1 低温下对多种氮源的脱氮特性及氮代谢机制 魏渤惠, 罗晓, 吕鹏翼, 马文凯, 苏金卫, 李伟, 崔建升 (5006)

大环内酯类抗生素在饮用水处理过程中的污染特征及其氯化反应机制 岑霞, 程思宇, 石宗民, 谢卓鸿, 张凌菱, 杨滨, 应光国 (5017)

不同堆肥工艺处理的城市污水污泥对滨海湿地土壤中养分释放特征和潜力的影响 贾培寅, 王馨, 花玉婷, 姜志翔 (5025)

淮河流域安徽段水体和沉积物微塑料赋存特征及风险评估 张海强, 高良敏, 葛娟, 赵兴兰, 张振, 慕明, 邱宇辉 (5036)

黄河三角洲湿地表层沉积物中微塑料的分布、来源和风险评估 耿娜, 赵广明, 张大海, 袁红明, 李先国 (5046)

固原市农田土壤微塑料的分布特征及风险评估 马贵, 丁家富, 周悦, 周炎炎, 廖影云, 海金涛, 王欢 (5055)

鄱阳湖湿地淹水与非淹水状态下微塑料表面细菌群落分布特征 赵俊凯, 陈旭, 胡婷婷, 廖轶颖, 邹龙, 简敏菲, 刘淑丽 (5063)

聚苯乙烯微塑料对铜绿假单胞菌生物膜形成和结构变化的影响 陶辉, 于多, 杨兰, 陈泽扬, 周灵沁, 罗雲鑫 (5071)

聚苯乙烯微塑料对小白菜生长、生理生化及冠层温度特性的影响 郭冰林, 丰晨晨, 陈悦, 林迪, 李岚涛 (5080)

聚乙烯与磺胺二甲嘧啶复合胁迫对大豆种子萌发及幼苗生长生理特征的影响 赵肖琼, 张恒慧, 赵润柱, 张新梅 (5092)

离子类型、强度和铁氧化物影响下微塑料的迁移行为及模型计算 张然, 于可飞, 黄磊, 陈雅丽, 马杰, 徐莉萍, 李永涛 (5102)

土地利用和气候变化对农牧交错带生态系统服务的影响 徐文彬, 饶良懿 (5114)

有机碳流失对土壤侵蚀的响应及其驱动因素: 基于 Meta 分析 刘小岚, 黄金权, 齐瑜洁, 李威闻, 刘纪根, 陈燕飞, 高绣纺 (5125)

平衡施肥与秸秆覆盖对紫色土坡耕地养分及其化学计量的影响 张高宁, 徐绮雯, 何丙辉, 李天阳, 冯梦蝶, 梁珂 (5135)

稀土-重金属共污染土壤中真菌群落结构特征及主导影响因素 罗颖, 李敬伟, 袁浩, 包智华 (5145)

周年轮作休耕对土壤 AMF 群落和团聚体稳定性的影响 鲁泽让, 夏梓泰, 芦美, 赵吉霞, 李永梅, 王自林, 范茂攀 (5154)

华北平原典型城市土壤微生物群落时空变化规律及其驱动因子 赵鑫宇, 陈慧, 常帅, 宋圆梦, 赵波, 卢梦淇, 崔建升, 张璐璐 (5164)

高量秸秆还田配施芽孢杆菌对沙化土壤细菌群落及肥力的影响 聂扬眉, 步连燕, 陈文峰, 安德荣, 韦革宏, 王红雷 (5176)

基于大田试验的铅镉复合污染土壤中甜糯玉米低积累特性 唐乐斌, 李龙, 宋波, 董心月, 韦美溜 (5186)

不同阻控措施对生菜中镉铅累积及品质的影响 周洪印, 李嘉琦, 包立, 夏运生, 王晟, 吴龙华, 张乃明 (5196)

纳米氧化铜对镉胁迫下小油菜生理生化和重金属累积的影响 王诗琪, 孙约兵, 黄青青, 徐应明, 董如茵, 孟庆尧 (5204)

不同污染区巨菌草生物炭内源污染物分布及其生物毒性 刘莉雅, 崔红标, 刘笑生, 张雪, 董婷婷, 章腾, 周静 (5214)

CuFeO₂ 改性生物炭对四环素的吸附特性 刘国成, 张新旺, 信帅帅, 王倩文, 阎清华, 周成智, 辛言君 (5222)

基于 Meta 分析的全氟化合物对鱼类生态毒性效应 陆宏, 周锦阳, 杨帆, 王蓓莉, 程治文, 申哲民, 袁涛 (5231)

基于 PMF 模型的县域尺度土壤重金属来源分析及风险评估 郑永立, 温汉辉, 蔡立梅, 罗杰, 汤端阳, 武妙, 李慧, 李鼎 (5242)

基于 PMF-PCA/APCS 与 PERI 的菏泽油田牡丹种植区表层土壤重金属潜在来源识别及生态风险评估 赵庆令, 李清彩, 安茂国, 于林松, 万鑫, 曹付恒, 韩文撑, 陈娟, 王天鸽 (5253)

重庆市煤矸山周边农产品镉健康风险评价及土壤环境基准值推导 马杰, 余泽蕾, 王胜蓝, 邓力, 孙静, 刘萍, 徐敏 (5264)

安徽典型硫铁矿集中开采区土壤重金属污染特征及来源解析 贾晗, 刘军省, 王晓光, 鞠林雪, 何鑫, 周建伟, 张羲 (5275)

湘东北典型河源区土壤重金属分布特征、来源解析及潜在生态风险评估 杨振宇, 廖超林, 邹炎, 谢伍晋, 陈晓威, 张驭飞 (5288)

不同含量外源镉在土壤中的变化特征 周子阳, 庞瑞, 宋波 (5299)

CO₂ 泡沫混凝土碳封存潜力分析 张源, 他旭鹏, 覃述兵, 郝佑民 (5308)

综合环境社会经济指标的优先污染物筛选方法研究: 以电子废物拆解为例 陈源, 蔡震, 李金惠 (5316)

《环境科学》征订启事(4808) 《环境科学》征稿简则(4831) 信息(4842, 5124, 5153)

白洋淀典型抗生素的源解析及其特定源风险评估

宋圆梦¹, 赵波¹, 卢梦淇¹, 赵鑫宇¹, 陈慧¹, 陈昊达¹, 高赛¹, 王琳静¹, 崔建升^{1,2}, 张璐璐^{1,2*}

(1. 河北科技大学环境科学与工程学院, 石家庄 050018; 2. 河北省污染防治生物技术实验室, 石家庄 050018)

摘要: 目前我国湖泊中抗生素污染形势严峻, 研究多集中于抗生素的时空分布与风险评价等, 而有关源解析的研究则较少. 鉴于此, 选取白洋淀为研究区, 探究典型抗生素的污染来源及其特定源风险. 运用高效液相色谱串联质谱法 (HPLC-MS) 测定样品中的四环素类 (TCs)、磺胺类 (SAs) 和喹诺酮类 (QNs) 抗生素, 并运用正定矩阵因子分解 (PMF) 模型和风险商值法 (RQ) 相结合的方法对典型抗生素进行源解析和特定源风险评估. 结果表明: ①水体和沉积物中抗生素含量范围分别为 ND ~ 2 635 ng·L⁻¹ 和 ND ~ 259.8 ng·g⁻¹; ②就水体中抗生素浓度的空间分布而言, QNs 呈“西高东低”, SAs 呈“中部高、南北低”, TCs 呈“中部低、南北高”的分布特征; 就沉积物中抗生素含量的空间分布而言, QNs 呈“中部高, 东西低”, 而 SAs 和 TCs 均呈“西高东低”的分布特征; ③就抗生素的来源而言, 水产养殖 (33.2%) 占比最高, 其次为污水处理厂 (29.2%)、畜禽养殖 (18.9%) 和生活污水 (18.7%); ④就生态风险而言, 恩诺沙星 (ENR) 和氟甲喹 (FLU) 处于中高风险水平; ⑤就特定源风险的空间分布而言, 除 S1 处水产养殖处于高风险水平, 其余样点各源均处于中低风险水平; 就源的种类而言, 水产养殖处于中高风险水平, 其余各源均处于中低风险水平. 因此, 针对白洋淀抗生素的主要来源及其特定源风险等级, 需采取更为精准科学的抗生素风险管控.

关键词: 白洋淀; 抗生素; 空间分异; 源解析; 特定源风险; PMF 模型

中图分类号: X524 文献标识码: A 文章编号: 0250-3301(2023)09-4927-14 DOI: 10.13227/j.hjxx.202210036

Source Apportionment and Source-specific Risk of Typical Antibiotics in Baiyangdian Lake

SONG Yuan-meng¹, ZHAO Bo¹, LU Meng-qi¹, ZHAO Xin-yu¹, CHEN Hui¹, CHEN Hao-da¹, GAO Sai¹, WANG Lin-jing¹, CUI Jian-sheng^{1,2}, ZHANG Lu-lu^{1,2*}

(1. College of Environmental Science and Engineering, Hebei University of Science and Technology, Shijiazhuang 050018, China; 2. Biotechnology Laboratory for Pollution Control in Hebei Province, Shijiazhuang 050018, China)

Abstract: The current situation of antibiotic pollution in lakes is critical. At present, most of the previous studies on antibiotics in lakes have focused on the spatiotemporal distribution and risk assessment, while less attention has been paid to the source apportionment. Ultra-high performance liquid chromatography-mass spectrometry was used to determine the concentration of tetracyclines (TCs), sulfonamides (SAs), and quinolones (QNs) in the samples. The source apportionment and source-specific risk of typical antibiotics in the study area were analyzed using the combination of a PMF model and risk quotients (RQ). The results showed that ① the total concentrations of target antibiotics (Σ antibiotics) ranged from ND to 2 635 ng·L⁻¹ for surface water and from ND to 259.8 ng·g⁻¹ for sediments. ② The spatial distribution of QNs in surface water decreased from west to east, SAs decreased from middle to north and south, and TCs increased from middle to north and south. In the sediment, QNs decreased from middle to east and west, whereas SAs and TCs increased from east to west. ③ Aquaculture was the major antibiotic source, accounting for the highest proportion (33.2%), followed by sewage treatment plants (29.2%), livestock activities (18.9%), and domestic sewage (18.7%). ④ The ecological risk assessment results showed that enrofloxacin and flumequine were at a medium-high risk level. ⑤ For the spatial distribution of source-specific risk, the results showed that the aquaculture at S1 was at a high risk level, whereas the source-specific risks for other sites were at a medium-low risk level. In terms of source types, aquaculture was at a medium-high risk level, whereas the other sources were at a medium-low risk level. Therefore, considering the major sources and source-specific risk level of antibiotics, more precise and scientific antibiotic risk control should be adopted in Baiyangdian Lake.

Key words: Baiyangdian Lake; antibiotics; spatial distribution; source apportionment; source-specific risk; PMF model

自 1928 年青霉素发现以来, 抗生素广泛用于疾病预防和治疗, 以及动物生长促进剂^[1,2]. 根据其化学结构, 抗生素可以分为喹诺酮类 (quinolones, QNs)、磺胺类 (sulfonamides, SAs)、大环内酯类 (macrolides, MLs)、四环素类 (tetracyclines, TCs) 和 β -内酰胺类 (β -lactam) 等^[3]. 目前, 我国已成为抗生素最大的消费国和生产国, 如 2013 年我国抗生素的生产量已达 24.8 万 t, 使用量高达 16.2 万 t, 其中 SAs、TCs 和 QNs 的使用量分别占 5%、7% 和 17%^[4]. 然而, 抗生素不能完全被人体和动物吸收, 约有 30%~90% 会以母体化合物或代谢产物的形式随

尿液或者粪便排出体外^[5-7]. 随后, 抗生素通过各种途径源源不断进入水环境中^[8], 例如: 城市污水处理厂尾水排放、畜禽养殖废水、医疗废水和农业排水等^[9-13]. 据统计我国每年约有 2.47 万 t 抗生素进入水环境中^[4]. 在水环境中抗生素可通过食物网在生物体中进行生物累积和营养放大, 进而对水生生物和生态系统造成危害^[14]. 此外, 抗生素还会诱导产生耐药

收稿日期: 2022-10-06; 修订日期: 2022-11-26

基金项目: 河北省自然科学基金项目 (D2019208152); 河北省教育厅重点项目 (ZD2021046)

作者简介: 宋圆梦 (1999~), 女, 硕士研究生, 主要研究方向为抗生素源解析及风险评估, E-mail: songym299011@163.com

* 通信作者, E-mail: zhanglulu19850703@163.com

菌(antibiotics resistance bacterias, ARBs)和耐药基因(antibiotics resistance genes, ARGs),对人体健康和生态安全构成严重威胁^[15].因此,抗生素耐药性问题已成为21世纪人类面临的重大挑战之一^[16].

目前,已在河流^[17]、河口^[18]、海湾^[19]和湖泊^[20]等多种水环境中检出70余种抗生素.其中,湖泊作为抗生素的重要储库,在2019年排放到我国湖泊中抗生素总量高达5711 t^[21].整体而言,我国湖泊中抗生素污染形势较为严峻,如:洞庭湖^[22]中已检出4大类12种抗生素(总浓度1.06~135.40 ng·L⁻¹),大通湖^[23]已检出4大类抗生素(总浓度0.162~61.89 ng·L⁻¹),鄱阳湖^[24]中已检出18种抗生素(总浓度ND~56.2 ng·L⁻¹).湖泊中抗生素的研究多集中于其时空分布及其风险评价等^[25~27],而抗生素的源解析则较少关注.目前,抗生素源解析的方法主要包括正定矩阵因子分解(positive matrix factor, PMF)模型^[18]、Unmix模型^[19]和多元线性回归主成分分析(PCA-MLR)模型^[28]等.其中,PMF模型对解析结果具有非负约束的特点,已广泛应用于抗生素的源解析.对环境管理者而言,定量解析抗生素的污染源将有助于抗生素及其风险的科学精准管控.

白洋淀作为雄安新区的核心生态功能区,将为新区的建设提供重要生态支撑^[29].然而,新区成立前,白洋淀长期接收上游城市污水、工业废水、生活污水和周边养殖废水等,导致淀区抗生素污染形势较为严峻.如水体中SAs检出率最高(78.1%),

其浓度为0.86~1563 ng·L⁻¹;沉积物中QNs检出率最高(2.22%~100%),其含量为65.5~1166 ng·g⁻¹^[30].然而,目前有关白洋淀中抗生素的研究主要集中于其污染特征、生物累积及其风险评估等^[31,32].因此,本研究选取白洋淀为研究区,根据其土地利用和人为干扰特征,选取13个样点,分别采集水体和沉积物样品,共选取3大类26种抗生素为目标物,明晰白洋淀中典型抗生素的空间分异特征;基于PMF模型定量解析水体和沉积物中抗生素的来源;结合源解析和风险商值法(risk quotients, RQ)来评估特定源风险,以期对白洋淀抗生素及其风险的精准管控提供理论支撑和科学依据.

1 材料与方法

1.1 研究区概况与样品采集

白洋淀位于华北平原,共有8条入淀河流,包括府河、瀑河和潞龙河等.淀内主要有143个大小不等的淀泊和3700条沟壕,且此前淀内养殖业发达,人口密集,大量生活污水和养殖废水直排入淀,加剧了白洋淀中抗生素的污染形势^[33,34].

2018年4月,根据白洋淀土地利用类型和人为干扰特征并结合现场实际情况共设置13个采样点(图1),分别为:南刘庄(S1)、鸳鸯岛(S2)、烧车淀(S3)、王家寨(S4)、寨南(S5)、杨庄子(S6)、枣林庄(S7)、圈头(S8)、东田庄(S9)、后塘(S10)、采蒲台(S11)、范峪淀(S12)和金龙淀(S13).水体样

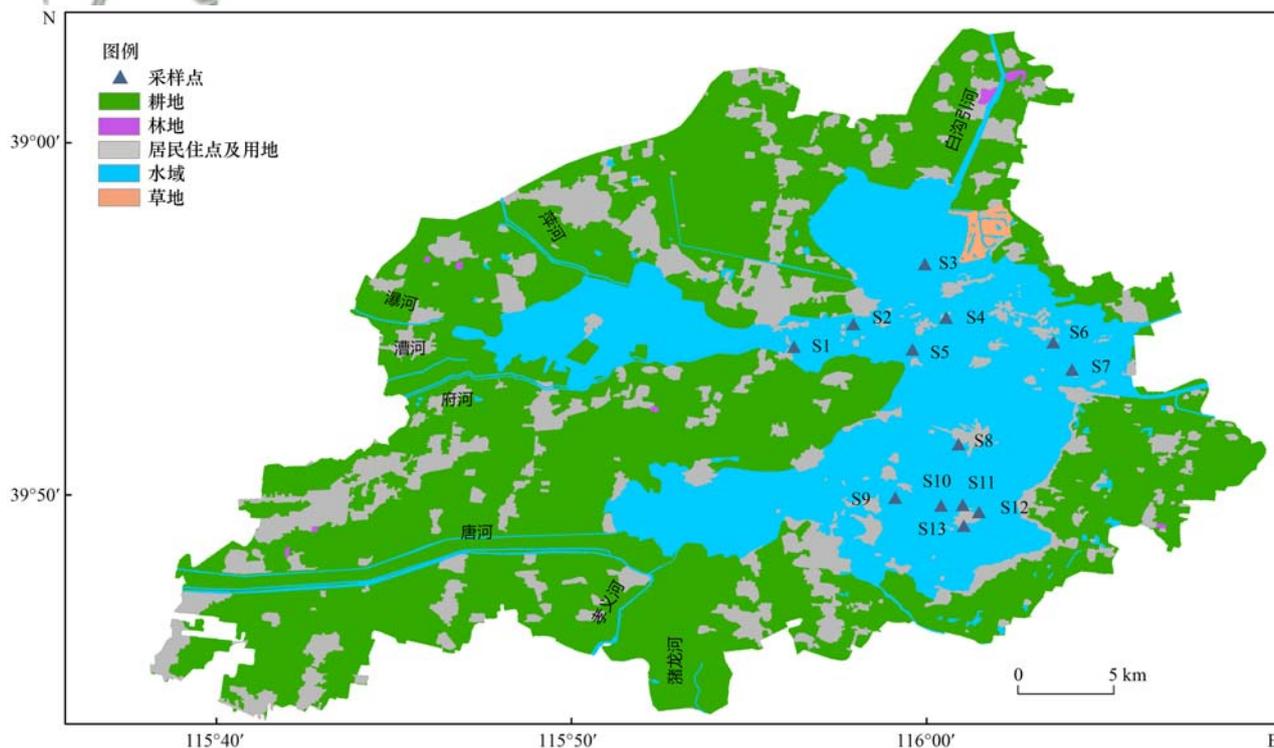


图1 白洋淀采样点

Fig. 1 Sampling sites of Baiyangdian Lake

品使用 5 L 棕色玻璃瓶采集,密封保存,使用保温箱避光运回实验室,进行适当过滤后存放在 4℃ 冰箱内,待后续分析^[35,36]. 沉积物使用彼得森采泥器在各样点 0~10 cm 处采集表层约 500 g 样品,去除碎屑和石子等异物,装入聚乙烯密封袋中并进行标记^[35,37],低温保存运回实验室,放在 -20℃ 冰箱中,保存备用. 使用便携式水质分析仪 (HYDROLAB, DS5X) 对水温 (temperature, T)、pH 和溶解性固体总量 (total dissolved solids, TDS) 等基本水质参数进行现场测定.

1.2 抗生素分析方法

1.2.1 化学试剂

目标抗生素共 3 大类 26 种:包括 6 种 QNs [氧氟沙星 (ofloxacin, OFL)、恩诺沙星 (enrofloxacin, ENR)、氟甲喹 (flumequine, FLU)、氟罗沙星 (fleroxacin, FLE)、诺氟沙星 (norfloxacin, NOR) 和马波沙星 (marbofloxacin, MAR)], 11 种 SAs [磺胺嘧啶 (sulfadiazine, SDZ)、磺胺噻唑 (sulfathiazole, STZ)、磺胺吡啶 (sulfapyridine, SPY)、磺胺甲基嘧啶 (sulfamerazine, SMR)、磺胺二甲嘧啶 (sulfamethazine, SMT)、磺胺对甲氧嘧啶 (sulfameter, SME)、磺胺间甲氧嘧啶 (sulfamonomethoxine, SMM)、磺胺氯吡嗪 (sulfachloropyridazine, SCP)、磺胺甲基异噁唑 (sulfamethoxazole, SMX)、磺胺二甲异噁唑 (sulfisoxazole, SIZ) 和磺胺甲氧嘧啶 (sulfamethoxypridazine, SMP)] 以及 9 种 TCs [四环素 (tetracycline, TC)、强力霉素 (doxycycline, DC)、土霉素 (oxytetracycline, OTC)、去甲金霉素 (demeclocycline, DMC)、金霉素 (chlortetracycline, CTC)、盐酸甲烯土霉素 (metacycline, MET)、米诺环素 (minocycline, MCN)、4-差向脱水四环素 (4-epi-anhydrotetracycline, EATC) 和脱水四环素 (anhydrotetracycline, ATC)]. 标准品购自 Sigma-Aldrich (steinheim, Germany), 纯度均大于 95%.

1.2.2 样品前处理

准确量取 1 L 水样经 0.45 μm 玻璃纤维滤膜过滤,加入 0.2 g 的乙二胺四乙酸二钠 (Na_2EDTA), 用 1 $\text{mol}\cdot\text{L}^{-1}$ 的硫酸溶液调节 pH 为 3.0. 用 6 mL 甲醇、3 mL 盐酸 (0.5 $\text{mol}\cdot\text{L}^{-1}$) 和 6 mL 超纯水液使 HLB 柱活化, 然后以 2~5 $\text{mL}\cdot\text{min}^{-1}$ 的流速通过 HLB 小柱进行萃取. 上样后, 用 10 mL 超纯水淋洗并弃去淋洗液, 负压条件下抽空干燥 30 min, 然后依次用 6 mL 体积比为 2% 的氨水甲醇溶液和 6 mL 纯甲醇溶液进行洗脱, 洗脱液经氮吹 (40℃) 至近干后, 用甲醇水溶液 (甲醇: 水 = 1:1, 体积比) 定容至 1

mL, 过 0.22 μm 滤膜并转移至棕色瓶中, 待上机分析^[38,39].

取部分冷冻干燥后的沉积物样品进行粉碎和研磨, 过 40 目筛, 放入 10 mL 离心管中. 准确称取样品 1 g, 与适量干燥的硅藻土 (Na_2EDTA 处理过的) 充分混合, 并以乙腈-磷酸盐缓冲液 (pH = 3) 作为萃取液. 使用 ASE 350 快速溶剂萃取仪 (Thermo, Germany) 进行萃取, 循环 2 次, 再用平行浓缩蒸发仪 (Buchi, Switzerland) 将萃取液浓缩至萃取剂小于 1 mL, 转移至锥形瓶中, 使用超纯水稀释至 200 mL, 其他操作遵循上面水样品的步骤^[35,40].

1.2.3 样品分析

采用超高效液相色谱-三重四级杆串联质谱联用仪 (HPLC-MS/MS) 对样品进行测定, 使用 Agilent 1200 系列 HPLC (色谱柱: C18, 2.1 $\text{mm}\times 50\text{mm}$, 1.8 μm), 质谱为安捷伦 6470 三重四级杆质谱系统. 流动相 A 为 0.1% 的甲酸水溶液, 流动相 B 为甲醇和 0.1% 的甲酸溶液, 流速 0.3 $\text{mL}\cdot\text{min}^{-1}$, 进样量 5 μL . 质谱条件为电喷雾离子源, 采用多重选择检测模式 (MRM), 干燥气温度为 350℃, 干燥气体流速为 11 $\text{L}\cdot\text{min}^{-1}$, 毛细管电压为 $\pm 3\ 500\text{V}$, 雾化气压力为 45 psi (310.5 kPa)^[32].

1.2.4 质量控制

采用内标法定量. 配制浓度分别为 0.1、0.5、1.0、5.0、10.0 和 100 $\text{ng}\cdot\text{mL}^{-1}$ 的 6 个系列标准溶液, 并设置空白组. 经 HPLC-MS 分析获得质量浓度与峰面积的标准曲线, 相关系数均 ≥ 0.99 , 各目标抗生素的回收率为 72.4%~104.6%.

1.3 源解析方法

PMF 模型通过将样品数据分解成两个矩阵: 因子贡献矩阵 (\mathbf{G}) 和因子分布矩阵 (\mathbf{F}), 以及一个残差矩阵 (\mathbf{E})^[41], 其计算公式如式 (1):

$$\mathbf{X}_{ij} = \sum_{k=1}^p \mathbf{G}_{ik} \mathbf{F}_{jk} + \mathbf{E}_{ij} \quad (1)$$

式中, i 为样品数; j 为污染物种类; p 为污染源数量.

通过 PMF 模型最小化累积残差 Q 值得到因子贡献与分布, 如公式 (2) 所示:

$$Q = \sum_{i=1}^n \sum_{j=1}^m \left(\frac{\mathbf{E}_{ij}}{\mathbf{u}_{ij}} \right) \quad (2)$$

式中, n 为样本数量; m 为抗生素数量; \mathbf{u}_{ij} 为抗生素 j 的不确定度, 计算公式如下

$$\mathbf{u}_{ij} = \begin{cases} \frac{5}{6} \text{MDL}, & c \leq \text{MDL} \\ \sqrt{(\sigma_i \times x_{ij})^2 + \text{MDL}^2}, & c > \text{MDL} \end{cases} \quad (3)$$

式中, σ_i 为抗生素浓度的相对标准偏差; c 为抗生

素浓度; MDL 为方法的检出限。

本研究选取水体和沉积物中检出率大于 30% 的抗生素,按(3)进行计算,输入 PMF 模型进行源解析。随机选取 20 作为初始起点进行迭代计算,取 3~8 个因子分别运算,对比发现选择因子数为 4 时, R^2 均大于 0.60 且所有抗生素的残差都在 -3 和 3 之间并服从正态分布,表明所选抗生素能够很好地被模拟。

1.4 生态风险评估

多种抗生素同时存在于水体中会导致毒性作用加强^[42],因此本研究采取联合风险商(RQ_{sum})来表征抗生素的生态风险,其计算公式如下:

$$RQ_{sum} = \sum RQ \quad (4)$$

$$RQ = MEC/PNEC \quad (5)$$

$$PNEC = L(E)C_{50}/AF \quad (6)$$

式中, RQ 为单一抗生素的生态风险商^[43,44]; RQ_{sum} 为联合风险商; MEC 为实测浓度; PNEC (predicted no-effect concentration) 为无效应浓度; LC_{50} 为半数致死浓度; EC_{50} 为半数有效浓度; AF (assessment factor) 为评价因子。 RQ_{sum} 的分类标准: $0.01 < RQ_{sum} \leq 0.1$ 为低风险; $0.1 < RQ_{sum} \leq 1$ 为中风险; $RQ_{sum} > 1$ 为高风险。已有研究的相关数据见表 1。

本研究中,将结合不同样点的 RQ_{sum} 和源的贡献率 C_p 进行特定源风险评估,如式(7)所示,

$$RQ_p = RQ_{sum} \times C_p \quad (7)$$

式中, C_p 为水体中不同污染源的贡献率。

表 1 不同抗生素对应最敏感生物毒理数据¹⁾

Table 1 Data of the most sensitive biotoxicology for different antibiotics

抗生素	对应最敏感生物	E(L)C ₅₀ /mg·L ⁻¹	评价因子(AF)	PNEC /ng·L ⁻¹	文献
OFL	<i>P. subcapitata</i>	14.400	1 000	14 400.0	[45]
ENR	<i>Microcystis aeruginosa</i>	0.049	1 000	49.0	[45]
FLU	藻类	1.960	1 000	1 960.0	[45]
FLE	藻类	1 128.329	1 000	1 128 329	[45]
MAR	藻类	148.890	1 000	148 890.0	[45]
SDZ	<i>S. capricornutum</i>	2.2	1 000	2 200	[46]
SMT	藻类	1.56	1 000	1 560	[47]
SCP	水蚤	8.03	1 000	8 030	[48]
SMP	藻类	3.82	1 000	3 820	[48]
SPD	<i>Lminor</i>	0.46	1 000	460	[49]
SMM	<i>Lemna minor</i>	8.56	1 000	8 560	[50]
SMX	<i>S. leopoliesis</i>	0.027	1 000	27	[51]
TC	<i>P. subcapitata</i>	3.31	1 000	3 310	[51]
DC	<i>Green algae</i>	0.316	1 000	316	[52]
OTC	<i>P. subcapitata</i>	1.04	1 000	1 040	[23]
CTC	<i>Chlorella vulgaris</i>	0.005	1 000	5	[52]

1) SME、DMC、MET、EATC、ATC 和 MCN 的 E(L)C₅₀、AF 和 PNEC 值暂缺

1.5 数据分析

使用 Microsoft Excel 2016 和 SPSS 26 软件进行数据处理和统计分析;用 EPA PMF 5.0 模型对抗生素进行源解析;使用 ArcGIS 10.7 和 Origin pro 2021 软件进行绘图。

2 结果与分析

2.1 白洋淀中典型抗生素的污染特征

在水体中(表 2),共检出 23 种抗生素,11 种抗生素的检出率高达 100%,总浓度范围为 252.1~2 957 ng·L⁻¹,均值为 35.57 ng·L⁻¹。就各类抗生素的平均检出率而言,TCs 的检出率最高(100%),其次为 QNs(76.9%)和 SAs(26.9%)。就各类抗生素的浓度而言, ρ (QNs) 范围为 243.3~2 946 ng·L⁻¹,平均值为 154.1 ng·L⁻¹; ρ (SAs) 范围为 ND~9.75

ng·L⁻¹,平均值为 0.25 ng·L⁻¹; ρ (TCs) 范围为 8.48~13.77 ng·L⁻¹,平均值为 1.14 ng·L⁻¹。就单种抗生素的浓度平均值而言,呈 FLU > OFL > FLE > MAR > ENR > ATC > DMC > CTC > MCN > SMX 的趋势。其中, ρ (FLU) 最高,其范围为 144.5~2635 ng·L⁻¹,占抗生素总浓度的 78.2%。

在沉积物中(表 2),26 种抗生素均检出,检出率均在 40% 以上,总含量范围为 26.14~346.8 ng·g⁻¹。其中,QNs 的平均检出率最低(87.7%),但其含量平均值最高(141.1 ng·g⁻¹),远高于 SAs(0.24 ng·g⁻¹)和 TCs(1.27 ng·g⁻¹)。就单个抗生素的含量平均值而言,呈 OFL > FLU > FLE > ENR > MAR > OTC > DMC > ATC > CTC > MCN 的趋势。其中 ω (OFL) 最高,其范围为 4.54~259.8 ng·g⁻¹,占抗生素总含量的 59.8%。

表 2 白洋淀水体和沉积物中抗生素的检出情况¹⁾

Table 2 Detection of antibiotics in surface water and sediments in Baiyangdian Lake

抗生素	水体				沉积物				
	检出率 /%	最小值 /ng·L ⁻¹	最大值 /ng·L ⁻¹	平均值 /ng·L ⁻¹	检出率 /%	最小值 /ng·g ⁻¹	最大值 /ng·g ⁻¹	平均值 /ng·g ⁻¹	
QNs	MAR	76.9	ND	75.60	21.94	76.9	ND	6.01	2.82
	FLE	69.2	ND	151.5	33.84	92.3	ND	11.26	5.55
	OFL	100	ND	428.1	109.2	100	4.54	259.8	32.47
	ENR	38.5	ND	110.7	13.17	69.2	ND	12.96	4.14
	FLU	100	144.5	2 635	602.6	100	0.54	46.15	9.28
TCs	MCN	100	1.01	1.64	1.16	100	1.29	1.56	1.38
	TC	100	0.63	0.67	0.60	100	0.42	0.85	0.69
	OTC	100	0.46	2.39	0.87	100	0.49	7.53	1.74
	DMC	100	1.00	3.54	1.48	100	1.55	3.53	1.71
	CTC	100	1.26	2.00	1.15	100	1.25	2.12	1.46
	MTC	100	0.84	2.71	0.90	100	0.82	1.48	0.96
	DC	100	1.03	1.45	1.15	100	1.03	1.32	1.11
	EATC	100	0.60	2.71	1.11	100	0.59	1.54	0.89
ATC	100	1.24	2.02	1.57	100	1.22	2.56	1.54	
SAs	SDZ	61.5	ND	2.45	0.55	100	ND	1.94	0.46
	STZ	0.0	ND	ND	0	100	ND	0.41	0.18
	SPY	23.1	ND	0.31	0.02	100	ND	5.59	0.81
	SMR	0.0	ND	ND	0	100	ND	0.28	0.11
	SMT	7.7	ND	0.35	0.03	100	ND	0.32	0.19
	SME	15.4	ND	0.12	0.02	92.3	ND	0.22	0.08
	SMP	23.1	ND	0.47	0.08	61.5	ND	0.24	0.09
	SMM	23.1	ND	0.58	0.11	100	ND	0.25	0.09
	SCP	7.7	ND	0.40	0.01	46.2	ND	0.29	0.16
	SMX	53.8	ND	6.47	1.16	100	ND	0.81	0.26
	SIZ	0.0	ND	ND	0	100	ND	0.34	0.18

1) ND 表示未检出

2.2 抗生素的空间分异特征

抗生素在水体和沉积物中的空间分布特征如图 2 和图 3 所示,相关分析表明水体中各类抗生素均无相关关系,而沉积物中 QNs 和 TCs 显著正相关($P < 0.01$).

2.2.1 水体中抗生素的空间分异特征

就水体中抗生素的空间分布而言,QNs 在 S5 浓度最高($2\,946\text{ ng}\cdot\text{L}^{-1}$),最小值出现在 S12($243.3\text{ ng}\cdot\text{L}^{-1}$),总体呈“西高东低”的分布特征. SAs 在 S6 浓度最高($9.75\text{ ng}\cdot\text{L}^{-1}$),而在 S12 未检出,呈“中部高,南北低”的分布特征. TCs 浓度总体呈“中部低,南北高”的分布特征,其浓度最大和最小值分别出现在 S13($13.8\text{ ng}\cdot\text{L}^{-1}$)和 S8($8.48\text{ ng}\cdot\text{L}^{-1}$).

2.2.2 沉积物中抗生素的空间分异特征

就沉积物中抗生素的空间分布而言, ω (QNs)最大值在 S2($334.6\text{ ng}\cdot\text{g}^{-1}$),最小值出现在 S5($15.68\text{ ng}\cdot\text{g}^{-1}$),总体呈“中部高,东西低”的空间分布规律. SAs 和 TCs 均呈“西高东低”的空间分布规律,且最大值均出现在 S1($8.54\text{ ng}\cdot\text{g}^{-1}$ 和 $19.47\text{ ng}\cdot\text{g}^{-1}$),而最小值分别出现在 S12($0.69\text{ ng}\cdot\text{g}^{-1}$)和 S5($9.20\text{ ng}\cdot\text{g}^{-1}$).

2.3 抗生素源解析及相对贡献

2.3.1 水体中抗生素源解析

水体中抗生素源解析结果如图 4 和图 5 所示. 因子 1 对 CTC 的贡献相对较高,贡献率为 56.8%,且相关性分析显示 CTC 与其他抗生素相关性较弱,则其可能具有单一来源. CTC 作为抗菌药物在渔业养殖中广泛应用,检出率较高^[53~55]. 丁慧君对环鄱阳湖水产养殖区的研究表明 ρ (CTC) 高达 $162.68\text{ ng}\cdot\text{L}^{-1}$ ^[56],而淀内有众多养殖区,因子 1 推断为水产养殖.

因子 2 对 SDZ 和 SMX 的贡献率较高,分别为 62.4% 和 62.8%,且二者显著正相关($P < 0.01$),表明其可能具有相同的来源. 其中,SDZ 是家用抗菌药的主要成分,已有研究表明 SDZ 主要通过生活污水进入环境,其浓度高达 $5.0 \times 10^4\text{ ng}\cdot\text{L}^{-1}$ ^[57]. 而 SMX 用于治疗人类尿道感染,其在各种废水中均占主导地位^[58~60]. 淀内有众多的村落且人口密集,此前大量生活污水直接排入淀^[61],因子 2 推断为生活污水.

因子 3 对 DMC 和 MCN 的贡献率相对较高,分别为 58.4% 和 44.3%,且二者显著正相关(P

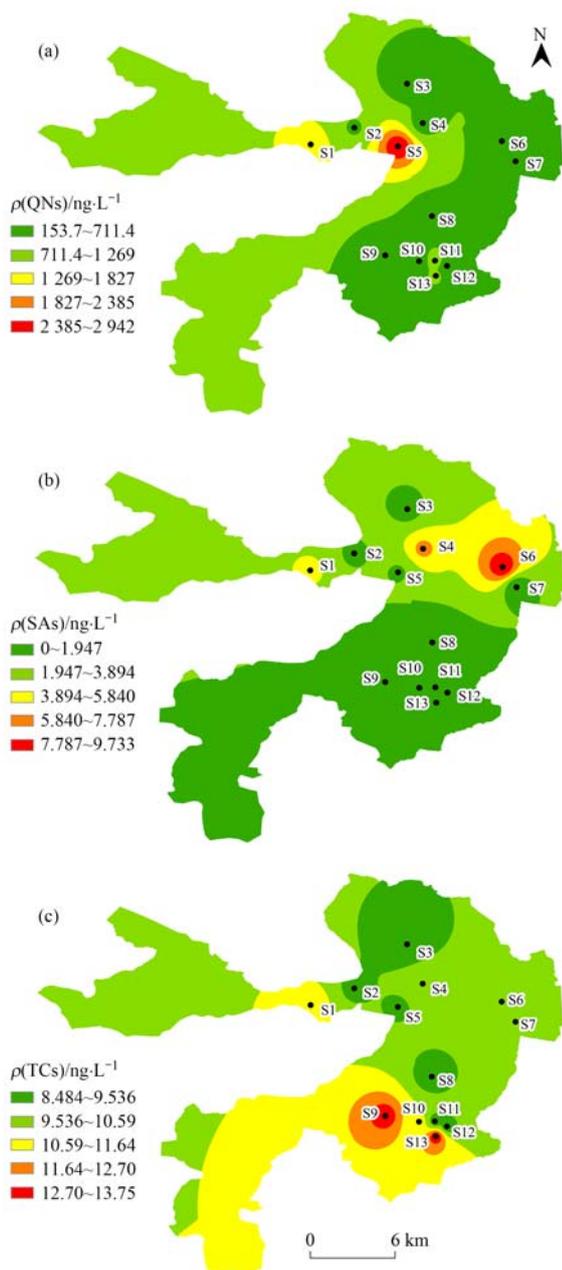


图2 白洋淀水体中喹诺酮类、磺胺类和四环素类抗生素的空间分布

Fig. 2 Spatial distribution of QNs, SAs, and TCs in the surface water of Baiyangdian Lake

< 0.01), 则其可能具有相同的来源. 研究表明 DMC 和 MCN 在制药工艺中常作为原料药和中间体^[62,63], 而河北省作为制药大省且研究区长期接收来自上游城市医药和工业等废水^[64], 加之, 目前的污水处理技术不完善, 使得未完全降解的抗生素排入自然水体^[65,66], 因子 3 推断为污水处理厂.

因子 4 对 MAR、FLE 和 OTC 的贡献率相对较高, 分别为 63.5%、64.0% 和 35.7%, 且 MAR、FLE 和 OTC 两两之间显著正相关 ($P < 0.01$), 表明其可能具有相同的来源. 作为典型的

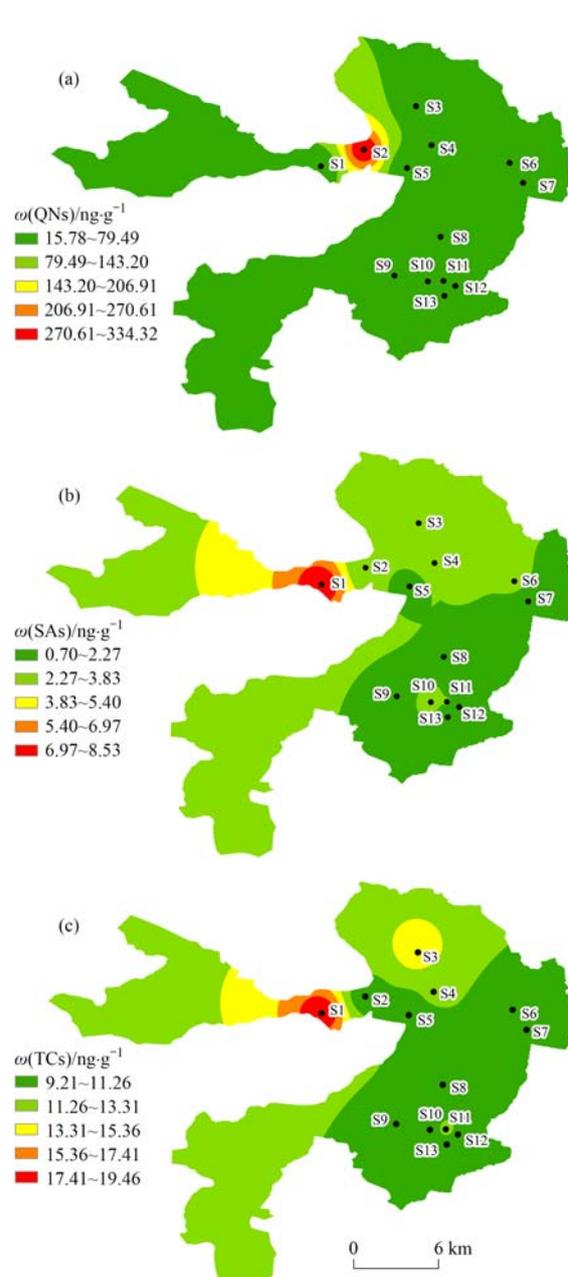


图3 白洋淀沉积物中喹诺酮类、磺胺类和四环素类抗生素的空间分布

Fig. 3 Spatial distribution of QNs, SAs, and TCs in the sediments of Baiyangdian Lake

兽用药物, MAR、FLE 和 OTC 在畜禽养殖中常用作饲料添加剂来预防和治疗疾病^[67-69]. 淀区内家禽畜牧业的废弃物、粪便直接或间接入淀^[70], 因子 4 推断为畜禽养殖.

2.3.2 沉积物中抗生素源解析

沉积物中抗生素源解析结果如图 6 和图 7 所示. 因子 1 对 SMX (64.9%) 贡献较高, 与水体中因子 2 相同, 且相关性分析显示 SMX 与其他抗生素相关性较弱, 则其可能具有单一来源, 因子 1 推断为生活污水.

因子 2 对 FLE (71.0%) 和 ENR (50.3%) 的贡

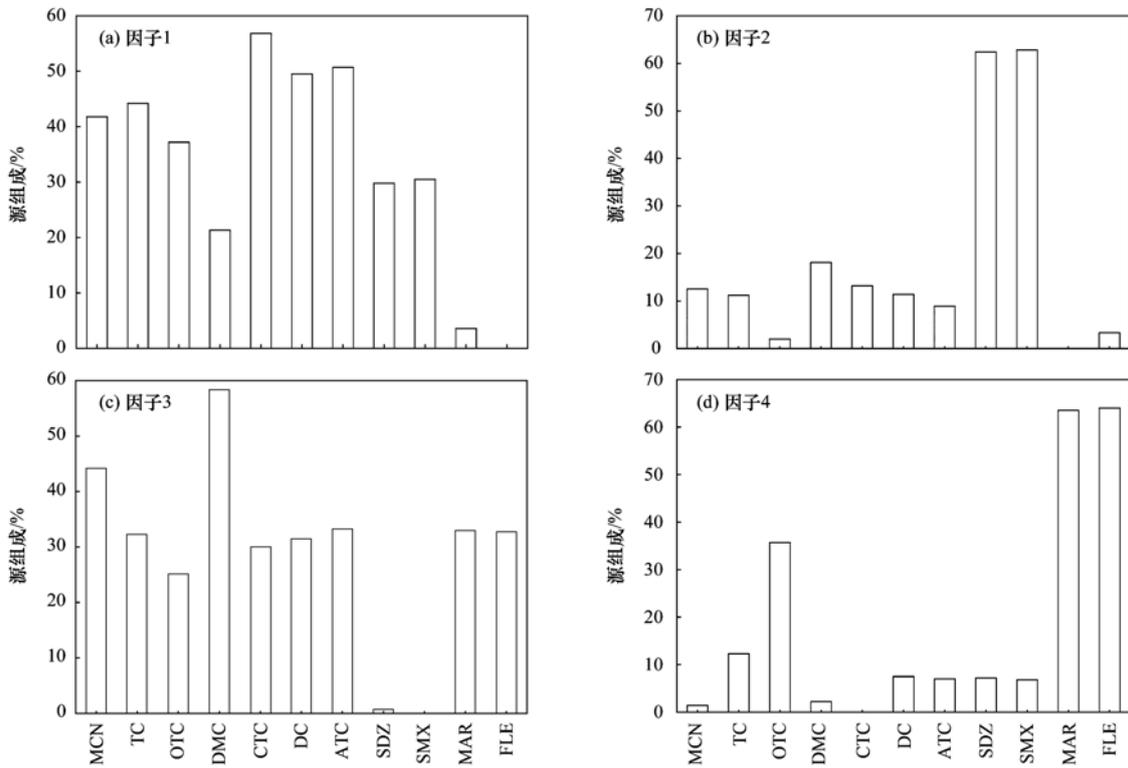


图 4 基于 PMF 模型水体中抗生素源解析

Fig. 4 Source profiles of antibiotics in surface water obtained with the PMF model

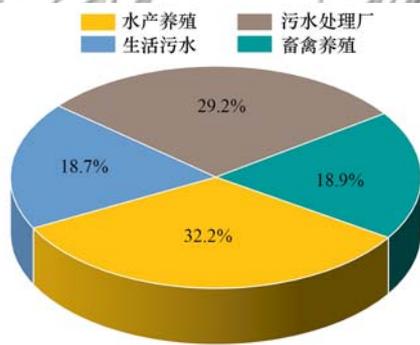


图 5 水体中各因子对抗生素总浓度的贡献

Fig. 5 Contribution of each factor to total antibiotic concentrations in surface water

相对较高,且二者显著正相关($P < 0.01$). 作为典型的 QNs,在养殖场常用来预防家禽疾病和感染,研究表明 ENR 在养殖场中的检出量 ($1.27 \times 10^4 \text{ ng} \cdot \text{g}^{-1}$) 远高于其他的抗菌药物^[71],因子 2 推断为畜禽养殖.

因子 3 对 SPY (93.0%) 的贡献较高,且相关性分析显示 SPY 与其他抗生素相关性较弱,则其可能具有单一来源. 因 SPY 本身很少用作抗菌,多源于其相关的代谢物^[72]. 而目前的处理工艺对其去除率较低,研究表明 SPY 在污水处理厂中的检出浓度高达 $35.9 \sim 64.8 \text{ ng} \cdot \text{L}^{-1}$ ^[73],因子 3 推断为污水处理厂.

因子 4 对 STZ (64.9%) 和 SCP (54.7%) 的贡献

相对较高,且二者显著正相关($P < 0.01$). STZ 和 SCP 因其成本低,常作为鱼用饲料以治疗和预防水产品疾病^[74,75]. 阮悦斐等^[76]已在天津近郊水产养殖区沉积物中检出 STZ 和 SCP,因子 4 推断为水产养殖. 综上所述,白洋淀中抗生素的主要来源为水产养殖.

2.4 风险评价

2.4.1 生态风险评价

本研究对水体中抗生素进行风险评估(图 8). 就各抗生素的生态风险而言,FLU 在 S5 ($RQ > 1.0$) 处于高风险水平,其余样点均为中低风险水平; ENR 在 S1 ($RQ > 1.0$) 为高风险水平, S4、S5、S9 和 S11 的 RQ 处于 $0.1 \sim 1.0$ 之间,为中风险水平; CTC 的 RQ 均处于 $0.1 \sim 1.0$ 之间,为中风险水平; SMX 在 S4 和 S6 的 RQ 处于 $0.1 \sim 1.0$ 之间,为中风险水平,其余样点均为低风险水平; 其余抗生素均处于低风险水平.

就抗生素联合生态风险而言, S1、S5 和 S11 样点的 $RQ_{\text{sum}} > 1.0$, 处于高风险水平,最大值出现在 S1 (3.03); 其余样点的 RQ_{sum} 处于 $0.1 \sim 1.0$ 之间,为中风险水平.

2.4.2 特定源生态风险评价

就各特定源生态风险的空间分布而言,水产养殖在 S1 处的 $RQ_p > 1.0$, 处于高风险水平,其余样点均为中风险水平; 生活污水和畜禽养殖在 S1、S2、

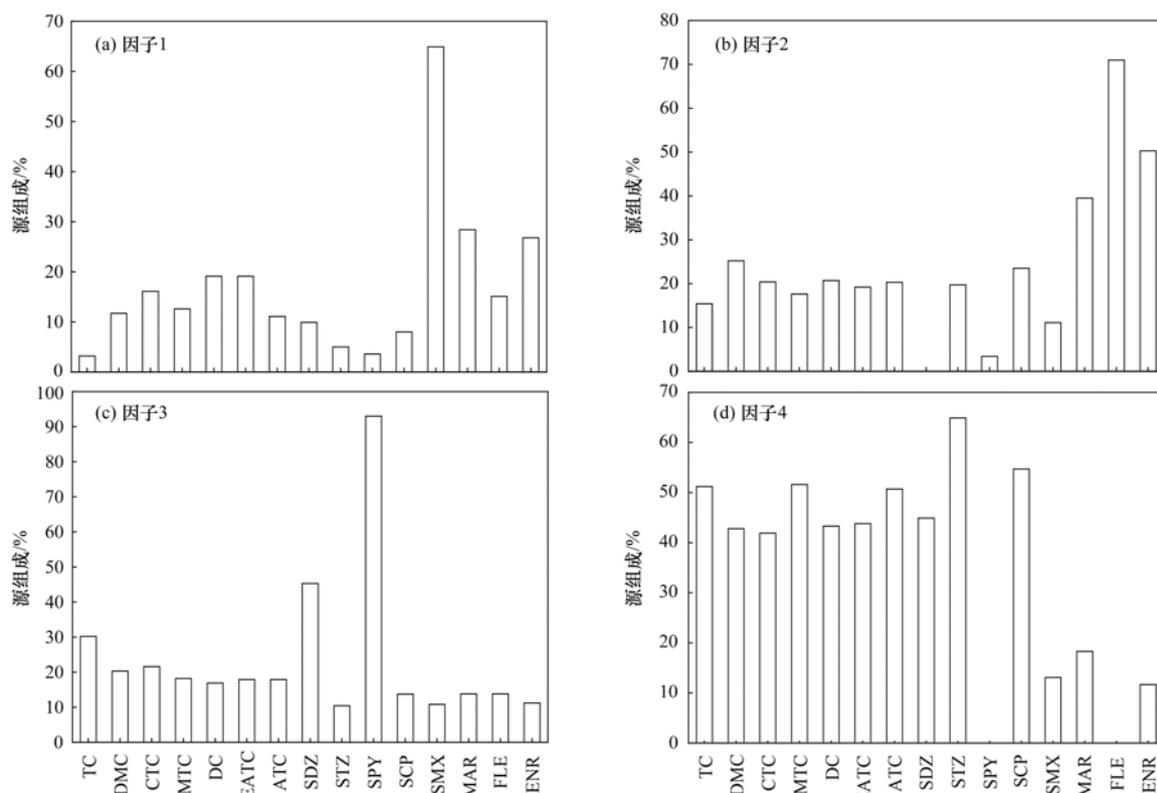


图 6 基于 PMF 模型沉积物中抗生素源解析

Fig. 6 Source profiles of antibiotics in sediments obtained with the PMF model



图 7 沉积物中各因子对抗生素总含量的贡献

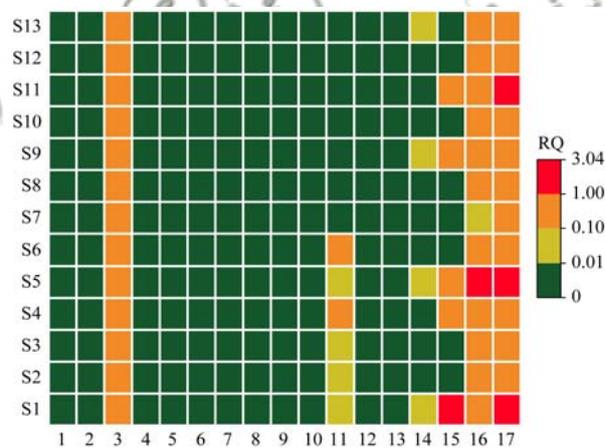
Fig. 7 Contribution of each factor to total antibiotic contents in sediment

S4、S5、S6、S9、S10 和 S11 样点的 RQ_p 处于 0.1 ~ 1.0 之间,为中风险水平,其余样点均为低风险水平;而污水处理厂在所有样点的 RQ_p 均处于 0.1 ~ 1.0 之间,为中风险水平。

3 讨论

3.1 国内外湖泊和河流中抗生素的污染特征

目前,在国内外河流和湖泊中 QNs、TCs 和 SAs 均已有检出。就水体中各抗生素的浓度而言(表 3), OFL 浓度最大值远高于洞庭湖($0.53 \text{ ng}\cdot\text{L}^{-1}$)^[78]、南四湖($10.30 \text{ ng}\cdot\text{L}^{-1}$)^[26]和骆马湖($13.30 \text{ ng}\cdot\text{L}^{-1}$)^[25]; FLU 浓度(最大值为 $2635 \text{ ng}\cdot\text{L}^{-1}$)远

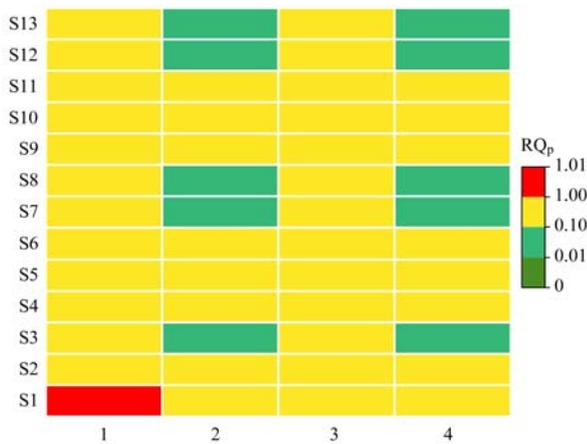


1. TC, 2. OTC, 3. CTC, 4. DC, 5. SDZ, 6. SPY, 7. SMT, 8. SMP, 9. SMM, 10. SCP, 11. SMX, 12. MAR, 13. FLE, 14. OFL, 15. ENR, 16. FLU, 17. RQ_{sum}

图 8 白洋淀水体中抗生素的生态风险评价

Fig. 8 Ecological risk assessment of antibiotics in the surface water of Baiyangdian Lake

高于石家庄河流(最大值 $645.7 \text{ ng}\cdot\text{L}^{-1}$)^[45]、潮白河(最大值 $95.59 \text{ ng}\cdot\text{L}^{-1}$)^[80]和塞纳河(最大值 $32.0 \text{ ng}\cdot\text{L}^{-1}$)^[82]; ENR 的浓度则略高于巢湖(最大值 $82.7 \text{ ng}\cdot\text{L}^{-1}$)^[77]。此外, SMX、SDZ、DC 和 CTC 的浓度均低于其它河流,如白洋淀中 SMX 浓度最大值($6.47 \text{ ng}\cdot\text{L}^{-1}$)远低于大通湖($50.90 \text{ ng}\cdot\text{L}^{-1}$)^[23]、洞庭湖($47.41 \text{ ng}\cdot\text{L}^{-1}$)^[78]、潮白河($63.78 \text{ ng}\cdot\text{L}^{-1}$)^[80]和辽河($16.40 \text{ ng}\cdot\text{L}^{-1}$)^[81],而与



1. 水产养殖, 2. 生活污水, 3. 污水处理厂, 4. 畜禽养殖

图9 白洋淀水体中特定源的生态风险 (RQ_p)

Fig. 9 RQ_p of antibiotics in the surface water of Baiyangdian Lake

鄱阳湖浓度大致相近 ($5.10 \text{ ng}\cdot\text{L}^{-1}$)^[24]; DC 的浓度最大值 ($1.45 \text{ ng}\cdot\text{L}^{-1}$) 与巢湖 ($5.70 \text{ ng}\cdot\text{L}^{-1}$)^[77]、鄱阳湖 ($8.10 \text{ ng}\cdot\text{L}^{-1}$)^[24] 处于一个量级, 但远低于南四湖 ($49.20 \text{ ng}\cdot\text{L}^{-1}$)^[26]; CTC 的浓度最大值为 $2.00 \text{ ng}\cdot\text{L}^{-1}$, 与巢湖 ($4.00 \text{ ng}\cdot\text{L}^{-1}$)^[77]、南四湖 ($3.24 \text{ ng}\cdot\text{L}^{-1}$)^[26]、洞庭湖 ($6.50 \text{ ng}\cdot\text{L}^{-1}$)^[78]、鄱阳湖 ($8.40 \text{ ng}\cdot\text{L}^{-1}$)^[24] 和辽河 ($9.50 \text{ ng}\cdot\text{L}^{-1}$)^[81] 相当。

就沉积物中各抗生素含量而言 (表 4), OFL 含量最大值 ($259.8 \text{ ng}\cdot\text{g}^{-1}$) 与滇池 ($108.9 \text{ ng}\cdot\text{g}^{-1}$)^[79] 大致接近, 远高于太湖 ($16.50 \text{ ng}\cdot\text{g}^{-1}$)^[84]、南湖 ($5.56 \text{ ng}\cdot\text{g}^{-1}$)^[85]、辽河 ($51.60 \text{ ng}\cdot\text{g}^{-1}$)^[89] 和黄河 ($49.69 \text{ ng}\cdot\text{g}^{-1}$)^[90] 流域^[90], 而低于海河 ($653 \text{ ng}\cdot\text{g}^{-1}$)^[88], 王同飞等^[83] 也证实白洋淀沉积物中

表3 国内外河流和湖泊水体中典型抗生素浓度比较¹⁾

Table 3 Comparison of typical antibiotic concentrations in the surface water of global rivers and lakes

位置	抗生素浓度/ $\text{ng}\cdot\text{L}^{-1}$							文献
	DC	CTC	SMX	SDZ	OFL	ENR	FLU	
白洋淀	1.03 ~ 1.45	1.26 ~ 2.00	ND ~ 6.47	ND ~ 2.45	ND ~ 428.1	ND ~ 110.7	144.5 ~ 2635	本研究
巢湖	ND ~ 5.70	ND ~ 4.00	—	ND ~ 8.40	ND ~ 50.60	ND ~ 82.70	—	[77]
南四湖	ND ~ 49.20	ND ~ 3.24	—	ND	ND ~ 10.3	ND	—	[26]
骆马湖	ND	—	2.95 ~ 20.24	ND ~ 87.26	ND ~ 13.30	ND ~ 9.39	—	[25]
大通湖	—	ND ~ 10.44	ND ~ 50.9	11.65 ~ 100.2	—	ND ~ 38.14	—	[23]
鄱阳湖	ND ~ 8.10	ND ~ 8.40	ND ~ 5.10	ND	≤LDQ	≤LDQ	—	[24]
洞庭湖	—	ND ~ 6.50	ND ~ 47.41	ND ~ 61.28	ND ~ 0.53	ND ~ 4.61	—	[78]
滇池	—	—	17.6 ~ 499	—	ND ~ 713.6	—	—	[79]
潮白河	—	—	ND ~ 63.78	—	ND ~ 137.8	—	ND ~ 95.59	[80]
辽河	—	ND ~ 9.50	ND ~ 16.40	ND ~ 2.50	2.00 ~ 32.00	ND	—	[81]
塞纳河	—	—	40	ND	30.00	ND ~ 19.33	12.00	[82]

1) “—”表示该抗生素未检出; ND 表示为未检出; ≤LDQ 表示低于定量限 (limit of quantitation)

OFL 含量最高 ($52.90 \text{ ng}\cdot\text{g}^{-1}$). OTC 含量最大值为 $7.53 \text{ ng}\cdot\text{g}^{-1}$, 与南湖 ($4.71 \text{ ng}\cdot\text{g}^{-1}$)^[85]、黄河 ($5.33 \text{ ng}\cdot\text{g}^{-1}$)^[90] 和乌伦古湖 ($6.60 \text{ ng}\cdot\text{g}^{-1}$)^[87] 含量水平相当, 而低于太湖 ($52.80 \text{ ng}\cdot\text{g}^{-1}$)^[84]、东洞庭湖 ($98.50 \text{ ng}\cdot\text{g}^{-1}$)^[86]、洪湖 ($74.73 \text{ ng}\cdot\text{g}^{-1}$)^[78] 和辽河 ($384.6 \text{ ng}\cdot\text{g}^{-1}$)^[89]. SMX 和 CTC 含量均处于较低水平 ($0.81 \text{ ng}\cdot\text{g}^{-1}$ 和 $2.12 \text{ ng}\cdot\text{g}^{-1}$), 远低于太湖 ($16.10 \text{ ng}\cdot\text{g}^{-1}$ 和 $19.00 \text{ ng}\cdot\text{g}^{-1}$)^[84]、洪湖 ($115.8 \text{ ng}\cdot\text{g}^{-1}$ 和 $55.57 \text{ ng}\cdot\text{g}^{-1}$)^[78] 和海河 ($2.59 \text{ ng}\cdot\text{g}^{-1}$ 和 $10.9 \text{ ng}\cdot\text{g}^{-1}$)^[88]; SPY 含量最大值为 $5.59 \text{ ng}\cdot\text{g}^{-1}$, 远高于太湖 ($0.32 \text{ ng}\cdot\text{g}^{-1}$)^[84] 和辽河 ($0.68 \text{ ng}\cdot\text{g}^{-1}$)^[89].

就各类抗生素而言, QNs 为主要抗生素, 其次为 TCs 和 SAs. 在郴州市东江湖中, QNs 亦为主要抗生素^[91], 与本研究的結果一致. QNs 作为一种人畜共用抗生素, 其消费量占位居抗菌药物前列, 因其具有较强的抗菌能力且价格低廉而被广泛应用^[92]. 加之, QNs 还具有较高的沉积物-水分配系数, 因此在

水体和沉积物中被广泛检出^[93]. 此外, 本研究中 TCs 的检出率均高达 100%, 这可能与 TCs 不仅用于人类和动物疾病防治, 还广泛用于水产养殖等有关^[94]; 且污水处理厂仅可去除废水中 24% 的 TCs^[95]. 其次, TCs 具有一定持久性, 其稳定性与光照、微生物和沉积物的吸附作用等多种因素有关^[88].

3.2 不同湖泊和河流源解析结果的成因与比较

此前河湖中抗生素的源解析主要集中于水体, 因此将本研究水体中抗生素的源解析结果与其他研究进行比较 (表 5). 当地政府自 2018 年 9 月开始禁止水产养殖, 而本研究结果表明水产养殖 (33.2%) 为白洋淀中抗生素主要来源, 这一现象可能与其周边密集的养殖区有关. 与其它结果比较, 不同河流或湖泊中抗生素的主要来源存在显著差异. 例如: 在东洞庭湖^[28] 中, 抗生素的主要来源为畜禽养殖 (79.6%), 这可能与洞庭湖周围有众多畜禽生产基地有关. 岳阳市作为洞庭湖第二大畜禽生产基地;

表 4 国内外河流和湖泊沉积物中主要抗生素的含量比较¹⁾

Table 4 Comparison of major antibiotic contents in the sediments of global rivers and lakes

位置	抗生素含量/ng·g ⁻¹								文献
	OTC	CTC	SMX	SDZ	SPY	OFL	FLE	FLU	
白洋淀	0.49~7.53	1.25~2.12	ND~0.81	ND~1.94	ND~5.59	4.54~259.8	ND~11.26	0.54~46.15	本研究
太湖	0.30~52.80	0.55~19.00	0.01~16.10	ND~0.39	0.01~0.32	2.18~16.50	1.59	—	[84]
南湖	ND~4.71	ND	ND~2.53	—	ND	1.32~5.56	—	—	[85]
东洞庭湖	7.48~98.5	ND~83.48	ND~15.43	1.54~38.6	—	—	—	—	[86]
洪湖	0.72~74.73	ND~55.57	ND~115.8	0.81~77.26	—	—	—	—	[78]
乌伦古湖	ND~6.60	2.79~42.83	ND	ND~1.52	—	0.65~6.47	—	—	[87]
海河流域	ND	ND~10.90	ND~2.59	ND	—	ND~653	—	—	[88]
辽河流域	ND~384.6	—	ND~2.63	—	ND~0.68	ND~51.6	ND~25.67	—	[89]
黄河流域	1.51~5.33	—	—	—	—	5.14~49.69	—	—	[90]
滇池	—	ND~92.10	—	—	—	ND~108.9	—	—	[79]

1) “—”表示该抗生素未检测; ND表示为未检出

而东洞庭湖作为洞庭湖中最大的湖区,会接收大量畜禽养殖废水^[22]。在汾河^[57]中,制药废水为主要源(30%)。据统计2020年山西省医疗机构已达14 343个^[96],汾河作为山西省内最大河流,接收大量的制药废水。而在潮白河中,生活污水(31.5%)是主要源^[100]。此外,湘江^[98]和上海市周边河流^[99]均以污水处理厂为主要源,其贡献率分别为40.0%和66.8%。据统计,上海每年处理的废水量高达26.6亿^[95]。而与传统污染物(有机物和氧化物等)相比,现有的污水处理工艺对抗生素的去除率较低,使得污水处理厂也是抗生素的主要来源。此前,基于

PCA-MLR模型对白洋淀流域中SAs、QNs、TCs以及其他药物等PPCPs进行源解析,结果表明生活污水为其主要污染源(63.5%)^[97]。因此,源解析的方法也可能会影响抗生素的源解析结果;此外,PPCPs与抗生素的种类也可能导致源解析的结果出现差异性。

综上所述,不同区域抗生素生产和使用情况存在差异,导致不同河湖污染源不同;不同的源解析方法,也会造成结果存在差异。因此,在进行源解析和污染防治时应根据实际情况选取和制定合适的方法和防治措施。

表 5 不同湖泊和河流中抗生素的源贡献率与方法比较

Table 5 Comparison of source contribution rate and methods for antibiotics in different lakes and rivers

湖泊和河流	主要源(贡献率)	源解析方法	文献
白洋淀	水产养殖(33.2%)、污水处理厂(29.2%)、畜禽养殖(18.9%)和生活污水(18.7%)	PMF	本研究
东洞庭湖	畜禽养殖场(79.6%)、污水处理排放(0.3%)和畜禽水产养殖(19.8%)	PCA-MLR	[28]
汾河	制药废水(30.0%)、水产畜禽养殖(32.0%)、污水处理厂(15.0%)、农业排水(12.0%)和生活污水(11.0%)	PMF	[57]
湘江	污水处理厂(40.0%)、处理过的废水(29.0%)、医院废水(21.0%)和畜禽水产养殖(10.0%)	PCA-MLR	[98]
上海市周边河流	污水处理厂(66.8%)、水产养殖和养牛场(21.2%)、人用药(11.9%)	PCA-MLR	[99]
潮白河	生活污水(31.5%)、鸡粪(26.4%)、污水处理厂(22.2%)和混合源(20.0%)	PMF	[100]

4 结论

(1) 各类抗生素含量在水体和沉积物中存在显著差异,QNs为白洋淀主要抗生素;各类抗生素具有不同的空间分布特征。

(2) 源解析研究表明,水体和沉积物中抗生素各来源占比存在差异。水产养殖、污水处理厂、生活污水和畜禽养殖是其主要来源,且均以水产养殖的贡献率最高。

(3) 除FLU和ENR处于高风险水平,白洋淀水体中抗生素的生态风险整体处于中低风险水平。

(4) 特定源的风险评估结果表明,除水产养殖源为中高风险水平,白洋淀中其余各源整体处于中

低风险水平。

参考文献:

- [1] Kümmerer K. Antibiotics in the aquatic environment-A review-part I[J]. Chemosphere, 2009, 75(4): 417-434.
- [2] 王冰,孙成,胡冠九. 环境中抗生素残留潜在风险及其研究进展[J]. 环境科学与技术, 2007, 30(3): 108-111.
Wang B, Sun C, Hu G J. Residue antibiotics in environment: potential risks and relevant studies[J]. Environmental Science & Technology, 2007, 30(3): 108-111.
- [3] 刘高燕. 抗生素残留对环境影响的调查研究[J]. 化工中间体, 2015, 11(1): 13-15.
Liu G Y. Investigations on the impact of antibiotic residues on the environment[J]. Chemical Intermediates, 2015, 11(1): 13-15.
- [4] Zhang Q Q, Ying G G, Pan C G, et al. Comprehensive evaluation of antibiotics emission and fate in the river basins of

- China: source analysis, multimedia modeling, and linkage to bacterial resistance[J]. *Environmental Science & Technology*, 2015, **49**(11): 6772-6782.
- [5] Sarmah A K, Meyer M T, Boxall A B A. A global perspective on the use, sales, exposure pathways, occurrence, fate and effects of veterinary antibiotics (VAs) in the environment [J]. *Chemosphere*, 2006, **65**(5): 725-759.
- [6] Carvalho I T, Santos L. Antibiotics in the aquatic environments: a review of the European scenario [J]. *Environment International*, 2016, **94**: 736-757.
- [7] Yao L L, Wang Y X, Tong L, *et al.* Seasonal variation of antibiotics concentration in the aquatic environment: a case study at Jiangnan Plain, central China [J]. *Science of the Total Environment*, 2015, **527-528**: 56-64.
- [8] Li S J, Ju H Y, Zhang J Q, *et al.* Occurrence and distribution of selected antibiotics in the surface waters and ecological risk assessment based on the theory of natural disaster [J]. *Environmental Science and Pollution Research*, 2019, **26**(27): 28384-28400.
- [9] 王龙, 朱丹, 曹云霄, 等. 北京市污水处理厂出水中药物和个人护理品的季节变化及其生态风险评价[J]. *环境科学学报*, 2021, **41**(7): 2922-2932.
Wang L, Zhu D, Cao Y X, *et al.* Seasonal changes and ecological risk assessment of pharmaceutical and personal care products in the effluents of wastewater treatment plants in Beijing [J]. *Acta Scientiae Circumstantiae*, 2021, **41**(7): 2922-2932.
- [10] 张俊华, 陈睿华, 刘吉利, 等. 宁夏养牛场粪污和周边土壤中抗生素及抗生素抗性基因分布特征[J]. *环境科学*, 2021, **42**(6): 2981-2991.
Zhang J H, Chen R H, Liu J L, *et al.* Distribution characteristics of antibiotics and antibiotic resistance genes in manure and surrounding soil of cattle farms in Ningxia [J]. *Environmental Science*, 2021, **42**(6): 2981-2991.
- [11] Chen H, Liu S, Xu X R, *et al.* Tissue distribution, bioaccumulation characteristics and health risk of antibiotics in cultured fish from a typical aquaculture area [J]. *Journal of Hazardous Materials*, 2018, **343**: 140-148.
- [12] Dinh Q T, Moreau-Guigon E, Labadie P, *et al.* Fate of antibiotics from hospital and domestic sources in a sewage network [J]. *Science of the Total Environment*, 2017, **575**: 758-766.
- [13] Pan L X, Feng X X, Cao M, *et al.* Determination and distribution of pesticides and antibiotics in agricultural soils from northern China [J]. *RSC Advances*, 2019, **9**(28): 15686-15693.
- [14] Zhang R J, Yu K F, Li A, *et al.* Antibiotics in coral reef fishes from the South China Sea: occurrence, distribution, bioaccumulation, and dietary exposure risk to human [J]. *Science of the Total Environment*, 2020, **704**, doi: 10.1016/j.scitotenv.2019.135288.
- [15] Zheng D S, Yin G Y, Liu M, *et al.* A systematic review of antibiotics and antibiotic resistance genes in estuarine and coastal environments [J]. *Science of the Total Environment*, 2021, **777**, doi: 10.1016/j.scitotenv.2021.146009.
- [16] Chen H Y, Jing L J, Teng Y G, *et al.* Characterization of antibiotics in a large-scale river system of China: occurrence pattern, spatiotemporal distribution and environmental risks [J]. *Science of the Total Environment*, 2018, **618**: 409-418.
- [17] 赵富强, 高会, 张克玉, 等. 中国典型河流域抗生素的赋存状况及风险评估研究 [J]. *环境污染与防治*, 2021, **43**(1): 94-102.
Zhao F Q, Gao H, Zhang K Y, *et al.* Occurrence and risk assessment of antibiotics in typical river basins in China [J]. *Environmental Pollution & Control*, 2021, **43**(1): 94-102.
- [18] Guo X Y, Feng C H, Gu E X, *et al.* Spatial distribution, source apportionment and risk assessment of antibiotics in the surface water and sediments of the Yangtze Estuary [J]. *Science of the Total Environment*, 2019, **671**: 548-557.
- [19] Wu Q, Pan C G, Wang Y H, *et al.* Antibiotics in a subtropical food web from the Beibu Gulf, South China: occurrence, bioaccumulation and trophic transfer [J]. *Science of the Total Environment*, 2021, **751**, doi: 10.1016/j.scitotenv.2020.141718.
- [20] Xu Z A, Li T, Bi J, *et al.* Spatiotemporal heterogeneity of antibiotic pollution and ecological risk assessment in Taihu Lake Basin, China [J]. *Science of the Total Environment*, 2018, **643**: 12-20.
- [21] Cai Y Y, Zhang Q Q, Yan X T, *et al.* Antibiotic pollution in lakes in China: emission estimation and fate modeling using a temperature-dependent multimedia model [J]. *Science of the Total Environment*, 2022, **842**, doi: 10.1016/j.scitotenv.2022.156633.
- [22] Liu X H, Lu S Y, Meng W, *et al.* Occurrence, source, and ecological risk of antibiotics in Dongting Lake, China [J]. *Environmental Science and Pollution Research*, 2018, **25**(11): 11063-11073.
- [23] 刘晓晖, 卢少勇. 大通湖表层水体中抗生素赋存特征与风险 [J]. *中国环境科学*, 2018, **38**(1): 320-329.
Liu X H, Lu S Y. Occurrence and ecological risk of typical antibiotics in surface water of the Datong Lake, China [J]. *China Environmental Science*, 2018, **38**(1): 320-329.
- [24] Ding H J, Wu Y X, Zhang W H, *et al.* Occurrence, distribution, and risk assessment of antibiotics in the surface water of Poyang Lake, the largest freshwater lake in China [J]. *Chemosphere*, 2017, **184**: 137-147.
- [25] 龚润强, 赵华玮, 高占啟, 等. 骆马湖及主要入湖河流表层水体中抗生素的赋存特征及风险评估 [J]. *环境科学*, 2022, **43**(3): 1384-1393.
Gong R Q, Zhao H J, Gao Z Q, *et al.* Occurrence characteristics and risk assessment of antibiotics in the surface water of Luoma Lake and its main inflow rivers [J]. *Environmental Science*, 2022, **43**(3): 1384-1393.
- [26] 张慧, 郭文建, 刘绍丽, 等. 南四湖和东平湖表层水体中抗生素污染特征和风险评估 [J]. *环境化学*, 2020, **39**(12): 3279-3287.
Zhang H, Guo W J, Liu S L, *et al.* Contamination characteristics and risk assessment of antibiotics in surface water of Nansi Lake and Dongping Lake [J]. *Environmental Chemistry*, 2020, **39**(12): 3279-3287.
- [27] 丁剑楠, 刘舒娇, 邹杰明, 等. 太湖表层水体典型抗生素时空分布和生态风险评估 [J]. *环境科学*, 2021, **42**(4): 1811-1819.
Ding J N, Liu S J, Zou J M, *et al.* Spatiotemporal distributions and ecological risk assessments of typical antibiotics in surface water of Taihu Lake [J]. *Environmental Science*, 2021, **42**(4): 1811-1819.
- [28] Liu X H, Liu Y, Lu S Y, *et al.* Occurrence of typical antibiotics and source analysis based on PCA-MLR model in the East Dongting Lake, China [J]. *Ecotoxicology and Environmental Safety*, 2018, **163**: 145-152.
- [29] 尹德超, 王旭清, 王雨山, 等. 近 60 年来白洋淀流域河川径流演变及湿地生态响应 [J]. *湖泊科学*, 2022, **34**(6): 2122-2133.

- Yin D C, Wang X Q, Wang Y S, *et al.* Runoff evolution and wetland ecological response in Lake Baiyangdian basin in recent 60 years[J]. *Journal of Lake Sciences*, 2022, **34**(6): 2122-2133.
- [30] Li W H, Shi Y L, Gao L H, *et al.* Occurrence of antibiotics in water, sediments, aquatic plants, and animals from Baiyangdian Lake in North China[J]. *Chemosphere*, 2012, **89**(11): 1307-1315.
- [31] 付雨, 刷泽佳, 付耀萱, 等. 白洋淀优势水生植物中喹诺酮类抗生素的生物富集特征及其与环境因子相关性研究[J]. *环境科学学报*, 2021, **41**(9): 3620-3630.
- Fu Y, Ju Z J, Fu Y X, *et al.* The bioaccumulation of Quinolones (QNs) in the dominant macrophytes and the correlation with environmental factors in Baiyangdian Lake [J]. *Acta Scientiae Circumstantiae*, 2021, **41**(9): 3620-3630.
- [32] 申立娜, 张璐璐, 秦珊, 等. 白洋淀喹诺酮类抗生素污染特征及其与环境因子相关性研究[J]. *环境科学学报*, 2019, **39**(11): 3888-3897.
- Shen L N, Zhang L L, Qin S, *et al.* The occurrence and distribution of quinolones (QNs) and correlation analysis between QNs and physical-chemical parameters in Baiyangdian Lake, North China [J]. *Acta Scientiae Circumstantiae*, 2019, **39**(11): 3888-3897.
- [33] 罗义, 马恺, 赵丙昊, 等. 白洋淀入淀河流水环境现状分析[J]. *建材与装饰*, 2020, (10): 144-145.
- [34] 吴新玲. 白洋淀水环境保护分析[J]. *黑龙江水利科技*, 2013, **41**(2): 191-192.
- [35] 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.
- [36] 朱琳, 张远, 渠晓东, 等. 北京清河水体及水生生物体内抗生素污染特征[J]. *环境科学研究*, 2014, **27**(2): 139-146.
- Zhu L, Zhang Y, Qu X D, *et al.* Occurrence of antibiotics in aquatic plants and organisms from Qing River, Beijing [J]. *Research of Environmental Sciences*, 2014, **27**(2): 139-146.
- [37] 童帮会. 淀山湖典型抗生素污染特征、来源及风险评价[D]. 上海: 华东师范大学, 2019.
- Tong B H. Pollution characteristics, sources and risk assessment of typical antibiotics in Dianshan Lake of Shanghai [D]. Shanghai: East China Normal University, 2019.
- [38] 孙秋根. 太湖平原河网典型抗生素的时空分布和风险评价[D]. 重庆: 重庆交通大学, 2018.
- Sun Q G. Spatial-temporal distribution and risk evaluation of four typical antibiotics in river networks of Taihu Lake Basin [D]. Chongqing: Chongqing Jiaotong University, 2018.
- [39] 刘晓晖. 洞庭湖流域水环境中典型抗生素污染特征、来源及风险评估[D]. 济南: 山东师范大学, 2017.
- Liu X H. Pollution level, source and ecological risk of typical antibiotics in the Dongting Lake, China [D]. Ji'nan: Shandong Normal University, 2017.
- [40] 孙奉翠. 土壤中四类典型抗生素的同时测定及其方法优化[D]. 济南: 山东大学, 2013.
- Sun F C. Simultaneous determination of four kinds of typical antibiotics in soil and method optimization [D]. Ji'nan: Shandong University, 2013.
- [41] Norris G, Duvall R, Brown S, *et al.* EPA positive matrix factorization (PMF) 5.0 fundamentals and user guide [R]. Washington: U. S. Environmental Protection Agency, 2014.
- [42] Cleuvers M. Aquatic ecotoxicity of pharmaceuticals including the assessment of combination effects[J]. *Toxicology Letters*, 2003, **142**(3): 185-194.
- [43] 金磊, 姜巍巍, 姜蕾, 等. 太浦河水体中抗生素赋存特征及生态风险[J]. *净水技术*, 2022, **41**(4): 35-40.
- Jin L, Jiang W W, Jiang L, *et al.* Occurrence characteristics and ecological risk of antibiotics in water body of Taipu River [J]. *Water Purification Technology*, 2022, **41**(4): 35-40.
- [44] Rodriguez-Mozaz S, Vaz-Moreira I, Giustina S V D, *et al.* Antibiotic residues in final effluents of European wastewater treatment plants and their impact on the aquatic environment [J]. *Environment International*, 2020, **140**, doi: 10.1016/j.envint.2020.105733.
- [45] 刷泽佳, 赵鑫宇, 陈慧, 等. 石家庄市水环境中喹诺酮类抗生素的空间分布特征与环境风险评估[J]. *环境科学学报*, 2021, **41**(12): 4919-4931.
- Ju Z J, Zhao X Y, Chen H, *et al.* The characteristics of spatial distribution and environmental risk assessment for quinolones antibiotics in the aquatic environment of Shijiazhuang City [J]. *Acta Scientiae Circumstantiae*, 2021, **41**(12): 4919-4931.
- [46] 封梦娟, 张芹, 宋宁慧, 等. 长江南京段水源水中抗生素的赋存特征与风险评估[J]. *环境科学*, 2019, **40**(12): 5286-5293.
- Feng M J, Zhang Q, Song N H, *et al.* Occurrence characteristics and risk assessment of antibiotics in source water of the Nanjing reach of the Yangtze River [J]. *Environmental Science*, 2019, **40**(12): 5286-5293.
- [47] Ma R X, Wang B, Yin L N, *et al.* Characterization of pharmaceutically active compounds in Beijing, China: occurrence pattern, spatiotemporal distribution and its environmental implication [J]. *Journal of Hazardous Materials*, 2017, **323**: 147-155.
- [48] Qin L T, Pang X R, Zeng H H, *et al.* Ecological and human health risk of sulfonamides in surface water and groundwater of Huixian karst wetland in Guilin, China [J]. *Science of the Total Environment*, 2020, **708**, doi: 10.1016/j.scitotenv.2019.134552.
- [49] 王若男, 曹阳, 高超, 等. 沱江干流抗生素污染的时空变化和生态风险评估[J]. *环境化学*, 2021, **40**(8): 2505-2514.
- Wang R N, Cao Y, Gao C, *et al.* Spatial and seasonal variation of antibiotics and their associated ecological risk in Tuojiang River [J]. *Environmental Chemistry*, 2021, **40**(8): 2505-2514.
- [50] 吴天宇, 李江, 杨爱江, 等. 赤水河流域水体抗生素污染特征及风险评估[J]. *环境科学*, 2022, **43**(1): 210-219.
- Wu T Y, Li J, Yang A J, *et al.* Characteristics and risk assessment of antibiotic contamination in Chishui River Basin, Guizhou Province, China [J]. *Environmental Science*, 2022, **43**(1): 210-219.
- [51] 薛保铭. 广西邕江水体典型抗生素污染特征与生态风险评估[D]. 南宁: 广西大学, 2013.
- Xue B M. Contamination and risks assessment of typical antibiotics in the Yongjiang River, Guangxi province [D]. Nanning: Guangxi University, 2013.
- [52] 张亚茹, 张国栋, 王永强, 等. 新疆赛里木湖近岸表层水典型抗生素的赋存与风险评估[J]. *湖泊科学*, 2021, **33**(2): 483-493.
- Zhang Y R, Zhang G D, Wang Y Q, *et al.* Occurrence and ecological risk of typical antibiotics in surface water of the Lake Sayram, Xinjiang [J]. *Journal of Lake Sciences*, 2021, **33**(2): 483-493.
- [53] 李贞金. 水产养殖环境中典型抗生素的分配和降解行为研究

- [J]. 能源环境保护, 2022, **36**(4): 54-64.
Li Z J. Study on distribution and degradation of typical antibiotics in aquaculture[J]. Energy Environmental Protection, 2022, **36**(4): 54-64.
- [54] 游富来. 抗菌药物在水产养殖中的应用[J]. 现代农村科技, 2013, (12): 44.
- [55] 冷向军, 李小勤. 水产饲料中抗生素的应用[J]. 饲料研究, 2003, (10): 38-41.
- [56] 李贞金. 水产养殖典型抗生素的残留水平与分布特征研究[D]. 上海: 华东理工大学, 2020.
Li Z J. Residual level and distribution characteristics of typical antibiotics in aquaculture[D]. Shanghai: East China University of Science and Technology, 2020.
- [57] Wang Y F, Wang L F, Liu R M, *et al.* Source-specific risk apportionment and critical risk source identification of antibiotic resistance in Fenhe River basin, China [J]. Chemosphere, 2022, **287**, doi: 10.1016/j.chemosphere.2021.131997.
- [58] Carneiro R B, Sabatini C A, Santos-Neto á J, *et al.* Feasibility of anaerobic packed and structured-bed reactors for sulfamethoxazole and ciprofloxacin removal from domestic sewage [J]. Science of the Total Environment, 2019, **678**: 419-429.
- [59] Prabhasankar V P, Joshua D I, Balakrishna K, *et al.* Removal rates of antibiotics in four sewage treatment plants in South India [J]. Environmental Science and Pollution Research, 2016, **23**(9): 8679-8685.
- [60] Wu Q, Xiao S K, Pan C G, *et al.* Occurrence, source apportionment and risk assessment of antibiotics in water and sediment from the subtropical Beibu Gulf, South China [J]. Science of the Total Environment, 2022, **806**, doi: 10.1016/j.scitotenv.2021.150439.
- [61] 孙添伟, 陈家军, 王浩, 等. 白洋淀流域府河干流村落非点源负荷研究[J]. 环境科学研究, 2012, **25**(5): 568-572.
Sun T W, Chen J J, Wang H, *et al.* Study on non-point source pollution loads in villages along the Fuhe River, Baiyangdian Watershed[J]. Research of Environmental Sciences, 2012, **25**(5): 568-572.
- [62] 李士杭, 叶蕊芳, 吕和平, 等. 去甲金霉素发酵培养基的优化及机制分析[J]. 中国医药工业杂志, 2012, **43**(11): 896-902.
Li S H, Ye R F, Lü H P, *et al.* Optimization of fermentation medium of demethylchlorotetracycline and mechanism analysis [J]. Chinese Journal of Pharmaceuticals, 2012, **43**(11): 896-902.
- [63] 吴春虎, 封玉彬. 替加环素的合成及市场前景[J]. 河北化工, 2008, **31**(10): 62, 65.
Wu C H, Feng Y B. The synthetic method and market prospects of tygacil[J]. Hebei Chemical Engineering and Industry, 2008, **31**(10): 62, 65.
- [64] 龙幸幸, 杨路华, 夏辉, 等. 白洋淀府河入淀口周边水质空间变异特征分析[J]. 水电能源科学, 2016, **34**(9): 35-38.
Long X X, Yang L H, Xia H, *et al.* Spatial variability characteristics analysis of water quality surrounding Fuhe River Entrance in Baiyangdian Lake[J]. Water Resources and Power, 2016, **34**(9): 35-38.
- [65] 孔维杰, 苏荣军, 唐礼燕, 等. 超声波-Fenton 氧化法处理米诺环素制药废水研究[J]. 哈尔滨商业大学学报(自然科学版), 2017, **33**(1): 29-32.
Kong W J, Su R J, Tang L Y, *et al.* Study on treatment of minocycline pharmaceutical wastewater using ultrasonic-Fenton oxidation process[J]. Journal of Harbin University of Commerce (Natural Sciences Edition), 2017, **33**(1): 29-32.
- [66] Tran N H, Chen H J, Reinhard M, *et al.* Occurrence and removal of multiple classes of antibiotics and antimicrobial agents in biological wastewater treatment processes [J]. Water Research, 2016, **104**: 461-472.
- [67] Zhao L, Dong Y H, Wang H. Residues of veterinary antibiotics in manures from feedlot livestock in eight provinces of China[J]. Science of the Total Environment, 2010, **408**(5): 1069-1075.
- [68] 陈军, 张淑华. 氟喹诺酮类抗菌药马波沙星的研究进展[J]. 中国兽药杂志, 2006, **40**(12): 38-43.
Chen J, Zhang S H. Advances in marbofloxacin of fluoroquinolone antibiotic [J]. Chinese Journal of Veterinary Drug, 2006, **40**(12): 38-43.
- [69] Wang L F, Wang Y F, Li H, *et al.* Occurrence, source apportionment and source-specific risk assessment of antibiotics in a typical tributary of the Yellow River basin [J]. Journal of Environmental Management, 2022, **305**, doi: 10.1016/j.jenvman.2021.114382.
- [70] 朱金峰, 周艺, 王世新, 等. 白洋淀湿地生态功能评价及分区[J]. 生态学报, 2020, **40**(2): 459-472.
Zhu J F, Zhou Y, Wang S X, *et al.* Ecological function evaluation and regionalization in Baiyangdian Wetland[J]. Acta Ecologica Sinica, 2020, **40**(2): 459-472.
- [71] 米彦飞, 李燕秀, 郭禹, 等. 山西省畜禽粪污兽药残留分析[J]. 中国饲料, 2022, (22): 72-78.
Mi Y F, Li Y X, Guo Y, *et al.* Investigation and study on veterinary drug residues in livestock and poultry manure in Shanxi province[J]. China Feed, 2022, (22): 72-78.
- [72] Göbel A, Thomsen A, McArdell C S, *et al.* Occurrence and sorption behavior of sulfonamides, macrolides, and trimethoprim in activated sludge treatment [J]. Environmental Science & Technology, 2005, **39**(11): 3981-3989.
- [73] 柯润辉, 蒋榆林, 黄清辉, 等. 上海某城市污水处理厂污水中药物类个人护理用品 (PPCPs) 的调查研究[J]. 生态毒理学报, 2014, **9**(6): 1146-1155.
Ke R H, Jiang Y L, Huang Q H, *et al.* Investigative screening of pharmaceuticals in a municipal wastewater treatment plant in Shanghai[J]. Asian Journal of Ecotoxicology, 2014, **9**(6): 1146-1155.
- [74] 窦琦玮, 段佳奇, 唐新宇, 等. 磺胺氯哒嗪在海水中的间接光降解[J]. 中国环境科学, 2023, **43**(1): 190-196.
Dou Q Y, Duan J Q, Tang X Y, *et al.* The indirect photodegradation of sulfapyridazine in seawater [J]. China Environmental Science, 2023, **43**(1): 190-196.
- [75] 周殿芳, 陈建武, 彭婕, 等. UPLC 法检测渔用饲料中八种磺胺类药物残留的研究[J]. 化学通报, 2015, **78**(5): 467-470.
Zhou D F, Chen J W, Peng J, *et al.* Study of determination of SAs residues in fish formula feed by UPLC [J]. Chemistry, 2015, **78**(5): 467-470.
- [76] 阮悦斐, 陈继森, 郭昌胜, 等. 天津近郊地区淡水养殖水体的表层水及沉积物中典型抗生素的残留分析[J]. 农业环境科学学报, 2011, **30**(12): 2586-2593.
Ruan Y F, Chen J M, Guo C S, *et al.* Distribution characteristics of typical antibiotics in surface water and sediments from freshwater aquaculture water in Tianjin suburban areas, China [J]. Journal of Agro-Environment Science, 2011, **30**(12): 2586-2593.
- [77] Tang J, Shi T Z, Wu X W, *et al.* The occurrence and distribution of antibiotics in Lake Chaohu, China: seasonal variation, potential source and risk assessment [J]. Chemosphere, 2015, **122**: 154-161.

- [78] Liu X H, Lu S Y, Guo W, *et al.* Antibiotics in the aquatic environments: a review of lakes, China[J]. *Science of the Total Environment*, 2018, **627**: 1195-1208.
- [79] Wei Y M, Zhang Y, Xu J, *et al.* Simultaneous quantification of several classes of antibiotics in water, sediments, and fish muscles by liquid chromatography-tandem mass spectrometry[J]. *Frontiers of Environmental Science & Engineering*, 2014, **8**(3): 357-371.
- [80] 任骄阳. 北京市潮白河流域抗生素污染分布与风险评估[D]. 北京: 北京交通大学, 2021.
Ren J Y. Distribution and risk assessment of antibiotic contamination in Chaobai River basin, Beijing[D]. Beijing: Beijing Jiaotong University, 2021.
- [81] 李晶, 曲健, 祝琳琳, 等. 辽河流域沈阳段典型抗生素污染分布及健康风险评价[J]. *科学技术创新*, 2022, (24): 53-56.
Li J, Qu J, Zhu L L, *et al.* Distribution and risk assessment of typical antibiotics pollution in Shenyang section of Liao River Basin [J]. *Scientific and Technological Innovation*, 2022, (24): 53-56.
- [82] Tamtam F, Mercier F, Le Bot B, *et al.* Occurrence and fate of antibiotics in the Seine River in various hydrological conditions [J]. *Science of the Total Environment*, 2008, **393**(1): 84-95.
- [83] 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.
- [84] 张晶晶, 陈娟, 王沛芳, 等. 中国典型湖泊四大类抗生素污染特征[J]. *中国环境科学*, 2021, **41**(9): 4271-4283.
Zhang J J, Chen J, Wang P F, *et al.* Pollution characteristics of four-type antibiotics in typical lakes in China [J]. *China Environmental Science*, 2021, **41**(9): 4271-4283.
- [85] 肖鑫鑫, 吴亦潇, 丁惠君, 等. 武汉城市湖泊抗生素及抗性基因的污染特征研究[J]. *环境科学与技术*, 2019, **42**(3): 9-16.
Xiao X X, Wu Y X, Ding H J, *et al.* Pollution characteristics of antibiotics and antibiotic resistance genes in urban lakes of Wuhan[J]. *Environmental Science & Technology*, 2019, **42**(3): 9-16.
- [86] Yang Y Y, Cao X H, Lin H, *et al.* Antibiotics and antibiotic resistance genes in sediment of Honghu Lake and East Dongting Lake, China [J]. *Microbial Ecology*, 2016, **72**(4): 791-801.
- [87] 雷晓宁. 新疆典型湖泊中抗生素的污染状况与分布特征[D]. 石河子: 石河子大学, 2014.
Lei X N. Distribution and pollution levels of antibiotics from typical lakes in Xinjiang [D]. Shihezi: Shihezi University, 2014.
- [88] Zhou L J, Ying G G, Zhao J L, *et al.* Trends in the occurrence of human and veterinary antibiotics in the sediments of the Yellow River, Hai River and Liao River in northern China [J]. *Environmental Pollution*, 2011, **159**(7): 1877-1885.
- [89] Bai Y W, Meng W, Xu J, *et al.* Occurrence, distribution and bioaccumulation of antibiotics in the Liao River Basin in China [J]. *Environmental Science: Processes & Impacts*, 2014, **16**(3): 586-593.
- [90] 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.
- [91] 王庆, 邱彬. 东江湖水域兽药抗生素污染特征和生态风险评估[J]. *山东化工*, 2021, **50**(11): 247-250.
Wang Q, Qiu B. Pollution characteristics and ecological risk assessment of veterinary antibiotics in Dongjiang Lake waters[J]. *Shandong Chemical Industry*, 2021, **50**(11): 247-250.
- [92] Zou M Y, Tian W J, Zhao J, *et al.* Quinolone antibiotics in sewage treatment plants with activated sludge treatment processes: a review on source, concentration and removal [J]. *Process Safety and Environmental Protection*, 2022, **160**: 116-129.
- [93] Zhao Y W, Jiang H C, Wang X Y, *et al.* Quinolone antibiotics enhance denitrifying anaerobic methane oxidation in Wetland sediments: counterintuitive results[J]. *Environmental Pollution*, 2022, **305**, doi: 10.1016/j.envpol.2022.119300.
- [94] 贺德春, 许振成, 吴根义, 等. 四环素类抗生素的环境行为研究进展[J]. *动物医学进展*, 2011, **32**(4): 98-102.
He D C, Xu Z C, Wu G Y, *et al.* Progress on residues and environmental behavior of tetracycline antibiotics[J]. *Progress in Veterinary Medicine*, 2011, **32**(4): 98-102.
- [95] Wang Z Y, Chen Q W, Zhang J Y, *et al.* Characterization and source identification of tetracycline antibiotics in the drinking water sources of the lower Yangtze River [J]. *Journal of Environmental Management*, 2019, **244**: 13-22.
- [96] 山西省统计局, 国家统计局山西调查总队. 山西统计年鉴2021[M]. 北京: 中国统计出版社, 2021.
- [97] 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.
- [98] Lin H J, Chen L L, Li H P, *et al.* Pharmaceutically active compounds in the Xiangjiang River, China: distribution pattern, source apportionment, and risk assessment [J]. *Science of the Total Environment*, 2018, **636**: 975-984.
- [99] Li D, Shao H Y, Huo Z H, *et al.* Typical antibiotics in the receiving rivers of direct-discharge sources of sewage across Shanghai: occurrence and source analysis[J]. *RSC Advances*, 2021, **11**(35): 21579-21587.
- [100] Zhang Y X, Chen H Y, Jing L J, *et al.* Ecotoxicological risk assessment and source apportionment of antibiotics in the waters and sediments of a peri-urban river [J]. *Science of the Total Environment*, 2020, **731**, doi: 10.1016/j.scitotenv.2020.139128.

CONTENTS

Pollution Characteristics and Transport contributions of Ambient Ozone and Volatile Organic Compounds in Southern Hebei Cities	ZHAO Jiang-wei, NIE Sai-sai, YU Yu-jie, <i>et al.</i> (4775)
Temporal and Spatial Distributions of O ₃ Concentration and Potential Source Area Analysis of Hexi Corridor Based on Satellite and Ground Monitoring	LI Jin-chao, CAO Chun, FANG Feng, <i>et al.</i> (4785)
Spatial and Temporal Variations in Ozone Pollution and Sensitivity Characteristics in Hainan Island	FU Chuan-bo, DAN Li, TONG Jin-he, <i>et al.</i> (4799)
Temporal and Spatial Characteristics of Troposphere O ₃ and Precursors HCHO and NO ₂ in East China	WANG Xiao-wen, LIU Min-xia, WANG Yang, <i>et al.</i> (4809)
Evolution Characteristics of Atmospheric Formaldehyde Emissions in Guangdong Province from 2006 to 2020	MING Gui-ying, ZHU Man-ni, SHA Qing-e, <i>et al.</i> (4819)
VOCs Emission Level and Emission Reduction Potential of Coating Industry in Zibo	HUANG Yue-run, YANG Wen, WANG Xiu-yan, <i>et al.</i> (4832)
Pollution Characteristics of Carbonaceous Components in PM ₁₀ and PM _{2.5} of Road Dust Fall and Soil Dust in Xi'an	SHEN Li-juan, WANG Hong-lei, SUN Jie-juan, <i>et al.</i> (4843)
Runoff Simulation and Its Response to Extreme Precipitation in the Yangtze River Basin	GAO Shuang, TI Chao-pu, TANG Shui-rong, <i>et al.</i> (4853)
Water Chemical Isotope Characteristics and Water Transformation Relationship in Mongolian Section of the Yellow River Basin	PEI Sen-sen, DUAN Li-min, MIAO Ping, <i>et al.</i> (4863)
Hydrochemical Characteristics and Formation Causes of Ground Karst Water Systems in Gudui Spring Catchment	TANG Chun-lei, SHEN Hao-yong, ZHAO Chun-hong, <i>et al.</i> (4874)
Source Analysis and Health Risk Assessment of Heavy Metals in the Groundwater of Shijiazhuang, a Typical City in North China Plain	CHEN Hui, ZHAO Xin-yu, CHANG Shuai, <i>et al.</i> (4884)
Spatial Distribution, Speciation, and Ecological Risk Assessment of Heavy Metals in Surface Sediments of Dongjiang Lake, Hunan Province	ZHANG Tong-liang, YI Li-xia, LI Chang-cheng, <i>et al.</i> (4896)
Spectral Characteristics and Source Analysis of Chromophoric Dissolved Organic Matter in Surface Water of Taihu Lake Before Cyanobacterial Blooming	WANG Yong-qiang, LU Shao-yong, HUANG Wei, <i>et al.</i> (4906)
Chemical Oxygen Demand(COD) Composition and Contribution in Typical Waters of Baiyangdian Lake	LI Qi, ZHANG Chao, ZHANG Wen-qiang, <i>et al.</i> (4915)
Source Apportionment and Source-specific Risk of Typical Antibiotics in Baiyangdian Lake	SONG Yuan-meng, ZHAO Bo, LU Meng-qi, <i>et al.</i> (4927)
Response of River Ecosystem Health Status to Water Environmental Factors in the Middle Reaches of Yarlung Zangbo River	LI Xiao-dong, YANG Qing, LIU Hui-qiu, <i>et al.</i> (4941)
Analysis on the Current Situation of Phytoplankton in the Typical River- Lake Ecotone of Lake Poyang	YU Xin-ping, CHEN Yu-wei, LIU Jin-fu, <i>et al.</i> (4954)
Phytoplankton Community Structure, Diversity, and Functional Groups in Urban River Under Different Black and Odorous Levels	ZHANG Qi-qi, ZENG Jie, YIN Zhuo, <i>et al.</i> (4965)
Influence of Denitrification on Cyanobacterial Blooms Trends in Lake Taihu, China	LI Chang-jie, XU Hai, ZHAN Xu, <i>et al.</i> (4977)
Effects of Nitrogen Speciation Transformation on Microbial Community Succession in Input Rivers of Miyun Reservoir	XIN Yuan, ZHANG Yao-fang, LI Tian-yu, <i>et al.</i> (4985)
Action Mechanism of <i>Bacillus</i> on Microalgae During Nitrogen Metabolism in Urban Tailwater	ZHAO Zhi-ni, MA Chao, YAN Jia-chen, <i>et al.</i> (4996)
Nitrogen Removal Characteristics and Metabolism Mechanism of High-Efficiency Cold-Tolerant Heterotrophic Nitrification-Aerobic Denitrification Bacterium <i>Glutamicibacter</i> sp. WS1 for Various Nitrogen Sources at Low Temperature	WEI Bo-hui, LUO Xiao, LÜ Peng-yi, <i>et al.</i> (5006)
Pollution Characteristics of Macrolide Antibiotics During Drinking Water Treatment and Their Chlorination Reaction Mechanism	CEN Xia, CHENG Si-yu, SHI Zong-min, <i>et al.</i> (5017)
Effects of Different Biochar and Effective Microorganism Agent Improvement Approaches on the Nutrient Release Characteristics and Potential of Compost	JIA Pei-yin, WANG Xin, HUA Yu-ting, <i>et al.</i> (5025)
Occurrence Characteristics and Risk Assessment of Microplastics in Water and Sediments of Anhui Section of Huaihe River Basin	ZHANG Hai-qiang, GAO Liang-min, GE Juan, <i>et al.</i> (5036)
Distribution, Sources, and Risk Assessment of Microplastics in Surface Sediments of Yellow River Delta Wetland	GENG Na, ZHAO Guang-ming, ZHANG Da-hai, <i>et al.</i> (5046)
Distribution Characteristics and Risk Assessment of Microplastics in Farmland Soil in Guyuan	MA Gui, DING Jia-fu, ZHOU Yue, <i>et al.</i> (5055)
Distribution Characteristics of Microplastic Surface Bacterial Communities Under Flooded and Non-flooded Conditions in Nanjishan Wetland of Poyang Lake	ZHAO Jun-kai, CHEN Xu, HU Ting-ting, <i>et al.</i> (5063)
Influence of Polystyrene Microplastics on the Formation and Structural Change of <i>Pseudomonas aeruginosa</i> Biofilm	TAO Hui, YU Duo, YANG Lan, <i>et al.</i> (5071)
Effects of Polystyrene Microplastics on Growth, Physiology, Biochemistry, and Canopy Temperature Characteristics of Chinese Cabbage Pakchoi (<i>Brassica chinensis</i> L.)	GUO Bing-lin, FENG Chen-chen, CHEN Yue, <i>et al.</i> (5080)
Effects of Combined Stress of Polyethylene and Sulfamethazine on Seed Germination, Seedling Growth, and Physiological Characteristics of Soybean	ZHAO Xiao-qiong, ZHANG Heng-hui, ZHAO Run-zhu, <i>et al.</i> (5092)
Transport and Model Calculation of Microplastics Under the Influence of Ionic Type, Strength, and Iron Oxide	ZHANG Ran, YU Ke-fei, HUANG Lei, <i>et al.</i> (5102)
Impacts of Land Use and Climate Change on Ecosystem Services in Agro-pastoral Ecotone	XU Wen-bin, RAO Liang-yi (5114)
Response of Organic Carbon Loss to Soil Erosion and Its Drivers; A Meta-analysis	LIU Xiao-lan, HUANG Jin-quan, QI Yu-jie, <i>et al.</i> (5125)
Effects of Balanced Fertilization and Straw Mulching on Soil Nutrients and Stoichiometry in Purple Soil Slope	ZHANG Gao-ning, XU Qi-wen, HE Bing-hui, <i>et al.</i> (5135)
Characteristics and Dominant Influencing Factors of the Fungal Community Structure in Soils Co-contaminated with Rare Earth Elements and Heavy Metals	LUO Ying, LI Jing-wei, YUAN Hao, <i>et al.</i> (5145)
Effects of Annual Crop Rotation and Fallow on Soil AMF Community and Aggregate Stability	LU Ze-rang, XIA Zi-tai, LU Mei, <i>et al.</i> (5154)
Spatial-temporal Changes and Driving Factors of Soil Microbial Communities in a Typical City of North China Plain	ZHAO Xin-yu, CHEN Hui, CHANG Shuai, <i>et al.</i> (5164)
Effect of High-volume Straw Returning and Applying <i>Bacillus</i> on Bacterial Community and Fertility of Desertification Soil	NIE Yang-mei, BU Lian-yan, CHEN Wen-feng, <i>et al.</i> (5176)
Low Accumulation Characteristics of Sweet-waxy Maize in Pb and Cd Complex Contaminated Soils Based on Field Trials	TANG Le-bin, LI Long, SONG Bo, <i>et al.</i> (5186)
Effects of Different Control Measures on Cadmium and Lead Accumulation and Quality in Lettuce	ZHOU Hong-yin, LI Jia-qi, BAO Li, <i>et al.</i> (5196)
Effects of Nano-copper Oxide on Physiobiochemical Properties of <i>Brassica chinensis</i> L. and Its Heavy Metal Accumulation Under Cadmium Stress	WANG Shi-qi, SUN Yue-bing, HUANG Qing-qing, <i>et al.</i> (5204)
Distribution and Biototoxicity of Endogenous Pollutants in <i>Pennisetum</i> sp. Biochar from Different Polluted Areas	LIU Li-ya, CUI Hong-biao, LIU Xiao-sheng, <i>et al.</i> (5214)
Adsorption Characteristics of Tetracycline by CuFeO ₂ -modified Biochar	LIU Guo-cheng, ZHANG Xin-wang, XIN Shuai-shuai, <i>et al.</i> (5222)
Ecological Toxic Effect of Perfluorinated Compounds on Fish Based on Meta-analysis	LU Hong, ZHOU Jin-yang, YANG Fan, <i>et al.</i> (5231)
Source Analysis and Risk Assessment of Heavy Metals in Soil of County Scale Based on PMF Model	ZHENG Yong-li, WEN Han-hui, CAI Li-mei, <i>et al.</i> (5242)
Potential Source Identification and Ecological Risk Assessment of Heavy Metals in Surface Soil of Heze Oil Peony Planting Area Based on PMF-PCA/APCS and PERI	ZHAO Qing-ling, LI Qing-cai, AN Mao-guo, <i>et al.</i> (5253)
Health Risk Assessment and Environmental Benchmark of Cadmium in Farmland Soils around the Gangue Heap of Coal Mine, Chongqing	MA Jie, SHE Ze-lei, WANG Sheng-lan, <i>et al.</i> (5264)
Pollution Characteristics and Sources of Heavy Metals in Soil of a Typical Pyrite Concentrated Mining Area in Anhui Province	JIA Han, LIU Jun-xing, WANG Xiao-guang, <i>et al.</i> (5275)
Distribution Characteristics, Source Analysis and Potential Ecological Risk Assessment of Soil Heavy Metals in Typical River Source Areas of Northeastern Hunan Province	YANG Zhen-yu, LIAO Chao-lin, ZOU Yan, <i>et al.</i> (5288)
Variation Characteristics of Exogenous Cadmium with Different Contents in Red Soil	ZHOU Zi-yang, PANG Rui, SONG Bo (5299)
Analysis of Carbon Storage Potential of CO ₂ Foamed Concrete	ZHANG Yuan, TA Xu-peng, QIN Shu-bing, <i>et al.</i> (5308)
Research on the Screening Method of Priority Pollutants with Integrated Environmental Socio-economic Indicators: Example of E-waste Dismantling	CHEN Yuan, CAI Zhen, LI Jin-hui (5316)