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城区第四系沉积柱中抗生素的垂向分布特征及环境影响因素

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摘要: 抗生素从地表向地下迁移时, 容易通过水-岩相互作用残留于沉积物中, 给地下水带来二次释放的风险. 为探究抗生素的垂向分布特征和环境影响因子, 于医院附近钻孔并分层采集了5个30 m第四系沉积柱, 测试分析了5大类抗生素和磺胺代谢物. 结果表明: ①沉积物中抗生素含量范围为3.05~107.03 $\mu\text{g}\cdot\text{kg}^{-1}$, 除洛美沙星外, 其他所有目标抗生素均有检出, 其中氧氟沙星和土霉素是研究区最主要的抗生素; ②抗生素在垂向上并不呈现严格的下降趋势, 而是随着岩性层位的变化而变化; ③抗生素主要赋存在黏粒沉积物中, 并随地下水位的波动而变化; ④抗生素与环境因子的冗余分析结果表明, pH和TOC通过影响沉积物对抗生素的吸附作用来控制抗生素的迁移转化. 医院废水渗漏对地下环境带来的抗生素污染的风险应引起重视.

关键词: 抗生素; 钻孔沉积物; 金属; 垂向分布; 环境因子

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Characteristics of Vertical Distribution and Environmental Factors of Antibiotics in Quaternary Sedimentary Column in Urban Areas

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Abstract: Antibiotics easily remain in sediments after migrating from the surface to the subsurface due to water-rock interactions, posing a risk of secondary release to groundwater. To investigate the vertical distribution characteristics and environmental impact factors of antibiotics, five 30 m quaternary sediment columns were drilled and stratified near the hospital, and five major classes of antibiotics and sulfonamide metabolites were tested and analyzed. The results showed that: ① the antibiotic content in the sediments ranged from 3.05 to 107.03 $\mu\text{g}\cdot\text{kg}^{-1}$, and all of the target antibiotics were detected except lomefloxacin, of which ofloxacin and oxytetracycline were the most important antibiotics in the study area. ② The antibiotics did not show a strict downward trend in the vertical direction but varied with the lithological stratification. ③ Antibiotics were primarily deposited in the clay layer and varied with the fluctuation of the groundwater level. ④ The results of redundancy analysis between antibiotics and environmental factors suggested that pH and TOC controlled the fate and transformation of antibiotics through influencing the adsorption of antibiotics by sediments. The risk of antibiotic contamination from hospital wastewater seepage into the subsurface environment should be taken seriously.

Key words: antibiotics; borehole sediments; metals; vertical distribution; environmental factors

过去几十年, 抗生素因其高效的抑菌作用而广泛应用于人类医疗和畜牧养殖业中. 而现有的废水处理工艺不能完全去除抗生素残留, 导致其排放至自然环境中. 湖泊^[1-3]、河流^[4,5]、地下水^[6-8]和沉积物^[9,10]等环境介质中已经普遍检出一定含量的抗生素. 而环境中抗生素的残留不仅会对微生物及动植物产生毒性效应, 还会诱导致病菌产生抗生素抗性基因, 从而对人类生命健康产生威胁^[11,12].

地表环境中广泛存在的抗生素可通过地表水-地下水交互作用、垂直入渗和管道渗漏等方式进入地下水^[13]. 地下水中的抗生素易被沉积物颗粒吸附截留, 它们可以与砂粒强烈结合, 而不易被降解, 且可以通过化学或生物扰动再重新释放进入水体中, 这意味着沉积物可以成为抗生素污染的次生来源^[5,14]. 水相和固相之间的相互作用是抗生素等有机

微污染物在水-沉积物中持久性的关键^[15,16]. 因此, 确定沉积物中的抗生素含量对研究抗生素在水和沉积物中的迁移和转化是非常重要的.

武汉市第四系松散沉积物覆盖率达90%, 邻近长江, 地下水位较高, 地表水与地下水交互作用强烈^[17]. 抗生素极易随水流动至地下水环境, 并被沉积物截留. 目前对沉积物中抗生素的研究普遍集中在湖泊底泥或污染区表层土壤上, 对深层沉积物的研究较少, 无法提供抗生素在地下深部环境中迁移转化的规律. 本研究通过采集武汉市医院附近的多个

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钻孔沉积物,选取 26 种典型抗生素及其代谢物,分析其在沉积柱垂向上的分布特征,并探究了抗生素与金属、粒度、酸碱度、矿物组成和有机质含量等环境因子之间的相关性。

1 材料与方法

1.1 研究地点及样品采集

研究区位于湖北省武汉市,在江汉平原东部和长江中部,市内湖泊纵横,降雨量丰富。武汉市拥有

丰富的地下水资源,地下水主要为孔隙水和岩溶水,地下水位较高^[18]。医院废水是环境中抗生素污染的主要来源之一,医院内污水管网渗漏可能会污染至邻近地下水及沉积物^[19, 20]。本研究中 5 个钻孔分别选在 5 个医院附近, P02 采样点距离医院 100 m 内,其余 4 个沉积柱均布设在医院内部靠近污水管网处。由于密集的人群会带来较高的抗生素使用量,因此所选医院分布在人口密度较大的武汉市主城区,具体点位如图 1 所示。

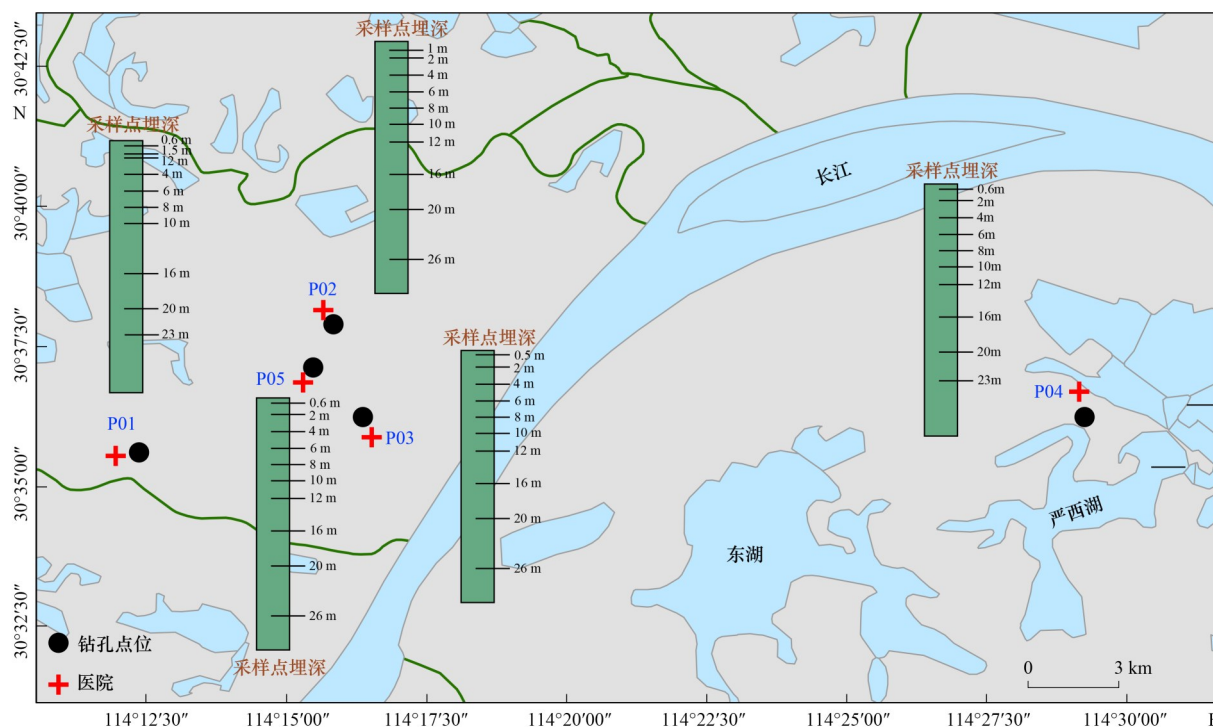


图 1 采样点位示意

Fig. 1 Sampling sites

于 2020 年 11 月依次在 5 个医院附近钻孔,待沉积柱取出后,立即采集沉积物样品。沉积物采集前先去掉表层受干扰的部分,取内部新鲜的沉积物样品用保鲜膜密封以减少氧化作用,再用铝箔纸包裹,避免抗生素的光降解。当天将样品带回实验室放在 -20°C 冷库中保存,并及时进行抗生素的前处理。5 个钻孔均深至 30 m,每个钻孔采集 10 份沉积物样品。考虑到浅层有污水管网密布,沉积物更易受到渗漏污染。且地下水位(4 m 左右)较高,水位的波动会影响抗生素的迁移,以及岩性变化速度从浅至深趋慢,因此在浅层采样加密。而由于深层砂质沉积物较为松散,钻出的沉积物难以区分具体深度,因此在深层降低采样密度。各点位具体的采样深度见图 1。

1.2 抗生素的测试与分析

目标抗生素主要有:大环内酯类(macrolides, MLs)、磺胺类(sulfonamides, SAs)、四环素类(tetracyclines, TCs)、氟喹诺酮类(fluoroquinolones,

FQs)和磺胺代谢物类(sulfonamide metabolites, Ac-SAs)。其中 MLs 包括:脱水红霉素(anhydro erythromycin, AEM)、克拉霉素(clarithromycin, CTM)、罗红霉素(roxithromycin, RTM)和阿奇霉素(azithromycin, AZM); SAs 包括:磺胺甲基嘧啶(sulfamerazine, SMR)、磺胺嘧啶(sulfadiazine, SDZ)、磺胺甲噁唑(sulfamethoxazole, SMX)、磺胺甲氧吡嗪(sulfamethoxypyridazine, SMP)、磺胺喹啉(sulfaquinoxaline, SQX)、磺胺噻唑(sulfathiazole, STZ)、磺胺吡啶(sulfapyridine, SPD)和磺胺二甲嘧啶(sulfamethazine, SMZ); FQs 包括:恩诺沙星(enrofloxacin, ENR)、洛美沙星(lomefloxacin, LOM)、氧氟沙星(ofloxacin, OFL)、环丙沙星(ciprofloxacin, CIP)、诺氟沙星(norfloxacin, NOR)和司帕沙星(sparfloxacin, SPA); TCs 包括:四环素(tetracycline, TC)、土霉素(oxytetracycline, OTC)、强力霉素(doxycycline, DOC)和金霉素(chlorotetracycline,

CTC); Ac-SAs 包括: N^4 -乙酰基-磺胺嘧啶(N^4 -acetyl-sulfadiazine, Ac-SDZ)、 N^4 -乙酰基-磺胺甲基嘧啶(N^4 -acetyl-sulfamerazine, Ac-SMR)、 N^4 -乙酰基-磺胺二甲基嘧啶(N^4 -acetyl-sulfamethazine, Ac-SMZ)和 N^4 -乙酰基-磺胺甲噁唑(N^4 -acetyl-sulfamethoxazole, Ac-SMX). 26 种抗生素标准品(纯度 $\geq 95\%$)均购自德国 Dr. Ehrenstorfer 公司. 一个内标 $^{13}\text{C}_6$ -磺胺嘧啶($^{13}\text{C}_6$ -sulfadiazine)购自上海安谱实验科技股份有限公司.

野外采集的沉积物样品经冷冻干燥粉碎后过 60 目筛,取 2 g 样品置于 Teflon 消解罐中,加入 10 mL 提取液[含 50% 乙腈的 Na_2EDTA -Mcllvaine 缓冲液($\text{pH} = 3$)],涡旋振荡 1 min 后,微波消解(CEM MARS Xpress, 美国 CEM 公司)30 min 进行第一次提取. 提取完后离心($8\,000\text{ r}\cdot\text{min}^{-1}$, 3 min)取上清液,重复提取 3 次,将上清液合并,氮吹至有机相挥发完后,稀释至 100 mL 进行固相萃取.

先后过 6 mL 甲醇、6 mL 纯水和 6 mL Na_2EDTA -Mcllvaine 缓冲液($\text{pH} = 4$)活化平衡 Oasis HLB 小柱(200 mg, 6 mL, Waters),以不超过 $10\text{ mL}\cdot\text{min}^{-1}$ 的速度上样. 然后用 4 mL 5% 氨水甲醇、3 mL 甲醇和 4 mL 2% 甲酸甲醇依次洗脱至 10 mL 玻璃离心管中. 最后,用温和的氮气流将洗脱液吹至近干,加入 20 μL 内标 $^{13}\text{C}_6$ -磺胺嘧啶. 用 10% 的甲醇定容至 1 mL 待上机检测.

用液相色谱-三重四极杆质谱 LC-MS/MS(岛津 30A UPLC 系统+AB SCIEX 4500 QQQ MS/MS 系统)对抗生素进行检测. 色谱条件为: Hypersil Gold C18 柱($100\text{ mm}\times 2.1\text{ mm}$, $1.9\text{ }\mu\text{m}$);进样量: 10 μL ;流速: $0.3\text{ mL}\cdot\text{min}^{-1}$;流动相: A 相为 0.1% 甲酸水溶液, B 相为乙腈. 洗脱梯度: 0 ~ 3 min, 90% A 降至 60% A; 维持 4.5 min; 7.5 ~ 10 min, 60% A 降至 10% A; 10 ~ 10.2 min, 10% A 升至 90% A; 维持 2.8 min.

1.3 环境因子测试与分析

样品粒度采用 Mastersizer 3000 型激光粒度分析仪进行测试. 金属包括 K、Na、Ca、Mg、Al、Mn、Fe、Cr、Co、Ni、Ti、Cu、Zn、Pb、Cd、Sb 和 Sn 通过电感耦合等离子体光谱仪(ICP-OES, OPTIMA8000, 美国 PE 公司)测定. 矿物组成采用 X 射线衍射仪(XRD, D8-FOCUS, 德国 Bruker 公司)分析. 用 TOC 分析仪(Vario, 德国 Elementar 公司)检测沉积物中的有机碳含量.

1.4 数据处理及质量控制与保证

采用 Analyst 1.6.2 软件处理抗生素数据,所有标准曲线线性相关系数均大于 0.99. 样品设置 10% 的平行样(每个沉积柱随机选取一个样品点)进行精密度测试,相对标准偏差(RSD)小于 10%. 沉积物加标

水平为 $20\text{ ng}\cdot\text{g}^{-1}$ 和 $50\text{ ng}\cdot\text{g}^{-1}$,方法检出限范围为 0.01 ~ $2.23\text{ ng}\cdot\text{g}^{-1}$,抗生素回收率范围为 45.6% ~ 98.2%. 本研究 RDA 分析使用 Canoco 5.0 完成,相关性分析使用 SPSS 26.0 完成.

2 结果与分析

2.1 环境因子的分布特征

2.1.1 粒度分布及矿物组成

P01、P02、P03 和 P05 这 4 个钻孔从浅至深依次为浅黄色人工填土、黄色粉质黏土、灰色淤泥质粉质黏土和灰黑色细砂. P04 从浅至深岩性变化不大,均为黄色黏土,但从浅至深均呈现中度风化. 5 个钻孔黏粒($< 4\text{ }\mu\text{m}$)、粉粒($4\sim 63\text{ }\mu\text{m}$)和砂粒($> 63\text{ }\mu\text{m}$)占比不同,黏粒占比介于 3.42% ~ 46.87%,平均值为 20.39%. 粉粒占比介于 15.58% ~ 81.57%,平均值为 63.30%. 砂粒占比介于 0% ~ 80.94%,平均值为 16.31%. 整体上从浅至深砂粒占比增大,黏粒占比减小. 具体分布情况如图 2 所示. 沉积物中矿物组成主要为石英、钠长石、钾长石、云母、绿泥石和蒙脱石. 不同层位主要矿物含量平均值如表 1 所示. 其中石英最为丰富,占比介于 24.09% ~ 93.41%,主要富集在砂层中. 蒙脱石等黏土矿物主要富集于浅层黏土层中.

2.1.2 金属

5 个钻孔沉积物中金属含量分布如图 2 所示. 所有目标金属均有检出,5 个剖面中金属总含量变化范围大体一致. 金属含量从大到小依次为: $\text{Al} > \text{Fe} > \text{Ca} > \text{K} > \text{Mg} > \text{Na} > \text{Ti} > \text{Mn} > \text{Zn} > \text{Cr} > \text{Ni} > \text{Cu} > \text{Pb} > \text{Co} > \text{Sn} > \text{Sb} > \text{Cd}$. 其中 Al、Fe、Ca、K、Mg 和 Na 等造岩元素的含量在 $\text{g}\cdot\text{kg}^{-1}$ 级别,而 Zn、Cr、Ni、Cu、Pb、Co、Sn、Sb 和 Cd 等重金属的含量在 $\text{mg}\cdot\text{kg}^{-1}$ 级别. 宏量金属主要是 Al 和 Fe, $\omega(\text{Al})$ 范围为: 51.41 ~ 102.49 $\text{g}\cdot\text{kg}^{-1}$, 含量平均值为 70.39 $\text{g}\cdot\text{kg}^{-1}$. $\omega(\text{Fe})$ 范围为: 22.10 ~ 64.70 $\text{g}\cdot\text{kg}^{-1}$, 含量平均值为 36.80 $\text{g}\cdot\text{kg}^{-1}$. 微量金属主要是 Zn 和 Cr, $\omega(\text{Zn})$ 范围为 46.7 ~ 150.0 $\text{mg}\cdot\text{kg}^{-1}$, 含量平均值为 83.51 $\text{mg}\cdot\text{kg}^{-1}$. $\omega(\text{Cr})$ 范围为 47.8 ~ 118.0 $\text{mg}\cdot\text{kg}^{-1}$, 含量平均值为 80.02 $\text{mg}\cdot\text{kg}^{-1}$.

2.2 沉积物中抗生素的分布

2.2.1 沉积物中抗生素的含量分布

武汉市医院附近沉积柱所有样品均有抗生素检出,沉积柱中抗生素的含量范围及检出频率见表 2. 结果显示,除了 LOM 之外,目标抗生素在沉积物中均有检出. OTC、DOC、CTC、OFL、RTM 和 SMX 检出率最高(100%),其次为 Ac-SMX(98%)、NOR(78%)、Ac-SDZ(76%)、TC(60%)、AEM(60%)和 AZM(52%),其余抗生素检出率均低于 50%. 26 种抗生素

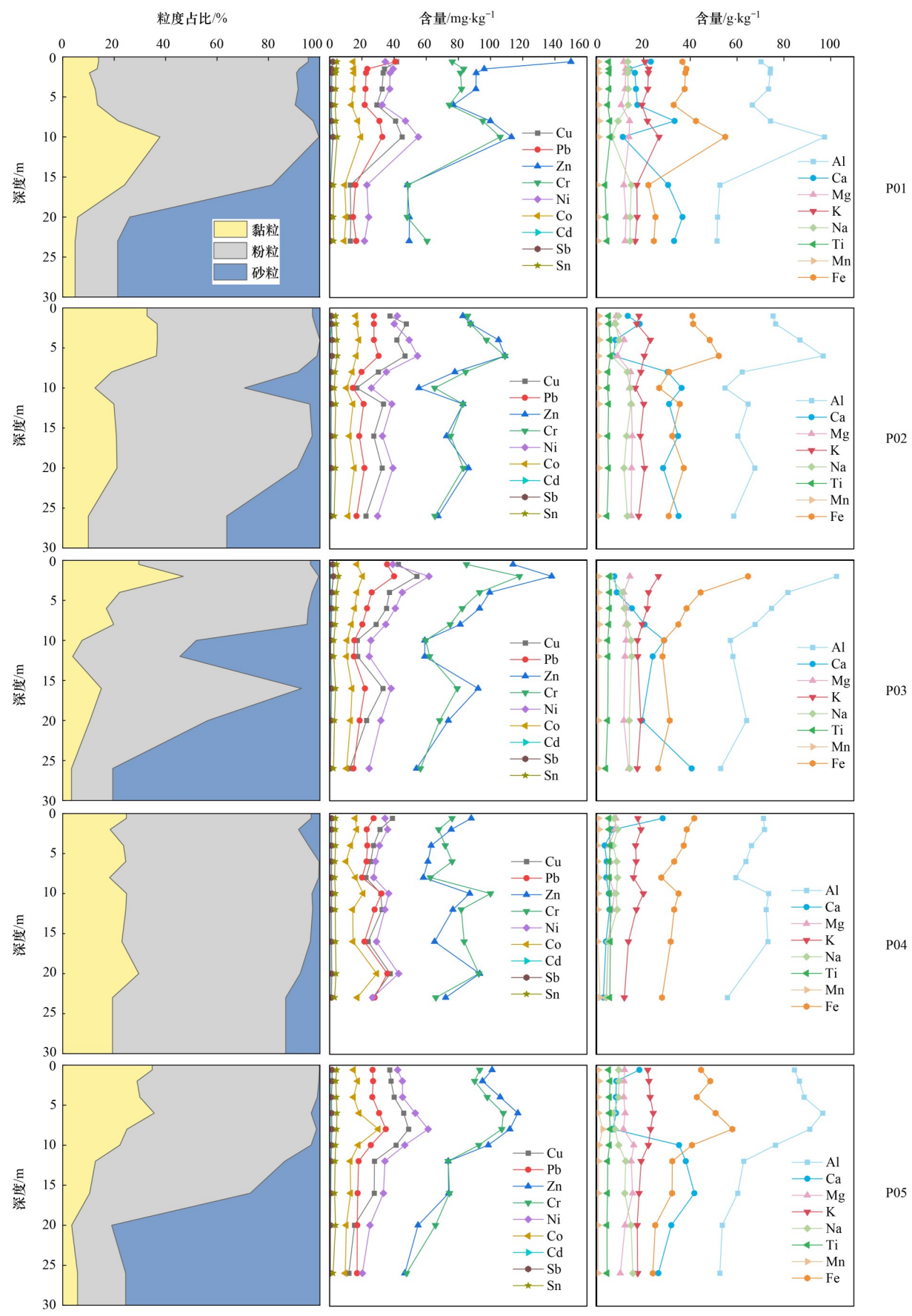


图2 剖面沉积物的粒度占比及金属的含量变化

Fig. 2 Grain size distribution and metal variations of the profile sediments

表 1 沉积物中不同层位矿物含量平均值
Table 1 Average mineral content of sediments in different layers

钻孔	层位	$\omega/\%$						
		石英	云母	钠长石	钾长石	蒙脱石	绿泥石	其他
P01	浅层	33.96	0.00	15.38	13.76	17.21	14.90	0.00
	中层	18.13	9.55	7.29	8.51	20.98	24.86	0.00
	深层	42.58	0.00	15.67	11.67	9.19	10.52	2.27
P02	浅层	28.16	9.32	10.82	6.13	14.93	21.88	0.00
	中层	37.86	0.00	15.39	11.73	10.58	11.27	3.53
	深层	34.43	0.00	14.46	12.74	12.73	13.47	2.07
P03	浅层	29.50	6.19	12.41	9.05	16.26	20.11	0.00
	中层	38.57	0.00	16.95	12.47	12.40	12.71	0.08
	深层	38.67	0.00	15.24	12.31	9.22	11.16	3.21
P04	浅层	71.46	4.96	7.78	5.79	8.12	4.23	1.89
	中层	67.22	0.00	6.13	13.20	4.00	8.70	0.75
	深层	52.71	9.02	8.27	5.22	9.75	10.55	4.48
P05	浅层	29.39	11.10	10.59	4.11	15.31	19.38	0.00
	中层	31.53	0.00	13.10	12.88	14.36	14.10	2.07
	深层	43.31	0.00	17.54	12.47	9.20	10.87	0.00

的总含量范围为 3.05 ~ 107.03 $\mu\text{g}\cdot\text{kg}^{-1}$. 从含量平均值来看, OFL(11.87 $\mu\text{g}\cdot\text{kg}^{-1}$) > OTC(7.42 $\mu\text{g}\cdot\text{kg}^{-1}$) > SMX(1.12 $\mu\text{g}\cdot\text{kg}^{-1}$) > NOR(0.08 $\mu\text{g}\cdot\text{kg}^{-1}$) > DOC = RTM(0.06 $\mu\text{g}\cdot\text{kg}^{-1}$) > TC(0.05 $\mu\text{g}\cdot\text{kg}^{-1}$) > Ac-SMX (0.04 $\mu\text{g}\cdot\text{kg}^{-1}$). 其中 OFL 和 OTC 的含量最高, 范围分别在 2.11 ~ 88.63 $\mu\text{g}\cdot\text{kg}^{-1}$ 和 1.49 ~ 96.42 $\mu\text{g}\cdot\text{kg}^{-1}$ 之间. CTC、DOC 和 RTM 检出率虽高, 其含量最大值仅 1.73、0.27 和 0.20 $\mu\text{g}\cdot\text{kg}^{-1}$.

表 2 沉积物中抗生素的含量水平和检出率¹⁾
Table 2 Concentration levels and detection rates of antibiotics in sediments

抗生素		含量范围/ $\mu\text{g}\cdot\text{kg}^{-1}$	平均值/ $\mu\text{g}\cdot\text{kg}^{-1}$	检出率/%
TCs	OTC	1.49 ~ 96.42	7.42	100
	DOC	LOQ ~ 0.27	0.06	100
	TC	ND ~ 0.95	0.05	60
	CTC	0.78 ~ 1.73	1.00	100
FQs	CIP	ND ~ 0.05	0	2
	NOR	ND ~ 1.11	0.08	78
	LOM	ND	0	0
	ENR	ND ~ LOQ	0	4
	OFL	2.11 ~ 88.63	11.87	100
	SPA	ND ~ LOQ	0	4
MLs	AZM	ND ~ 0.07	0	52
	CTM	ND ~ 0.06	0	22
	RTM	0.05 ~ 0.20	0.06	100
	AEM	ND ~ 0.07	0.01	60
SAs	STZ	ND ~ 0.19	0.01	16
	SMZ	ND ~ 0.16	0.01	30
	SMX	0.04 ~ 19.63	1.12	100
	SDZ	ND ~ 0.03	0	18
	SQX	ND ~ LOQ	0	38
	SMP	ND ~ 0.21	0.01	16
	SPD	ND ~ 0.04	0	10
	SMR	ND ~ 0.03	0	14
Ac-SAs	Ac-SMZ	ND ~ LOQ	0	30
	Ac-SMR	ND ~ LOQ	0	48
	Ac-SDZ	ND ~ LOQ	0	76
	Ac-SMX	ND ~ 0.27	0.04	98

1) LOQ 表示低于定量限, ND 表示未检出

2.2.2 抗生素的垂向分布特征

武汉市医院附近沉积柱中抗生素的垂向分布如图3所示,不同沉积柱中抗生素的垂向变化较大,其含量不随深度的增加而单向减少,受不同层位岩性的影响而波动.整体上来看,P01、P02、P03和P05这4个岩性变化类似的沉积柱的下部砂层(15~30 m)

中抗生素含量要低于上部黏土层和淤泥层.推测与砂粒组分增加而黏粒减少,对抗生素的吸附量减少有关.黏土层厚至30 m的沉积柱P04中抗生素含量最高,深层沉积物中仍有较高含量的抗生素检出,含量范围为16.15~107.03 $\mu\text{g}\cdot\text{kg}^{-1}$,这与其黏粒分布均匀,对抗生素的吸附能力较强有关.

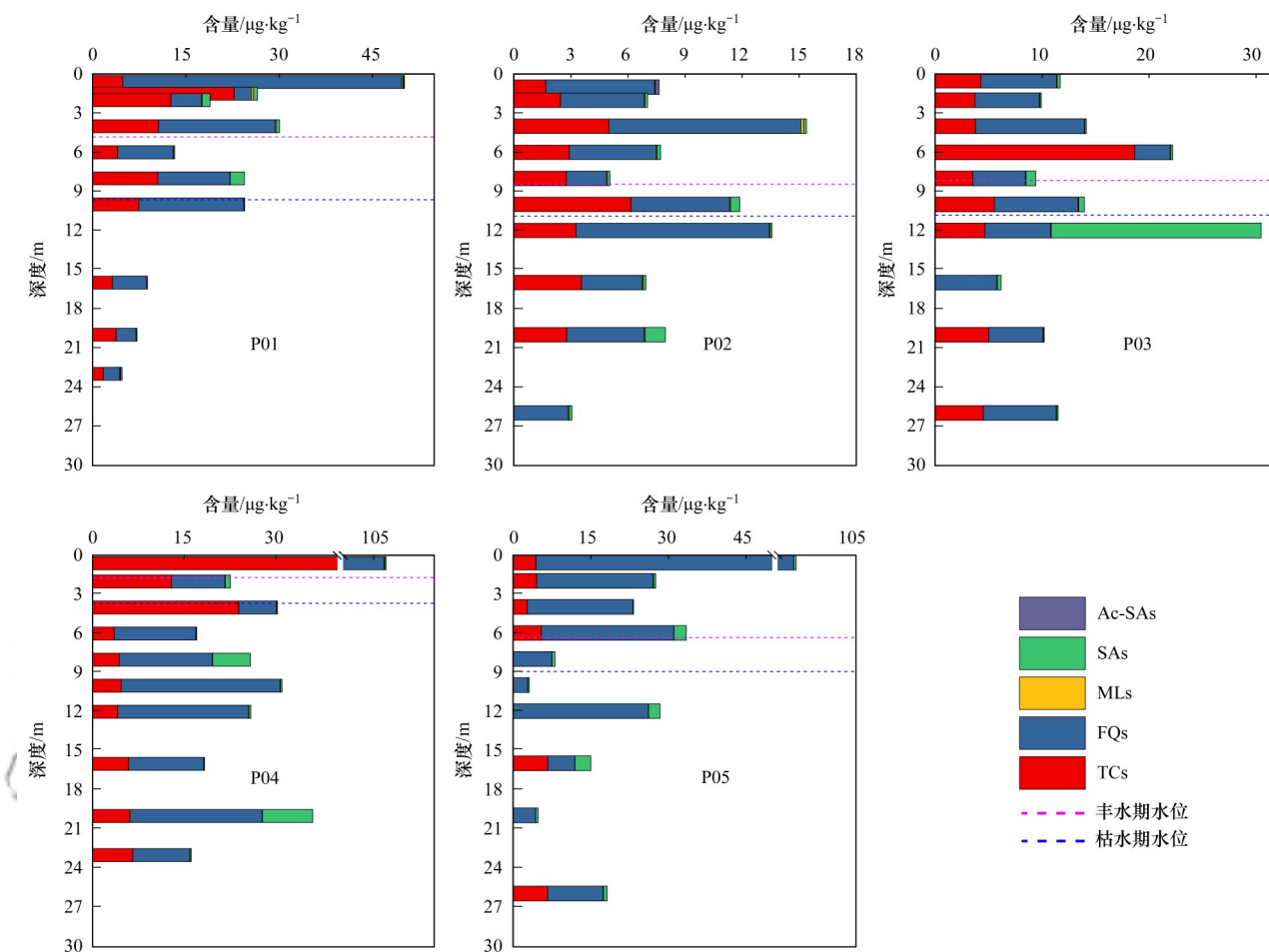


图3 沉积柱中抗生素含量的垂向分布特征

Fig. 3 Vertical distribution of antibiotics in different sediment profiles

在地下水位波动区段,有4个沉积柱的抗生素含量随深度增加出现递增趋势,推测是因为地下水水位的波动促进了抗生素的迁移.这一结果与江汉平原沉积物结论一致^[9].P01、P04和P05沉积柱中的抗生素最高含量均出现在表层,推测可能是医疗废物淋滤或医院污水管网渗漏所致.除了四环素类和氟喹诺酮类抗生素之外,磺胺类抗生素在深处也有较高检出,如P03,表层磺胺类抗生素几乎没有检出,而在12 m处检测处最高的 $\omega(\text{SMX})$ (19.63 $\mu\text{g}\cdot\text{kg}^{-1}$),这可能是因为磺胺类抗生素迁移性强,易随地下水的波动迁移至深层^[21].

2.3 抗生素与环境因子之间的相关性

环境因子的变化影响着抗生素在沉积物中的

赋存.本研究将不同深度的抗生素与环境因子(粒径组成、金属、pH和TOC)作冗余分析.结果如图4所示,图中呈现的仅为相关性较强的部分指标.由于环境介质及影响因素的复杂性,所选环境因子并不能完全解释抗生素在沉积物中的分布成因.然而RDA输出结果表明整个模型是显著的($P < 0.05$),因此RDA分析结果可以为抗生素分布提供有效的解释.所选指标中pH和TOC对抗生素分布的影响最显著,pH与TCs、MLs和FQs均呈现显著正相关($P < 0.05$),TOC与MLs和FQs呈显著正相关($P < 0.05$),与SAs呈显著负相关($P < 0.05$).除此之外,Cu、Fe、Zn和黏粒占比等也与抗生素分布有一定相关性.

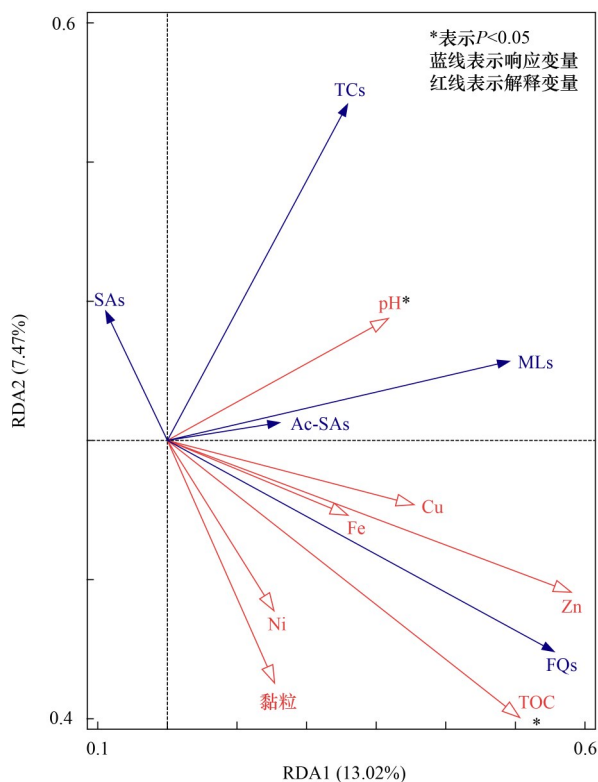


图4 抗生素与环境因子的冗余分析

Fig. 4 Redundancy analysis of antibiotics and environmental factors

3 讨论

3.1 沉积物中抗生素的污染特征

我国一些典型表层沉积物中抗生素的含量水平如表3所示,抗生素的含量分布特征随土地利用类型的不同而变化^[22-28].与其他沉积物类似,抗生素污染以FQs和TCs为主.从源头使用来看,TCs和FQs抗生素广泛应用于人类医药及兽药,使用量大.从抗生素自身性质来看,FQs和TCs抗生素具有更高 K_d (土壤-水分配系数)值,更容易被沉积物颗粒吸附.而具有较少官能团的MLs和SAs抗生素对固相介质的吸附较弱,迁移性更强,易在地下水中扩散^[21].整体上,武汉市表层沉积物中抗生素的残留水平与其他沉积物相比处于较低水平^[9, 29-33].就TCs抗生素而言,武汉市沉积物中 ω (DOC)和 ω (CTC)最大值($0.27 \mu\text{g}\cdot\text{kg}^{-1}$ 和 $1.73 \mu\text{g}\cdot\text{kg}^{-1}$)均低于白洋淀($1.32 \mu\text{g}\cdot\text{kg}^{-1}$ 和 $2.12 \mu\text{g}\cdot\text{kg}^{-1}$)、重庆菜地($11.25 \mu\text{g}\cdot\text{kg}^{-1}$ 和 $13.50 \mu\text{g}\cdot\text{kg}^{-1}$)和江汉平原养殖场($70.8 \mu\text{g}\cdot\text{kg}^{-1}$ 和 $28.9 \mu\text{g}\cdot\text{kg}^{-1}$)沉积物,而 ω (OTC)最大值($96.42 \mu\text{g}\cdot\text{kg}^{-1}$)却远高于白洋淀($7.53 \mu\text{g}\cdot\text{kg}^{-1}$)、重庆菜地($42.88 \mu\text{g}\cdot\text{kg}^{-1}$)、上海青浦区($22.76 \mu\text{g}\cdot\text{kg}^{-1}$)和江汉平原养殖场($35.5 \mu\text{g}\cdot\text{kg}^{-1}$)沉积物.对于FQs抗生素来说,除了OFL,武汉市沉积物中剩余几种FQs抗生素含量均低于其他沉积物.武汉市沉积物中 ω (OFL)最大值为 88.63

$\mu\text{g}\cdot\text{kg}^{-1}$,低于白洋淀($259.80 \mu\text{g}\cdot\text{kg}^{-1}$)和雄安新区($176.24 \mu\text{g}\cdot\text{kg}^{-1}$)沉积物,高于重庆菜地($7.87 \mu\text{g}\cdot\text{kg}^{-1}$)、上海青浦区(未检出)和石家庄市($12.09 \mu\text{g}\cdot\text{kg}^{-1}$)沉积物.武汉市表层沉积物中 ω (MLs)均低于 $0.5 \mu\text{g}\cdot\text{kg}^{-1}$,低于其他地区沉积物.与上海青浦区沉积物结果类似,在所有SAs抗生素中,武汉市沉积物中 ω (SMX)最大值($19.63 \mu\text{g}\cdot\text{kg}^{-1}$)最高,但远低于青浦区沉积物($688.59 \mu\text{g}\cdot\text{kg}^{-1}$).

在垂向分布上,武汉市沉积物中抗生素含量并不随着深度增加而单向减少,这与污染来源和地下环境的复杂性有关.与江汉平原养殖场沉积物中抗生素的分布类似,抗生素主要在浅部的黏土层富集^[9].但是在江汉平原养殖场20 m的深层沉积物中未检测出任何抗生素,而武汉沉积物深部依然有少量OFL和OTC的检出.同样的,垃圾填埋场沉积物中抗生素在垂向上也呈现着随着深度的增加而波动的趋势^[34],这与太湖、玄武湖和五龙潭30 cm深的湖泊沉积柱中抗生素的含量随着深度的增加而降低不同^[35].整体上,武汉市沉积物中抗生素的迁移主要受沉积物粒径分布和地下水位波动的控制.

武汉市医院附近深层沉积物中仍有抗生素残留,除了部分从医院废水渗漏进入地下环境外,还有部分可能是从地下水中截留.武汉市上层滞水埋深浅,受地表水直接补给,长江武汉段深切孔隙承压水,地表水-地下水交互作用强烈^[17,18].因此抗生素随生活污水、医院废水和养殖废水进入湖泊河流后,易随地表水补给地下水进入地下水中,并被沉积物颗粒截留.在城市地区,医院常常被看作抗生素排放的主要热库^[19,20,36].在发展较早的城市中,污水管网老化渗漏的情况时常发生,医院废水外溢进入地下环境并迁移至含水层中会给城市供水安全带来风险和挑战.因此,未来在城市地区尤其是医院和垃圾填埋场周边管网系统进行渗漏排查至关重要,另外,还需定期做好医院周边地下水和沉积物中抗生素污染的监测,以便及时做好抗生素污染的风险管控.

3.2 影响沉积物中抗生素分布的环境因子

已有研究发现,抗生素在沉积物中迁移受抗生素自身的性质、沉积物中黏土矿物的种类、铁锰矿物的含量、酸碱度和有机质含量的高低等多种因素共同影响^[37-40].本研究中抗生素含量与部分环境因子呈现相关关系,其中pH与多类抗生素呈显著正相关关系($P < 0.05$),pH可以通过改变抗生素的表面电荷分布,进而影响沉积物对抗生素的吸附作用^[41].当pH在7~8之间时,TCs在水中以阴离子呈现,沉积物中存在较高含量的二价阳离子如 Ca^{2+} ,可以通过阳离子桥键的方式,把TCs结构中的负电荷和黏土表面

表 3 典型表层沉积物中抗生素的含量水平¹⁾/μg·kg⁻¹
Table 3 Concentration levels of antibiotics in typical surface sediments/μg·kg⁻¹

抗生素		白洋淀	重庆菜地	上海青浦区	石家庄市	江汉平原养殖场	雄安新区
TCs	OTC	0.49 ~ 7.53	ND ~ 42.88	ND ~ 22.76	—	ND ~ 35.50	—
	DOC	1.03 ~ 1.32	ND ~ 11.25	ND ~ 2.42	—	ND ~ 70.80	—
	TC	0.42 ~ 0.85	ND ~ 25.31	—	—	—	—
	CTC	1.25 ~ 2.12	ND ~ 13.50	—	—	ND ~ 28.90	—
FQs	CIP	—	ND ~ 34.34	—	7.03 ~ 20.47	ND ~ 39.30	0.02 ~ 21.91
	NOR	—	1.75 ~ 32.23	—	4.21 ~ 82.54	ND ~ 54.40	ND ~ 15.30
	LOM	—	ND ~ 14.06	—	—	ND ~ 15.50	—
	ENR	ND ~ 12.96	ND ~ 6.45	ND	1.46 ~ 7.27	ND ~ 33.70	ND ~ 36.21
	OFL	4.54 ~ 259.80	0.58 ~ 7.87	ND	0.02 ~ 12.09	—	ND ~ 176.24
	SPA	—	—	—	—	—	—
MLs	AZM	—	ND ~ 6.45	—	—	ND ~ 1.10	ND ~ 2.47
	CTM	—	—	—	—	ND ~ 1.00	ND ~ 4.95
	RTM	—	ND	—	—	ND ~ 1.10	ND ~ 47.23
	AEM	—	ND	ND ~ 0.96	—	ND ~ 20.80	ND ~ 0.80
SAs	STZ	ND ~ 0.41	ND ~ 0.29	—	—	ND	ND
	SMZ	ND ~ 0.32	ND	ND ~ 3.18	—	ND	ND ~ 5.77
	SMX	ND ~ 0.81	ND	1.27 ~ 688.59	—	ND ~ 3.50	ND ~ 0.58
	SDZ	ND ~ 1.94	ND	—	—	ND ~ 2.50	ND
	SQX	—	ND ~ 10.63	—	—	—	ND ~ 3.20
	SMP	ND ~ 0.24	—	—	—	—	ND
	SPD	ND ~ 5.59	—	ND	—	—	ND ~ 12.82
	SMR	ND ~ 0.28	—	ND ~ 0.98	—	ND	ND
Ac-SAs	Ac-SMZ	—	—	—	—	—	—
	Ac-SMR	—	—	—	—	—	—
	Ac-SDZ	—	—	—	—	—	—
	Ac-SMX	—	—	—	—	—	—

1)ND 表示未检出,“—”表示无数据

的负电荷连接起来,从而增加了土壤对四环素类抗生素的吸附^[42]. TOC 与 FQs 抗生素呈显著正相关($P < 0.05$),沉积物中的矿质组分对 FQs 抗生素有较强的吸附作用,且有机质的吸附作用强于土壤矿物^[43]. 此外,Cu、Fe 和 Zn 等金属阳离子和黏粒组分也影响着抗生素的分布. 金属阳离子的桥键作用会对黏土矿物吸附抗生素产生影响,抗生素与二价金属阳离子络合可以显著增强蒙脱石类黏土矿物对抗生素的吸附^[44]. 研究区沉积物中铁含量较高,在富铁的沉积物中铁氧化物对抗生素有一定的吸附作用^[45].

4 结论

(1)武汉市医院附近沉积物中检出 25 种抗生素,主要抗生素为 OFL、OTC、SMX 和 NOR,对应的含量平均值分别为 11.87、7.42、1.12 和 0.08 μg·kg⁻¹.

(2)武汉市表层沉积物中抗生素的残留水平与其他区域沉积物相比处于较低水平,抗生素主要富集在上部黏土层,但是在 20 ~ 30 m 的深层沉积物中仍然有抗生素检出.

(3)不同于其他类抗生素,SAs 抗生素在深处有

较高检出,P03 柱 12 m 处检测出最高的 ω(SMX) (19.63 μg·kg⁻¹),这与 SAs 抗生素迁移性好、易随地下水的波动迁移至深层有关.

(4)多种因素如 pH、TOC、Fe 的含量和黏粒占比通过影响沉积物对抗生素的吸附来控制抗生素在沉积物中的迁移.

参考文献:

[1] Yang Y Y, Song W J, Lin H, *et al.* Antibiotics and antibiotic resistance genes in global lakes: a review and meta-analysis [J]. *Environment International*, 2018, **116**: 60-73.

[2] Chen X P, Lei L, Liu S T, *et al.* Occurrence and risk assessment of pharmaceuticals and personal care products (PPCPs) against COVID-19 in lakes and WWTP-river-estuary system in Wuhan, China[J]. *Science of the Total Environment*, 2021, **792**, doi: 10.1016/j.scitotenv. 2021. 148352.

[3] 杨聪, 童蕾, 马乃进, 等. 洪湖水体和沉积物中抗生素的分布特征及其影响因素研究[J]. *安全与环境工程*, 2022, **29**(5): 78-90.

Yang C, Tong L, Ma N J, *et al.* Distribution characteristics and influencing factors of antibiotics in water and sediments of Honghu lake [J]. *Safety and Environmental Engineering*, 2022, **29**(5): 78-90.

[4] Singh R, Singh A P, Kumar S, *et al.* Antibiotic resistance in major rivers in the world: a systematic review on occurrence, emergence,

- and management strategies [J]. *Journal of Cleaner Production*, 2019, **234**: 1484-1505.
- [5] Kim S C, Carlson K. Temporal and spatial trends in the occurrence of human and veterinary antibiotics in aqueous and river sediment matrices [J]. *Environmental Science & Technology*, 2007, **41** (1): 50-57.
- [6] Zainab S M, Junaaid M, Xu N, *et al.* Antibiotics and antibiotic resistant genes (ARGs) in groundwater: a global review on dissemination, sources, interactions, environmental and human health risks [J]. *Water Research*, 2020, **187**, doi: 10.1016/j.watres.2020.116455.
- [7] Gray A D, Todd D, Hershey A E. The seasonal distribution and concentration of antibiotics in rural streams and drinking wells in the piedmont of North Carolina [J]. *Science of the Total Environment*, 2020, **710**, doi: 10.1016/j.scitotenv.2019.136286.
- [8] Huang F Y, Zou S Z, Deng D D, *et al.* Antibiotics in a typical karst river system in China: Spatiotemporal variation and environmental risks [J]. *Science of the Total Environment*, 2019, **650**: 1348-1355.
- [9] Tong L, Qin L T, Xie C, *et al.* Distribution of antibiotics in alluvial sediment near animal breeding areas at the Jiangnan Plain, Central China [J]. *Chemosphere*, 2017, **186**: 100-107.
- [10] Xu W H, Yan W, Li X D, *et al.* Antibiotics in riverine runoff of the Pearl River Delta and Pearl River Estuary, China: concentrations, mass loading and ecological risks [J]. *Environmental Pollution*, 2013, **182**: 402-407.
- [11] Harrower J, McNaughtan M, Hunter C, *et al.* Chemical fate and partitioning behavior of antibiotics in the aquatic environment-A review [J]. *Environmental Toxicology and Chemistry*, 2021, **40** (12): 3275-3298.
- [12] Kümmerer K. Antibiotics in the aquatic environment-A review-Part I [J]. *Chemosphere*, 2009, **75**(4): 417-434.
- [13] Gao F Z, Zou H Y, Wu D L, *et al.* Swine farming elevated the proliferation of *Acinetobacter* with the prevalence of antibiotic resistance genes in the groundwater [J]. *Environment International*, 2020, **136**, doi: 10.1016/j.envint.2020.105484.
- [14] Liu H, Liang H C, Liang Y, *et al.* Distribution of phthalate esters in alluvial sediment: a case study at Jiangnan Plain, Central China [J]. *Chemosphere*, 2010, **78**(4): 382-388.
- [15] Zhou J L, Fileman T W, Evans S, *et al.* The partition of fluoranthene and pyrene between suspended particles and dissolved phase in the Humber Estuary: a study of the controlling factors [J]. *Science of the Total Environment*, 1999, **243-244**: 305-321.
- [16] Maskaoui K, Zhou J L. Colloids as a sink for certain pharmaceuticals in the aquatic environment [J]. *Environmental Science and Pollution Research*, 2010, **17**(4): 898-907.
- [17] Gan Y Q, Wang Y X, Duan Y H, *et al.* Hydrogeochemistry and arsenic contamination of groundwater in the Jiangnan Plain, central China [J]. *Journal of Geochemical Exploration*, 2014, **138**: 81-93.
- [18] 梁杏, 张婧玮, 蓝坤, 等. 江汉平原地下水化学特征及水流系统分析 [J]. *地质科技通报*, 2020, **39**(1): 21-33.
- Liang X, Zhang J W, Lan K, *et al.* Hydrochemical characteristics of groundwater and analysis of groundwater flow systems in Jiangnan Plain [J]. *Bulletin of Geological Science and Technology*, 2020, **39**(1): 21-33.
- [19] Herrmann M, Olsson O, Fiehn R, *et al.* The significance of different health institutions and their respective contributions of active pharmaceutical ingredients to wastewater [J]. *Environment International*, 2015, **85**: 61-76.
- [20] Verlicchi P, Al Aukidy M, Jelic A, *et al.* Comparison of measured and predicted concentrations of selected pharmaceuticals in wastewater and surface water: a case study of a catchment area in the Po Valley (Italy) [J]. *Science of the Total Environment*, 2014, **470-471**: 844-854.
- [21] Tolls J. Sorption of veterinary pharmaceuticals in soils: a review [J]. *Environmental Science & Technology*, 2001, **35**(17): 3397-3406.
- [22] Li Y W, Wu X L, Mo C H, *et al.* Investigation of sulfonamide, tetracycline, and quinolone antibiotics in vegetable farmland soil in the Pearl River Delta area, southern China [J]. *Journal of Agricultural and Food Chemistry*, 2011, **59**(13): 7268-7276.
- [23] Sun J T, Zeng Q T, Tsang D C W, *et al.* Antibiotics in the agricultural soils from the Yangtze River Delta, China [J]. *Chemosphere*, 2017, **189**: 301-308.
- [24] Hu X G, Zhou Q X, Luo Y. Occurrence and source analysis of typical veterinary antibiotics in manure, soil, vegetables and groundwater from organic vegetable bases, northern China [J]. *Environmental Pollution*, 2010, **158**(9): 2992-2998.
- [25] Li C, Chen J Y, Wang J H, *et al.* Occurrence of antibiotics in soils and manures from greenhouse vegetable production bases of Beijing, China and an associated risk assessment [J]. *Science of the Total Environment*, 2015, **521-522**: 101-107.
- [26] An J, Chen H W, Wei S H, *et al.* Antibiotic contamination in animal manure, soil, and sewage sludge in Shenyang, Northeast China [J]. *Environmental Earth Sciences*, 2015, **74**(6): 5077-5086.
- [27] 赵方凯, 杨磊, 李守娟, 等. 长三角典型城郊土壤抗生素空间分布的影响因素研究 [J]. *环境科学学报*, 2018, **38**(3): 1163-1171.
- Zhao F K, Yang L, Li S J, *et al.* Affecting factors of the spatial distribution of antibiotics in soils in typical periurban area of Yangtze River Delta [J]. *Acta Scientiae Circumstantiae*, 2018, **38** (3): 1163-1171.
- [28] 赵方凯, 陈利顶, 杨磊, 等. 长三角典型城郊不同土地利用土壤抗生素组成及分布特征 [J]. *环境科学*, 2017, **38**(12): 5237-5246.
- Zhao F K, Chen L D, Yang L, *et al.* Composition and distribution of antibiotics in soils with different land use types in a typical periurban area of the Yangtze River Delta [J]. *Environmental Science*, 2017, **38**(12): 5237-5246.
- [29] 宋圆梦, 赵波, 卢梦淇, 等. 白洋淀典型抗生素的源解析及其特定源风险评估 [J]. *环境科学*, 2023, **44**(9): 4927-4940.
- Song M Y, Zhao B, Lu M Q, *et al.* Source apportionment and source-specific risk of typical antibiotics in Baiyangdian lake [J]. *Environmental Science*, 2023, **44**(9): 4927-4940.
- [30] 方林发, 叶苹苹, 方标, 等. 重庆开州区菜地土壤抗生素污染特征及潜在生态环境风险评估 [J]. *环境科学*, 2022, **43**(11): 5244-5252.
- Fang L F, Ye P P, Fang B, *et al.* Pollution characteristics and ecological risk assessment of antibiotics in vegetable field in Kaizhou, Chongqing [J]. *Environmental Science*, 2022, **43**(11): 5244-5252.
- [31] 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.
- [32] 赵鑫宇, 陈慧, 赵波, 等. 石家庄市土壤中喹诺酮类抗生素时空分布及其风险评估[J]. *环境科学*, 2023, **44**(4): 2223-2233.
Zhao X Y, Chen H, Zhao B, *et al.* Spatial-temporal distribution and risk assessment of Quinolone antibiotics in soil for Shijiazhuang city[J]. *Environmental Science*, 2023, **44**(4): 2223-2233.
- [33] Fu C X, Xu B T, Chen H, *et al.* Occurrence and distribution of antibiotics in groundwater, surface water, and sediment in Xiong'an New Area, China, and their relationship with antibiotic resistance genes [J]. *Science of the Total Environment*, 2022, **807**, doi: 10.1016/j.scitotenv.2021.151011.
- [34] Li H, Qiu L B, Chen B H, *et al.* Vertical distribution of antibiotics and antibiotic resistance genes in a representative municipal solid waste landfill, China[J]. *Ecotoxicology and Environmental Safety*, 2022, **242**, doi: 10.1016/j.ecoenv.2022.113919.
- [35] Ohore O E, Addo F G, Han N N, *et al.* Profiles of ARGs and their relationships with antibiotics, metals and environmental parameters in vertical sediment layers of three lakes in China[J]. *Journal of Environmental Management*, 2020, **255**, doi: 10.1016/j.jenvman.2019.109583.
- [36] Cai M, Wang Z L, Gu H T, *et al.* Occurrence and temporal variation of antibiotics and antibiotic resistance genes in hospital inpatient department wastewater: impacts of daily schedule of inpatients and wastewater treatment process [J]. *Chemosphere*, 2022, **292**, doi: 10.1016/j.chemosphere.2021.133405.
- [37] Kemper N. Veterinary antibiotics in the aquatic and terrestrial environment[J]. *Ecological Indicators*, 2008, **8**(1): 1-13.
- [38] Förster M, Laabs V, Lamshöft M, *et al.* Sequestration of manure-applied sulfadiazine residues in soils[J]. *Environmental Science & Technology*, 2009, **43**(6): 1824-1830.
- [39] Boy-Roura M, Mas-Pla J, Petrovic M, *et al.* Towards the understanding of antibiotic occurrence and transport in groundwater: Findings from the Baix Fluvià alluvial aquifer (NE Catalonia, Spain) [J]. *Science of the Total Environment*, 2018, **612**: 1387-1406.
- [40] Loftin K A, Adams C D, Meyer M T, *et al.* Effects of ionic strength, temperature, and pH on degradation of selected antibiotics [J]. *Journal of Environmental Quality*, 2008, **37**(2): 378-386.
- [41] Zhao K, Gao L, Zhang Q R, *et al.* Accumulation of sulfamethazine and ciprofloxacin on grain surface decreases the transport of biochar colloids in saturated porous media [J]. *Journal of Hazardous Materials*, 2021, **417**, doi: 10.1016/j.jhazmat.2021.125908.
- [42] Hari A C, Paruchuri R A, Sabatini D A, *et al.* Effects of pH and cationic and nonionic surfactants on the adsorption of pharmaceuticals to a natural aquifer material [J]. *Environmental Science & Technology*, 2005, **39**(8): 2592-2598.
- [43] 王春红, 梁巍, 薛爱芳, 等. 兽药抗生素在土壤中行为的研究进展[J]. *华中农业大学学报*, 2010, **29**(2): 245-250.
Wang C H, Liang W, Xue A F, *et al.* Advances on the performance of veterinary antibiotics in soil [J]. *Journal of Huazhong Agricultural University*, 2010, **29**(2): 245-250.
- [44] Wang Y J, Jia D A, Sun R J, *et al.* Adsorption and cosorption of tetracycline and copper (II) on montmorillonite as affected by solution pH [J]. *Environmental Science & Technology*, 2008, **42**(9): 3254-3259.
- [45] Figueroa R A, MacKay A A. Sorption of oxytetracycline to iron oxides and iron oxide-rich soils [J]. *Environmental Science & Technology*, 2005, **39**(17): 6664-6671.

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