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《环境科学》征订启事(4061) 《环境科学》征稿简则(4132) 信息(4233, 4293, 4304)

# 莲花水库水体中抗生素污染特征及生态风险评价

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**摘要:** 采用固相萃取-高效液相色谱串联质谱法对厦门市新建饮用水源地莲花水库中4类(四环素类、喹诺酮类、大环内酯类和磺胺类)13种典型抗生素进行了检测,并评价了其污染特征和生态风险等级.结果表明,除红霉素、磺胺二甲嘧啶和磺胺甲噁唑外,其余10种抗生素均有不同程度检出,总浓度范围为 n. d. ~925.26 ng·L<sup>-1</sup>. 其中阿奇霉素的浓度最高(n. d. ~232.61 ng·L<sup>-1</sup>),检出率为75%;其次为恩诺沙星(n. d. ~187.69 ng·L<sup>-1</sup>)、四环素(n. d. ~155.05 ng·L<sup>-1</sup>)和环丙沙星(n. d. ~83.66 ng·L<sup>-1</sup>),检出率均超过60%. 抗生素浓度随采样点呈现出上游莲花溪 S1 > 澳溪支流 S2 > 库区下游 S3 > 入库口 S4 > 库区中心 S5 的趋势. 抗生素季节分布特征较为明显,枯水期总浓度明显高于丰水期和平水期. 生态环境风险评价表明氧氟沙星、恩诺沙星和环丙沙星的生态环境风险较高,环丙沙星为主要风险因子;枯水期的抗生素联合风险商值比丰水期和平水期高,且大于1,对生态环境存在较高风险,应引起相关部门足够重视.

**关键词:** 抗生素; 污染特征; 生态风险评价; 饮用水源; 莲花水库

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## Pollution Characteristics and Risk Assessment of Antibiotics in Lianhua Reservoir

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**Abstract:** Thirteen typical antibiotics in surface water of the Lianhua Reservoir were analyzed using HPLC/MS/MS to assess the pollution characteristics and risk levels. Ten antibiotics except for erythromycin, sulfadiazine, and sulfamethoxazole were detected in surface water and the total concentration of antibiotics varied between non-detectable (n. d.) and 925.26 ng·L<sup>-1</sup>. Azithromycin had the highest concentration (n. d. ~232.61 ng·L<sup>-1</sup>) with the detection frequency of 75%, followed by enrofloxacin (n. d. ~187.69 ng·L<sup>-1</sup>), tetracycline (n. d. ~155.05 ng·L<sup>-1</sup>), and ciprofloxacin (n. d. ~83.66 ng·L<sup>-1</sup>) with the detection frequencies over 60%. The spatial distribution of antibiotics was as follows: total concentration of upstream (sampling point 1) > Aoxi River stream tributary (sampling point 2) > reservoir downstream (sampling point 3) > reservoir entrance (sampling point 4) > reservoir area (sampling point 5). The seasonal variations in the concentrations of antibiotics were evident; total concentrations in the dry season were significantly higher than those in the wet and normal seasons. The results of the environmental risk assessment indicated that ofloxacin, enrofloxacin, and ciprofloxacin pose significant risks to the environment. In the Lianhua Reservoir, ciprofloxacin showed high potential risk to the ecological environment, while the environmental risks of other antibiotics in the reservoir were below the medium level. The combined risk value of the antibiotics in the dry season was higher than that in the wet and normal seasons.

**Key words:** antibiotics; pollution characteristics; ecological risk assessment; drinking water source; Lianhua Reservoir

抗生素是由微生物或高等动植物在生产活动中所产生的具有抗病原体或其它活性的一类次级代谢产物,除被广泛应用于医疗领域,还在畜牧业和水产养殖业中大量使用,主要用于防治感染性疾病以及作为抗菌生长促进剂促进动物生长<sup>[1]</sup>.但是,大部分抗生素并没有得到有效利用,常常未经代谢便通过粪便或者尿液排出体外<sup>[2]</sup>.由于该类药物在水中浓度低、难降解、易重构,且对微生物具有抑制作用,使得它们在水中得以长期存在<sup>[3,4]</sup>.残留的抗生素最终进入自然水体中影响饮用水源地水质安

全<sup>[5]</sup>.近年来,抗生素污染特征的研究主要集中在河流<sup>[6,7]</sup>、河口湾<sup>[8]</sup>、地下水<sup>[9]</sup>和污水处理厂<sup>[10]</sup>等水环境中,而作为我国近年来才广受关注的新型有机污染物之一,抗生素在饮用水源地水体中的污染

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情况还鲜有报道。

莲花水库是厦门市新建的重要饮用水源型水库. 目前, 对于莲花水库的抗生素的污染特征和风险评价等研究还尚属空白. 因此, 本研究以莲花水库这一典型饮用水源水库为对象, 采集其丰水期、平水期和枯水期的水库库区及上游支流的水样, 分析水样中 4 类 13 种典型抗生素的污染浓度水平, 并基于风险商模型评价莲花水库水体中抗生素的生态环境风险, 有助于揭示莲花水库的抗生素的空间分布特征和季节变化规律, 以期为莲花水库的抗生素风险评价及饮用水源保障提供基础数据和决策依据。

## 1 材料与方 法

### 1.1 样品采集

2018 年分别在丰水期(4 月)、平水期(8 月)和枯水期(11 月)进行采样. 根据莲花水库及其主要入库支流的环境与水文基本特征, 本研究布设了 5 个采样点, 分别为上游莲花溪采样点 S1、入库支流澳溪采样点 S2、莲花水库库区采样点 S3 ~ S5, 采用北斗 GPS 手持机定位, 具体位置见图 1. 使用不锈钢水样采集器采集表层水, 采集深度为水面以下 0.5 m 处, 置于棕色玻璃瓶内, 用冰块保持低温环境, 运回实验室并尽快进行水样预处理。

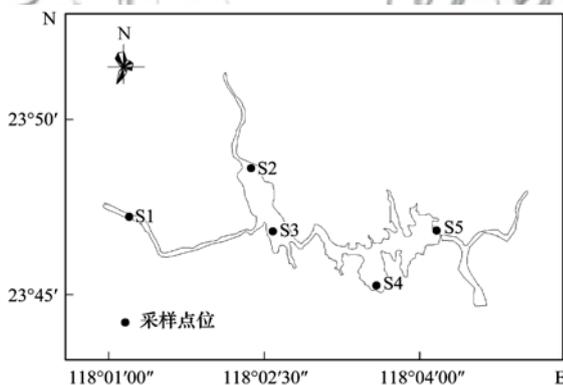


图 1 莲花水库采样点位示意

Fig. 1 Sampling sites in Lianhua Reservoir

### 1.2 仪器与试剂

仪器: 超高效液相色谱串联质谱仪 (ABI3200Q TRAP HPLC/MS/MS System, Agilent, USA), 色谱柱 Kinetex<sup>®</sup> C18 柱 (2.6  $\mu\text{m}$ , 100  $\times$  4.6 mm, Phenomenex), 固相萃取装置 (Waters 公司, USA), OASIS HLB 固相萃取小柱 (500 mg, 6 mL, CNW), 恒温水浴氮吹仪 (N-EVAP<sup>TM</sup> 111 氮吹仪, OA-SYS<sup>TM</sup> 水浴加热装置, Organomation 公司, USA), 真空干燥箱 (DZF-6050, 中国), 北斗 GPS 手持机 (彩途 F32, 中国), 酸碱 pH 计 (pH2100, 中国), 玻璃纤维滤膜 (上海半岛实业有限公司净化器材厂, 孔径 0.45

$\mu\text{m}$ ).

试剂药品及耗材: 标准品土霉素 (oxytetracycline, OTC)、四环素 (tetracycline, TC)、金霉素 (chlortetracycline, CTC)、罗红霉素 (roxithromycin, RTM)、红霉素 (erythromycin, ETM)、阿奇霉素 (azithromycin, AZM)、磺胺甲噁唑 (sulfamethoxazole, SMX)、磺胺嘧啶 (sulfadiazine, SDZ)、SMZ (sulfamethazine, SMZ)、氧氟沙星 (ofloxacin, OFL)、环丙沙星 (ciprofloxacin, CIP)、恩诺沙星 (enrofloxacin, ENR) 和二氟沙星 (difloxacin, DIF) 均购自生工生物工程(上海)股份有限公司(纯度均大于 95%), 甲酸购自天津科密欧化学试剂有限公司(色谱纯), 甲醇和乙腈购自 Tedia 公司(色谱纯), 实验中用水均为超纯水 (Millipore 超纯水系统, USA)。

### 1.3 仪器分析条件

采用超高效液相色谱串联质谱仪进行分析检测. 色谱条件: 采用梯度洗脱, 柱温 40 $^{\circ}\text{C}$ ; 进样量 10  $\mu\text{L}$ ; 流速为 0.5  $\text{mL}\cdot\text{min}^{-1}$ . 正离子模式时流动相 A 路为 5  $\text{mmol}\cdot\text{L}^{-1}$  乙酸铵的 0.1% 甲酸水溶液, 流动相 B 路为甲醇. 具体梯度洗脱程序如表 1.

质谱条件: 采用 ESI 电离源, 检测方式为多反应监测 (MRM); 离子源 I (GS1) 和 II (GS2) 的气流量分别为 50  $\text{mL}\cdot\text{min}^{-1}$  和 60  $\text{mL}\cdot\text{min}^{-1}$ , 电力电压为 5 500 V; 辅助加热气温度为 550 $^{\circ}\text{C}$ .

表 1 梯度洗脱程序

时间/min	流动相 A/%	流动相 B/%
0.01	90	10
6.50	80	20
8.00	80	20
8.01	90	10
12.0	90	10

### 1.4 样品预处理

准确量取 1 L 水样, 过 0.45  $\mu\text{m}$  玻璃纤维滤膜过滤, 加入 0.2 g  $\text{Na}_2\text{EDTA}$ , 用 1  $\text{mol}\cdot\text{L}^{-1}$  盐酸调节 pH 值为 3. HLB 固相萃取小柱依次用 6 mL 甲醇和 6 mL 超纯水活化. 水样以 3 ~ 5  $\text{mL}\cdot\text{min}^{-1}$  流速通过 HLB 固相萃取小柱, 水样萃取完后, 用 6 mL 超纯水冲淋, 将萃取柱放入真空干燥箱干燥 30 min, 最后用 6 mL 甲醇洗脱. 收集的洗脱液在水浴 40 $^{\circ}\text{C}$  条件下经氮气缓慢地吹干, 用 20% 的甲醇水溶液定容至 1 mL, 经 0.22  $\mu\text{m}$  滤膜过滤后 -20 $^{\circ}\text{C}$  保存, 待进样分析。

### 1.5 质量控制

采用外标法进行定量分析, 线性方程浓度范围

由 0、10、20、50、100、200 和 250  $\mu\text{g}\cdot\text{L}^{-1}$  这 7 个浓度值组成,其  $R^2$  值大于 0.99. 在 1 L 的纯水和原水中加入 20 ng 和 200 ng 的 13 种抗生素混标,同时测空白组分中抗生素含量,计算加标回收率,每组 3 个平行样. 结果表明,13 种抗生素的纯水加标回收率为 86.67% ~ 121.52%,原水的加标回收率为 80.70% ~ 102.90%,相对标准偏差(RSD)为 3.45% ~ 12.85%.

### 1.6 生态风险评价

根据欧洲技术指导文件(European commission technical guidance document, TGD)中关于环境风险的评价方法,采用风险商值法(risk quotient, RQ)评

估厦门市莲花水库的生态环境风险,计算公式如下:

$$RQ = MEC/PNEC \quad (1)$$

$$RQ_{\text{sum}} = \sum RQ_i \quad (2)$$

式中,RQ 表示生态风险商;MEC 表示水体中抗生素被检出的浓度,  $\text{ng}\cdot\text{L}^{-1}$ ;PNEC 表示抗生素的预测无效应浓度,  $\text{ng}\cdot\text{L}^{-1}$ ;本研究中 PNEC 值参考相关研究(表 2),除了 DIF 未有相关研究外,其余 12 种抗生素急性或者慢性的毒理数据见表 2.  $RQ_{\text{sum}}$  表示叠加的联合抗生素生态风险商. 根据 RQ 值的大小,可分为 4 个生态环境风险等级. 当 RQ 小于 0.01 为无风险,在 0.01 ~ 0.1 之间为低风险,在 0.1 ~ 1 之间为中等风险,大于 1 为高风险.

表 2 抗生素对应最敏感物种的毒理数据

Table 2 Toxicological data of antibiotics for the most sensitive aquatic species

抗生素	受试物种	毒性类型	评估因子	PNEC/ $\text{ng}\cdot\text{L}^{-1}$	文献
OTC	<i>P. subcapitata</i>	急性	1 000	1 040	[11]
TC	<i>P. subcapitata</i>	急性	1 000	3 310	[12]
CTC	<i>Chlorella vulgaris</i>	急性	1 000	9 310	[13]
RTM	<i>P. subcapitata</i>	急性	1 000	100	[14]
ETM	<i>P. subcapitata</i>	急性	1 000	20	[15]
AZM	<i>Daphnia sp.</i>	急性	1 000	12 000	[16]
SDZ	<i>S. capricornutum</i>	急性	100	2 200	[17]
SMZ	<i>Lemna minor</i>	急性	1 000	17 400	[18]
SMX	<i>S. leopoliensis</i>	急性	1 000	27	[19]
OFL	<i>P. subcapitata</i>	慢性	100	11.3	[20]
CIP	<i>M. aeruginosa</i>	急性	1 000	5	[11]
ENR	<i>M. aeruginosa</i>	急性	1 000	49	[21]

## 2 结果与讨论

### 2.1 莲花水库水体中抗生素污染水平

莲花水库不同采样点抗生素的检测结果显示.

由表 3 可知,在莲花水库的 5 个点除 ETM、SMZ

和 SMX 未检出外,10 种抗生素均有不同程度地检出. AZM 的检出率最高,为 75%. TC、CTC、CIP 和 OTC 检出率为 55% ~ 65%,其余 5 种抗生素的检出率在 10% ~ 50%. 总浓度水平在 n. d. ~ 925.26  $\text{ng}\cdot\text{L}^{-1}$ ,检出浓度最高的为 AZM,其次为 ENR、TC、CIP、RTM、CTC 和 OFL,其余抗生素的浓度均低于 50  $\text{ng}\cdot\text{L}^{-1}$ .

表 3 莲花水库水体中抗生素的总体检出水平/ $\text{ng}\cdot\text{L}^{-1}$

Table 3 Summary of antibiotic concentrations in Lianhua Reservoir/ $\text{ng}\cdot\text{L}^{-1}$

项目	OTC	TC	CTC	RTM	ETM	AZM	SDZ	SMZ	SMX	OFL	CIP	ENR	DIF	总和
最大值	40.93	155.05	58.69	72.58	0.00	232.61	11.96	0.00	0.00	54.03	83.66	187.69	28.04	925.26
最小值	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.	n. d.
平均值	8.25	24.53	11.04	8.14	0.00	39.09	0.73	0.00	0.00	6.53	13.86	20.43	4.28	136.88
中位数	3.43	1.60	2.51	n. d.	n. d.	3.19	n. d.	n. d.	n. d.	n. d.	1.07	n. d.	n. d.	11.80
检出率/%	55	65	65	40	0	75	10	0	0	50	60	45	45	

1) n. d. 表示未检出.

喹诺酮类抗生素的总检出浓度最高,为 352.43  $\text{ng}\cdot\text{L}^{-1}$ ,ENR 检出浓度最高,为 n. d. ~ 187.69  $\text{ng}\cdot\text{L}^{-1}$ ,平均 20.43  $\text{ng}\cdot\text{L}^{-1}$ ;其次是 CIP,为 83.66  $\text{ng}\cdot\text{L}^{-1}$ ,平均 13.86  $\text{ng}\cdot\text{L}^{-1}$ . 本研究中 CIP 浓度远低于海河流域天津地区(n. d. ~ 383  $\text{ng}\cdot\text{L}^{-1}$ ),但 ENR

浓度略高于海河流域天津地区(n. d. ~ 117  $\text{ng}\cdot\text{L}^{-1}$ )<sup>[22]</sup>. 白洋淀水体中 OFL (0.38 ~ 32.6  $\text{ng}\cdot\text{L}^{-1}$ )和 CIP(n. d. ~ 60.3  $\text{ng}\cdot\text{L}^{-1}$ )与本研究中的浓度较接近<sup>[23]</sup>. 这可能与近年来喹诺酮类抗生素的使用量增长较快密切相关<sup>[24,25]</sup>.

大环内酯类抗生素中 AZM 为 n. d. ~ 232.61  $\text{ng}\cdot\text{L}^{-1}$ , 平均 39.09  $\text{ng}\cdot\text{L}^{-1}$ , 居所有抗生素之首; 其次为 RTM, 达 72.58  $\text{ng}\cdot\text{L}^{-1}$ , 平均 8.14  $\text{ng}\cdot\text{L}^{-1}$ . 本研究中 RTM 浓度低于塞纳河 (n. d. ~ 350  $\text{ng}\cdot\text{L}^{-1}$ ) 而高于渭河关中段表层水 (7.6 ~ 114.46  $\text{ng}\cdot\text{L}^{-1}$ )<sup>[26,27]</sup>. 大环内酯类抗生素是一类微生物产生的具有内酯键的大环状生物活性物质, 结构稳定, 主要用于人类呼吸和消化系统疾病<sup>[28]</sup>. 莲花水库附近有居民生活区, 人口相对密集. 居民所产生的生活污水未经处理, 直接排入水体中, 因此可能导致该类抗生素浓度较高.

四环素类抗生素中 TC 为 n. d. ~ 155.05  $\text{ng}\cdot\text{L}^{-1}$ , 平均 24.53  $\text{ng}\cdot\text{L}^{-1}$ . TC 和 OTC 低于珠江广州段枯季的调查结果<sup>[29]</sup>. 吕敏等<sup>[30]</sup> 调查表明九龙江流域的 TC 浓度 (n. d. ~ 106  $\text{ng}\cdot\text{L}^{-1}$ ), 与本研究较为接近. 四环素类抗生素在水环境中性质不稳定, 较容易受到光照和微生物的影响而降解<sup>[31]</sup>, 因此在水环境中的检出浓度不高.

3 种磺胺类抗生素的检出浓度相对于喹诺酮类、大环内酯类和四环素类处于较低水平. 其中只有检出磺胺嘧啶, 且检出浓度处于较低的水平, 为 n. d. ~ 11.96  $\text{ng}\cdot\text{L}^{-1}$ , 检出率也最低. 金磊等<sup>[32]</sup> 研究了华东地区某饮用水源中磺胺类抗生素 (10.5 ~ 238.5  $\text{ng}\cdot\text{L}^{-1}$ ), 远高于本研究的水平. 磺胺类抗生素主要用于畜禽养殖业, 说明在该研究区域没有大量的畜禽养殖废水的排入.

总体来说, 除 AZM 和 CIP 处于较高的污染水平, 其余抗生素基本处于中等以下水平, 且抗生素在不同区域的使用和习惯等不同, 导致检出浓度和种类有着较大差异性.

## 2.2 莲花水库水体中抗生素的空间分布特征

抗生素在莲花水库的空间分布特征如图 2 所示. 莲花水库各采样点的抗生素总浓度处于 87.19 ~ 225.35  $\text{ng}\cdot\text{L}^{-1}$ . S1 点的抗生素总浓度最高 (225.35  $\text{ng}\cdot\text{L}^{-1}$ ), 该点处于水库上游莲花溪的中上游, 附近有林场, 树木种植区较常施用畜禽粪便可有机肥. 这可能是由于畜禽养殖业中使用的抗生素, 导致有机肥中有较高的抗生素浓度, 这些肥料经降雨冲刷后成为地表径流汇入周围的溪流中, 再加上溪边有零星分布的小型餐饮食杂店污水排放, 污染源较多, 导致了该处的抗生素浓度最高. 其次为 S5 点和 S2 点, 抗生素总浓度分别为 162.86  $\text{ng}\cdot\text{L}^{-1}$  和 158.17  $\text{ng}\cdot\text{L}^{-1}$ , 均低于上游莲花溪. S5 点位于水库库区出库口附近的下游区域, 周边居民人口密度较大, 村民有饲养家禽的习惯, 从而导致该点的抗生素浓度偏高. S2 点位于另一条入库支流澳溪上, 该点

附近有零散的居民区, 居住密度较小, 污染源较少, 只有生活污水的排放. S3 点位于莲花水库入库口, 抗生素总浓度较低 (101.85  $\text{ng}\cdot\text{L}^{-1}$ ); S4 点位于莲花水库库区的中间点, 抗生素总浓度最低 (87.19  $\text{ng}\cdot\text{L}^{-1}$ ), 这两个点受到人为活动影响较少, 污染源较少. 因此, 抗生素总浓度水平呈现为上游莲花溪 > 澳溪支流 > 库区下游 > 入库口 > 库区中心的趋势. 这与其污染输入来源及其扩散方向较为一致.

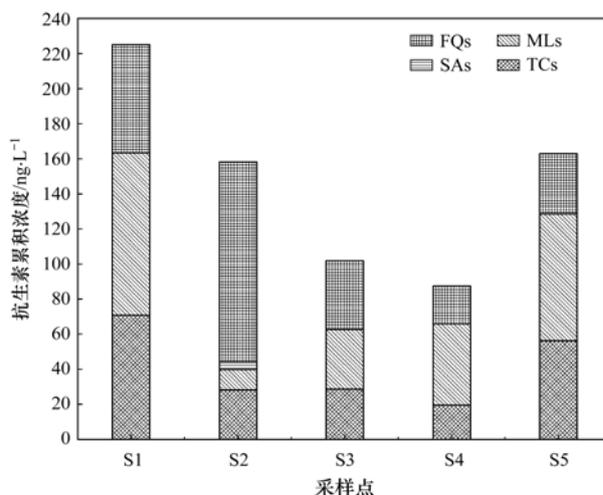


图 2 莲花水库各采样点抗生素累积浓度

Fig. 2 Accumulative concentration of detected antibiotics at each sampling site in Lianhua Reservoir

## 2.3 莲花水库水体中抗生素季节变化特征

莲花水库水体中抗生素季节变化特征如图 3 所示. 丰水期、平水期和枯水期的抗生素平均浓度的总和分别为 20.58、35.02 和 385.66  $\text{ng}\cdot\text{L}^{-1}$ . 枯水期的抗生素总浓度是丰水期和平水期的 11.01 ~ 18.50 倍, 呈现出枯水期明显高于丰水期和平水期的趋势, 这与中国香港维多利亚港和珠江广州河段的研究结果一致<sup>[33]</sup>. 由于上游莲花溪和澳溪支流都属于山间溪流, 比较短小, 受降雨量和地形的影响, 流量在丰水期和枯水期悬殊较大, 枯水期降雨量少, 溪流流量较小, 水体自净能力较差, 导致枯水期的抗生素残留浓度最高.

抗生素的季节变化特征不仅与降雨量、温度、光照强度和微生物活性等因素有关, 还与农田播种、水产养殖投苗、病虫害防治时抗生素药物的使用方式和时期密切相关<sup>[34,35]</sup>. 四环素类和大环内酯类抗生素在不同水期的浓度变化较大, 四环素类抗生素易光解, 而枯水期的光解及微生物代谢等作用较弱; 大环内酯类抗生素广泛用于人类, 冬季属于流感高发季节, 病毒活跃, 抗生素的使用量更大; 喹诺酮类抗生素变化幅度较小, 可能是因为喹诺酮类抗生素具有水解稳定性, 不易水解, 且光解能力较弱<sup>[36]</sup>; 磺胺类抗生素因检出浓度较低, 季节变化特征不明显.

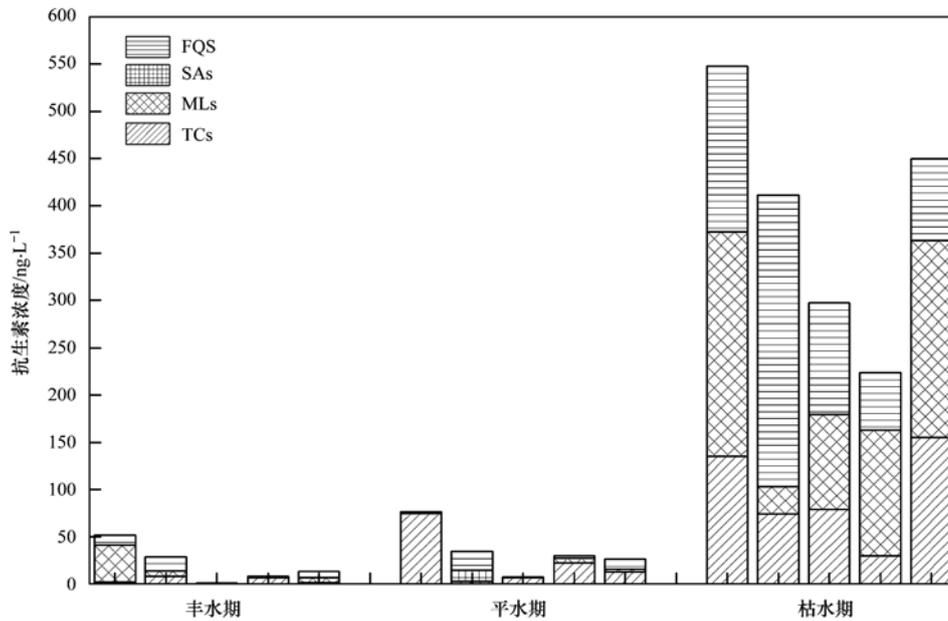


图 3 抗生素在莲花水库中的季节变化特征

Fig. 3 Seasonal changes in concentrations of antibiotics in Lianhua Reservoir

2.4 莲花水库水体中抗生素的生态风险评价  
基于最严重的风险情况, 选取 10 种抗生素的最

大检出浓度计算 RQ, 抗生素生态风险评价结果见  
表 4.

表 4 莲花水库水体抗生素的 RQ 和 RQ<sub>sum</sub>

Table 4 RQ and RQ<sub>sum</sub> for antibiotics in Lianhua Reservoir

抗生素	RQ	抗生素	RQ	采样点	RQ <sub>sum</sub>		
					丰水期	平水期	枯水期
OTC	0.039	SDZ	0	S1	0.261	0.360	19.84
TC	0.047	SMZ	0	S2	1.206	0.789	17.91
CTC	0.006	SMX	0	S3	0.161	0.030	8.798
RTM	0.726	OFL	4.782	S4	0	0.036	10.93
ETM	0	CIP	16.73	S5	0	0.040	9.014
AZM	0.019	ENR	3.83				

由表 4 可知, OFL、ENR 和 CIP 的 RQ 值均大于 1, 说明喹诺酮类抗生素处于较高的风险水平, 对莲花水库的生态环境有严重的潜在风险, 其中 CIP 最为突出, RQ 值最高达 16.73, 为莲花水库的主要风险因子. RTM 的 RQ 值介于 0.1 ~ 1, 处于中等风险水平; AZM、TC 和 OTC 的 RQ 值介于 0.01 ~ 0.1, 处于低风险水平; CTC、ETM 和磺胺类抗生素的 RQ 值均小于 0.01, 属于无风险. 虽然水环境中的抗生素残留对莲花水库的影响基本处于中等以下风险水平, 但有研究表明抗生素长期残留可诱导抗性基因的产生, 而抗性基因污染已成为新的环境问题<sup>[37]</sup>, 势必会对原有的水生生态系统产生影响.

由表 4 可知, 在丰水期, S2 点位的 RQ<sub>sum</sub> 大于 1, S1 和 S3 点的 RQ<sub>sum</sub> 均介于 0.1 ~ 1, 表现为中等风险; 在平水期, S1 和 S2 点位的 RQ<sub>sum</sub> 均大于 0.1; 其余点位都介于 0.01 ~ 0.1, 表现为低风险; 而在枯水期, 5 个采样点位的 RQ<sub>sum</sub> 均高于 1, 以 S1 点位较为突出, RQ<sub>sum</sub> 达 19.84. 因此, 枯水期的抗生素

RQ<sub>sum</sub> 比丰水期和平水期高, 且大于 1, 对生态环境存在较高风险. 由于水环境中抗生素的污染不是单一存在, 而是多种抗生素共同存在的复杂体系. 有研究表明水环境中多种抗生素共存时会产生毒性协同或加成作用进而增大水质健康风险<sup>[38]</sup>, 本研究仅仅用简单叠加风险商法来进行评价, 未考虑抗生素与其他类型污染物的协同和加成作用.

3 结论

(1) 莲花水库水体中 13 种抗生素, 除 ETM、SMZ 和 SMX 外, 均有不同程度检出. 总浓度水平在 n. d. ~ 232.61 ng·L<sup>-1</sup>, 检出浓度最高为 AZM, 其次为 ENR、TC、CIP、RTM、CTC 和 OFL. 除 AZM 和 CIP 处于较高的污染水平, 其余抗生素基本处于中等以下水平.

(2) 莲花水库各采样点抗生素总浓度在空间上具有一定的差异性, 呈现为上游莲花溪 > 澳溪支流 > 库区下游 > 入库口 > 库区中心的趋势, 与其污染

输入来源及其扩散方向较为一致;在时间上呈现出较为明显的季节分布特征,枯水期明显高于丰水期和平水期。

(3)生态风险评价结果表明,OFL、ENR 和 CIP 的生态环境风险较高,其中 CIP 为莲花水库的主要风险因子。枯水期的抗生素  $RQ_{sum}$  比丰水期和平水期高,大于 1,对生态环境存在较高风险。因此,开展对莲花水库的全面环境监测非常必要。

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