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三峡库区澎溪河河段间水华程度差异及其机制

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摘要: 三峡大坝蓄水以来, 库区 50% 一级支流水华频发, 且不同支流水华高发断面的地理位置不同, 受干流影响程度存在差异。为探讨水华暴发的河段差异, 及其与长江回水的关系, 以库区一级支流澎溪河为例, 在 2019 年春季水华季, 进行了间隔期一周、总时长一个月的采样, 从河口至上游设置 7 个采样断面 (PX1 ~ PX7), 根据各断面的垂向水温和电导率特征推断长江回水的影响范围和形式; 并通过对水华高发的高阳平湖断面 (PX5) 和分别距其 4 km 的上游断面 (PX6) 和下游断面 (PX4) 的水文、水质和底泥营养盐等指标, 探究断面间水华暴发程度的差异及其机制。结果表明, 水华季澎溪河下游 (PX1 ~ PX4) 的 $\rho(\text{Chl-a})$ 较低, 为 $14.55 \sim 44.00 \mu\text{g}\cdot\text{L}^{-1}$, 上游 (PX5 ~ PX7) 则达到 $42.66 \sim 175.40 \mu\text{g}\cdot\text{L}^{-1}$, 其中 PX5 的 $\rho(\text{Chl-a})$ 最高时达 $413.00 \mu\text{g}\cdot\text{L}^{-1}$, 显著高于其余位点 ($P < 0.05$)。温度和电导率结果显示, 4 ~ 5 月长江干流回水从中下层潜入澎溪河, 下游 (PX1 ~ PX4) 处于长江干流回水与澎溪河上游来水的交汇区域, 水体不稳定, 不利于水华暴发; 而澎溪河中上游 (PX5 ~ PX7) 未直接受到长江干流回水的影响, 营养交换以垂向为主。PX4 ~ PX6 的水体各层的 $n(\text{TN})/n(\text{TP})$ 和 $n(\text{DTN})/n(\text{DTP})$ 均值多数远高于 16, 水体营养盐为磷限制状态。采样期内, PX5 底泥全磷均值为相距仅 4 km 的上游 PX6 断面的 91%, 而其表层水体总磷为 PX6 的 180%。产生该现象的原因为 PX5 水面宽度是 PX6 的 3.6 ~ 4.7 倍, PX5 过风距离更长, 在库区多河谷少风和低风速条件下, 风浪对 PX5 的扰动强于 PX6, 导致 PX5 底泥释放的营养盐更易补给表层水体, 故 PX5 处水华最严重。可见, 导致库区支流水华的主要原因是水体分层稳定性和内源磷的供应。水体分层稳定性主要受干流回水影响; 而中上游水体内源磷的供应受库区支流特殊水体分层现象 (表密度层) 的影响, 其受天气扰动的时间和程度可用于预测预警水华暴发的时间和规模。

关键词: 三峡库区; 澎溪河; 断面; 水华; 长江回水; 内源磷迁移

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Severity Differences and Mechanisms of Algal Blooms Among Sections in Pengxi River of the Three Gorges Reservoir

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Abstract: Since the impoundment of the Three Gorges Dam, 50% of the first-order tributaries in the reservoir area have had frequent algal blooms but with variations regarding the geographical locations of the seriously bloomed sections and the scope of the latter being influenced by the mainstream. This study took the Pengxi River, a first-order tributary of the reservoir area, as an example in order to explore the difference in eutrophication among the river sections and the influence of the Yangtze River on its tributaries. During the spring bloom season of 2019, sampling was carried out in one-week intervals for a total duration of one month. Seven sampling sections (PX1-PX7) were set up from the confluence to upstream. According to the profiles of vertical water temperature and conductivity of each section, the influence scope and form of the backwater of the Yangtze River were inferred; in addition, severity differences and mechanisms of algal blooms among sections were explored through the comparison of the hydrology, water quality, and sediment nutrients among Gaoyang Lake (PX5), which has had serious algal blooms, and the upstream (PX6) and downstream (PX4) sections of PX5, which are both 4 km away from PX5. The results showed that during the sampling month, the average $\rho(\text{Chl-a})$ in the confluence area of the Pengxi River (PX1-PX4) and in the upstream (PX5-PX7) were in the range of $14.55 \sim 44.00 \mu\text{g}\cdot\text{L}^{-1}$ and $42.66 \sim 175.40 \mu\text{g}\cdot\text{L}^{-1}$, respectively. The $\rho(\text{Chl-a})$ of PX5 was up to $413.00 \mu\text{g}\cdot\text{L}^{-1}$, which was significantly higher than that of other sections ($P < 0.05$). Temperature and conductivity results showed that the backwater from Yangtze River flowed into the Pengxi River from the middle and bottom layers during the period from April to May. The confluence (PX1-PX4) sections were in the intersection area of the backwater from Yangtze River and the upstream of the Pengxi River; thus, the waterbody was unstable, which was not conducive to the formation of algal blooms. However, the upstream (PX5-PX7) sections were not directly affected by the backwater from Yangtze River, leading the nutrient exchange mainly vertically. Most averages of $n(\text{TN})/n(\text{TP})$ and $n(\text{DTN})/n(\text{DTP})$ of PX4-PX6 were all greater than 16, indicating a phosphorus-limited state. During sampling, the average sediment total phosphorus of PX5 was 91% of that in upstream PX6, which was only 4 km away, whereas the surface water total phosphorus of PX5 was 180% of that in PX6. The important reason for this phenomenon is that the water surface width of PX5 was 3.6-4.7 times that of PX6, indicating longer wind fetch in the former section. Owing to the mountainous landscape in the Three Gorges Reservoir (TGR) region where windy weather is rare, the disturbance effect of wind and waves on PX5 was stronger than that of PX6, and the nutrients released from the sediment at the PX5 section caused by wind and waves resupplied the surface water more easily, causing more serious algal blooms at PX5 than those at the remaining sections in the Pengxi River. The main causes of the algal blooms in the tributaries of the TGR area lied in the stability of water stratification and the supply of

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internal phosphorus. The stability of water stratification was mainly affected by the backwater from Yangtze River, and the supply of internal phosphorus in the algal bloom season was affected by the special water stratification phenomenon of the tributaries of TGR—the “surface density layers.” The duration and degree of weather disturbance to the surface density layers can be used to predict the time and scale of algal blooms.

Key words: Three Gorges Reservoir area; Pengxi River; sections; algal blooms; backwater from Yangtze River; migration of internal phosphorus

目前世界上有 70% 的河流被大坝阻断,且随着世界银行重启水电贷款项目和各国对可再生能源的重视,未来水库数量还将不断增加^[1]. 大坝建设在给人类社会带来经济效益的同时,也会对水环境产生负面影响. 作为当今世界最大的水利发电工程的三峡大坝,自 2003 年蓄水以来,其一级支流随大坝调度在河湖两态间切换,支流流速降低,水体滞留时间变长^[2,3]、干流倒灌、水温分层^[4]导致三峡库区 38 条一级支流中有 50% 在每年 3~8 月出现不同程度的水华现象^[5]. 虽然库区近年来治理点源和面源污染的措施力度很大^[6,7],外源磷得到一定程度的控制,但库区支流的水华问题依旧突出.

澎溪河位于三峡库区中段,是库区北岸流域面积最大的支流,其中游的过水型湖泊——高阳平湖的水华尤为严重^[8~10]. 受长江回水的影响,库区支流及其断面存在不同程度的异重流现象,影响水体的物质和能量交换形式^[11],导致水华的暴发的时空和规模存在差异^[12~15],如香溪河、大宁河和澎溪河的水华均多发于中上游区域,但其水华暴发程度在断面间存在差异^[13]. 故探明长江回水对支流的影响范围,了解断面水华程度差异及其机制,对库区支流水华的预警和防控具有重要意义. 目前主要通过三维点式流速仪精确判断长江干流回水对支流的影响情况^[16],但该仪器成本较高,如何用已有指标推断长江干流回水情况需进一步拓展. 鉴于此,本文通过澎溪河 4~5 月水华季全河的水温和电导率垂向分布,间接反映长江干流对澎溪河水体的影响形式和范围;并通过比较水华高发期高阳平湖断面与其上游和下游河道断面的水文和水质环境,揭示其水华暴发程度存在差异的机制,以期提升三峡库区支流和其它大型水库支流水华的预测预警水平.

1 材料与方法

1.1 采样区概况

澎溪河(30°49′~31°42′N, 107°56′~108°54′E),河口距三峡大坝约 247 km,流域面积 5 173 km²,全长约 182 km^[17],发源于重庆市开县,是三峡库区中段和北岸流域面积最大的一级支流[图 1(a)]. 受库区独有的调水制度影响,澎溪河一年四季水位在海拔 145~175 m 间波动.

高阳平湖(31°03′~31°07′N, 108°39′~108°

42′E)位于澎溪河中游[图 1(b)]. 夏季澎溪河水位为海拔 145 m 时,高阳平湖水域最宽处近 1 km,面积近 5 km²,平均水深不足 10 m,平均流速约为 0.32 m·s⁻¹;冬季澎溪河水位为海拔 175 m 时,高阳平湖平均水深超过 40 m,流速低于 0.05 m·s⁻¹^[9],春末和秋季分别为放水和蓄水阶段. 高阳平湖呈现出“浅水河道性湖泊-深水湖泊”的交替变化特征,和普通湖泊存在很大差异^[18]. 已有研究表明澎溪河的水华集中于每年 4~5 月暴发^[19],高阳平湖为澎溪河水华最严重的区域,也是整个三峡库区水华最严重的区域之一^[9]. 有研究表明,2018 年 5 月高阳平湖水华以蓝藻(藻密度占比:10%~27%)和绿藻(藻密度占比:26%~84%)为主,2019 年 5 月高阳平湖水华则以蓝藻为主(平均藻密度占比>99%),其中具缘微囊藻占据绝对优势^[20].

根据安置于高阳湖边的气象站(30°05′N, 108°40′E; HQZD-S, 武汉,汉秦信通科技有限公司, <http://www.cnqxpt.com/>)的数据,2019 年 4 月 23 日至 5 月 23 日,只有 5 月 7 日有持续 4 h 的 5.4 m·s⁻¹ 的大风,其余时间平均风速小于 1 m·s⁻¹.

1.2 采样断面和时间设置

根据澎溪河流域的地理特征和水华发生频繁程度,从澎溪河上游到长江口沿河道中泓线设置 7 个断面[图 1(b)],坐标见表 1. 分别于 2019 年的 4 月 23 日、4 月 29 日、5 月 9 日、5 月 17 日和 5 月 23 日进行监测. 每次采样开始于当天 07:00,并于当天中午完成. 其中 PX6(高阳湖上游)和 PX4(高阳平湖下游)为狭长的峡谷性河道断面,而 PX5(高阳平湖)为过水性湖泊断面,与 PX4 和 PX6 断面间依河道分别相距约 4 km,经无人船(华微 3 号,上海华测导航技术股份有限公司,上海)测定,夏季 PX6、PX5 和 PX4 河道宽度分别为 170、800 和 140 m;冬季分别为 240、880 和 170 m.

1.3 样品的采集与处理

水温(water temperature, T)、电导率(conductivity, Cond.)和水深(depth)参数由水质多参数仪 RBR maestro³(RBR, Ltd., 加拿大)现场测定. 用有机玻璃采水器(格雷斯普科技开发公司,北京市)分别采集各断面表层(0.5 m 深)、中层(有温跃层时,采集温跃层中部水样;水体不分层时则采集水柱中部水样)和底层(底泥以上 0~0.5 m)水样

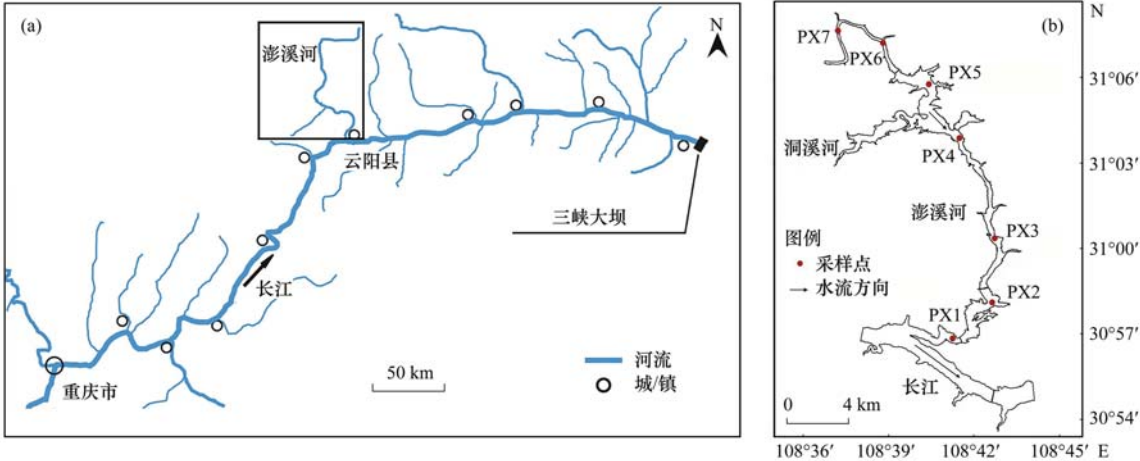


图 1 澎溪河采样断面示意
Fig. 1 Map of sampling sites in Pengxi River

表 1 采样断面 GPS 坐标

Table 1 GPS data of the sampling sites

采样位点	GPS 坐标
PX7	31°07'N, 108°37'E
PX6	31°07'N, 108°38'E
PX5	31°05'N, 108°40'E
PX4	31°04'N, 108°41'E
PX3	31°00'N, 108°42'E
PX2	30°58'N, 108°42'E
PX1	31°56'N, 108°41'E

各 500 mL 于聚乙烯瓶中,于 4℃ 下冷藏,并在采样后 48 h 带回实验室分析. 每 500 mL 水样中,100 mL 水样直接用于总氮浓度 (total nitrogen, TN)、总磷浓度 (total phosphorus, TP) 的测定; 剩余 400 mL 水样经 0.45 μm 混合膜过滤后,滤膜用于测定叶绿素浓度 (chlorophyll-a, Chl-a); 滤液用于测定溶解性总磷 (dissolved total phosphorus, DTP) 浓度、溶解性总氮 (dissolved total nitrogen, DTN) 浓度^[21]; 底泥用国产的 ETC-200 污泥采集器 (金坛区白塔新宝仪器厂,江苏省)采集,取底泥表面 0~2 cm 样品,带回实验室风干,分别用钼锑抗比色法和浓硫酸消化-凯氏定氮法测定底泥全磷 (total phosphorus in sediment, TPs) 和总氮 (total nitrogen in sediment, TNs) 含量^[22].

1.4 数据分析与处理

1.4.1 水体垂向稳定系数

考虑水体密度的垂直变化,用水体垂向稳定系数 (N^2) 评价水体分层状态^[11],单位为 s^{-2} ,其表达式为:

$$N^2 = \frac{g}{D_{avg}} \frac{D_b - D_s}{H} \tag{1}$$

式中, D_s 和 D_b 分别为表、底层水体密度 ($kg \cdot m^{-3}$); D_{avg} 为垂向水体密度均值 ($kg \cdot m^{-3}$); H

为水深 (m); g 为重力加速度 ($m \cdot s^{-2}$). 忽略泥沙的影响,水温 ($^{\circ}C$) 对应水体密度按公式 (2)^[23] 计算:

$$D_t = \left[1 - \frac{T + 288.9414}{508929.2(T + 68.12936)} \times (T - 3.9863)^2 \right] \times 1000 \tag{2}$$

式中, D_t 为水体密度 ($kg \cdot m^{-3}$); T 为水温 ($^{\circ}C$).

1.4.2 浪高

将风速、风的持续时间、水深和河面宽度 (过水距离) 输入浪高计算网站 (<https://planetcalc.com/4442/>) 计算,可得各断面在相应天气条件形成的浪高.

1.4.3 统计和作图

用 Excel 2019 进行数据统计; 通过 SPSS 16.0 软件单因素 ANOVA 检验法进行方差分析,以 $P < 0.05$ 作为显著水平,比较 4~5 月各断面的 Chl-a 浓度、水体各形态营养盐浓度和底泥总氮、全磷含量的差异性; 用 Origin 2018 进行相关图形的绘制.

2 结果与分析

2.1 全河水温垂向分布特征

三峡大坝蓄水后,澎溪河受长江干流回水的影响,从河口到上游水温垂向分布特性存在差异 (图 2). 4 月 23 日下游 (PX1~PX3) 表层水温较低,表底水温差为 4.83~6.24℃ 且中部存在明显的等温层,而中上游 (PX4~PX7) 表底温差为 7.14~8.39℃,大于下游,水温随着深度的增加持续降低,只在水体较深的 PX4 和 PX7 底部出现等温层. 4 月 29 日,下游和中上游表底温差分别为 2.73~4.96℃ 和 6.72~10.27℃,下游表底温差小,与 4 月 23 日相似. 5 月 7 日出现采样期间最高风速 ($5.4 m \cdot s^{-1}$),导致 5

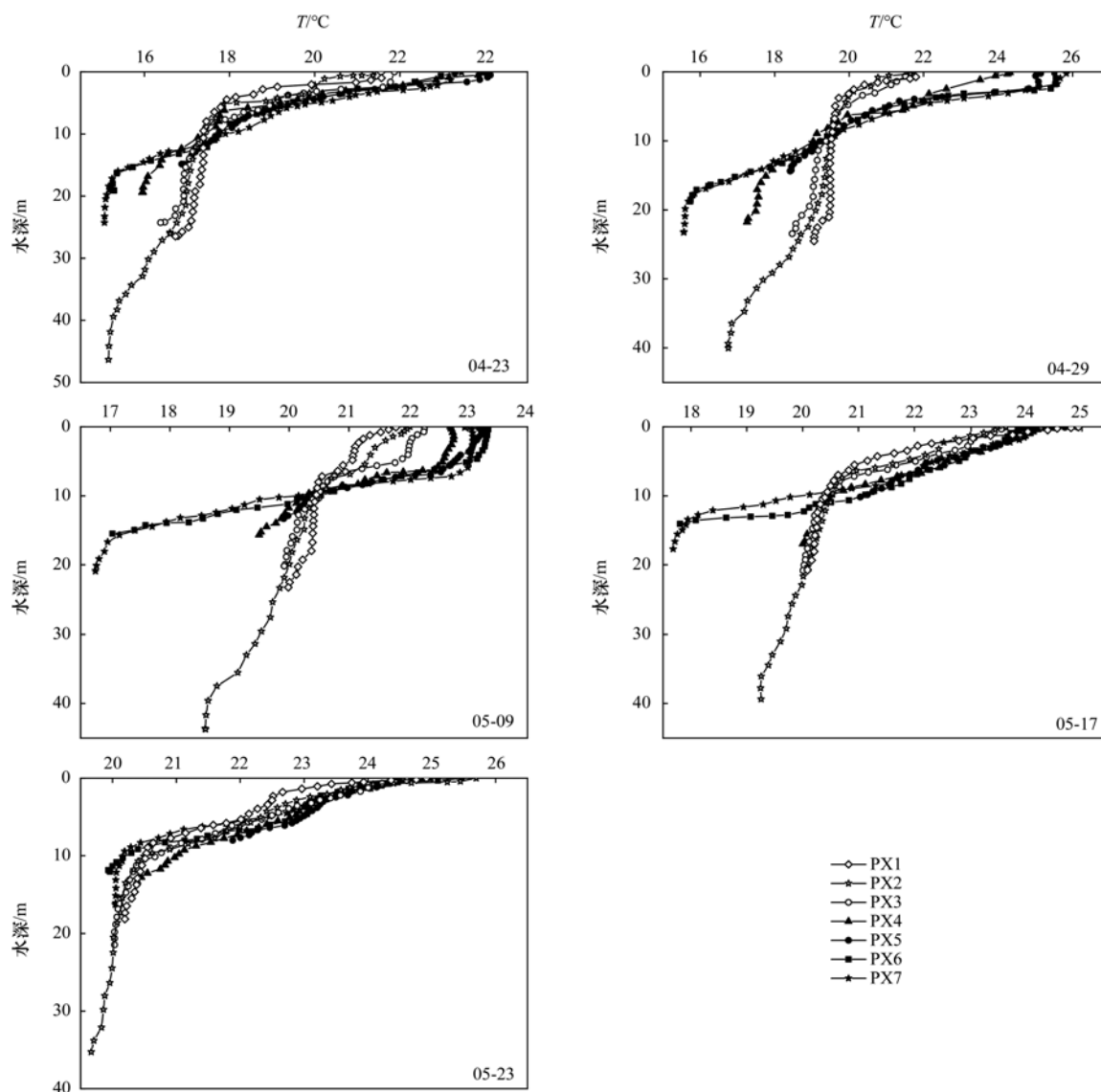


图2 澎溪河各断面水温垂向变化(2019年4月23日至5月23日)

Fig. 2 Vertical water temperature profiles at various sections of Pengxi River from April 23rd to May 23rd, 2019

月9日全河表层水体均出现混合层,下游表底水温差降至1.81~3.42℃,中下层水体仍为等温层,而中上游底表温差为3.21~6.26℃。5月17日,出现三峡库区特殊分层现象,即表层水体为温跃层,无混合层,PX1~PX4中下层水体为等温层,表底温差介于3.60~4.85℃;PX5水深仅10.19 m,整个水体呈现温跃层特征;PX5~PX7分层相似,但表底温差达到6.18~6.37℃。5月23日,PX1~PX7各断面表层水水温变化情况相似,表底层温差介于2.96~6.03℃。

2.2 全河电导率垂向分布特征

各断面间电导率空间分布差异明显(图3)。4月23日至5月23日,PX1~PX7的电导率变化范围分别为392.82~430.12、414.00~522.92、415.51~440.31、389.68~569.78、371.76~627.02、371.57~707.94和374.063~715.18 $\mu\text{S}\cdot\text{cm}^{-1}$ 。下

游(PX1~PX3)水体电导率变化特征相似,且均低于上游,只有水体较深的PX2断面底层水体电导率随水深略有增加。而中上游(PX5~PX7)电导率均随着水深的增加而持续增加,表底层水体电导率差较大。PX4的电导率值介于上游和下游之间。

2.3 全河表层 Chl-a 特征分析

$\rho(\text{Chl-a})$ 与浮游植物生物量间有紧密联系^[24],故可用 $\rho(\text{Chl-a})$ 表征浮游植物的生长及分布特征^[25]。水华季PX1~PX7的 $\rho(\text{Chl-a})$ 均值差异较大,PX5均值显著高于其余位点($P=0.001<0.05$,表2),其 $\rho(\text{Chl-a})$ 在5月9日最高达413.00 $\mu\text{g}\cdot\text{L}^{-1}$,为2019年水华最严重的区域,故下文将重点分析PX5和其上下游PX6和PX4的水华暴发程度差异的机制。

2.4 PX4、PX5、PX6断面水动力特征分析

PX4~PX6表层水体流速均值分别为0.087、

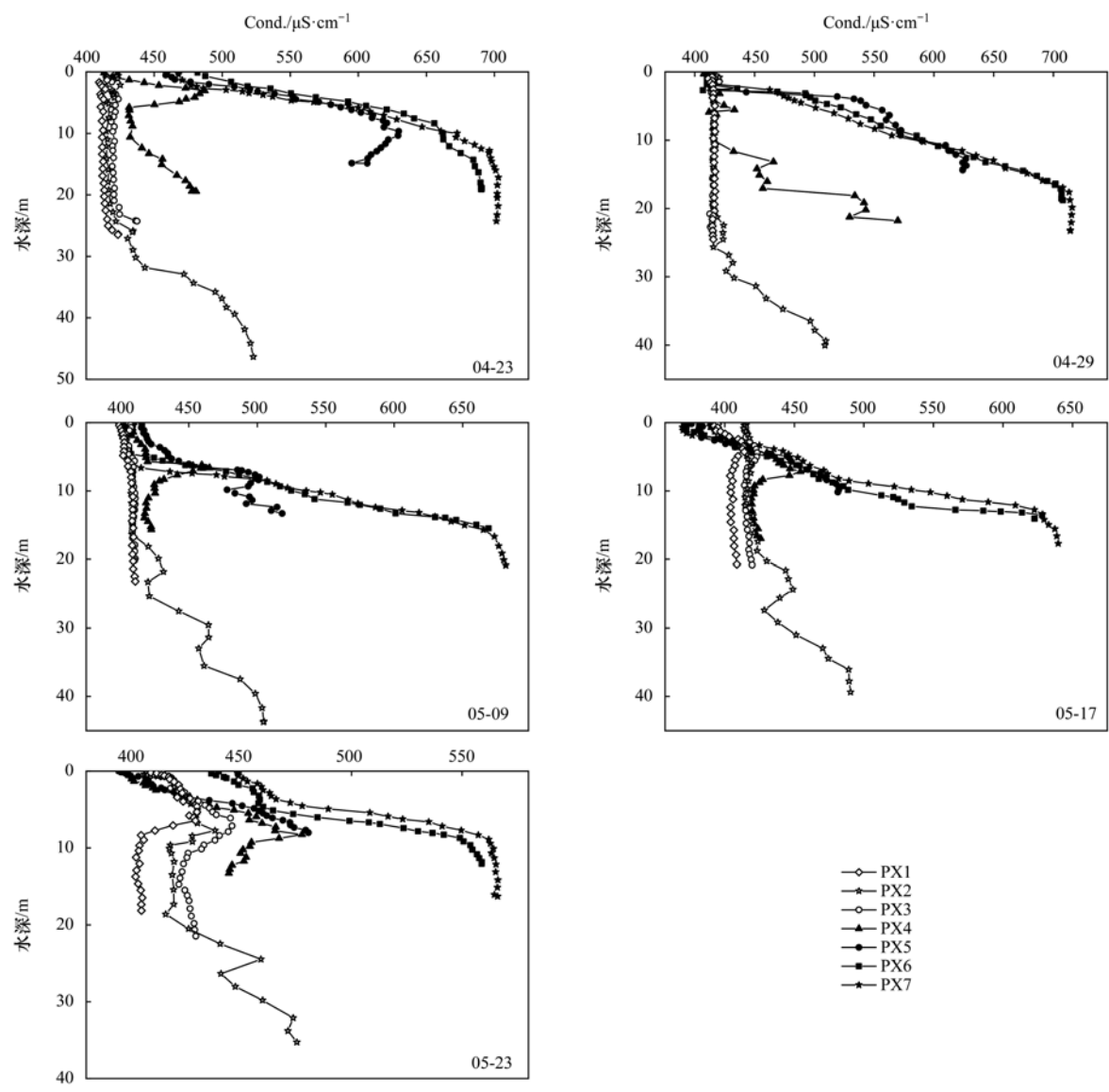


图3 澎溪河各断面电导率垂向变化(2019年4月23日至5月23日)

Fig. 3 Vertical water conductivity profiles at various sections of Pengxi River from April 23rd to May 23rd, 2019

表2 2019年4月23日至5月23日澎溪河各断面表层水体叶绿素a浓度¹⁾/μg·L⁻¹

Table 2 Chl-a concentration in surface waters at the sampling sites of Pengxi River from April 23rd to May 23rd, 2019/μg·L⁻¹

采样位点	PX7	PX6	PX5	PX4	PX3	PX2	PX1
$\rho(\text{Chl-a})$	42.66 ± 27.06b	52.00 ± 39.72b	175.40 ± 137.62a	44.00 ± 7.65b	14.55 ± 5.05b	15.48 ± 13.72b	17.82 ± 12.06b

1) 数据表示平均值 ± 标准差,不同小写字母表示断面间差异显著($P < 0.05$)

0.048 和 0.119 $\text{m}\cdot\text{s}^{-1}$, PX5 流速最慢, PX6 流速最快, 3 个断面间流速存在极显著差异 [$P = 0.001$, 图 4(a)]. 如图 4(b) 所示, PX4、PX5 和 PX6 断面 N^2 均值分别为 0.000 66、0.000 86 和 0.000 95 s^{-2} . 越往上游, 水体分层现象越明显. PX5 和 PX6 在采样期内一直为分层水体; PX4 在 5 月 9 日为弱分层水体外, 其余时间为分层水体.

2.5 PX4、PX5 和 PX6 断面水体营养分析

表 3 展示了 2019 年 4~5 月 PX4、PX5 和 PX6 的表层、中层和底层水体营养盐的差异性, 不同水层间 DTP、TN 和 DTN 存在显著差异 ($P < 0.05$), 水

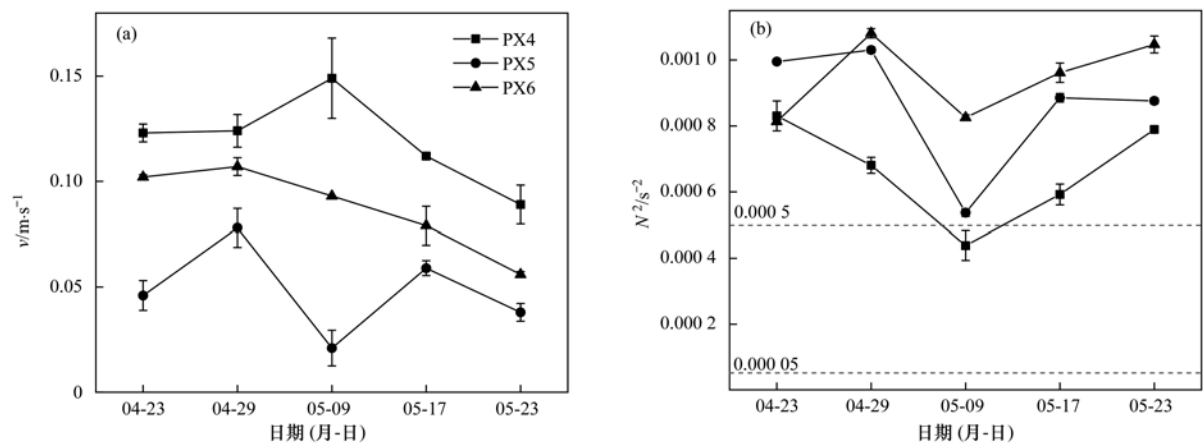
体营养盐也存在分层现象, 下文将进行详细分析.

表3 断面表、中、底层水体间营养盐浓度差异性¹⁾/mg·L⁻¹

Table 3 Differences in nutrient concentration among surface, middle, and bottom layers/mg·L⁻¹

项目	$\rho(\text{TP})$	$\rho(\text{DTP})$	$\rho(\text{TN})$	$\rho(\text{DTN})$
表层	0.13 ± 0.10a	0.03 ± 0.02b	1.80 ± 0.58a	1.32 ± 0.49a
中层	0.09 ± 0.03a	0.03 ± 0.02b	1.42 ± 0.32b	1.09 ± 1.15b
底层	0.16 ± 0.10a	0.05 ± 0.03a	1.38 ± 0.25b	1.04 ± 0.20b
F	2.624	4.246	4.887	3.419
P	0.084	0.021 *	0.012 *	0.042 *

1) 数据表示 PX4、PX5 和 PX6 这 3 个断面各营养盐浓度的平均值 ± 标准差, 不同小写字母和 * 表示不同水层间差异显著 ($P < 0.05$)



N^2 为水体垂向稳定系数,当 $N^2 < 0.00005 \text{ s}^{-2}$ 时为混合水体, $0.00005 \text{ s}^{-2} \leq N^2 < 0.0005 \text{ s}^{-2}$ 时为弱分层水体, $N^2 \geq 0.0005 \text{ s}^{-2}$ 为分层水体

图4 澎溪河PX4~PX6断面表层水体流速和水体垂向稳定系数分布(2019年4月23日至5月23日)

Fig. 4 Distribution of surface water velocity and N^2 at sections of PX4-PX6 of Pengxi River from April 23rd to May 23rd, 2019

水华季PX4~PX6断面 $\rho(\text{TP})$ 均值变化范围为0.02~0.44 $\text{mg}\cdot\text{L}^{-1}$ [图5(a)]. PX4~PX6表层水体 $\rho(\text{TP})$ 均值分别为0.10、0.18和0.10 $\text{mg}\cdot\text{L}^{-1}$,虽然只相距4 km, PX5表层TP浓度却为PX4和PX6的180% [图5(a)],但各断面间无显著差异($P=0.384$). PX4~PX6底层水体 $\rho(\text{TP})$ 均值分别为0.17、0.15和0.15 $\text{mg}\cdot\text{L}^{-1}$,各断面间无显著差异 [$P=0.932$,图5(a)]. $\rho(\text{DTP})$ 均值的变化范围为0.01~0.09 $\text{mg}\cdot\text{L}^{-1}$,占 $\rho(\text{TP})$ 的20%~40%.各断面均表现出中层<表层<底层的特点,但只有PX4存在显著差异($P=0.021$). PX4~PX6表层水体 $\rho(\text{DTP})$ 均值分别为0.02、0.04和0.04 $\text{mg}\cdot\text{L}^{-1}$,底层的分别为0.04、0.05和0.06 $\text{mg}\cdot\text{L}^{-1}$,各断面间均无显著差异($P>0.05$);相同层次DTP浓度从上游到下游逐渐降低[图5(b)].

$\rho(\text{TN})$ 均值的变化范围为0.86~2.72 $\text{mg}\cdot\text{L}^{-1}$,3个断面表层水体TN浓度均显著高于中层和底层. PX4~PX6表层水体 $\rho(\text{TN})$ 均值分别为1.75、2.04和1.62 $\text{mg}\cdot\text{L}^{-1}$,底层水体的分别为1.46、1.33和1.35 $\text{mg}\cdot\text{L}^{-1}$,各断面间无显著差异 [$P>0.05$,图5(c)]. $\rho(\text{DTN})$ 均值在0.61~2.23 $\text{mg}\cdot\text{L}^{-1}$ 间变动,占TN浓度的70%~79%. PX4~PX6表层水体 $\rho(\text{DTN})$ 均值分别为1.31、1.50和1.14 $\text{mg}\cdot\text{L}^{-1}$,底层的分别为1.02、1.05和1.04 $\text{mg}\cdot\text{L}^{-1}$,各断面间无显著差异 [$P>0.05$,图5(d)].

Redfield^[26]提出浮游植物N、P元素的量比(n/n)为16:1,该比例被广泛应用到水体营养状态的评价中,而藻类生境中的可溶性N、P营养盐浓度在很大程度上影响着藻类的生长情况^[27].故本文对 $n(\text{TN})/n(\text{TP})$ 和 $n(\text{DTN})/n(\text{DTP})$ 均进行分析.结果表明,3个断面表层和底层水体 $n(\text{TN})/n(\text{TP})$ 多

远大于16,表层和底层水体多数时候处于磷限制状态 [图6(a)]. $n(\text{TN})/n(\text{TP})$ 的变化范围为10.55~117.21, PX4~PX6表层水体 $n(\text{TN})/n(\text{TP})$ 均值分别为52.12、32.34和49.04,底层的分别为31.68、29.02和24.70,各断面间均无显著差异 ($P>0.05$).断面间表层和底层水体 $n(\text{DTN})/n(\text{DTP})$ 均值均大于或远大于16 [图6(b)],表层和底层水体均表现为溶解性磷限制或极度限制状态.表层水体 $n(\text{DTN})/n(\text{DTP})$ 的变化范围为28.75~196.82, PX4~PX6的均值分别为154.51、98.74和69.20, PX4显著高于PX5和PX6 ($P<0.05$).底层水体 $n(\text{DTN})/n(\text{DTP})$ 的变化范围为24.57~120.53, PX4、PX5和PX6的均值分别为66.70、50.41和53.66,各断面间无显著差异 ($P>0.05$).

2.6 PX4、PX5和PX6断面底泥营养盐分析

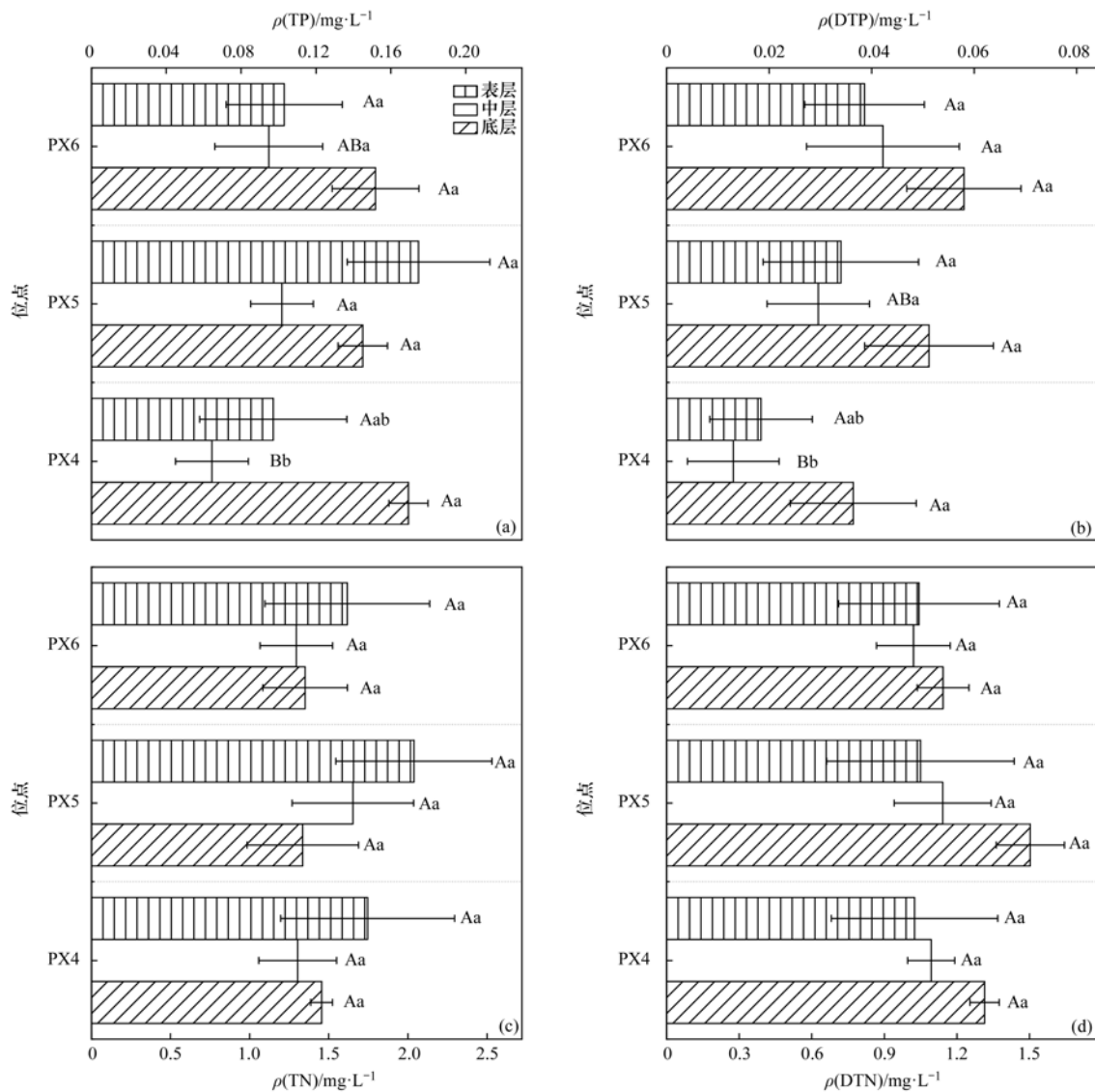
如表4所示,虽相距只约4 km,但PX5的TNs和TPs含量均显著低于 ($P<0.05$) 上游(PX6)和下游(PX4),PX5的TPs含量只有PX6的91%.澎溪河5月水华较4月严重, PX4~PX6断面5月TNs含量均低于4月; PX4的TPs含量在4月和5月间无显著差异,而5月PX5和PX6的TPs含量则显著高

表4 澎溪河PX4~PX6采样期内断面底泥总氮和全磷含量变化特征¹⁾/ $\text{g}\cdot\text{kg}^{-1}$

Table 4 Variation characteristics of total nitrogen and total phosphorus contents in sediment at PX4-PX6, Pengxi River during sampling/ $\text{g}\cdot\text{kg}^{-1}$

位点	$\omega(\text{TNs})$		$\omega(\text{TPs})$	
	4月	5月	4月	5月
PX6	1.05 ± 0.03Aa	0.94 ± 0.01Bb	0.75 ± 0.00Ba	0.78 ± 0.00Aa
PX5	0.95 ± 0.00Aa	0.88 ± 0.03Ab	0.68 ± 0.00Bc	0.71 ± 0.03Ab
PX4	1.20 ± 0.01Aa	1.15 ± 0.01Aa	0.72 ± 0.01Ab	0.71 ± 0.03Ab

1) 数据表示平均值 ± 标准差,不同大写字母表示月份间差异显著 ($P<0.05$),不同小写字母表示断面间差异显著 ($P<0.05$)



误差线表示4月23日至5月23日各指标间的标准差,不同大写字母表示断面间差异显著($P < 0.05$),不同小写字母表示水层间差异显著($P < 0.05$)

图5 澎溪河PX4~PX6各断面TP、DTP、TN和DTN浓度的垂向变化特征(2019年4月23日至5月23日)

Fig. 5 Vertical change characteristics of TP, DTP, TN, and DTN in sections of PX4-PX6, Pengxi River from April 23rd to May 23rd, 2019

于4月的($P < 0.05$).

3 讨论

3.1 长江干流回水位置判断及其意义

随着三峡大坝的运行,库区支流出现不同形式的干流倒灌现象,杨正健等^[11]和黄佳维等^[13]的研究表明水温差是引起库区支流异重流的主要原因.夏季干流回水水温介于支流的表层和底层水温之间^[28],干流以中层异重流的形式潜入澎溪河、大宁河和香溪河,且由于不同支流和干流水温差不同,干流潜入的厚度和深度也不同.目前主要通过三维点式流速仪进行库区支流异重流的测定,但其仪器条件要求较高.本研究表明,在仪器条件不足时可通过测定断面的垂向电导率和水温间接反映干流回水的情况.

淡水河流中水体电导率(Cond.)表征水体离子

的总浓度或含盐量^[29],不易在水体中发生化学反应,具有较好的化学保守行为^[30],可用于不同性质水体交换过程的示踪^[31].长江干流回水与支流上游来水交汇处电导率变化明显^[13],而澎溪河上游水体电导率显著高于长江干流水体^[32].黄佳维等^[13]发现澎溪河、大宁河和香溪河电导率与流速的分布规律相似.此外,支流不同断面间水温存在差异.澎溪河下游(PX1~PX3)中下部水体出现等温层,可见采样期间长江干流以中下层倒灌入澎溪河.因此,可以从水温分层和电导率角度分析长江干流回水在春季水华季到达澎溪河的位置.本研究中,4~5月澎溪河下游(PX1~PX3)水体下部出现明显的等温层.而中上游(PX5~PX7)水体随着深度增加水温持续降低;PX4的水温分层则介于上游和下游之间;同期下游(PX1~PX3)水体电导率均低于上游

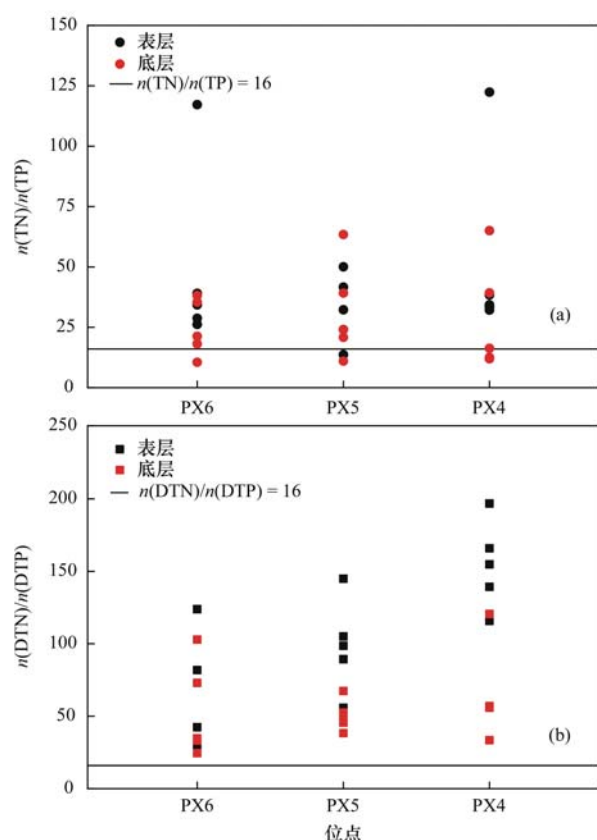


图6 澎溪河 PX4~PX6 断面表层和底层水体的 $n(\text{TN})/n(\text{TP})$ 和 $n(\text{DTN})/n(\text{DTP})$ (2019 年 4 月 23 日至 5 月 23 日)

Fig. 6 The $n(\text{TN})/n(\text{TP})$ and $n(\text{DTN})/n(\text{DTP})$ of surface and bottom layers in PX4-PX6 sections of Pengxi River from April 23rd to May 23rd, 2019

(PX5~PX7) 水体, PX4 的电导率介于上、下游断面之间。综上, 4~5 月长江回水倒灌至澎溪河 PX4 附近, PX5 以下。

水体温度分层情况会影响水华的强度^[13,33], 受长江回水的影响, 澎溪河下游 (PX1~PX4) 水体电导率波动较小, 温度分层较上游水体明显减弱, 说明水体垂向混合频繁, 水体不稳定, 不利于水华的暴发。相关研究也表明长江回水会导致支流水体热分层被破坏而抑制水华的暴发^[6,7]。研究期间上游 (PX5~PX7) 受干流回水顶托作用影响, 水体流速较缓近似湖泊[图 4(a)], PX5 在 4~5 月水体滞留时间达 79~170d^[3], 垂向混合较弱, 热分层持续存在, 导致藻类大量繁殖的风险更高^[11,12]。此外, 澎溪河上游下部水体电导率高, 一定程度上说明其底部水体营养盐浓度高^[29], 下部水体营养盐受到天气等因素扰动会向上迁移从而增大水华暴发的风险。

3.2 PX4、PX5 和 PX6 断面水华暴发程度差异的机制分析

在水体生态系统中, 添加 P 导致生物固 N 速率上升, 从而使 N 的总量最终达到与 P 供给量相匹配

的水平^[34]。从各断面 $n(\text{TN})/n(\text{TP})$ 和 $n(\text{DTN})/n(\text{DTP})$ 来看, 澎溪河水体处于磷限制状态, 故澎溪河水华的治理需要控制好磷源。水体中的氮、磷营养的来源主要有外源营养盐输入和内源营养盐释放^[35], 其中外源营养主要受人类活动的影响; 内源磷主要来自底泥营养的释放。近年来三峡库区流域点源污染和面源污染都得到较好控制^[6,7], 但澎溪河的水华问题依旧突出, 原因可能在于内源磷, 这一点被高阳平湖底泥磷呈逐年增加的趋势^[3]所佐证。

PX5 和 PX6 处于澎溪河中上游, 未直接受长江干流回水影响, 即长江回水未能为其提供磷源。在外源磷得到控制的前提下, 上层水体浮游植物的生长程度和底泥的磷素供应有很大关联。气温较高时, 水温分层导致的密度分层限制了水体的垂向交换^[36], 限制了氧的垂向传递, 水体底部出现厌氧区域, 促进了底泥中不溶性磷向可溶性磷的转化和可溶性磷在下层水体的积累^[37,38], 和本研究[图 5(b)]相符。但水体温度分层导致的水密度差异和水体深度会阻碍营养盐在上下层水体间的交换, 只有打破阻碍水体底部的磷素才能向上迁移, 风浪便成了促进水体混合的关键因素^[39]。三峡库区超过 95% 的区域是山地^[40], 虽然大坝蓄水导致库区支流水面显著加宽, 但山地地形决定了其水面宽度有限 (<1 km), 而水面和山峰之间的地形高差均值约 2 000 m^[41], 导致库区河道表面风速低至 0.9~2.1 m·s⁻¹^[42], 无法同湖泊一样在表面形成混合层, 而是出现温度和密度从表面随深度持续而迅速降低的表密度层 (surface density layers, SDLs)^[9]。表密度层与下部水体密度的差异, 影响底泥及其上覆水中营养盐的上移, 从而影响水华的暴发。5 月 7 日澎溪河持续 4 h 的 5.4 m·s⁻¹ 的有风天气, 在 PX6、PX5 和 PX4 分别形成 0、0.1~0.2 和 0 m 的浪高, 故 5 月 9 日 PX4~PX6 断面出现明显的混合层, 而其它取样期 PX4~PX6 表层水体均未出现混合层 (图 2); PX5 河道宽度为 PX6 的近 5 倍, 过风距离相对较大, 相同天气条件下形成的风浪强于 PX6, 故 PX5 的 $\rho(\text{Chl-a})$ 高于 PX6 及其它断面, 并于 5 月 9 日达到 413.00 $\mu\text{g}\cdot\text{L}^{-1}$ 的峰值。PX5 的 TP 含量低于 PX6, 而表层水体的 TP 浓度远高于 PX6, 这是其底泥磷长期更易向上层水体迁移的结果。加之 PX5 表层水体流速显著低于 PX6, 加剧了 PX5 水华。而 PX4 的水体垂向稳定系数表现最低, 且处于长江干流回水和澎溪河上游来水的交汇处, 水体不稳定, 且其表层水体流速较快, 不利于水华的暴发。

澎溪河水体营养为磷限制型。总氮主要为溶解性氮, 而总磷则主要为颗粒磷, 磷主要存在于藻类细

胞中^[43]. 水华季后, 水华断面水体底泥总氮较水华前减少, 而底泥全磷则由于藻细胞沉降而较水华前增加(表4), 增加了水华再次暴发的风险.

综上, 不仅三峡库区 38 条易发水华的支流其发生水华的机制有差异^[12,13,44,45], 即使是同一条支流, 不同断面间水华发生的机制也存在区别, 导致水华程度不同. 在水华的预测预警和防控实践中, 可以根据不同机制制定精准的措施. 譬如澎溪河水华防控的重点应该是高阳平湖, 其水华主要受内源磷向上迁移情况的影响, 需要密切关注 SDLs 动态和天气变化. 另外, 在其它水华水体曾经使用过防控措施, 例如通气法, 会导致高阳平湖水体分层被破坏, 更利于下部磷素向上层水体迁移, 反而会对高阳平湖的水华起到推波助澜的作用.

4 结论

(1) 三峡库区独特的地貌、调水机制, 使得库区支流受长江干流回水的影响程度不同. 可通过不同断面的垂向水温和电导率分布特征间接推断长江干流回水对支流的影响形式和范围. 4~5 月, 长江回水倒灌至澎溪河 PX4 附近, PX5 以下.

(2) 4~5 月, 澎溪河位于干流回水范围内的断面(PX1~PX4)上下层水体混合, 不易发生水华; 未受干流回水直接影响的中上游断面(如 PX5 和 PX6), 其水华程度主要受其内源磷向上层水体的迁移情况的影响. 库区独特的表密度层现象和气象因素影响内源磷的上移, 可用于水华暴发时间和规模的预警预测.

参考文献:

- [1] Wang F S, Maberly S C, Wang B L, *et al.* Effects of dams on riverine biogeochemical cycling and ecology[J]. *Inland Waters*, 2018, **8**(2): 130-140.
- [2] Xiang R, Wang L J, Li H, *et al.* Water quality variation in tributaries of the Three Gorges Reservoir from 2000 to 2015[J]. *Water Research*, 2021, **195**, doi: 10.1016/j.watres.2021.116993.
- [3] 黄伟, 张铎, 罗晓佼, 等. 三峡库区支流的河-湖两态及其对沉积物不同形态磷含量的影响[J]. *环境科学*, 2022, **43**(3): 1356-1364.
Huang W, Zhang X, Luo X J, *et al.* River-Lake states in the tributary of the Three Gorges Reservoir area and their effects on the phosphorus content of different forms in the sediment[J]. *Environmental Science*, 2022, **43**(3): 1356-1364.
- [4] Chen Q, Huang M T, Tang X D. Eutrophication assessment of seasonal urban lakes in China Yangtze River Basin using landsat 8-derived Forel-Ule index: a six-year (2013-2018) observation[J]. *Science of the Total Environment*, 2020, **745**, doi: 10.1016/j.scitotenv.2019.135392.
- [5] 周理玥, 黄刚, 朱书景. 三峡库区水位变化下小江流域富营养化的时空变化特征[J]. *人民珠江*, 2020, **41**(2): 56-60.
Zhou X Y, Huang G, Zhu S J. Research on temporal and spatial variation characteristics of eutrophication in the Xiaojiang River basin under the change of water level in the Three Gorges Reservoir area[J]. *Pearl River*, 2020, **41**(2): 56-60.
- [6] 刘新, 王秀, 赵珍, 等. 风浪扰动对底泥内源磷钝化效果的影响[J]. *中国环境科学*, 2017, **37**(8): 3064-3071.
Lui X, Wang X, Zhao Z, *et al.* Effect of wind and wave disturbance on passivation of internal phosphorus in sediment[J]. *China Environmental Science*, 2017, **37**(8): 3064-3071.
- [7] 吕平毓, 张铎, 熊中福, 等. 三峡库区成库前后干流万州段水体总磷特征[J]. *西南大学学报(自然科学版)*, 2020, **42**(7): 162-167.
Lv P Y, Zhang X, Xiong Z F, *et al.* Characteristics of total phosphorus in Changjiang mainstream at Wanzhou section before and after Three Gorges Reservoir impoundment[J]. *Journal of Southwest University (Natural Science)*, 2020, **42**(7): 162-167.
- [8] 张磊, 蔚建军, 付莉, 等. 三峡库区回水区营养盐和叶绿素 a 的时空变化及其相互关系[J]. *环境科学*, 2015, **36**(6): 2061-2069.
Zhang L, Wei J J, Fu L, *et al.* Temporal and spatial variation of nutrients and chlorophyll a, and their relationship in Pengxi River backwater area, Three Gorges Reservoir[J]. *Environmental Science*, 2015, **36**(6): 2061-2069.
- [9] Zhang L, Xia Z Q, Zhou C, *et al.* Unique surface density layers promote formation of harmful algal blooms in the Pengxi River, Three Gorges reservoir[J]. *Freshwater Science*, 2020, **39**(4): 722-734.
- [10] 秦榕聪, 肖艳, 郭劲松, 等. 三峡库区澎溪河典型优势藻细胞 N/P 比与限制性评价的原位分析[J]. *湖泊科学*, 2018, **30**(5): 1284-1294.
Qin R C, Xiao Y, Guo J S, *et al.* In situ research of relationship between cellular N/P of dominate algae species and limitation evaluation in Pengxi River of the Three Gorges Reservoir[J]. *Journal of Lake Sciences*, 2018, **30**(5): 1284-1294.
- [11] 杨正健, 刘德富, 马骏, 等. 三峡水库香溪河库湾特殊水温分层对水华的影响[J]. *武汉大学学报(工学版)*, 2012, **45**(1): 1-9, 15.
Yang Z J, Liu D F, Ma J, *et al.* Effects of special vertical layered water temperatures on algal bloom in Xiangxi Bay of Three Gorges Reservoir[J]. *Engineering Journal of Wuhan University*, 2012, **45**(1): 1-9, 15.
- [12] Long L H, Ji D B, Yang Z J, *et al.* Density-driven water circulation in a typical tributary of the Three Gorges Reservoir, China[J]. *River Research and Applications*, 2019, **35**(7): 833-843.
- [13] 黄佳维, 纪道斌, 宋林旭, 等. 三峡水库夏季不同支流倒灌特性及其影响分析[J]. *水力发电学报*, 2019, **38**(4): 63-74.
Huang J W, Ji D B, Song L X, *et al.* Characteristics and effects of different density flows in tributaries of Three Gorges Reservoir in summer[J]. *Journal of Hydroelectric Engineering*, 2019, **38**(4): 63-74.
- [14] 方海涛, 宋林旭, 纪道斌, 等. 香溪河夏季水华暴发差异性研究及其机制分析[J]. *环境科学与技术*, 2019, **42**(9): 68-74.
Fang H T, Song L X, Ji D B, *et al.* Regional differences and mechanism analysis of summer blooms in Xiangxihe Reservoir Bay[J]. *Environmental Science & Technology*, 2019, **42**(9): 68-74.
- [15] 霍静, 崔玉洁, 宋林旭, 等. 三峡水库神农溪库湾水体季节性分层特性[J]. *生态学报*, 2019, **38**(4): 1166-1174.

- Huo J, Cui Y J, Song L X, *et al.* Seasonal stratification of waters in the Shennong Stream of the Three Gorges Reservoir [J]. Chinese Journal of Ecology, 2019, **38**(4): 1166-1174.
- [16] 曾一恒, 沈旭舟, 张佳磊, 等. 分层异重流对香溪河浮游植物叶绿素 a 空间分布的影响[J]. 环境工程技术学报, 2022, **12**(2): 426-435.
- Zeng Y H, Shen X Z, Zhang J L, *et al.* Effects of stratified density flow on the spatial distribution of chlorophyll-a in phytoplankton in Xiangxi River [J]. Journal of Environmental Engineering Technology, 2022, **12**(2): 426-435.
- [17] 李哲, 白镭, 郭劲松, 等. 三峡水库两条支流水-气界面 CO₂、CH₄ 通量比较初探[J]. 环境科学, 2013, **34**(3): 1008-1016.
- Li Z, Bai L, Guo J S, *et al.* Comparative study on water-air CO₂, CH₄ flux in two tributaries in the Three Gorges Reservoir, China[J]. Environmental Science, 2013, **34**(3): 1008-1016.
- [18] 李哲, 姚晓, 何萍, 等. 三峡水库澎溪河水-气界面 CO₂、CH₄ 扩散通量昼夜动态初探[J]. 湖泊科学, 2014, **26**(4): 576-584.
- Li Z, Yao X, He P, *et al.* Diel variations of air-water CO₂ and CH₄ diffusive fluxes in the Pengxi River, Three Gorges Reservoir [J]. Journal of Lake Sciences, 2014, **26**(4): 576-584.
- [19] 周川, 蔺建军, 付莉, 等. 三峡库区支流澎溪河水华高发期环境因子和浮游藻类的时空特征及其关系[J]. 环境科学, 2016, **37**(3): 873-883.
- Zhou C, Wei J J, Fu L, *et al.* Temporal and spatial distribution of environmental factors and phytoplankton during algal bloom season in Pengxi River, Three Gorges Reservoir [J]. Environmental Science, 2016, **37**(3): 873-883.
- [20] 谭炳圆. 澎溪河水质变化及水华中浮游生物演替与环境因子间关系[D]. 重庆: 西南大学, 2020.
- Tan B Y. Changes of water quality in Pengxi River and the relationship between plankton succession and environmental factors during bloom [D]. Chongqing: Southwest University, 2020.
- [21] 国家环境保护总局. 水和废水监测分析方法[M]. (第四版). 北京: 中国环境科学出版社, 2002.
- [22] 鲍士旦. 土壤农化分析[M]. (第三版). 北京: 中国农业出版社, 2000.
- [23] Lawson R, Anderson M A. Stratification and mixing in Lake Elsinore, California; an assessment of axial flow pumps for improving water quality in a shallow eutrophic lake[J]. Water Research, 2007, **41**(19): 4457-4467.
- [24] 田盼, 李亚莉, 李莹杰, 等. 三峡水库调度对支流水体叶绿素 a 和环境因子垂向分布的影响[J]. 环境科学, 2022, **43**(1): 295-305.
- Tian P, Li Y L, Li Y J, *et al.* Effects of the Three Gorges Reservoir operation on vertical distribution of chlorophyll a and environmental factors in tributaries[J]. Environmental Science, 2022, **43**(1): 295-305.
- [25] 余茂蕾, 洪国喜, 朱广伟, 等. 风场对太湖梅梁湾水华及营养盐空间分布的影响[J]. 环境科学, 2019, **40**(8): 3519-3529.
- Yu M L, Hong G X, Zhu G W, *et al.* Wind field influences on the spatial distribution of cyanobacterial blooms and nutrients in meiliang bay of lake Taihu, China[J]. Environmental Science, 2019, **40**(8): 3519-3529.
- [26] Redfield A C. The biological control of chemical factors in the environment[J]. Science Progress, 1960, **11**: 150-170.
- [27] Galbraith E D, Martiny A C. A simple nutrient-dependence mechanism for predicting the stoichiometry of marine ecosystems [J]. Proceedings of the National Academy of Sciences of the United States of America, 2015, **112**(27): 8199-8204.
- [28] 纪道斌, 刘德富, 杨正健, 等. 三峡水库香溪河库湾水动力特性分析[J]. 中国科学: 物理学 力学 天文学, 2010, **40**(1): 101-112.
- Ji D B, Liu D F, Yang Z J, *et al.* Hydrodynamic characteristics of Xiangxi Bay in Three Gorges Reservoir[J]. Scientia Sinica: Physica, Mechanica & Astronomica, 2010, **40**(1): 101-112.
- [29] 王瑞, 代丹, 张弛, 等. 太湖不同介质电导率时空变化特征[J]. 环境科学, 2019, **40**(10): 4469-4477.
- Wang R, Dai D, Zhang C, *et al.* Temporal and spatial variations in the conductivity in different media in Taihu Lake, China[J]. Environmental Science, 2019, **40**(10): 4469-4477.
- [30] 韩超南, 秦延文, 马迎群, 等. 三峡支流大宁河库湾水质分布变化原因及其生态效应[J]. 环境科学研究, 2020, **33**(4): 893-900.
- Han C N, Qin Y W, Ma Y Q, *et al.* Cause of variation in water quality distribution and its ecological effects in the Daning Bay of the Three Gorges Reservoir [J]. Research of Environmental Sciences, 2020, **33**(4): 893-900.
- [31] 纪道斌, 方娇, 龙良红, 等. 三峡水库不同支流库湾蓄水期溶解氧分层特性及差异性[J]. 环境科学, 2022, **43**(7): 3543-3551.
- Ji D B, Fang J, Long L H, *et al.* Characteristics and differences of dissolved oxygen stratification in different tributaries of Three Gorges Reservoir during impoundment period[J]. Environmental Science, 2022, **43**(7): 3543-3551.
- [32] 姜伟, 周川, 纪道斌, 等. 三峡库区澎溪河与磨刀溪电导率等水质特征与水华的关系比较[J]. 环境科学, 2017, **38**(6): 2326-2335.
- Jiang W, Zhou C, Ji D B, *et al.* Comparison of relationship between conduction and algal bloom in Pengxi River and Modao River in Three Gorges Reservoir [J]. Environmental Science, 2017, **38**(6): 2326-2335.
- [33] 刘流. 三峡水库支流库湾水温分层及其对水华的影响[D]. 宜昌: 三峡大学, 2012.
- Liu L. Thermal stratification and its effects on phytoplankton blooms in tributary bays of Three Gorges Reservoir [D]. Yichang: China Three Gorges University, 2012.
- [34] 王洪铸, 王海军, 李艳, 等. 湖泊富营养化治理: 集中控磷, 或氮磷皆控? [J]. 水生生物学报, 2020, **44**(5): 938-960.
- Wang H Z, Wang H J, Li Y, *et al.* The control of lake eutrophication: focusing on phosphorus abatement, or reducing both phosphorus and nitrogen? [J]. Acta Hydrobiologica Sinica, 2020, **44**(5): 938-960.
- [35] 李步东, 刘畅, 刘晓波, 等. 大型水库热分层的水质响应特征与成因分析[J]. 中国水利水电科学研究院学报, 2021, **19**(1): 156-164.
- Li B D, Liu C, Liu X B, *et al.* Water quality response characteristics and cause analysis of thermal stratification of large reservoirs[J]. Journal of China Institute of Water Resources and Hydropower Research, 2021, **19**(1): 156-164.
- [36] Yoshimizu C, Yoshiyama K, Tayasu I, *et al.* Vulnerability of a large monomictic lake (Lake Biwa) to warm winter event [J]. Limnology, 2010, **11**(3): 233-239.
- [37] Marcé R, Moreno-Ostos E, García-Barcina J M, *et al.* Tailoring dam structures to water quality predictions in new reservoir projects: assisting decision making using numerical modeling [J]. Journal of Environmental Management, 2010, **91**(6): 1255-1267.

- [38] Boehrer B, Schultze M. Stratification of lakes [J]. Reviews of Geophysics, 2008, **46**(2), doi: 10.1029/2006RG000210.
- [39] Qin B Q, Zhou J, Elser J J, *et al.* Water depth underpins the relative roles and fates of nitrogen and phosphorus in lakes [J]. Environmental Science & Technology, 2020, **54**(6): 3191-3198.
- [40] Peng J, Wang Y L, Wu J S, *et al.* Ecological effects associated with land-use change in China's southwest agricultural landscape [J]. International Journal of Sustainable Development & World Ecology, 2006, **13**(4): 315-325.
- [41] Li J J, Xie S Y, Kuang M S. Geomorphic evolution of the Yangtze Gorges and the time of their formation [J]. Geomorphology, 2001, **41**(2-3): 125-135.
- [42] 杨兵, 何丙辉, 王德宝. 三峡前置库汉丰湖试运行年水文水质变化特征[J]. 环境科学, 2017, **38**(4): 1366-1375.
- Yang B, He B H, Wang D B. Hanfeng pre-reservoir commissioning time variation feature of the hydrology and water quality in Three Gorges reservoir [J]. Environmental Science, 2017, **38**(4): 1366-1375.
- [43] 岳晓丽. 帕米尔绿球藻去除猪粪沼液废水中氮磷的效果研究 [J]. 大众科技, 2019, **21**(1): 4-6.
- Yue X L. Effect of *Chlorococcum pamirum* on removal of nitrogen and phosphorus from piggery biogas slurry wastewater [J]. Popular Science & Technology, 2019, **21**(1): 4-6.
- [44] 吕林鹏, 纪道斌, 龙良红, 等. 汛末蓄水期神农溪库湾倒灌异重流特性及其对水华的影响 [J]. 水生态学杂志, 2018, **39**(1): 9-15.
- Lv L P, Ji D B, Long L H, *et al.* Effect of reverse slope density flow on algal blooms in Shennong Bay during Three Gorges Reservoir impoundment [J]. Journal of Hydroecology, 2018, **39**(1): 9-15.
- [45] 王耀耀, 徐涛, 崔玉洁, 等. 神农溪水体季节热分层特征及其对水华影响 [J]. 水生态学杂志, 2020, **41**(4): 19-26.
- Wang Y Y, Xu T, Cui Y J, *et al.* Seasonal thermal stratification in Shennong Bay and its effect on algae blooms [J]. Journal of Hydroecology, 2020, **41**(4): 19-26.



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