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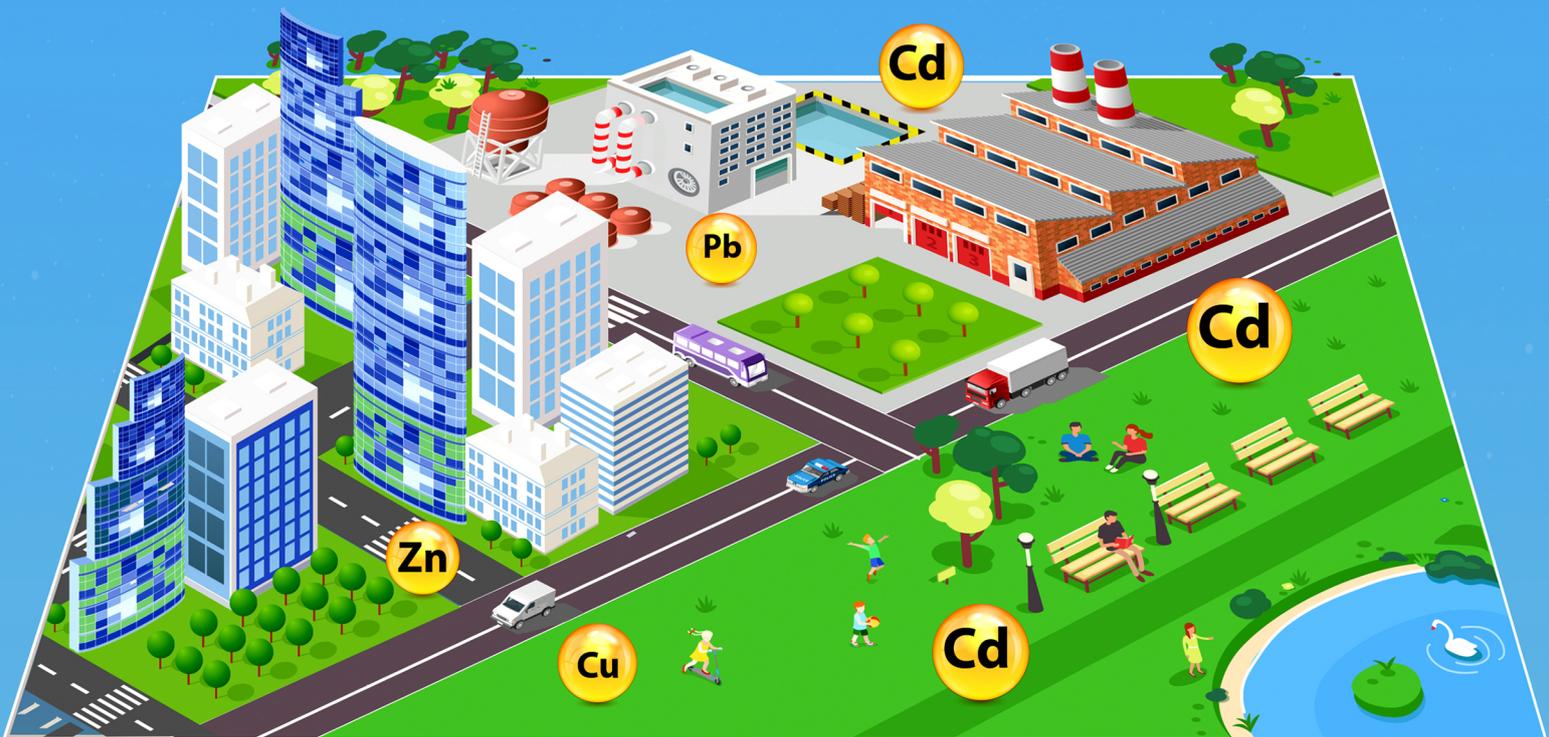
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中国主要城市土壤重金属累积特征与风险评价

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目次

中国主要城市土壤重金属累积特征与风险评价 彭驰, 何亚磊, 郭朝晖, 肖细元, 张严 (1)

植物生长调节剂在土壤中的环境行为综述 陈亮, 侯杰, 胡晓蕾, 张纪兆, 王浩达 (11)

基于铁泥的磁性水处理材料制备及应用进展 曾辉平, 翟龙雪, 李冬, 张杰 (26)

不同臭氧度量指标对我国人群总死亡影响的 Meta 分析 阮芳芳, 刘纪新, 陈芷薇, 曾贤刚 (37)

北京市海坨山冬季不同污染过程下气溶胶化学组分及其潜在来源分析 赵德龙, 王飞, 刘丹彤, 田平, 盛久江, 周崑, 肖伟, 杜远谋, 卢俐, 黄梦宇, 何晖, 丁德平 (46)

武汉冬季大气 PM_{2.5} 小时分辨率源贡献识别及潜在影响域分析 蒋书凝, 孔少飞, 郑煌, 曾昕, 陈楠, 祁士华 (61)

运城市 PM_{2.5} 时空分布特征和潜在源区季节分析 王姝涛, 张强, 温肖宇, 冀乃超, 赵文婷, 罗淑贞, 陈志, 翟程凯 (74)

中国东部冷锋推进中的 PM_{2.5} 三维结构变化特征 牟南南, 朱彬, 卢文 (85)

粤港澳大湾区大气中硝基多环芳烃污染特征与风险评估 李彦希, 谢丹平, 黎玉清, 金梦, 丁紫荣, 闫雅楠, 赵波 (93)

西南地区大型综合工业区和周边区域大气 VOCs 污染特征及健康风险评估 李陵, 张丹, 胡伟, 徐芹, 吴虹, 袁睿, 蒲茜, 郝宇杭, 唐志欣, 赖明敏 (102)

拉萨市挥发性有机物的组成特征、季节变化和来源解析 余家燕, 韩燕, 陈木兰, 张惠芳, 陈阳, 刘建国 (113)

杭州 COVID-19 期间大气 VOCs 体积分数变化特征 林旭, 严仁嫦, 金嘉佳, 许凯儿, 何曦, 叶辉, 何纪平 (123)

上海城郊夏季大气 VOCs 在臭氧生成中的作用 金丹 (132)

铜川市秋冬季大气 VOCs 特征及其 O₃ 和 SOA 形成潜势分析 易宵霄, 李姜豪, 李光华, 路珍珍, 孙智钢, 高健, 邓顺熙 (140)

电子垃圾拆解回收 VOCs 排放特征与排放因子 谢丹平, 黄忠辉, 刘旺, 聂鹏, 黄钟坤, 贺辉, 陈晓燕 (150)

不同传输通道下珠江三角洲臭氧与前体物非线性响应关系 伍永康, 陈伟华, 颜丰华, 毛敬英, 袁斌, 王伟文, 王雪梅 (160)

淄博市城郊臭氧污染特征及影响因素分析 王雨燕, 杨文, 王秀艳, 王帅, 白瑾丰, 程颖 (170)

昭通市周边扬尘重金属污染特征及健康风险 庞晓晨, 韩新宇, 史建武, 包宇斋, 宁平, 张朝能, 向峰 (180)

城市路面积尘微塑料污染特征 方芹, 牛司平, 陈予东, 于江华 (189)

塔里木河流域东部降水稳定同位素特征与水汽来源 宋洋, 王圣杰, 张明军, 石玉东 (199)

赤水河流域水体抗生素污染特征及风险评估 吴天宇, 李江, 杨爱江, 李彦澄, 陈瑀, 何强, 马凯, 胡霞, 王斌, 艾佳, 钟雄 (210)

无定河流域地表地下水的水化学特征及控制因素 李书鉴, 韩晓, 王文辉, 李志 (220)

白洋淀府河影响区沉积物营养盐和重金属污染特征及风险评估 陈兴宏, 李立青, 张美一, 张伟军, 王东升, 王洪杰 (230)

九龙江口红树林湿地表层沉积物中微塑料赋存特征与重金属的关系 刘倡君, 罗专溪, 闫钰, 林惠荣, 胡恭任, 于瑞莲 (239)

北京市北运河水系底栖动物群落与水环境驱动因子的关系及水生态健康评价 胡小红, 左德鹏, 刘波, 黄振芳, 徐宗学 (247)

城市河道再生水特征水质因子空间变异机制分析 刘全忠, 彭柯, 苏振华, 邸琰茗, 郭道宇 (256)

苏州景观河道表层沉积物间隙水-上覆水中 DOM 特性分析 李超男, 何杰, 朱学惠, 李学艳 (267)

苏州城区雨水管道沉积物典型污染物分布特征 叶蓉, 盛铭军, 姜永波, 武宇圣, 黄天寅 (277)

信号分子强化改性挂膜沸石持续抑制沉积物中氨氮释放 徐金兰, 许洋, 李修民, 国森, 刘成海 (285)

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 田盼, 李亚莉, 李莹杰, 李虹, 王丽婧, 宋林旭, 纪道斌, 赵星星 (295)

李家河水库春季分层期 nirS 型反硝化菌群特征分析 梁伟光, 黄廷林, 张海涵, 杨尚业, 刘凯文, 李程遥, 温成成, 李伟涛, 蔡晓春 (306)

岗南水库沉积物好氧反硝化菌群落时空分布特征 张紫薇, 陈召莹, 张甜娜, 周石磊, 崔建升, 罗晓 (314)

宁夏地区地下水金属元素分布特征及健康风险评估 王晓东, 田伟, 张雪艳 (329)

快速城镇化三角洲地区高碘地下水赋存特征及驱动因素; 以珠江三角洲为例 吕晓立, 刘景涛, 韩占涛, 周冰, 李备 (339)

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 张智博, 段艳平, 沈嘉豪, 俞文韬, 罗鹏程, 涂耀仁, 高峻 (349)

洞庭湖及入湖河流中 209 种多氯联苯同类物分布特征与风险评估 黄智峰, 郑丙辉, 尹大强, 崔婷婷, 赵兴茹 (363)

基于流量和溶存浓度的河流水系氧化亚氮释放量估算 李冰清, 胡敏鹏, 王铭烽, 张育福, 吴昊, 周佳, 吴锴彬, 戴之舟, 陈丁江 (369)

三峡库区万州段河流水-气界面 CO₂ 通量支干流对比及影响机制初探 秦宇, 欧阳常悦, 王雨潇, 方鹏 (377)

功能化凹凸棒吸附材料的制备及其对重金属废水中 Pb²⁺ 的吸附行为 廖晓峰, 钟静萍, 陈云嫩, 邱延省, 任嗣利 (387)

铁氮共掺杂生物炭对二级水溶解性有机物的吸附特性与长效性评价 吴晨曦, 许路, 金鑫, 石烜, 金鹏康 (398)

沸石悬浮填料生物移动床的亚硝化特性 邓翠兰, 郭露, 汪晓军, 陈振国 (409)

温度对 ANAMMOX 生物膜工艺的脱氮影响与菌群结构分析 吴珊, 王淑雅, 王芬, 季民 (416)

填料对 ANAMMOX 污泥活性恢复的影响及菌群特征 罗景文, 杨津津, 李绍康, 赵昕宇, 杨一飞, 韩嘉琛, 李翔 (424)

基于 PMF 模型的宁南山区小流域土壤重金属空间分布及来源解析 夏子书, 白一茹, 王幼奇, 高小龙, 阮晓晗, 钟艳霞 (432)

浙中典型硫铁矿田土壤重金属含量特征及健康风险 成晓梦, 孙彬彬, 吴超, 贺灵, 曾道明, 赵辰 (442)

农产品视角的城郊黑土地田土壤重金属风险分区 吴松泽, 王冬艳, 李文博, 王兴佳, 闫卓冉 (454)

基于 DGT 技术的广西碳酸盐岩区稻米镉含量主控因素 宋波, 肖乃川, 马丽钧, 李龙, 陈同斌 (463)

调理剂耦合水分管理对双季稻镉和铅累积的阻控效应 李林峰, 王艳红, 李义纯, 唐明灯, 李奇, 艾绍英 (472)

设施叶菜类蔬菜重金属镉、铅和砷累积特征及健康风险评估 董俊文, 高培培, 孙洪欣, 周昶, 张香玉, 薛培英, 刘文菊 (481)

电子垃圾拆解固废渣-土壤-蔬菜中多氯联苯污染特征与健康风险评估 张亚萍, 吕占禄, 王先良, 张晗, 郭凌川, 丁秀丽, 张金良 (490)

雷州半岛南部典型农用地土壤-作物的有机氯农药残留特征和健康风险评估 梁晓晖, 解启来, 郑芊, 杨北辰, 叶金明, 唐成金 (500)

重金属含量对城市土壤真菌群落结构的影响 郭大陆, 张建, 申思, 余子洁, 杨军顺, 罗红燕 (510)

长期施肥对黄土高原梯田土壤养分特征和微生物资源限制的影响 吴春晓, 高小峰, 闫本帅, 梁彩群, 陈佳瑞, 王国梁, 刘国彬 (521)

土地利用变化后不同种植年限香榧土壤微生物群落的组成及多样性 姜霓雯, 梁辰飞, 张勇, 蒋仲龙, 董佳琦, 吴家森, 傅伟军 (530)

化肥和有机肥配施生物炭对土壤磷酸酶活性和微生物群落的影响 杨文娜, 余添, 罗东海, 熊子怡, 王莹燕, 徐曼, 王子芳, 高明 (540)

秦岭中段撂荒地植被恢复过程中土壤微生物代谢特征 薛悦, 康海斌, 杨航, 冰德叶, 晁志, 张凯, 王得祥 (550)

全生物降解地膜原料颗粒对土壤性质、小麦生长和养分吸收转运的影响 闵文豪, 王春丽, 王莉玮, 易廷辉, 卞京军, 支梅, 孙琪惠, 宿锦锦, 赵秀兰 (560)

秸秆还田对冬小麦-夏玉米农田土壤固碳、氧化亚氮排放和全球增温潜势的影响 万小楠, 赵珂悦, 吴雄伟, 白鹤, 杨学云, 顾江新 (569)

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

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摘要: 采用2018年三峡水库7~8月(低水位期)和10月(蓄水变动期)对库区支流香溪河和神农溪水文水动力和环境因子的监测数据,分析香溪河和神农溪的叶绿素 a 等指标在不同调度时期垂向分布特征,讨论不同时期影响其垂向分布的原因. 结果表明,低水位期香溪河和神农溪的溶解氧、水温、pH值和叶绿素 a 垂向分布规律较为一致,各指标在0~10 m(叶绿素 a 在0~5 m)分层明显且整体上随水深增加而减小,热分层稳定指数(RWCS/H)为13.71~29.07 m⁻¹,分层稳定,水深10 m(叶绿素 a 为5 m)后各指标沿水深趋于稳定;蓄水变动期,各指标无明显分层,热分层稳定指数为0~0.50 m⁻¹,水体稳定性较弱,各指标垂向上变化相对稳定;香溪河和神农溪表层水体综合营养状态指数(TLI)在低水位期分别为55和53,处于轻度富营养状态,在蓄水变动期分别为39和46,处于中营养状态. 线性回归分析显示,低水位期两支流水体中的叶绿素 a、溶解氧、水温和pH值在垂向上相关性显著,溶解氧、水温分层和pH值是影响叶绿素 a 垂向分布的重要因素. 高水位期干流水体的大量倒灌、支流较大的水位波动和RWCS/H的降低等是水体未分层且各指标垂向变化较小的重要影响因素;水体垂向掺混的增强和 Z_{cu}/Z_{mix} 的减小是影响水体营养状态的关键因素.

关键词: 香溪河; 神农溪; 叶绿素 a; 溶解氧; 低水位期; 蓄水变动期; 水体分层

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Effects of the Three Gorges Reservoir Operation on Vertical Distribution of Chlorophyll a and Environmental Factors in Tributaries

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Abstract: The hydrodynamics and environmental factors in the Xiangxi River (XXR) and Shennong River (SNR), which are tributaries of the Three Gorges Reservoir (TGR), were monitored from July to August (the low water level period) and in October (the impoundment period) in 2018. The vertical distribution characteristics of chlorophyll a and other indicators of the two tributaries were analyzed during the different operation periods, and the factors that affected the vertical distribution in each period were discussed. The results showed that the vertical distribution of dissolved oxygen, water temperature, pH value, and chlorophyll a of the XXR and SNR during the low water level period was relatively consistent. The indexes 0-10 m (0-5 m for chlorophyll a) from the surface of the XXR and SNR, respectively, showed significant stratification and decreased with increasing water depth; the stability index of thermal stratification (RWCS/H) was 13.71-29.07 m⁻¹, which was stable. After the water depth reached 10 m (5 m for chlorophyll a), the indexes tended to be stable along the water depth. During the impoundment period, there was no obvious stratification for each index; the stability index of thermal stratification was 0-0.5 m⁻¹, the stability of the water body was weak, and the vertical variation of each index was relatively stable. The comprehensive trophic state index (TLI) of the XXR and SNR were 55 and 53 during the low water level period, respectively, indicating that they were in a slightly eutrophic state, and 39 and 46 during the impoundment period, respectively, indicating a mesotrophic state. Linear regression analysis showed that chlorophyll a, dissolved oxygen, water temperature, and pH in the two tributaries were significantly correlated in the vertical direction in the low water level period, indicating that dissolved oxygen, water temperature stratification, and pH were important factors affecting the vertical distribution of chlorophyll a. During the impoundment period, a large amount of backflow from the Yangtze River, a large fluctuation in tributary water level, and the decrease in RWCS/H were the important factors that affected the small vertical change in the water body. The enhancement of vertical mixing and the decrease in Z_{cu}/Z_{mix} were the key factors affecting the nutritional status of the water.

Key words: Xiangxi River; Shennong River; chlorophyll a; dissolved oxygen; low water level period; impoundment period; water stratification

水体富营养化是淡水生态系统面临的威胁之一,也是造成水质恶化最常见的原因之一^[1,2]. 浮游藻类是水生态系统的初级生产者,叶绿素 a 是衡量水体初级生产力的重要指标,反映着水体富营养化程度,是水环境科学十分关键的参数^[3,4]. 水体形成季节性的物理分层是水库的重要特征之一^[5,6],众多研究者对分层型湖库藻类分布研究发现,藻类数量及群落结构主要受溶解氧、水温^[7,8]、水位波动、透明

度^[9,10]、营养因子和光照强度^[11]等因素影响,藻类多样性和水质因子均表现出时空差异性. 藻类能够通过光合作用增加水体溶解氧的含量,呼吸作用又会降低

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水体溶解氧含量,而溶解氧是维系水生态安全的重要要素之一,参与着水化学反应及水生物等相互作用的过程^[12,13],当水体遭受污染后则会使溶解氧含量大幅度降低,水质便会恶化^[14]. 水体分层影响着水库理化因子的垂向分布和物质的迁移转换^[15,16],而水体分层往往又具有季节性的变化. 故对不同时期水体中叶绿素 a 和溶解氧等理化因子在垂向上的分布特征及其影响因素进行研究有重要意义.

三峡库区自 2003 年蓄水以来,产生着巨大的经济社会效益,但也改变了库区的水文水动力,使原来的河流生态系统转变成水库型生态系统,给库区的生态环境等带来了不利影响,干流倒灌和分层等水文水动力因素和人为因素的影响,加重了支流富营养化问题,导致部分支流水华暴发频繁,库区水质安全受到严重威胁^[17,18]. 霍静等^[19]的研究将神农溪水温季节分层分为了阶梯型、双混斜型和半 U 型,田盼等^[20]和杨凡等^[21]的研究发现,香溪河和神农溪水体中叶绿素 a 和溶解氧等理化因子垂向上在 2 月、7 月和蓄水初期(9 月)存在明显分层. 但在蓄水中期(10 月),库区水位变化大,长江干流水体大量倒灌,来自长江倒灌的水体对支流库湾水体的掺混强度有着显著影响^[22,23]. 故对于库区不同的调度时期,尤其是蓄水位快速上升时期,支流库湾大纵深断面的各指标垂向分布变化特征及其驱动因素为何,其认识还需要进一步拓展. 鉴于此,本研究以三

峡库区一级支流香溪河和神农溪为例,于 2018 年低水位期(香溪河 7 月、神农溪 8 月)和蓄水变动期(10 月)对其进行垂向水环境监测,分析不同调度时期垂向水环境变化特征及其形成机制,明晰两支流在三峡调度大背景下的垂向水环境的共性特征,以期为库区水环境管理和生态调度提供参考依据,也为我国水库生态学研究积累重要的资料.

1 材料与方法

1.1 研究区域概况

香溪河流域位于湖北宜昌兴山县,河口距离三峡大坝约 34.5 km,流域总面积约 3 099.0 km²,河流全长约 94.0 km. 神农溪流域位于湖北恩施巴东县,河口到三峡大坝距离约 69.9 km,河流全长约 60.6 km,流域总面积约 1 047.0 km². 两支流均为库区典型一级支流,受到三峡水库调度的影响明显.

1.2 样点布设

7~8 月水位相对稳定,水库水体环境变化相对较小;10 月为蓄水变动期,库湾水位急剧变化,水体环境变化大^[24]. 故于 2018 年分别于低水位期(香溪河 7 月,神农溪 8 月)和蓄水期变动期(10 月)对神农溪和香溪河进行水环境监测. 在香溪河布设 6 个监测点分别为 XX01、XX02、XX03、XX04、XX05 和 XX06,神农溪布设 4 个监测点分别为 SN01、SN02、SN03 和 SN04,具体位置如图 1 所示.

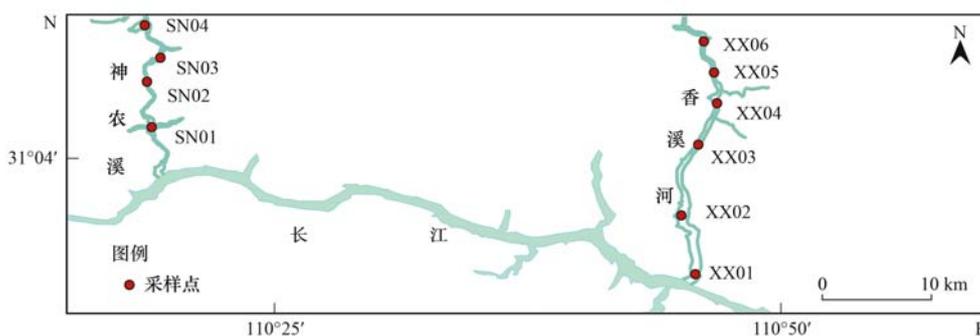


图 1 采样点示意

Fig. 1 Locations of sampling sites

1.3 数据采集

监测指标包括溶解氧(DO)、水温(WT)、pH 值(pH)、叶绿素 a(Chl-a)、总氮(TN)、总磷(TP)和光合有效辐射(PAR)等,其中 TN 和 TP 作为营养指标,DO 反映氧化条件,WT 反映水温变化,pH 反映水体酸碱状态,Chl-a 反映浮游植物生物量^[25]. DO、WT、pH 和 Chl-a 用 YSI-EXO 多参数水质分析仪(美国)对各监测点进行现场监测,用 2.5 L 采水器采集水面 0~0.5 m 处水样,放入 350 mL 水样瓶冷冻保存,带回实验室测定,水样测定均设置 3 组平

行样,取均值作为最后的结果,TN 采用过硫酸钾氧化紫外分光光度计法,TP 采用钼锑抗分光光度计法,PAR 用 International Light4100 光照计(美国)测定.

1.4 数据处理

1.4.1 数据分析

Chl-a 垂向上整理有效值后,仅对水深 0~20 m 范围进行分析. 真光层深度(Z_{eu})取 1% 表面光强对应的水深^[26,27],混合层深度(Z_{mix})则选取与表面水温相差 0.5℃ 对应的水深^[28,29]. 用 Arcgis10.2 绘制

采样点图,用 Origin2019 绘制垂向分布等,用 SPSS 进行线性拟合分析和单因素方差分析(ANOVA)。

1.4.2 热分层稳定指数计算

热分层稳定指数(RWCS/H)用于评价热分层稳定水平^[30],其计算公式为:

$$RWCS/H = (D_b - D_s) \times (D_4 - D_5)^{-1} \times H^{-1} \quad (1)$$

式中, D_s 和 D_b 分别为底层和表层水体密度, $\text{kg}\cdot\text{m}^{-3}$; D_5 和 D_4 分别为 5.0°C 和 4.0°C 时纯水密度, $\text{kg}\cdot\text{m}^{-3}$; H 为水深, m 。当 $RWCS/H > 2.00 \text{ m}^{-1}$ 时,为稳定分层状态, $RWCS/H$ 越大,水体越易分层, $RWCS/H$ 越小,则水体越易发生混合。为便于描述,将水面下 $0 \sim 0.5 \text{ m}$ 处定为表层水深, $8 \sim 10 \text{ m}$ 处定为中层水深,底层水深 H 取水温垂向上有效值的最后数值所对应的水深。

忽略水体泥沙影响,水温对应的水体密度计算公式为^[31,32]:

$$\rho_T = 1000 [1 - (T + 288.9414) \times (T - 3.9863)^2 \times (T + 68.1294)^{-1} / 508929.2] \quad (2)$$

式中, T 为水体温度, $^\circ\text{C}$; ρ_T 为水温对应的水体密度, $\text{kg}\cdot\text{m}^{-3}$ 。

1.4.3 综合营养状态指数计算

采用综合营养状态指数法(TLI)作为富营养化

的评价方法^[33],该方法通过 $0 \sim 100$ 系列数字将水体营养状态分级,即贫营养($TLI < 30$),中营养($30 \leq TLI \leq 50$),轻度富营养($50 < TLI \leq 60$),中度富营养($60 < TLI \leq 70$),重度富营养($TLI > 70$)^[34]。本研究结合已有监测资料,选取 Chl-a、TN 和 TP 作为评价因子^[35],其具体计算方法参见文献[36]。

2 结果与分析

2.1 不同时期叶绿素 a 垂向分布特征

叶绿素 a 在不同时期的垂向分布特征如图 2 所示,低水位期,整体上香溪河 Chl-a 在 $0 \sim 5 \text{ m}$ 水深分层明显,在 1 m 左右达到最大值, $5 \sim 20 \text{ m}$ 水深范围内,Chl-a 沿水深趋于稳定,无分层现象;神农溪 Chl-a 在 $0 \sim 5 \text{ m}$ 水深分层明显,在 3 m 左右达到最大值, $5 \sim 20 \text{ m}$ 水深范围内,Chl-a 沿水深趋于稳定,无分层现象。香溪河和神农溪表层水体 $\rho(\text{Chl-a})$ 的平均值分别为 $8.93 \mu\text{g}\cdot\text{L}^{-1}$ 和 $13.18 \mu\text{g}\cdot\text{L}^{-1}$,且测得香溪河和神农溪表层水体 $\rho(\text{TN})$ 的平均值分别为 $3.15 \text{ mg}\cdot\text{L}^{-1}$ 和 $1.29 \text{ mg}\cdot\text{L}^{-1}$, $\rho(\text{TP})$ 的平均值分别为 $0.05 \text{ mg}\cdot\text{L}^{-1}$ 和 $0.06 \text{ mg}\cdot\text{L}^{-1}$,计算得 TLI 分别为 55 和 53(表 1),呈轻度富营养状态。

蓄水变动期,整体上香溪河和神农溪的 Chl-a 均无明显的分层现象, $0 \sim 20 \text{ m}$ 沿水深趋于稳定,

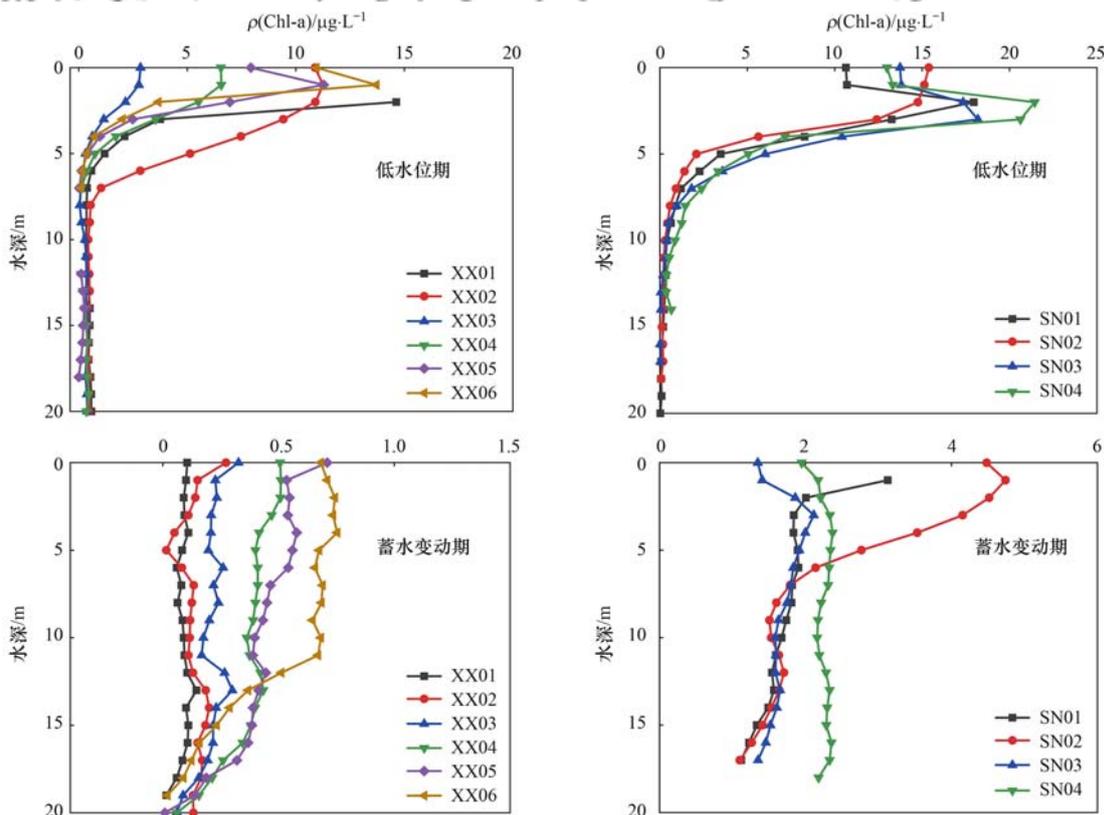


图 2 三峡水库各支流不同调度时期 Chl-a 垂向分布特征

Fig. 2 Vertical distribution characteristics of Chl-a in tributaries of TGR in different operation periods

垂向上变化范围分别为 0 ~ 0.70 $\mu\text{g}\cdot\text{L}^{-1}$ 和 1.40 ~ 4.40 $\mu\text{g}\cdot\text{L}^{-1}$. 香溪河和神农溪表层水体 $\rho(\text{Chl-a})$ 的平均值分别为 0.43 $\mu\text{g}\cdot\text{L}^{-1}$ 和 2.64 $\mu\text{g}\cdot\text{L}^{-1}$, 显著低于低水位期 ($P < 0.01$), 又测得香溪河和神农溪表层水体 $\rho(\text{TN})$ 的平均值分别为 1.62 $\text{mg}\cdot\text{L}^{-1}$ 和 1.61 $\text{mg}\cdot\text{L}^{-1}$, $\rho(\text{TP})$ 的平均值分别为 0.06 $\text{mg}\cdot\text{L}^{-1}$ 和 0.05 $\text{mg}\cdot\text{L}^{-1}$, 计算得 TLI 分别为 39 和 46(表 1), 呈中营养状态.

表 1 不同时期香溪河和神农溪综合营养状态指数

Table 1 Comprehensive nutritional status index of Xiangxi River and Shennong River in different periods

指标	时期	香溪河	神农溪
综合营养状态指数(TLI)	低水位期	55	53
	蓄水变动期	39	46

2.2 低水位期理化因子垂向分布特征

各理化因子低水位期的垂向分布特征如图 3 所示, 香溪河的溶解氧在 1 m 左右达到最大值, $\rho(\text{DO})$ 为 10.0 ~ 16.0 $\text{mg}\cdot\text{L}^{-1}$, 水深 0 ~ 10 m 分层明显, 在此范围内 $\rho(\text{DO})$ 随水深沿程降低至 4.0 ~ 6.5 $\text{mg}\cdot\text{L}^{-1}$, 水深 10 m 后, DO 整体上沿水深趋于稳定, 仅 XX05 和 XX06 点存在一定的波动. 水温在 1 m 左右达到最大值, 其范围为 28 ~ 32 $^{\circ}\text{C}$, 水深 0 ~ 10 m, 其 RWCS/H 处于 13.71 ~ 29.07 m^{-1} , 大于 2 m^{-1} (表 2), 分层明显且稳定, 水深 10 m 后, 其 RWCS/H 降至 0.05 ~ 0.36 m^{-1} , 无明显分层, 水温沿水深趋于稳定. pH 值在 0.5 ~ 1.0 m 水深范围达到最大值, 其范围为 8.3 ~ 9.0, 水深 0 ~ 10 m 分层明显, 在此范围内随水深沿程降低至 7.6 ~ 7.8, 水体呈偏碱

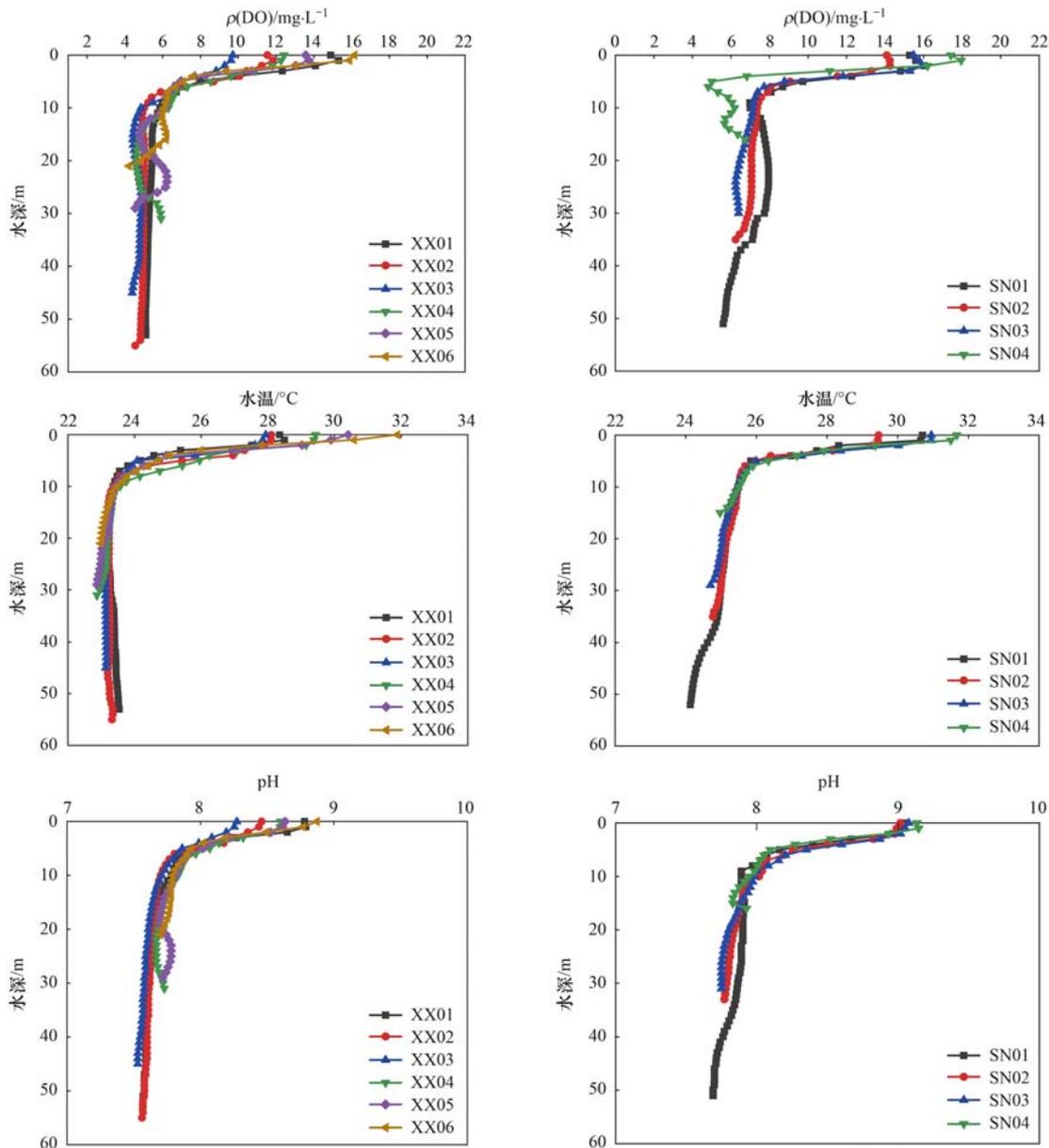


图 3 三峡水库低水位期各支流环境因子的垂向分布特征

Fig. 3 Vertical distribution characteristics of environmental factors in tributaries of TGR in the low water level period

性状态,水深 10 m 后,pH 值沿水深趋于稳定。

神农溪的溶解氧在 1 m 左右达到最大值, $\rho(\text{DO})$ 为 $14.0 \sim 18.0 \text{ mg}\cdot\text{L}^{-1}$,水深 0 ~ 8 m 分层明显,在此范围内 $\rho(\text{DO})$ 随水深沿程降低至 $4.0 \sim 7.0 \text{ mg}\cdot\text{L}^{-1}$,水深 8 m 后,DO 整体上沿水深趋于稳定,SN06 点存在一定的波动。水温在 1m 左右达到最大值,其范围为 $29 \sim 32^\circ\text{C}$,水深 0 ~ 8 m,其 RWCS/H 处于 $13.71 \sim 29.07 \text{ m}^{-1}$ (表 2),分层明显且稳定,水深 8 m 后, RWCS/H 处于 $0.05 \sim 0.36 \text{ m}^{-1}$,水温沿水深趋于稳定。pH 值在 0.5 ~ 1.0 m 范围达到最大值,其值为 9.0 左右,水深 0 ~ 8 m 分层明显,在此范围内随水深沿程降低至 8.0 左右,水体呈偏碱性状

态;水深 8 m 后,pH 值沿水深趋于稳定。

表 2 不同时期典型支流的热分层稳定指数/ m^{-1}

Table 2 Thermal stratification stability index of typical tributaries in different periods/ m^{-1}			
指标	时期	表-中	中-底
热分层稳定指数 (RWCS/H)	低水位期	13.71 ~ 29.07	0.05 ~ 0.36
	蓄水变动期	0 ~ 0.50	0.24 ~ 0.48

2.3 蓄水变动期理化因子垂向分布特征

各理化因子蓄水变动期的垂向分布特征如图 4 所示,蓄水变动期,香溪河在垂向上,各指标均无明显分层现象, $\rho(\text{DO})$ 在各点垂向变化量为 $0 \sim 2.5 \text{ mg}\cdot\text{L}^{-1}$,水温变化量为 $0 \sim 0.5^\circ\text{C}$,pH 值变化量为 0

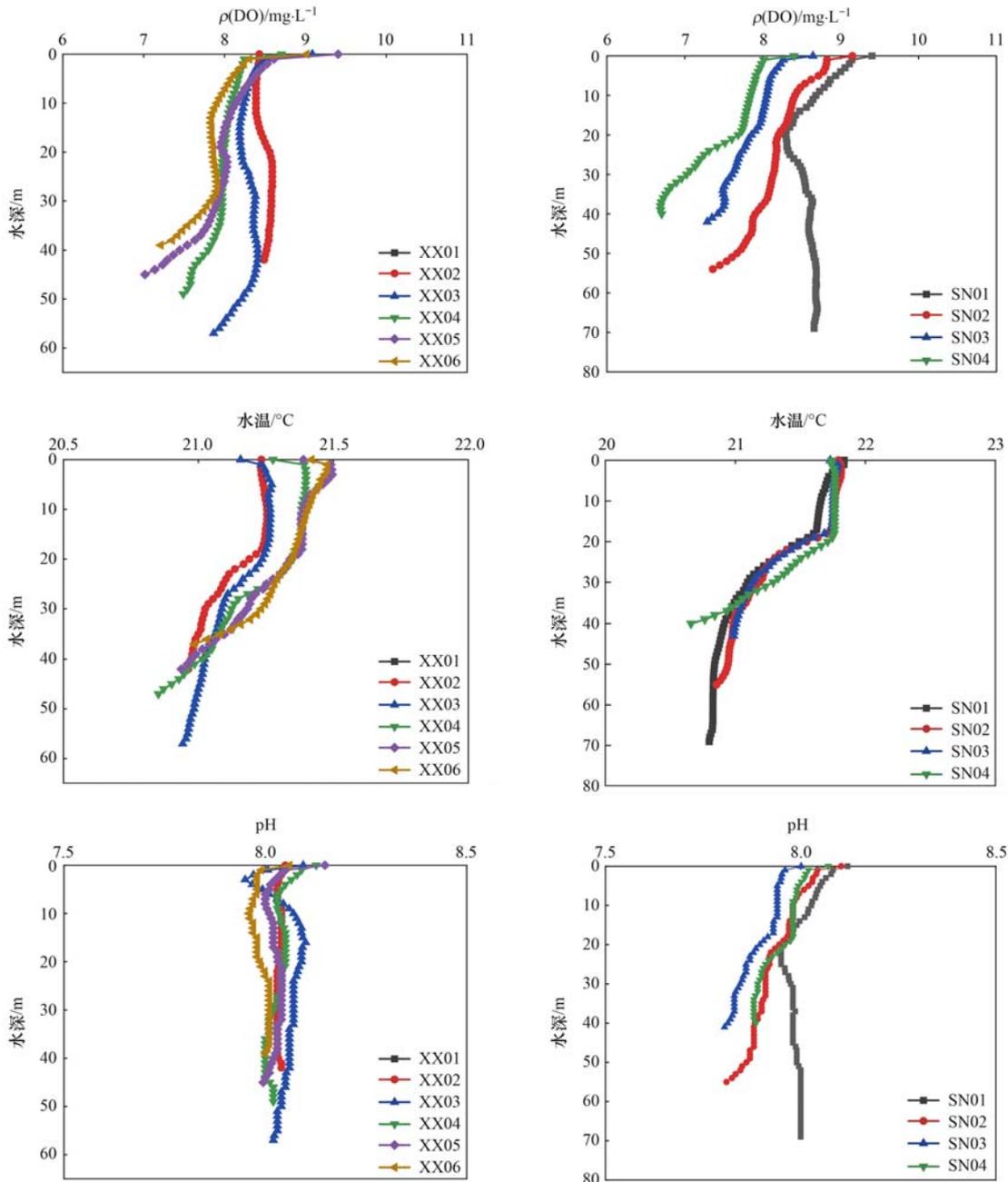


图 4 三峡水库蓄水变动期各支流环境因子的垂向分布特征

Fig. 4 Vertical distribution of environmental factors in tributaries of TGR in the impoundment period

~0.3. 神农溪垂向上,整体来看各指标均无明显的分层现象, $\rho(\text{DO})$ 在各点垂向变化量为 $0 \sim 2.0 \text{ mg} \cdot \text{L}^{-1}$, 水温变化量为 $0 \sim 1^\circ\text{C}$, pH 值变化量为 $0 \sim 0.5$, 但以水深 20 m 为界, 上半层分层现象不明显, 下半层存在微弱的分层现象. 此时期香溪河和神农溪 RWCS/H 整体处于 $0 \sim 0.50 \text{ m}^{-1}$ (表 2), 表明水体稳定性弱, 上下水体间易发生混合.

2.4 线性回归分析

在低水位期水体分层的条件下, 香溪河和神农溪的叶绿素 a 与 DO、WT 和 pH 值之间的线性分析

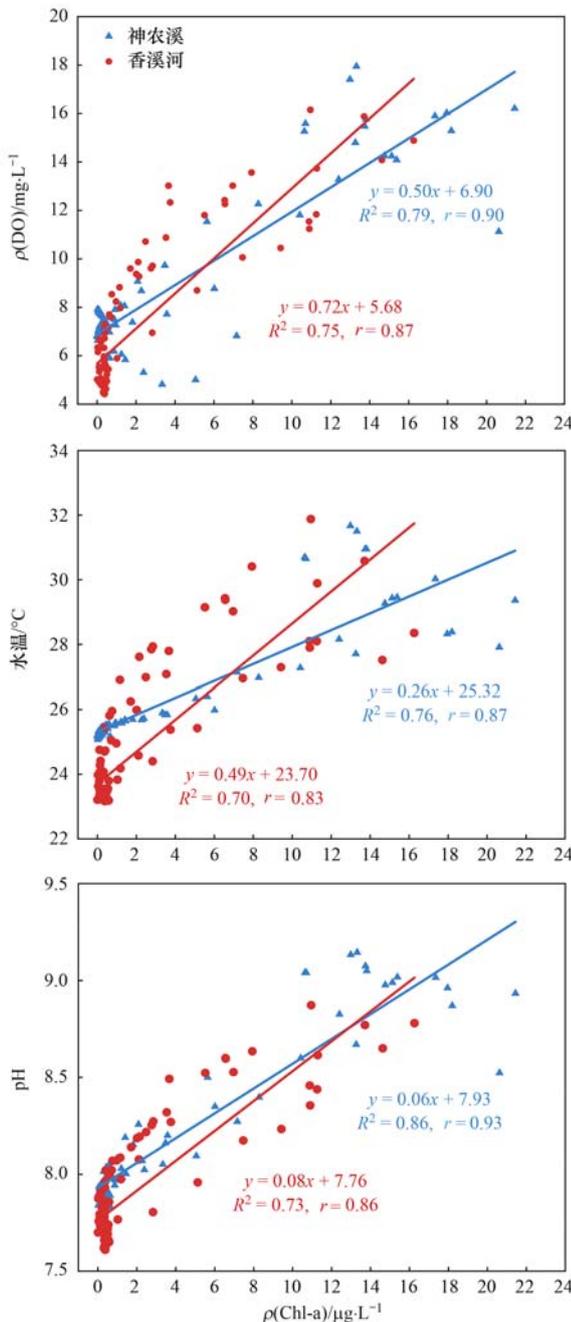


图 5 三峡水库低水位期各支流 Chl-a 与 DO、WT 和 pH 值的相关性

Fig. 5 Correlation of Chl-a with DO, WT, and pH in tributaries of TGR in the low water level period

结果如图 5 所示, 香溪河(神农溪)叶绿素 a 与 DO、WT 和 pH 值均呈明显的线性关系, 相关系数(r)分别为 $0.87(0.90)$ 、 $0.83(0.87)$ 和 $0.86(0.93)$, 表明分层水体中叶绿素 a 的垂向分布与 DO、WT 和 pH 值等理化因子联系紧密;

在低水位期水体分层的条件下, 香溪河(神农溪)的 DO、WT 和 pH 值之间的线性分析结果如图 6 所示, 香溪河(神农溪)DO 与 WT 和 pH 值之间呈明显的线性关系, 相关系数分别为 $0.95(0.93)$ 和 $0.98(0.93)$, 表明分层水体中 DO 与 WT 和 pH 值等联系紧密.

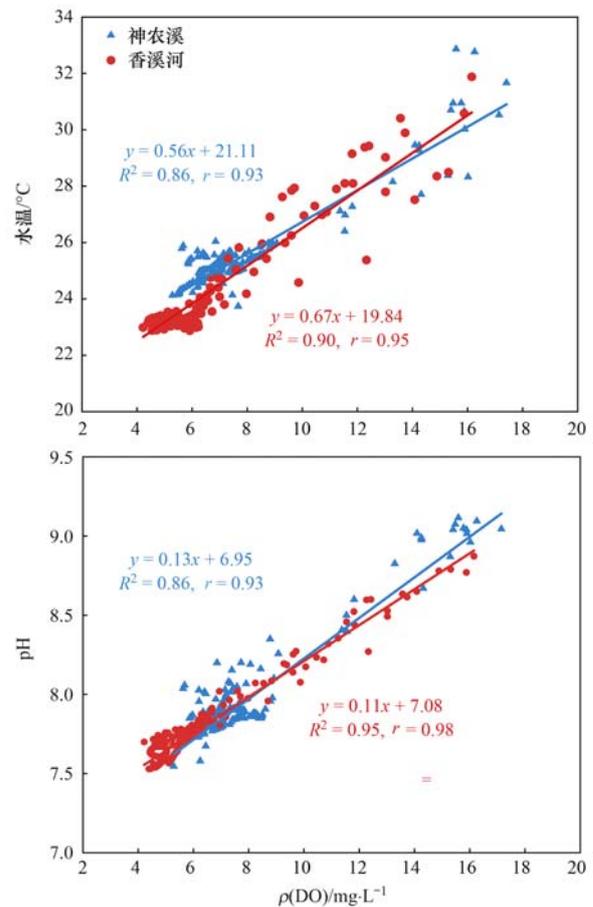


图 6 三峡水库低水位期各支流 DO 与 WT 和 pH 值的相关性

Fig. 6 Correlation of DO with WT and pH in tributaries of TGR in the low water level period

3 讨论

3.1 低水位期各指标垂向分布特征成因分析

如图 2 和图 3 所示, 香溪河和神农溪水体在低水位期存在明显的 DO 分层、温跃层、pH 值分层和叶绿素 a 分层, 前三者分层深度较为一致在 $0 \sim 10 \text{ m}$ 范围内, 叶绿素 a 分层深度在 $0 \sim 5 \text{ m}$ 范围. 如图 5 和图 6 所示, DO、WT、pH 值和 Chl-a 在垂向上呈明显的线性关系, 表明各指标间垂向上联系紧密. 低水位期支流在水深 $0 \sim 10 \text{ m}$ 范围, 其 RWCS/H 处于

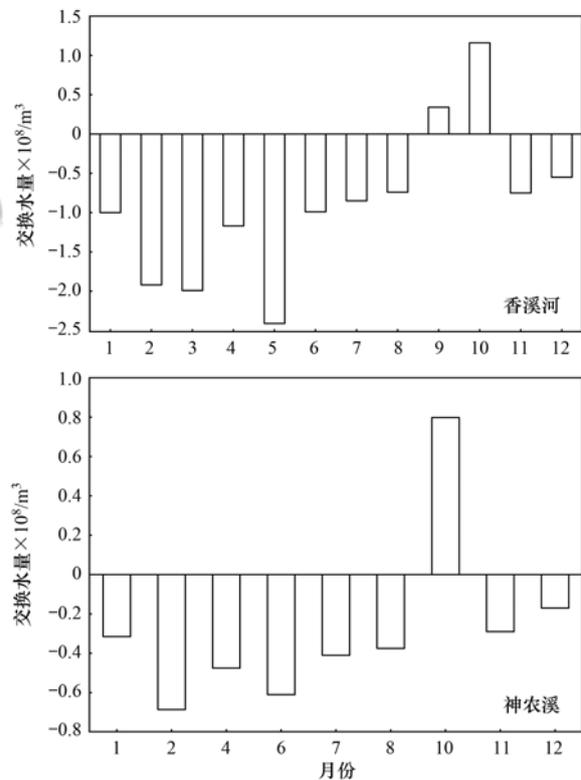
13.71 ~ 29.07 m⁻¹, 而中底层的 RWCS/H 处于 0.05 ~ 0.36 m⁻¹ (表 2), 加上此时期库湾水位波动较小, 干支流水量交换也较小 (图 7), 水体产生明显的分层现象且分层稳定. 水体被强烈分层后, 水体的垂向混合和物质的迁移转换便被抑制^[37]. 因为中底层的 RWCS/H 较小, 水体稳定性较弱, 故底层温度分布较均匀, 在表中层之间便形成了一个过渡层, 过渡层的水温梯度较大时, 便产生了温跃层^[38,39]. 深层水体中的 DO 主要通过表层水体中的 DO 垂向对流交换来获得补充^[40,41], 表层水体 DO 则主要来源于空气中氧气的溶解和浮游植物的光合作用^[42], 而由于温跃层的存在, 其较大的温度梯度限制了垂向掺混, 且热分层强稳定期温跃层垂向扩散系数小, 阻碍了表层水体 DO 对中底层的补充^[43,44], 使香溪河和神农溪中上层 $\rho(\text{DO})$ 明显高于中下层. 由于表层光合作用较强, 浮游植物大量生长, 故 $\rho(\text{Chl-a})$ 也较高, 但观察到 $\rho(\text{Chl-a})$ 在 1 m 或 3 m 处达到最大值, 其原因在于表层水体受到强光作用, 部分藻种会向下迁移至次表层, 发生藻类下沉聚集的现象^[45]. 浮游植物增加, 光合作用就会消耗更多的 CO₂, 根据二氧化碳-碳酸盐体系 ($\text{CO}_2 + \text{H}_2\text{O} \rightleftharpoons \text{HCO}_3^- + \text{H}^+ \rightleftharpoons \text{CO}_3^{2-} + 2\text{H}^+$)^[46], 水体 H⁺ 浓度因此下降, 加上藻类主要利用体内羧化酶将 HCO₃⁻ 转化为 CO₂ 进行光合作用, 从而置换出 OH⁻, 故水体 pH 值偏碱性.

但是, 随着水深的增加, 水温的降低会弱化浮游植物体内酶的活性, 减弱浮游植物的光合作用, 从而降低浮游植物的生物量^[47,48], $\rho(\text{Chl-a})$ 便降低, 从而减少 CO₂ 的消耗量. 光合作用减弱, 则呼吸作用增强, 加上浮游植物在死亡后会被微生物分解而消耗氧气, 故 $\rho(\text{DO})$ 降低^[49]. CO₂ 的增加使 pH 值下降, H⁺ 沿水深逐渐增加直至稳定, 过程中促进水体本身的氧化还原反应 ($4\text{H}^+ + \text{O}_2 + 4\text{e} \rightleftharpoons 2\text{H}_2\text{O}$)^[50] 向正向发生, 也能降低水体中的 $\rho(\text{DO})$.

3.2 蓄水变动期各指标垂向分布特征成因分析

如图 2 和图 4 所示, 蓄水变动期, 香溪河和神农溪垂向上 Chl-a、DO、WT 和 pH 值趋于一致, 没有出现明显的分层现象. 研究证明香溪河和神农溪库湾混合层的深度随水位波动幅度的增加而增加^[51], 水位的快速抬升会增强干支流的水体交换, 如田盼等^[52] 和韩超南等^[53] 的研究通过水量平衡方程计算出蓄水变动期干支流水量交换以干流倒灌为主 (图 7). 水体的紊动条件是决定水体分层状况的主要变量之一, 华逢耀等^[54]、Wang 等^[55] 和 Holbach 等^[56] 的研究发现, 高入库流量会加剧水体的扰动, 使水体更易混合, 能显著降低水体分层的稳定性. 香溪河和

神农溪在蓄水变动期水位波动约 20 m, 水位波动改变了异重流潜入模式, 大量干流水体以表中层异重流形式倒灌入支流, 加上此时期表层水温降低, 与中下层水体水温趋于一致且水体密度增加, 库湾水体下沉, RWCS/H 值低至 0 ~ 0.50 m⁻¹ (表 2), 支流的热分层稳定指数减小, 水体稳定性变弱, 垂向混合增强, 便破坏了支流水体蓄水前的稳定分层状态, 促进了水体掺混能力^[57,58], 各层水体产生对流现象, 与干流倒灌水均匀掺混, 使库湾水温达到了均匀分布, 故没有形成稳定的温跃层, 从而中底层水体的 DO 在垂向掺混的作用下得到充分补充^[59], 溶解氧由此也未产生明显地分层. 但观察到香溪河和神农溪垂向上, 整体的 $\rho(\text{DO})$ 是向上游降低的, 可能是倒灌强度和垂向掺混作用沿上游减弱, 而水体间的掺混作用越大时, 水体更容易溶解氧气造成的. 另外, 因浮游植物本身的减少和光合作用强度的降低, CO₂ 消耗较低, 呼吸作用占优, 故 0 ~ 10 m 的水体 $\rho(\text{DO})$ 和 pH 值较低水位期明显要小. 综上, 蓄水变动期支流库湾水体垂向分层不明显.



正值表示交换水量以干流倒灌为主, 负值表示支流流出为主, 修改自文献^[52]

图 7 三峡水库干支流月交换水量变化

Fig. 7 Monthly water exchange quantity of the Yangtze River and tributaries in TGR

3.3 水库调度对叶绿素 a 的影响分析

如表 1 所示, 低水位期水体呈轻度富营养状态, 蓄水变动期呈中营养状态. 有研究表明除营养盐外,

水位波动和气象条件是水库中藻类和 $\rho(\text{Chl-a})$ 变化的重要驱动因子^[60,61]. 而三峡水库蓄水期由于蓄水造成的水位波动能有效控制支流库湾水华现象的发生^[62,63], 藻类的生长位置会随着水体紊动程度频繁改变(藻类具有随流输移和悬浮生长的特性), 故其生境要素也频繁发生变化, 进而其生长速率受到抑制^[64,65]. $\rho(\text{Chl-a})$ 在干流大量倒灌, 从而打破库湾支流温度分层的情况下急剧下降^[66]. 蓄水位的上升, 增加了混合层深度, 根据临界层理论, 当 $Z_{\text{eu}}/Z_{\text{mix}}$ 低于“临界值”时, 通常不会发生水华现象, 陈洋等^[67]的研究通过香溪河围格实验发现, 藻类净初级生产力与 Z_{mix} 存在负相关性, 论证了临界层理论在香溪河的适用性, Liu 等^[66]和刘心愿等^[68]的研究也发现香溪河临界值范围晚秋至早春为 0.35, 晚春至早秋为 0.20 较为适宜, 如图 8 所示, 香溪河和神农溪的 $Z_{\text{eu}}/Z_{\text{mix}}$ 和 $\rho(\text{Chl-a})$ 整体上变化趋势一致, 均在低水位期较大, 在蓄水变动期均明显降低, 此时期 $Z_{\text{eu}}/Z_{\text{mix}}$ 均小于 0.35, 结果表明将该范围作为香溪河和神农溪的临界值均具有有效性.

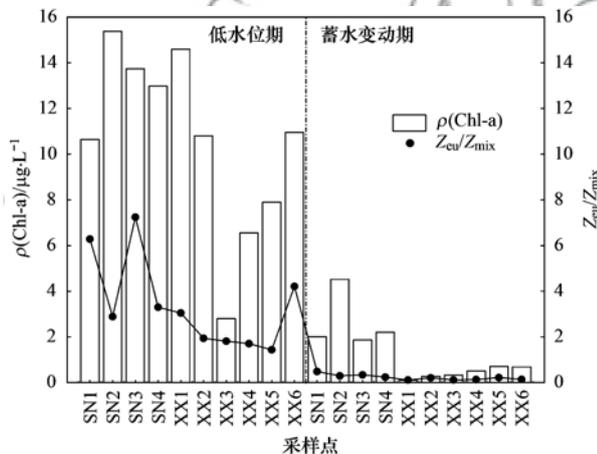


图 8 三峡水库各支流不同调度时期 $Z_{\text{eu}}/Z_{\text{mix}}$ 与 Chl-a 的变化特征

Fig. 8 Response relationship between $Z_{\text{eu}}/Z_{\text{mix}}$ and Chl-a in tributaries of TGR in different operation periods

4 结论

(1) 低水位期香溪河和神农溪水体的 $\rho(\text{DO})$ 、水温、pH 值和 $\rho(\text{Chl-a})$ 均在水深 1m 左右达到最大值, 在 0~10 m (叶绿素 a 在 0~5 m) 范围内分层明显, 且表-中层热分层稳定指数为 13.71~29.07 m^{-1} , 水体分层处于稳定状态, 中-底层各指标垂向上无明显波动, 热分层稳定指数为 0.05~0.36 m^{-1} , 水体稳定性较弱. 各指标垂向上呈显著的线性关系, 溶解氧、水温分层和 pH 值影响着浮游植物的分布.

(2) 蓄水变动期, 由于库区蓄水, 支流库湾水位大幅上升和干流水体大量倒灌, 加上表层水温的降

低, 破坏了水体稳定分层状态, 热分层稳定指数降至 0~0.50 m^{-1} , 水体稳定性变弱, 使得上下水体间充分掺混, 使香溪河和神农溪水体垂向上各指标的值得趋于一致, 各指标间无相关性.

(3) 香溪河和神农溪低水位期, 其表层水体 $\rho(\text{Chl-a})$ 显著高于蓄水变动期 ($P < 0.01$), 综合营养状态指数分别为 55 和 53, 水体呈轻度富营养状态; 蓄水变动期, 两支流表层水体综合营养状态指数分别为 39 和 46, 水体呈中营养状态, 水体掺混强度的增强、水体分层的消失和水位的上升使混合层深度增加导致 $Z_{\text{eu}}/Z_{\text{mix}}$ 的减小等, 使浮游植物的生长受到限制, 故 $\rho(\text{Chl-a})$ 较低.

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CONTENTS

Characteristics and Risk Assessment of Heavy Metals in Urban Soils of Major Cities in China	PENG Chi, HE Ya-lei, GUO Zhao-hui, <i>et al.</i>	(1)
Environmental Behaviors of Plant Growth Regulators in Soil; A Review	CHEN Liang, HOU Jie, HU Xiao-lei, <i>et al.</i>	(11)
Preparation and Application of Magnetic Water Treatment Materials Based on Iron Sludge	ZENG Hui-ping, ZHAI Long-xue, LI Dong, <i>et al.</i>	(26)
Meta-analysis of the Impact of Different Ozone Metrics on Total Mortality in China	RUAN Fang-fang, LIU Ji-xin, CHEN Zhi-wei, <i>et al.</i>	(37)
Variation Characteristics and Potential Sources of the Mt. Haituo Aerosol Chemical Composition in Different Pollution Processes During Winter in Beijing, China	ZHAO De-long, WANG Fei, LIU Dan-tong, <i>et al.</i>	(46)
Real-time Source Apportionment of PM _{2.5} and Potential Geographic Origins of Each Source During Winter in Wuhan	JIANG Shu-ning, KONG Shao-fei, ZHENG Huang, <i>et al.</i>	(61)
Spatiotemporal Distribution and Seasonal Characteristics of Regional Transport of PM _{2.5} in Yuncheng City	WANG Yun-tao, ZHANG Qiang, WEN Xiao-yu, <i>et al.</i>	(74)
Three-dimensional Structure Variation of PM _{2.5} During Cold Front Advance in Eastern China	MOU Nan-nan, ZHU Bin, LU Wen	(85)
Pollution Characteristics and Risk Assessment of Nitrated Polycyclic Aromatic Hydrocarbons in the Atmosphere of Guangdong-Hong Kong-Macao Greater Bay Area	LI Yan-xi, XIE Dan-ping, LI Yu-qing, <i>et al.</i>	(93)
Atmospheric VOCs Pollution Characteristics and Health Risk Assessment of Large-scale Integrated Industrial Area and Surrounding Areas in Southwest China	LI Ling, ZHANG Dan, HU Wei, <i>et al.</i>	(102)
Characteristics and Source Apportionment of Ambient VOCs in Lhasa	YU Jia-yan, HAN Yan, CHEN Mu-lan, <i>et al.</i>	(113)
Variation Characteristics of Ambient Volatile Organic Compounds (VOCs) Volume Fraction During Hangzhou COVID-19 Period	LIN Xu, YAN Ren-chang, JIN Jia-jia, <i>et al.</i>	(123)
Role of Atmospheric VOCs in Ozone Formation in Summer in Shanghai Suburb	FANG Qin, NIU Si-ping, CHEN Yu-dong, <i>et al.</i>	(132)
Characteristics of VOCs and Formation Potentials of O ₃ and SOA in Autumn and Winter in Tongchuan, China	YI Xiao-xiao, LI Jiang-hao, LI Guang-hua, <i>et al.</i>	(140)
Emission Characteristics and Emission Factors of Volatile Organic Compounds from E-waste Dismantling and Recycling Processes	XIE Dan-ping, HUANG Zhong-hui, LIU Wang, <i>et al.</i>	(150)
Nonlinear Response Relationship Between Ozone and Precursor Emissions in the Pearl River Delta Region Under Different Transmission Channels	WU Yong-kang, CHEN Wei-hua, YAN Feng-hua, <i>et al.</i>	(160)
Characteristics of Ozone Pollution and Influencing Factors in Urban and Suburban Areas in Zibo	WANG Yu-yan, YANG Wen, WANG Xiu-yan, <i>et al.</i>	(170)
Pollution Characteristics and Health Risk of Heavy Metals in Fugitive Dust Around Zhaotong City	PANG Xiao-chen, HAN Xin-yu, SHI Jian-wu, <i>et al.</i>	(180)
Characteristics of Microplastic Present in Urban Road Dust	FANG Qin, NIU Si-ping, CHEN Yu-dong, <i>et al.</i>	(189)
Stable Isotopes of Precipitation in the Eastern Tarim River Basin and Water Vapor Sources	SONG Yang, WANG Sheng-jie, ZHANG Ming-jun, <i>et al.</i>	(199)
Characteristics and Risk Assessment of Antibiotic Contamination in Chishui River Basin, Guizhou Province, China	WU Tian-yu, LI Jiang, YANG Ai-jiang, <i>et al.</i>	(210)
Hydrochemical Characteristics and Controlling Factors of Surface Water and Groundwater in Wuding River Basin	LI Shu-jian, HAN Xiao, WANG Wen-hui, <i>et al.</i>	(220)
Pollution Characteristics and Risk Assessment of Nutrients and Heavy Metals in Sediments of the Fuhe River Influenced Area, Baiyangdian Lake	CHEN Xing-hong, LI Li-qing, ZHANG Mei-yi, <i>et al.</i>	(230)
Occurrence Characteristics of Microplastics in Mangrove Sediments in the Jiulong River Estuary and the Association with Heavy Metals	LIU Chang-jun, LUO Zhuan-xi, YAN Yu, <i>et al.</i>	(239)
Quantitative Analysis of the Correlation Between Macroenthos Community and Water Environmental Factors and Aquatic Ecosystem Health Assessment in the North Canal River Basin of Beijing	HU Xiao-hong, ZUO De-peng, LIU Bo, <i>et al.</i>	(247)
Analysis on the Spatial Variability Mechanism of the Characteristic Water Quality Factors of Urban River Channel Reclaimed Water	LIU Quan-zhong, PENG Ke, SU Zhen-hua, <i>et al.</i>	(256)
DOM Characteristics Analysis of Surface Sediment-overlying Water in Suzhou Landscape River Course	LI Chao-nan, HE Jie, ZHU Xue-hui, <i>et al.</i>	(267)
Distribution of Typical Pollutants from Rainwater Sewer Sediments in Suzhou City	YE Rong, SHENG Ming-jun, JIANG Yong-bo, <i>et al.</i>	(277)
Persistent Inhibition of Ammonium Released from Contaminated Sediments Through a Modified Zeolite and Biofilm System Enhanced by Signaling Molecules	XU Jin-lan, XU Yang, LI Xiu-min, <i>et al.</i>	(285)
Effects of the Three Gorges Reservoir Operation on Vertical Distribution of Chlorophyll a and Environmental Factors in Tributaries	TIAN Pan, LI Ya-li, LI Ying-jie, <i>et al.</i>	(295)
Characteristic Analysis of <i>nirS</i> Denitrifying Bacterial Community in Lijiahe Reservoir During Stratification	LIANG Wei-guang, HUANG Ting-lin, ZHANG Hai-han, <i>et al.</i>	(306)
Spatial and Temporal Distribution of Aerobic Denitrification Bacterial Community in Sediments of Gangan Reservoir	ZHANG Zi-wei, CHEN Zhao-ying, ZHANG Tian-na, <i>et al.</i>	(314)
Distribution Characteristics and Health Risk Assessment of Metal Elements for Groundwater in the Ningxia Region of China	WANG Xiao-dong, TIAN Wei, ZHANG Xue-yan	(329)
Geochemical Characteristics and Driving Factors of High-Iodine Groundwater in Rapidly Urbanized Delta Areas: A Case Study of the Pearl River Delta	LU Xiao-li, LIU Jing-tao, HAN Zhan-tao, <i>et al.</i>	(339)
Multimedia Distribution Characteristics and Risk Assessment of 22 PPCPs in the Water Environment of Qingpu District, Yangtze River Delta Demonstration Area	ZHANG Zhi-bo, DUAN Yan-ping, SHEN Jia-hao, <i>et al.</i>	(349)
Distribution Characteristics and Risk Assessment of 209 Polychlorinated Biphenyls in Dongting Lake and the Inflow Rivers	HUANG Zhi-feng, ZHENG Bing-hui, YIN Da-qiang, <i>et al.</i>	(363)
Estimation of Nitrous Oxide Emission from River System Based on Water Discharge and Dissolved Nitrous Oxide Concentration	LI Bing-qing, HU Min-peng, WANG Ming-feng, <i>et al.</i>	(369)
Comparison Between Tributary and Main Stream and Preliminary Influence Mechanism of CO ₂ Flux Across Water-air Interface in Wanzhou in the Three Gorges Reservoir Area	QIN Yu, OUYANG Chang-yue, WANG Yu-xiao, <i>et al.</i>	(377)
Preparation of Functional Attapulgite Composite and Its Adsorption Behaviors for Congo Red	LIAO Xiao-feng, ZHONG Jing-ping, CHEN Yun-nen, <i>et al.</i>	(387)
Adsorption Characteristics and Long-term Effectiveness Evaluation of Iron-nitrogen Co-doped Biochar for Secondary Water-Soluble Organic Matter	WU Chen-xi, XU Lu, JIN Xin, <i>et al.</i>	(398)
Nitritation Performance of Zeolite Moving Bed Biofilm Reactor for Ammonium Wastewater Treatment	DENG Cui-lan, GUO Lu, WANG Xiao-jun, <i>et al.</i>	(409)
Effect of Temperature on ANAMMOX Process in Sequencing Batch Biofilm Reactors; Nitrogen Removal Performance and Bacterial Community	WU Shan, WANG Shu-ya, WANG Fen, <i>et al.</i>	(416)
Effects of Carriers on ANAMMOX Sludge Activity Recovery and Microbial Flora Characteristics	LUO Jing-wen, YANG Jin-jin, LI Shao-kang, <i>et al.</i>	(424)
Spatial Distribution and Source Analysis of Soil Heavy Metals in a Small Watershed in the Mountainous Area of Southern Ningxia Based on PMF Model	XIA Zi-shu, BAI Yi-ru, WANG You-qi, <i>et al.</i>	(432)
Heavy Metal Concentration Characteristics and Health Risks of Farmland Soils in Typical Pyrite Mining Area of the Central Zhejiang Province, China	CHENG Xiao-meng, SUN Bin-bin, WU Chao, <i>et al.</i>	(442)
Risk Zoning of Heavy Metals in a Peri-urban Area in the Black Soil Farmland Based on Agricultural Products	WU Song-ze, WANG Dong-yan, LI Wen-bo, <i>et al.</i>	(454)
Main Control Factors of Cadmium Content in Rice in Carbonate Rock Region of Guangxi Based on the DGT Technique	SONG Bo, XIAO Nai-chuan, MA Li-jun, <i>et al.</i>	(463)
Inhibitory Effects of Soil Amendment Coupled with Water Management on the Accumulation of Cd and Pb in Double-Cropping Rice	LI Lin-feng, WANG Yan-hong, LI Yi-chun, <i>et al.</i>	(472)
Characteristics and Health Risk Assessment of Cadmium, Lead, and Arsenic Accumulation in Leafy Vegetables Planted in a Greenhouse	DONG Jun-wen, GAO Pei-pei, SUN Hong-xin, <i>et al.</i>	(481)
Pollution Characteristics and Health Risk Assessment of Polychlorinated Biphenyls in E-waste Disposal Residue-Soil-Vegetable	ZHANG Ya-ping, LU Zhan-lu, WANG Xian-jiang, <i>et al.</i>	(490)
Soil-crop Distribution and Health Risk Assessment of Organochlorine Pesticides on Typical Agricultural Land in Southern Leizhou Peninsula	LIANG Xiao-hui, XIE Qi-lai, ZHENG Qian, <i>et al.</i>	(500)
Effects of Heavy Metal Content on Fungal Community Structure in Urban Soil	GUO Da-lu, ZHANG Jian, SHEN Si, <i>et al.</i>	(510)
Effects of Long-term Fertilization on Soil Nutrient Characteristics and Microbial Resource Restrictions in a Terrace on the Loess Plateau	WU Chun-xiao, GAO Xiao-feng, YAN Ben-shuai, <i>et al.</i>	(521)
Microbial Composition and Diversity in Soil of <i>Torreya grandis</i> cv. <i>Merrillii</i> Relative to Different Cultivation Years After Land Use Conversion	JIANG Ni-wen, LIANG Chen-fei, ZHANG Yong, <i>et al.</i>	(530)
Effect of Combined Application of Biochar with Chemical Fertilizer and Organic Fertilizer on Soil Phosphatase Activity and Microbial Community	YANG Wen-na, YU Luo, LUO Dong-hai, <i>et al.</i>	(540)
Extracellular Enzyme Stoichiometry and Microbial Metabolism Limitation During Vegetation Restoration Process in the Middle of the Qinling Mountains, China	XUE Yue, KANG Hai-bin, YANG Hang, <i>et al.</i>	(550)
Effects of Biodegradable Film Raw Material Particles on Soil Properties, Wheat Growth, and Nutrient Absorption and Transportation	MIN Wen-hao, WANG Chun-li, WANG Li-wei, <i>et al.</i>	(560)
Effects of Stalk Incorporation on Soil Carbon Sequestration, Nitrous Oxide Emissions, and Global Warming Potential of a Winter Wheat-Summer Maize Field in Guanzhong Plain	WAN Xiao-nan, ZHAO Ke-yue, WU Xiong-wei, <i>et al.</i>	(569)