环境科学
(HUANJING KEXUE)
ENVIRONMENTAL SCIENCE
第44卷 第5期
2023年5月15日

目 次

Eco-Environmental Knowledge Web

环 境 科 学
Environmental Science

第44卷第5期 2023年5月
Vol.44, No.5 May, 2023

三峡库区支流库湾消落带土壤磷形态赋存特征及其释放风险

张雪[1,2], 朱波[1*]
(1. 中国科学院成都山地灾害与环境研究所山地表生过程与生态调控重点实验室, 成都 610041; 2. 中国科学院大学, 北京 100049)

摘要：三峡库区消落带经历反复的淹水-落干循环影响,消落带土壤磷迁移转化过程加快,可能加剧支流库湾水体富营养化. 采集了三峡库区腹心支流库湾典型消落带土壤,测定磷赋存形态与磷素饱和度(DPS)等,分析磷释放风险. 结果表明,①消落带土壤 ω[总磷(TP)]、ω[无机磷(IP)]和 ω[有机磷(OP)]均值分别为 771.80、485.33 和 166.30 $mg\cdot kg^{-1}$,IP 和 OP 均以非活性形态磷为主. ②消落带土壤形态磷的赋存格局受落干-淹水方式影响,Ex-P 和 $NaHCO_3$-Po 含量显著高于对照土壤,Fe-P、HCl-Po 和 Fulvic-Po 含量沿高程下降而显著降低($P<0.05$),反复的干湿交替促进了消落带土壤活性磷的生成和中等活性磷的释放和积累. ③消落带土壤生物 ω[有效磷(Bio-P)]为 49.19 ~ 148.78 $mg\cdot kg^{-1}$,占 TP 的质量分数为 7.71% ~ 24.78%,磷素饱和度(DPS)为 5.85% ~ 22.00%. 目前,支流库湾消落带土壤整体磷释放风险较低,170 m 高程土壤需要重点关注. Fe-P、HCl-Po 和 Fulvic-Po 在消落带土壤磷释放过程中贡献较大,pH 升高会促进 Fe-P 的释放,碱性磷酸酶(ALP)是有机磷转化的重要参与者,有机质(OM)是有机磷的主要来源.

关键词：三峡库区; 消落带(WLFZ); 磷形态; 生物有效磷(Bio-P); 磷素饱和度(DPS); 释放风险
中图分类号：X52 **文献标识码**：A **文章编号**：0250-3301(2023)05-2574-09 **DOI**：10.13227/j.hjkx.202205097

Distribution and Release Potential of Soil Phosphorus Fractions in Water-level Fluctuation Zone of the Tributary Bay, Three Gorges Reservoir

ZHANG Xue[1,2], ZHU Bo[1*]
(1. Key Laboratory of Mountain Surface Processes and Ecological Regulation, Institute of Mountain Hazards and Environment, Chinese Academy of Sciences, Chengdu 610041, China; 2. University of Chinese Academy of Sciences, Beijing 100049, China)

Abstract: After repeated wetting-drying cycles, the migration and transformation of phosphorus in the water-level fluctuation zone (WLFZ) are accelerated, and the eutrophication of tributary bays in the reservoir becomes increasingly serious. Soils in the WLFZ of a typical tributary of the Three Gorges Reservoir were collected, and then phosphorus forms and the degree of phosphorus saturation (DPS) were determined to analyze the phosphorus release potential. The results showed that, ① the average contents of total phosphorus (TP), inorganic phosphorus (IP), and organic phosphorus (OP) of soils in the WLFZ were 771.80, 485.33, and 166.30 $mg\cdot kg^{-1}$, respectively. The non-labile IP and OP were the dominate speciation of IP and OP, respectively. ② The distribution of P forms of soils in the WLFZ was affected by wetting-drying cycle. The contents of Ex-P and $NaHCO_3$-Po of soils in the WLFZ were significantly higher than those in the contrasted soils, whereas the contents of Fe-P, HCl-Po, and Fulvic-Po decreased significantly along the elevation ($P<0.05$). The alternative wetting-drying cycle promoted the generation of labile P and the release and accumulation of moderately labile P of soils in the WLFZ. ③The content and proportion of bioavailable phosphorus (Bio-P) of soils in the WLFZ were in the range of 49.19-148.78 $mg\cdot kg^{-1}$ and 7.17%-24.78%, and the degree of phosphorus sorption (DPS) was in the range of 5.85%-22.00%. At present, the phosphorus release risk of soils in the WLFZ was low. The soil at 170 m elevation requires further attention. Fe-P, HCl-Po, and Fulvic-Po contributed significantly to phosphorus release. The increase in pH promoted the release of Fe-P. Alkaline phosphomonoesterase (ALP) was an important participant in the transformation of OP. Additionally, organic matter (OM) was the main source of OP.

Key words: Three Gorges Reservoir; water-level fluctuation zone (WLFZ); phosphorus fractions; bioavailable phosphorus (Bio-P); degree of phosphorus sorption (DPS); release risk

三峡水库为达到"蓄清排浊"目的,采用春夏排水和秋冬蓄水的运行调度方式,导致在库区高程 145 ~ 175 m 之间形成与天然河流涨落季节相反,面积约 349 km^2 的消落带(water-level fluctuation zone, WLFZ)[1]. 库区消落带反复经历"淹水-落干"循环,消落带土壤处于反复的干湿交替变化之中,强烈的物理、化学和生物等过程交替发生,导致突出的土壤结构变化[2]、有机质分解矿化[3]、离子迁移转化[4]和微生物群落转变[5]等问题,显著影响磷的生物地球化学循环. 土壤磷主要分为无机磷和有机磷,因其本底、形态结构和生物有效性的不同,各形态磷在水-土界面的迁移转化过程差异显著[6],对上覆水磷污染负荷的贡献也有较大区别[7,8]. 因此,研究消落带土壤磷形态赋存特征对于了解磷释放风险具有重要意义.

三峡水库运行以后,支流流速减缓,水体自净能

收稿日期: 2022-05-09; **修订日期**: 2022-07-21
基金项目: 国家自然科学基金重大项目(41430750)
作者简介: 张雪(1994 ~),女,博士研究生,主要研究方向为三峡库区消落带土壤-植物磷素循环,E-mail:zx2017@imde.ac.cn
* 通信作者,E-mail:bzhu@imde.ac.cn

力下降. 同时,陆地向水体输入的营养元素显著增加,易在支流库湾处累积,加上适宜的温度,使得支流库湾"水华"现象频发[9,10]. 目前,针对库区水体富营养化问题,从控源角度出发,除了关于库区水质时空分布特征[11,12]、营养物质来源解析[13]、沉积物各形态磷生物有效性[14,15]、吸附-释放性能[16]和迁移转化规律研究[7,17]以外,有关消落带土壤磷释放的研究主要集中在降雨时期不同土地利用方式下[18]和不同农业种植模式下[19,20]水土流失造成的面源污染上,对库区特有的反复"淹水-落干"状态下,消落带土壤磷释放过程与机制关注不够. 且经过十多年的干湿交替后,消落带土壤磷分布格局又产生了新的变化,而消落带磷的释放特征仍不清楚,对于未来三峡水库支流水污染控制构成新的挑战.

目前,国际上学者大多选择磷素饱和度(degree of phosphorus sorption, DPS)作为土壤磷释放风险的指标. DPS 是土壤中可提取态磷(soil text phosphorus, STP)占土壤磷最大吸附容量(phosphorus sorption capacity, PSC)的百分比[21,22]. STP 根据提取方式的不同而呈现较大差异,选择土壤中生物有效性较高的形态磷之和作为生物有效磷(bioavailable phosphorus, Bio-P)[23],涵盖范围更全面,在评价三峡消落带土壤磷释放风险中得到了较好运用[23]. 本文也将利用学者提出的 DPS 经验公式和阈值研究三峡库区消落带土壤磷流失现状和风险.

1　材料与方法

1.1　研究区概况和样品采集

三峡库区重庆段消落带占库区消落带总面积的 87.8%,重庆段涪陵以下至云阳的库区腹心段区县消落带面积占全市消落带面积的 84.3%[24]. 其中,涪陵多为斜坡淹没形成的消落带,忠县多为台地和阶地淹没后形成的消落带,且为大暴雨集中中心. 该地区为亚热带湿润季风气候, 年平均气温为 18.5℃,年平均降水量为1 140 mm,其中约 70% 发生在雨季(5 ~ 9 月). 因此, 选择涪陵珍溪河(FLZX)、忠县黄金河(ZXHJ)和忠县汝溪河坪山(ZXPS)库湾作为研究地点(图 1),代表三峡库区腹心库湾消落带. 3 个研究地点分别距离长江干流约 0.7、1.5 和 3.0 km,整体坡度分别为 30° ~ 60°左右. 消落带 150 m 以下为沉积泥沙; 150 ~ 160 m 优势植物为狗牙根和水蓼,狗牙根占比约 90% 以上; 160 ~ 175 m 优势植物为苍耳、鬼针草和蒿草,植被盖度随高程增加逐渐提高. 珍溪河和黄金河 175 m 以上土壤被开垦成农田,种植豆类和玉米等农作物,而坪山库湾多种植果树,如柑橘等.

2019 年 6 月 18 ~ 19 日,待库区水位降至 148 m 左右进行采样. 分别在各个研究点设置 3 条采样断

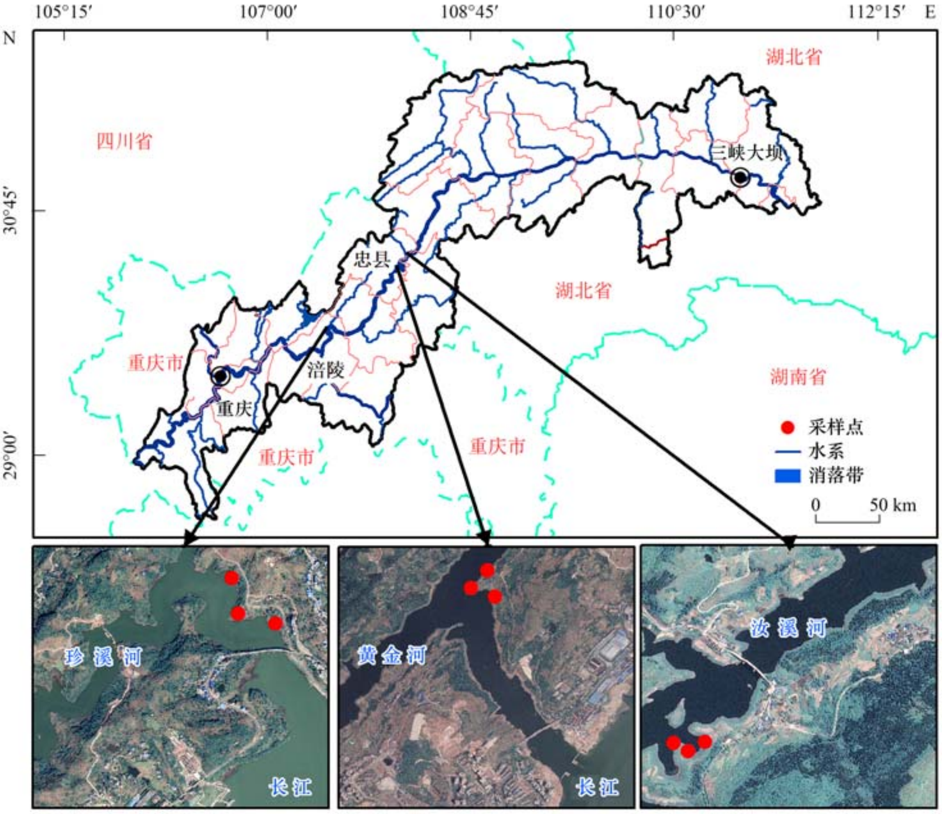


图 1　三峡库区消落带采样样点

Fig. 1　Location of sampling sites in tributaries, Three Gorges Reservoir

面,各断面之间距离约 200 m 左右. 断面由低到高设置 4 个采样高程,分别为 150、160、170 和 180 m. 选择 175 m 以上、未被人为活动干扰和未经历过干湿交替影响的区域采集 180 m 土壤样品,作为下方消落带的对照土壤. 根据均匀分布和典型代表原则,在各个高程采集 3 ~5 处表层土壤样品(0 ~20 m),将土壤样品装袋带回实验室. 将同一断面、同一高程的土壤样品混合均匀,挑出植物根系,分出小部分冷藏保存,剩余样品自然风干,粉碎后过 10 目和 100 目筛,室温保存.

1.2 指标测定

土壤鲜样直接测定无机磷(IP)形态、碱性磷酸酶(alkaline phosphomonoesterase, ALP)和磷酸二酯酶(phosphodiesterase, PDE),风干土测定粒径组成、pH、总磷(TP)、有机质(OM)和有机磷(OP)形态. 吸管法测定粒径组成,分为黏粒(<0.002 mm)、粉粒(0.002 ~0.05 mm)和砂粒(0.05 ~2 mm)[25]. NaOH 熔融法提取 TP. pH 计测定土壤 pH(水土比, 2.5∶1). 重铬酸钾-硫酸亚铁铵法测定 OM. ALP 和 PDE 活性采用对-硝基苯磷酸二钠和双(对-硝基苯基)磷酸酯比色法测定(以 *p*-NP 计)[26].

IP 形态采用 Chang 等[27]和 Buehler 等[28]提出的改进后的无机磷分级方法, 1.0 $mol \cdot L^{-1}$ NH_4Cl (pH 值为 8.0)提取交换态磷(Ex-P); 0.5 $mol \cdot L^{-1}$ NH_4F(pH 值为 8.2)提取铝结合态磷(Al-P); 0.1 $mol \cdot L^{-1}$ NaOH 提取铁结合态磷(Fe-P); 0.3 $mol \cdot L^{-1}$柠檬酸钠 + 连二亚硫酸钠混合溶液提取闭蓄态磷(Oc-P); 0.5 $mol \cdot L^{-1}$ H_2SO_4 提取钙结合态磷(Ca-P).

OP 形态采用 Ivanoff 等[29]提出的有机磷分级方法, 0.5 $mol \cdot L^{-1}$ $NaHCO_3$(pH 值为 8.5)提取活性有机磷($NaHCO_3$-Po); 1 $mol \cdot L^{-1}$ HCl 提取酸结合态有机磷(HCl-Po); 0.5 $mol \cdot L^{-1}$ NaOH 提取富里酸结合态有机磷(Fulvic-Po)和胡敏酸结合态有机磷(Humic-Po),分别为上清液和沉淀中的有机磷; 剩余样品灼烧后用 1 $mol \cdot L^{-1}$ H_2SO_4 提取残余态有机磷(Residual-Po).

1.3 土壤生物有效磷、磷吸附指数和磷素饱和度

根据无机磷和有机磷中各形态磷的活性大小,以 Ex-P、Al-P、Fe-P、$NaHCO_3$-Po、HCl-Po 和 Fulvic-Po 之和作为土壤 Bio-P[30].

PSC 包含土壤可吸附磷和已固存磷,通常利用浸提液中铝和铁的含量代替 PSC,但这种方法多适用于酸性土壤. 针对这一问题,学者提出利用磷吸附指数(phosphorus sorption index, PSI)与特定系数的乘积代替 PSC[31]. PSI 是按照 Bache 等[32]建议的方法,土壤样品(1 g 风干土)用 20 mL 0.01 $mol \cdot L^{-1}$ $CaCl_2$ 溶液(含 75 $mg \cdot L^{-1}$ H_2PO_4-P)平衡 24 h,并在(25 ± 1)℃下振荡,滤液测定残余磷含量. PSI 计算公式如下:

$$\mathrm{PSI} = \frac{X}{\lg c} \tag{1}$$

式中, *X* 为土壤吸附磷含量($mg \cdot kg^{-1}$), *c* 为滤液残余磷浓度($mg \cdot L^{-1}$).

根据 ω(Bio-P)和 PSC 计算土壤 DPS(%),公式如下:

$$\mathrm{DPS} = \frac{\omega(\text{Bio-P})}{\mathrm{PSC} + \omega(\text{Bio-P})} \times 100\% \tag{2}$$

1.4 统计分析

数据经 Excel 2016 处理后,采用 One way-ANOVA 方法对数据进行显著性分析,用最小显著极差法(Duncan)确定差异显著性水平. 用冗余分析(RDA)辨别土壤磷形态的分布转化特征,以及与土壤理化性质之间的相关性. 数据的统计分析用 IBM SPSS 22 和 CANOCO 5.0,使用 Origin 9.0 绘图. 文中所示误差,如无说明,均为 3 个重复测定的标准差($n = 3$).

2 结果与分析

2.1 土壤理化性质

各支流库湾土壤理化性质如表 1 所示. 土壤均以砂粒和黏粒为主,质量分数均值达 30% 以上. 除黄金河 170 m 高程土壤外,其余支流土壤 pH 均为中性和弱碱性. 支流消落带土壤 OM 含量随高程增加逐渐增大,160 m 高程以上土壤 OM 含量显著高于对照土壤($P < 0.05$). 160 m 高程土壤 ALP 和 PDE 活性均显著高于其余高程土壤($P < 0.05$).

2.2 磷赋存形态

2.2.1 总磷

消落带土壤 ω(TP)为 524.36 ~ 1 092.66 $mg \cdot kg^{-1}$,均值为 771.80 $mg \cdot kg^{-1}$(图 2). 各消落带土壤 TP 含量在高程间分布趋势不明确,与对照土壤差异不一致.

2.2.2 无机磷形态

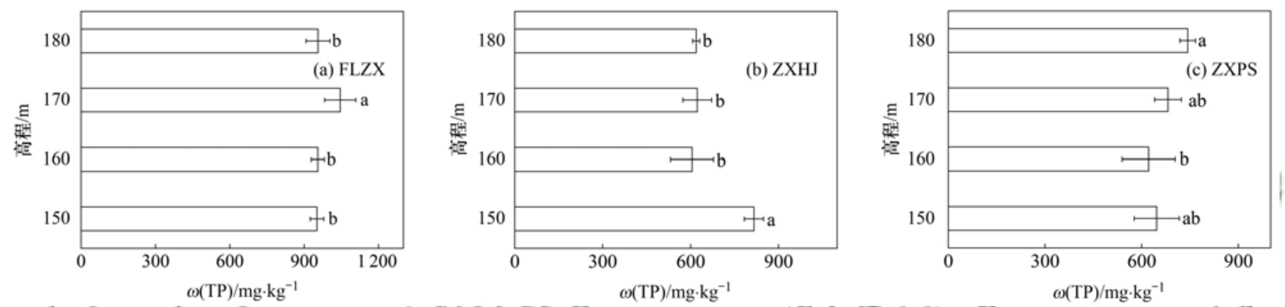
消落带土壤可提取 ω(IP)为 272.78 ~762.41 $mg \cdot kg^{-1}$,均值为 485.33 $mg \cdot kg^{-1}$(图 3). 土壤 IP 形态以 Ca-P 为主,其余依次为 Oc-P、Fe-P、Al-P 和 Ex-P,不同形态磷含量排序与已有研究的结果相似[33,34]. 3 个库湾消落带土壤整体 Ex-P 和 Oc-P 含量均显著高于对照土壤. Fe-P 含量随高程下降而显著降低, Oc-P 含量随高程降低表现出先减小后增大

表 1　三峡库区不同高程土壤理化性质[1)]

Table 1　Physical and chemical properties of soils with altitude in the Three Gorges Reservoir

采样点	高程/m	pH	ω(砂粒) /%	ω(粉粒) /%	ω(黏粒) /%	ω(OM) /g·kg^{-1}	ALP 活性 /μmol·(kg·h)$^{-1}$	PDE 活性 /μmol·(kg·h)$^{-1}$
FLZX	150	8.11 ±0.07a	34.84 ±4.13a	33.95 ±2.18b	31.21 ±2.09ab	15.10 ±0.72b	1.10 ±0.10d	0.61 ±0.24c
	160	7.95 ±0.15a	35.16 ±0.78a	32.88 ±2.45b	32.30 ±2.14a	34.22 ±2.96a	5.30 ±0.41a	2.76 ±0.56a
	170	7.98 ±0.17a	25.33 ±4.25b	46.28 ±2.62a	28.40 ±2.10b	39.17 ±11.92a	4.63 ±0.46b	2.25 ±0.37ab
	180	8.16 ±0.08a	23.30 ±0.61b	46.34 ±1.54a	30.36 ±1.11ab	15.57 ±0.41b	2.26 ±0.05c	1.66 ±0.08b
ZXHJ	150	8.12 ±0.08a	34.81 ±6.67ab	23.45 ±6.89b	41.74 ±1.61a	15.79 ±3.98ab	1.15 ±0.29bc	0.55 ±0.06b
	160	6.98 ±0.28b	42.49 ±7.90a	30.83 ±7.83b	26.68 ±0.61b	17.57 ±4.51a	3.57 ±0.80a	3.38 ±1.05a
	170	6.28 ±0.19c	40.78 ±4.31a	32.60 ±1.10ab	26.95 ±4.83b	16.81 ±3.19a	1.94 ±0.32b	1.25 ±0.19b
	180	6.88 ±0.11b	28.11 ±1.84b	41.90 ±1.65a	29.99 ±0.99b	9.55 ±0.50b	0.60 ±0.07c	0.81 ±0.06b
ZXPS	150	8.16 ±0.20a	44.68 ±3.45a	36.47 ±2.64b	18.85 ±1.50b	7.34 ±0.73b	0.91 ±0.23b	0.59 ±0.14b
	160	7.94 ±0.04a	37.96 ±5.72a	32.76 ±6.14b	29.28 ±1.03a	12.62 ±0.85ab	1.06 ±0.15ab	1.28 ±0.14b
	170	7.10 ±0.51b	34.14 ±8.71a	38.78 ±4.51ab	27.08 ±5.73a	15.13 ±5.37a	4.28 ±1.18a	3.80 ±1.28a
	180	7.21 ±0.16b	34.01 ±1.02a	45.09 ±2.31a	21.90 ±1.67b	11.10 ±0.66ab	2.54 ±0.05b	1.33 ±0.07b

1) 小写字母为同一地点不同高程比较，不同小写字母表示 4 个高程差异显著($P<0.05$)



不同小写字母表示不同高程差异显著($P<0.05$)

图 2　三峡库区支流不同高程土壤总磷含量

Fig. 2　Contents of TP in soils with altitude in tributaries, Three Gorges Reservoir

的趋势，Ex-P、Al-P 和 Ca-P 含量无明确分布趋势($P<0.05$).

2.2.3　有机磷形态

消落带土壤可提取 ω(OP) 为 90.02 ~ 239.42 mg·kg^{-1}，均值为 166.30 mg·kg^{-1}(图 4). 土壤 OP 以 Residual-Po 为主，其余依次为 Fulvic-Po、HCl-Po、Humic-Po 和 $NaHCO_3$-Po，与已有研究结果相似[35~37]. 消落带土壤 $NaHCO_3$-Po 含量显著高于对照土壤($P<0.05$). 在高程间，HCl-Po、Fulvic-Po 和 Residual-Po 含量均随高程降低而显著降小，$NaHCO_3$-Po 和 Humic-Po 分布趋势不明确($P<0.05$).

2.3　生物有效磷和磷素饱和度

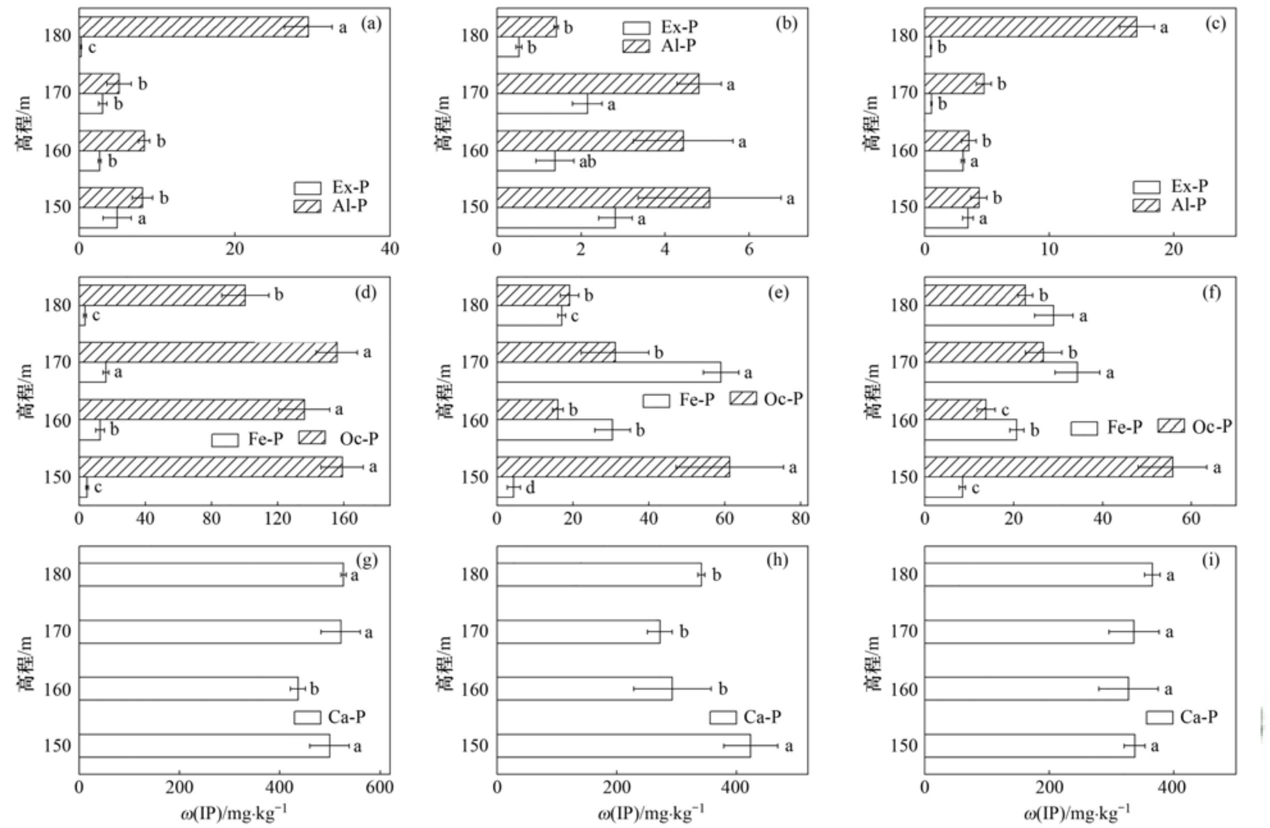
支流库湾消落带土壤 ω(Bio-P) 为 49.19 ~ 148.78 mg·kg^{-1}，占 TP 的质量分数为 7.71% ~ 24.78%(表 2). Bio-P 含量和质量分数均沿高程降低而显著下降，PSI 与之类似($P<0.05$). 消落带土壤 DPS 为 5.85% ~ 22.00%，分布趋势与 Bio-P 一致. 除黄金河 160 m 高程以上土壤外，其余消落带土壤 DPS 均显著低于对照土壤($P<0.05$).

表 2　三峡库区支流不同高程土壤有效磷和磷素饱和度[1)]

Table 2　Bioavailable phosphorus and degree of phosphorus saturation in soils with altitude in tributaries, Three Gorges Reservoir

地点	高程/m	Bio-P 含量/mg·kg^{-1}	Bio-P 质量分数/%	PSI	DPS/%
FLZX	150	102.36 ±5.57b	10.76 ±0.54b	438.55 ±59.86a	8.69 ±1.20c
	160	123.62 ±6.64ab	12.94 ±0.60ab	427.55 ±2.50a	10.42 ±0.55c
	170	142.29 ±20.43a	13.57 ±1.23a	335.15 ±41.85b	14.18 ±2.86b
	180	126.39 ±15.04ab	13.30 ±2.28ab	181.20 ±3.36c	18.67 ±1.93a
ZXHJ	150	78.09 ±12.42b	9.60 ±1.82b	381.57 ±142.07a	7.81 ±1.93c
	160	148.78 ±6.13a	24.78 ±2.33a	170.80 ±17.95b	22.00 ±0.52a
	170	145.66 ±6.67a	23.43 ±1.01a	185.70 ±22.28b	20.70 ±0.67a
	180	71.08 ±2.26b	11.48 ±0.27b	125.38 ±4.14b	14.09 ±0.62b
ZXPS	150	49.19 ±2.07d	7.71 ±0.53c	302.82 ±52.83a	5.85 ±0.90d
	160	101.28 ±4.22c	16.50 ±2.51b	163.34 ±4.50bc	16.50 ±0.53c
	170	146.83 ±5.01a	21.58 ±2.51a	201.13 ±30.76b	19.99 ±1.78b
	180	126.93 ±15.93b	17.10 ±2.15b	113.00 ±12.00c	23.73 ±2.65a

1) 质量分数为 Bio-P 含量在 TP 含量中的占比；小写字母为同一地点不同高程比较，不同小写字母代表不同高程差异显著($P<0.05$)



(a)、(d)和(g)FLZX，(b)、(e)和(h)ZXHJ，(c)、(f)和(i)ZXPS；小写字母为同一形态磷的不同高程比较，不同小写字母表示不同高程差异显著($P<0.05$)

图 3 三峡库区支流不同高程土壤无机磷形态含量

Fig. 3 Contents of IP in soils with altitude in tributaries, Three Gorges Reservoir

3 讨论

3.1 反复干湿交替对消落带土壤磷形态赋存的影响

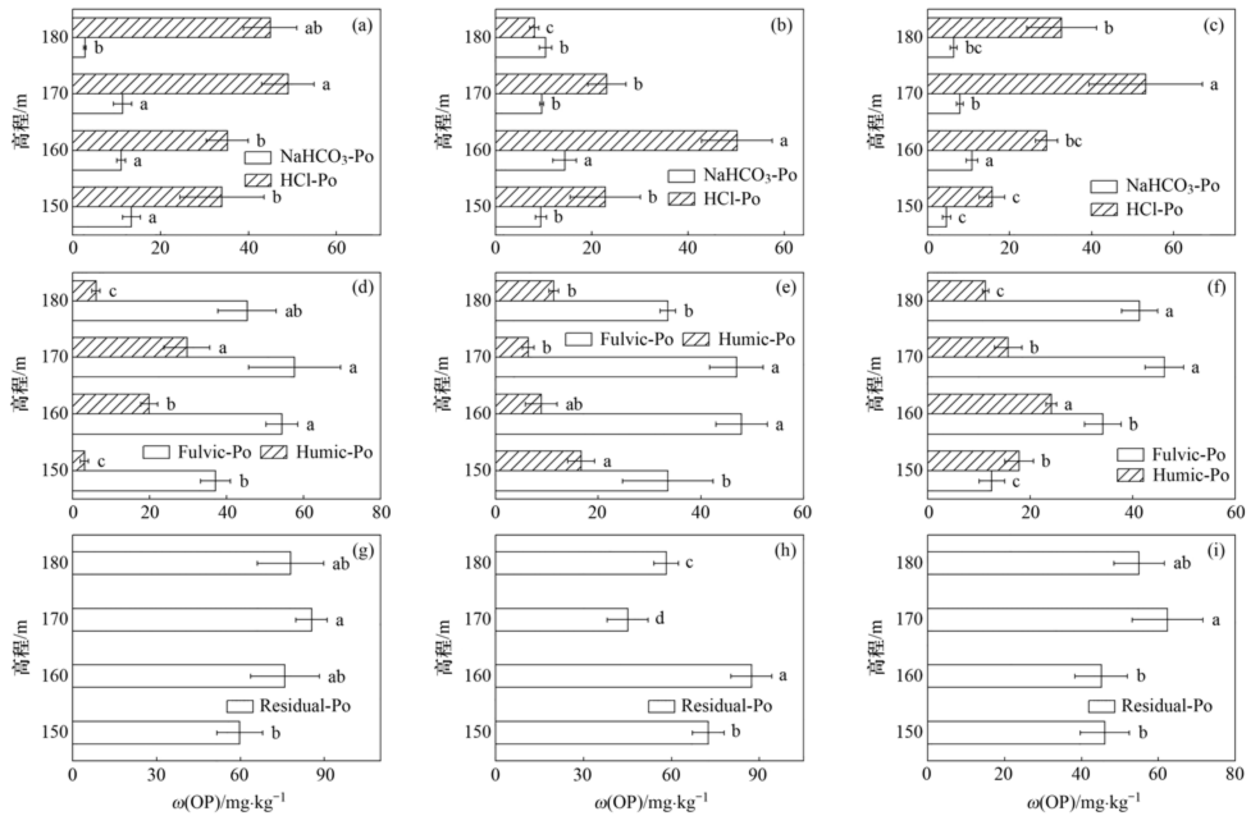
IP 形态中，Ex-P、Al-P 和 Fe-P 均属于生物可利用无机磷[38,39]．多年干湿交替作用下，Fe-P 在高程间形成逐级减少的格局，与已有研究结果相似[33]．150 m 高程土壤淹水时间较长，缺氧环境下还原作用加强，使得铁氧化物被持续还原，磷酸盐大量释放；170 m 高程土壤落干时间较长，氢氧化铁氧化后吸附游离的磷酸盐重新保存下来[33,40]．Ex-P 靠物理吸附附着于土壤微粒和有机质表面，当环境水分变化时，吸附的磷可直接脱落进入间隙水[41]．Al-P 活性较高，铝氧化物形态受 pH 影响较大．

OP 形态中，$NaHCO_3$-Po、HCl-Po 和 Fulvic-Po 属于生物可利用有机磷．$NaHCO_3$-Po 与 Ex-P 类似，消落带土壤 Ex-P 和 $NaHCO_3$-Po 均显著高于对照土壤(图 3)，这与前人研究的结果相反[41～44]．在考虑活性磷流失的同时，可能忽略了 Fe-P 转化和非活性有机磷活化等过程(图 5)．HCl-Po 和 Fulvic-Po 赋存格局与 Fe-P 类似，在已有研究中也有相似的发现[45,46]．以上 2 种形态磷在有机磷中占大部分比例，其含量变化与微生物和植物的生长死亡过程密切相关．春夏出露期，光照降雨集中，有利于动植物生长和微生物繁殖，增加了表层土壤有机磷的内源积累；秋冬覆水时，消落带土壤大部分微生物细胞因渗透压的突变，导致细胞破裂，溶解释放磷素，有机磷含量降低[39]．在此过程中，消落带各高程土壤水分、雨热和营养物质差异较大，优势植物分层显著，动植物的生长死亡过程导致有机磷呈逐级递减的特征．

因此，干湿交替对消落带土壤生物可利用形态磷的影响机制包括：①土壤水分环境的变化直接影响活性磷的附着状态；②土壤氧化还原条件和 pH 的变化使得铁铝氧化物与磷酸盐的结合方式发生转变，磷酸盐被释放或重新结合；③植物和微生物生长死亡过程使得土壤有机质迅速积累和消耗，淹水-落干的时间差异导致有机磷梯级分布．

3.2 消落带土壤磷释放风险

吴起鑫等[41]和徐德星等[47]对消落带形成初期土壤 Bio-P 质量分数的研究结果分别为 25.18%～65.38% 和 54%，本研究中 Bio-P 质量分数均低于 25%，表明多年干湿交替使得消落带土壤 Bio-P 大量流失．在已有研究中，DPS≥25% 可作为一个临界值，高于该临界值时土壤具有较高的可解吸磷会随

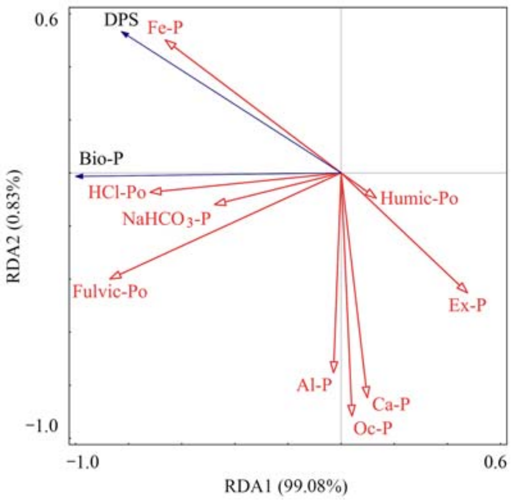


(a)、(d)和(g)FLZX,(b)、(e)和(h)ZXHJ,(c)、(f)和(i)ZXPS；小写字母为同一形态磷的不同高程比较，不同小写字母表示不同高程差异显著($P<0.05$)

图 4　三峡库区支流不同高程土壤有机磷形态含量

Fig. 4　Contents of OP in soils with altitude in tributaries, Three Gorges Reservoir

径流或壤中流释放[22]. 3 个消落带土壤 DPS 均低于 22%，且在高程间逐级降低. 目前，当处于淹水状态且水流无较大波动时，支流库湾消落带土壤磷素释放风险较低，170 m 高程土壤磷释放风险最高. 结合三峡库区消落带坡耕地土壤磷流失过程的原位监测研究，消落带土壤主要的磷释放途径可能集中在夏季时期降雨导致的水土流失，即不可逆转的磷素迁移过程[48~50].



红蓝线分别表示解释和响应变量，下同

图 5　三峡库区支流消落带土壤磷形态与土壤有效磷和磷素饱和度冗余分析

Fig. 5　Redundancy analysis of soil phosphorus forms with Bio-P and DPS in WLFZ of tributaries, Three Gorges Reservoir

经历干湿交替时，各形态磷结合方式的不同导致土-水界面磷酸盐释放过程差异较大[7]. 通过各形态磷与 Bio-P 和 DPS 的冗余分析可知，HCl-Po 和 Fulvic-Po 与 Bio-P 以及 Fe-P 与 DPS 之间夹角较小且箭头长度较长，存在显著的正相关关系(图 5). 以上形态磷在磷释放过程中的贡献率可达 98.6%，是生物可利用磷的主要来源，与含量大小有直接关系. 三者与土壤理化性质的冗余分析显示，pH、OM 和 ALP 的解释度可达 68.5%(图 6). pH 对 Fe-P 为负反馈作用，ALP 和 OM 对 HCl-Po 和 Fulvic-Po 均为正反馈作用. 有研究表明，土壤中较高的 OH^- 可以与磷酸盐阴离子争夺氧化物吸附点位，导致与铁氧化物结合的磷酸根释放量增加[33]. 磷酸酶主要由植物和微生物分泌，是土壤磷素循环和能量流动的重要参与者. 高艺伦[51] 对澎溪河消落带不同高程土壤磷形态和磷酸酶活性进行了研究，发现整体上消落带土壤磷酸酶活性与各有机磷含量呈显著正相关. OM 是有机磷的重要来源，在土壤缺磷时可被磷酸酶活化，形成新的有机磷参与土壤磷素循环[46].

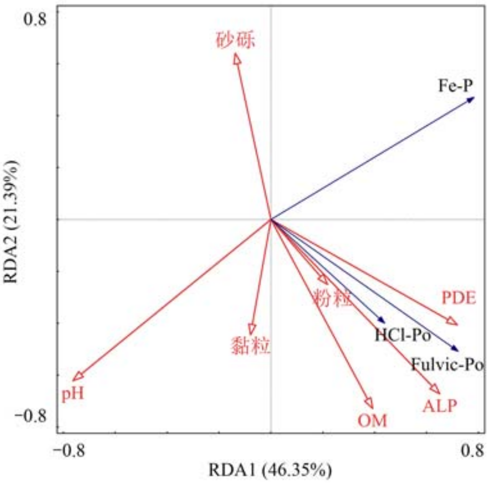


图 6 三峡库区消落带土壤高释放风险磷形态与土壤理化性质冗余分析

Fig. 6 Redundancy analysis of phosphorus forms of high release risk with soil physical and chemical properties in WLFZ of tributaries, Three Gorges Reservoir

4 结论

（1）消落带土壤 ω(TP)、ω(IP) 和 ω(OP) 均值分别为 771.80、485.33、166.30 mg·kg^{-1}. 无机磷和有机磷不同形态磷含量排序分别为：Ca-P > Oc-P > Fe-P > Al-P > Ex-P 和 Residual-Po > Fulvic-Po > HCl-Po > Humic-Po > $NaHCO_3$-Po，均以非活性磷为主，整体生物有效性较低.

（2）消落带土壤 Ex-P 和 $NaHCO_3$-Po 含量显著高于对照土壤，Fe-P、HCl-Po 和 Fulvic-Po 含量随高程下降而显著降低. 活性磷和中等活性磷在高程间的赋存格局与干湿交替下土壤环境的变化有关.

（3）消落带土壤 ω(Bio-P) 为 49.19 ~ 148.78 mg·kg^{-1}，占 TP 的质量分数为 7.71% ~ 24.78%，远低于消落带形成初期研究结果. 消落带土壤 DPS 为 5.85% ~ 22.00%，低于已有研究中根据土壤磷释放风险划定的最低阈值（25%）. 目前，当处于淹水状态且水流无较大波动时，消落带土壤磷释放风险较低. Fe-P、HCl-Po 和 Fulvic-Po 在磷释放过程中贡献率最大，土壤 pH、OM 和 ALP 活性的变化是导致磷释放的主要原因，在后续库区支流水环境治理防护中以上形态磷需要重点关注.

参考文献：

[1] Ji D B, Wells S A, Yang Z J, *et al*. Impacts of water level rise on algal bloom prevention in the tributary of Three Gorges Reservoir, China[J]. Ecological Engineering, 2017, **98**: 70-81.

[2] Wu Y H, Wang X X, Zhou J, *et al*. The fate of phosphorus in sediments after the full operation of the Three Gorges Reservoir, China[J]. Environmental Pollution, 2016, **214**: 282-289.

[3] Wang S C, Li H Y, Wei X R, *et al*. Dam construction as an important anthropogenic activity disturbing soil organic carbon in affected watersheds[J]. Environmental Science & Technology, 2020, **54**(13): 7932-7941.

[4] 程瑞梅，王晓荣，肖文发，等. 三峡库区消落带水淹初期土壤物理性质及金属含量初探[J]. 水土保持学报，2009，**23**(5)：156-161.

Cheng R M, Wang X R, Xiao W F, *et al*. Study on the soil physical properties and metal content in the early submerged water-level-fluctuating zone of Three Gorges Reservoir[J]. Journal of Soil and Water Conservation, 2009, **23**(5): 156-161.

[5] 邱权，陈雯莉. 三峡库区小江流域消落区土壤微生物多样性[J]. 华中农业大学学报，2013，**32**(3)：15-20.

Qiu Q, Chen W L. Microbial community diversity of water-level-fluctuation zone of Xiaojiang Watershed in Three Gorges Reservoir[J]. Journal of Huazhong Agricultural University, 2013, **32**(3): 15-20.

[6] Zhang B, Fang F, Guo J S, *et al*. Phosphorus fractions and phosphate sorption-release characteristics relevant to the soil composition of water-level-fluctuating zone of Three Gorges Reservoir[J]. Ecological Engineering, 2012, **40**: 153-159.

[7] Zhang Z Y, Hu H Q, Wan C Y, *et al*. Lateral and longitudinal variation in phosphorus fractions in surface sediment and adjacent riparian soil in the Three Gorges Reservoir, China[J]. Environmental Science and Pollution Research, 2018, **25**(31): 31262-31271.

[8] Chen C Y, Deng W M, Xu X M, *et al*. Phosphorus adsorption and release characteristics of surface sediments in Dianchi Lake, China[J]. Environmental Earth Sciences, 2015, **74**(5): 3689-3700.

[9] 杨正健，俞焰，陈钊，等. 三峡水库支流库湾水体富营养化及水华机理研究进展[J]. 武汉大学学报(工学版)，2017，**50**(4)：507-516.

Yang Z J, Yu Y, Chen Z, *et al*. Mechanism of eutrophication and phytoplankton blooms in Three Gorges Reservoir, China: a research review[J]. Engineering Journal of Wuhan University, 2017, **50**(4): 507-516.

[10] Chen Z L, Fang F, Shao Y, *et al*. The biotransformation of soil phosphorus in the water level fluctuation zone could increase eutrophication in reservoirs [J]. Science of the Total Environment, 2021, **763**, doi: 10.1016/j.scitotenv.2020.142976.

[11] Xiang R, Wang L J, Li H, *et al*. Temporal and spatial variation in water quality in the Three Gorges Reservoir from 1998 to 2018 [J]. Science of the Total Environment, 2021, **768**, doi:10.1016/j.scitotenv.2020.144866.

[12] 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.

[13] Han C N, Zheng B H, Qin Y W, *et al*. Analysis of phosphorus import characteristics of the upstream input rivers of Three Gorges Reservoir[J]. Environmental Earth Sciences, 2016, **75**(12), doi:10.1007/s12665-016-5832-x.

[14] Wang X X, Zhou J, Wu Y H, *et al*. Fine sediment particle microscopic characteristics, bioavailable phosphorus and environmental effects in the world largest reservoir [J]. Environmental Pollution, 2020, **265**, doi: 10.1016/j.envpol.2020.114917.

[15] Wang S, Rao W B, Qian J, *et al*. Phosphorus species in bottom sediments of the Three Gorges Reservoir during low and high water level periods[J]. Environmental Science and Pollution

Research, 2020, **27**(15): 17923-17934.

[16] Meng J, Yao Q Z, Yu Z G. Particulate phosphorus speciation and phosphate adsorption characteristics associated with sediment grain size[J]. Ecological Engineering, 2014, **70**: 140-145.

[17] Han C N, Qin Y W, Zheng B H, *et al*. Geochemistry of phosphorus release along transect of sediments from a tributary backwater zone in the Three Gorges Reservoir[J]. Science of the Total Environment, 2020, **722**, doi:10.1016/j.scitotenv.2020.136964.

[18] 曾立雄，黄志霖，肖文发，等. 三峡库区不同土地利用类型氮磷流失特征及其对环境因子的响应[J]. 环境科学, 2012, **33**(10): 3390-3396.
Zeng L X, Huang Z L, Xiao W F, *et al*. Nitrogen and phosphorus loss in different land use types and its response to environmental factors in the Three Gorges Reservoir area[J]. Environmental Science, 2012, **33**(10): 3390-3396.

[19] 罗芳，鲁伦慧，李哲，等. 农业耕作对三峡水库支流库湾消落带土壤氮、磷含量及流失的影响[J]. 环境科学, 2021, **42**(8): 3763-3772.
Luo F, Lu L H, Li Z, *et al*. Effects of farming practices on soil nitrogen and phosphorus concentrations and its loss in the drawdown area of the tributary embayment of the Three Gorges Reservoir[J]. Environmental Science, 2021, **42**(8): 3763-3772.

[20] Ma X, Li Y, Li B L, *et al*. Nitrogen and phosphorus losses by runoff erosion: field data monitored under natural rainfall in Three Gorges Reservoir area, China[J]. CATENA, 2016, **147**: 797-808.

[21] Sekhon B S, Bhumbla D K, Sencindiver J, *et al*. Using soil survey data for series-level environmental phosphorus risk assessment[J]. Environmental Earth Sciences, 2014, **72**(7): 2345-2356.

[22] Jalali M, Jalali M. Relation between various soil phosphorus extraction methods and sorption parameters in calcareous soils with different texture[J]. Science of the Total Environment, 2016, **566-567**: 1080-1093.

[23] Wang C, Fang F, Yuan Z Y, *et al*. Spatial variations of soil phosphorus forms and the risks of phosphorus release in the water-level fluctuation zone in a tributary of the Three Gorges Reservoir[J]. Science of the Total Environment, 2020, **699**, doi:10.1016/j.scitotenv.2019.134124.

[24] 张虹. 三峡库区消落带土地资源特征分析[J]. 水土保持通报, 2008, **28**(1): 46-49.
Zhang H. Characteristic analyses of the water-level-fluctuating zone in the Three Gorges Reservoir[J]. Bulletin of Soil and Water Conservation, 2008, **28**(1): 46-49.

[25] Gee G W, Bauder J W. Particlesize analysis by hydrometer: a simplified method for routine textural analysis and a sensitivity test of measurement parameters[J]. Soil Science Society of America Journal, 1979, **43**(5): 1004-1007.

[26] Fu D G, Wu X N, Duan C Q, *et al*. Response of soil phosphorus fractions and fluxes to different vegetation restoration types in a subtropical mountain ecosystem[J]. CATENA, 2020, **193**, doi: 10.1016/j.catena.2020.104663.

[27] Chang A C, Page A L, Sutherland F H, *et al*. Fractionation of phosphorus in sludge-affected soils[J]. Journal of Environmental Quality, 1983, **12**(2): 286-290.

[28] Buehler S, Oberson A, Rao I M, *et al*. Sequential phosphorus extraction of a ^{33}P-labeled oxisol under contrasting agricultural systems[J]. Soil Science Society of America Journal, 2002, **66**(3): 868-877.

[29] Ivanoff D B, Reddy K R, Robinson S. Chemical fractionation of organic phosphorus in selected histosols[J]. Soil Science, 1998, **163**(1): 36-45.

[30] 王婷，王坤，姜霞. 东洞庭湖沉积物覆水后磷形态变化及其释放量[J]. 湖泊科学, 2018, **30**(4): 937-947.
Wang T, Wang K, Jiang X. Influence of rewetting process on distribution and release of phosphorus in sediments of East Lake Dongting[J]. Journal of Lake Sciences, 2018, **30**(4): 937-947.

[31] Li M, Hou Y L, Zhu B. Phosphorus sorption-desorption by purple soils of China in relation to their properties[J]. Australian Journal of Soil Research, 2007, **45**(3): 182-189.

[32] Bache B W, Williams E G. A phosphate sorption index for soils[J]. Journal of Soil Science, 1971, **22**(3): 289-301.

[33] 方博，王超，王翀，等. 三峡库区澎溪河流域不同高程消落带土壤磷形态特征[J]. 重庆大学学报, 2018, **41**(12): 20-29.
Fang B, Wang C, Wang C, *et al*. Characterizations of phosphorus fractions in the soil at different altitudes of water-level-fluctuation zone, Three Gorges Reservoir[J]. Journal of Chongqing University, 2018, **41**(12): 20-29.

[34] 孙文彬，杜斌，赵秀兰，等. 三峡库区澎溪河底泥及消落区土壤磷的形态及吸附特性研究[J]. 环境科学, 2013, **34**(3): 1107-1113.
Sun W B, Du B, Zhao X L, *et al*. Fractions and adsorption characteristics of phosphorus on sediments and soils in water level fluctuating zone of the Pengxi River, a tributary of the Three Gorges Reservoir[J]. Environmental Science, 2013, **34**(3): 1107-1113.

[35] 霍守亮，李青芹，昝逢宇，等. 我国不同营养状态湖泊沉积物有机磷形态分级特征研究[J]. 环境科学, 2011, **32**(4): 1000-1007.
Huo S L, Li Q Q, Zan F Y, *et al*. Characteristics of organic phosphorus fractions in different trophic sediments of lakes, China[J]. Environmental Science, 2011, **32**(4): 1000-1007.

[36] 徐健，袁旭音，叶宏萌，等. 闽江上游溪流沉积物有机磷空间分布及其环境意义分析[J]. 环境科学, 2019, **40**(5): 2186-2193.
Xu J, Yuan X Y, Ye H M, *et al*. Spatial distribution of organic phosphorus in sediment and its environmental implication in the upper stream of Minjiang River[J]. Environmental Science, 2019, **40**(5): 2186-2193.

[37] 马双丽，倪兆奎，王圣瑞，等. 鄱阳湖沉积物有机磷形态及对水位变化响应[J]. 环境科学学报, 2016, **36**(10): 3607-3614.
Ma S L, Ni Z K, Wang S R, *et al*. Organic phosphorus forms in sediments and their relationship with the change of water level in Poyang Lake[J]. Acta Scientiae Circumstantiae, 2016, **36**(10): 3607-3614.

[38] 黎睿，潘婵娟，汤显强，等. 三峡水库蓄水至 175 m 后干流沉积物磷蓄积特征及释放潜力[J]. 环境科学, 2019, **40**(5): 2160-2169.
Li R, Pan C J, Tang X Q, *et al*. Vertical distribution profiles and release potential of mainstream column sediments in the Three Gorges Reservoir after impoundment to 175 m[J]. Environmental Science, 2019, **40**(5): 2160-2169.

[39] 曹琳，吉芳英. 三峡库区消落带干湿交替表层沉积物磷分布特征[J]. 地球与环境, 2013, **41**(2): 126-131.
Cao L, Ji F Y. Phosphorus distribution characteristics in dry-w*et* alteration sediment of fluctuation zone in Three Gorges Reservoir area[J]. Earth and Environment, 2013, **41**(2): 126-131.

[40] 潘婵娟, 黎睿, 汤显强, 等. 三峡水库蓄水至175 m后干流沉积物理化性质与磷形态分布特征[J]. 环境科学, 2018, **39**(6): 2615-2623.
Pan C J, Li R, Tang X Q, *et al*. Assessment of physico-chemical properties and phosphorus fraction distribution characteristics in sediments after impounding of the Three Gorges Reservoir to 175 m[J]. Environmental Science, 2018, **39**(6): 2615-2623.

[41] 吴起鑫, 韩贵琳. 三峡库区兰陵溪消落带土壤磷分布特征及生物可利用性评价[J]. 生态学杂志, 2018, **37**(3): 779-785.
Wu Q X, Han G L. Distribution and bio-availability of soil phosphorus at the riparian zone of Lanlingxi watershed in the Three Gorges[J]. Chinese Journal of Ecology, 2018, **37**(3): 779-785.

[42] 张雷, 秦延文, 贾静, 等. 三峡入库河流澎溪河回水区消落带与岸边土壤磷形态及其分布特征研究[J]. 环境科学学报, 2011, **31**(9): 1999-2007.
Zhang L, Qin Y W, Jia J, *et al*. Phosphorus forms and its distribution characteristics in soils of water-level-fluctuating zone of the backwater reach of the Pengxi River, input river of the Three Gorges Reservoir[J]. Acta Scientiae Circumstantiae, 2011, **31**(9): 1999-2007.

[43] 黄俊杰, 王超, 方博, 等. 三峡澎溪河流域消落区与岸边土壤磷形态特征[J]. 环境科学, 2017, **38**(9): 3673-3681.
Huang J J, Wang C, Fang B, *et al*. Characterization of phosphorus fractions in the soil of water-level-fluctuation zone and unflooded bankside in Pengxi River, Three Gorges Reservoir[J]. Environmental Science, 2017, **38**(9): 3673-3681.

[44] 周小明, 方芳, 王超, 等. 三峡库区澎溪河流域消落带土壤有机磷生物有效性研究[J]. 地球与环境, 2019, **47**(4): 495-501.
Zhou X M, Fang F, Wang C, *et al*. Bioavailability of organic phosphorus in soils of the water-level-fluctuating zone of the Pengxi River watershed, Three Gorges Reservoir[J]. Earth and Environment, 2019, **47**(4): 495-501.

[45] 刘娜, 李璐璐, 魏世强. 三峡库区消落带沉积物与土壤磷形态及分配特征研究[J]. 水土保持学报, 2016, **30**(4): 261-267, 287.
Liu L, Li L L, Wei S Q. Phosphorus forms and distribution characteristics in sediments and soils of water-level-fluctuatig zones of Three Gorges Reservoir area[J]. Journal of Soil and Water Conservation, 2016, **30**(4): 261-267, 287.

[46] Wang C, Guo J S, Zhang W, *et al*. Drying-rewetting changes soil phosphorus status and enzymatically hydrolysable organic phosphorus fractions in the water-level fluctuation zone of Three Gorges reservoir[J]. CATENA, 2021, **204**, doi: 10.1016/j.catena.2021.105416.

[47] 徐德星, 秦延文, 张雷, 等. 三峡入库河流大宁河回水区沉积物和消落带土壤磷形态及其分布特征研究[J]. 环境科学, 2009, **30**(5): 1337-1344.
Xu D X, Qin Y W, Zhang L, *et al*. Phosphorus forms and its distribution characteristics in sediments and soils of water-level-fluctuating zone of the backwater reach from input river of Three Gorges Reservoir[J]. Environmental Science, 2009, **30**(5): 1337-1344.

[48] 邓华, 高明, 龙翼, 等. 石盘丘小流域不同土地利用方式下土壤氮磷流失形态及通量[J]. 环境科学, 2021, **42**(1): 251-262.
Deng H, Gao M, Long Y, *et al*. Characteristics of soil nitrogen and phosphorus losses under different land-use schemes in the Shipanqiu watershed[J]. Environmental Science, 2021, **42**(1): 251-262.

[49] 刘莲, 刘红兵, 汪涛, 等. 三峡库区消落带农用坡地磷素径流流失特征[J]. 长江流域资源与环境, 2018, **27**(11): 2609-2618.
Liu L, Liu H B, Wang T, *et al*. Phosphorus loss from sloping cropland in water fluctuation zone of the Three Gorges Reservoir[J]. Resources and Environment in the Yangtze Basin, 2018, **27**(11): 2609-2618.

[50] 陈仕奇, 龙翼, 严冬春, 等. 三峡库区石盘丘小流域氮磷输出形态及流失通量[J]. 环境科学, 2020, **41**(3): 1276-1285.
Chen S Q, Long Y, Yan D C, *et al*. Characteristics of nitrogen and phosphorus output andloss flux in the Shipanqiu watershed, Three Gorges Reservoir area[J]. Environmental Science, 2020, **41**(3): 1276-1285.

[51] 高艺伦, 方芳, 唐子超, 等. 三峡库区澎溪河不同高程消落带土壤磷形态及磷酸酶活性分布特征[J]. 环境科学, 2022, **43**(10): 4630-4638.
Gao Y L, Fang F, Tang Z C, *et al*. Distribution characteristics of soil phosphorus forms and phosphatase activity at different altitudes in the soil of water-level-fluctuation zone in Pengxi River, Three Gorges Reservoir[J]. Environmental Science, 2022, **43**(10): 4630-4638.

HUANJING KEXUE

Environmental Science (monthly)

Vol. 44 No. 5

May 15, 2023

CONTENTS