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The accumulation and redistribution of heavy metals in the water-level fluctuation zone of the Nuozhadu Reservoir, Upper Mekong

Jingyi Song[a,1], Xingwu Duan[a,b,1], Xu Han[a], Yawen Li[a], Yuxiang Li[a], Daming He[a,b,*]

[a] Institute of International Rivers and Eco-security, Yunnan University, Kunming 650091, China
[b] Yunnan Key Laboratory of International Rivers and Trans-boundary Eco-security, Kunming 650091, China

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ABSTRACT

The accumulation and redistribution of heavy metals in soil in a water-level fluctuation zone (WLFZ) can create ecological risks to reservoirs and reduce river health. Little is known about how heavy metals are accumulated and redistributed in the WLFZ of reservoirs with a high background value of the heavy metal in soil. The site chosen for this case study is the Nuozhadu mega reservoir in the upper Mekong River Basin, which is held back by a dam with a height exceeding 250 m. Five sampling transects were established around the reservoir. Each transect contained three vertical sampling lines representing three land-use types: forest, farmland, and rubber plantations. Soil samples were collected both in the WLFZ and in the infralittoral reference zone (IRZ), and the concentrations of the heavy metals Zn, Cr, Ni, Cu, Mn, and Fe (%) were measured in these samples. We found that the average concentrations of each of these heavy metals were higher in the WLFZ than in the IRZ. The land-use types, especially the rubber plantations and farmlands, determine the redistribution of the heavy metals in the soil of the WLFZ. The heavy metals Cu, Mn, and Ni increased with increasing elevation within the WLFZ, but the metals Cr and Zn decreased with elevation. The results of analysis of variance indicate that the soil properties had certain differences under different land-use types and inundation durations at various elevations, which partly determined the accumulation and redistribution of heavy metals in the WLFZ. We suggest that long-term monitoring of the concentration of heavy metals is needed for soil and water management in the WLFZ of the Nuozhadu reservoir.

1. Introduction

The construction and operation of cascade dams can result in changes to river ecosystems (Dai and Liu, 2013; Li et al., 2013; Miao et al., 2015). The changes in both aquatic and terrestrial riparian ecosystems that occur in response to the construction of dams have become a key focus of river studies (Tealdi et al., 2011; Li et al., 2012; Benjankar et al., 2016). Water-level fluctuation zone (WLFZ) occur at the juncture between water-covered areas and land areas, and they experience alternating wet and dry conditions caused by the repeated inundation and exposure of soil within the reservoir area. WLFZ is ecologically fragile and display significant hydrological, biological, and physical variations (New and Xie, 2008).

Heavy metals are distributed throughout the water, soil, and plants in a WLFZ (Ye et al., 2013). They are classified as serious environmental pollutants due to their persistence, their tendency to bioaccumulate, and their high toxicity (Pavlović et al., 2016). Many studies have focused on the spatial variations and the assessment of heavy metals in water or sediment in reservoirs (Fu et al., 2012; Zhao et al., 2013; Dai and Liu, 2013). However, the soil in the WLFZ, which is influenced by inundation, erosion, and siltation, serves as a sink and a source for the accumulation and redistribution of heavy metals (Steiger et al., 2001). Furthermore, the soil in dammed WLFZ is often alternately submerged and exposed through the regular impoundment of a reservoir, and the resulting redistribution of soil with various forms of heavy metals may create a potential ecological risk to the quality of water in the reservoir (Huang et al., 2017). Analysis of the accumulation and redistribution of heavy metals in the soil of dammed WLFZ is crucial to ensure the health of reservoirs and rivers.

The accumulation and redistribution of heavy metals in the soil of a WLFZ is affected by many factors, including the background concentrations of the heavy metals in regional soil, erosion, soil properties, land use, and the complex exchanges of matter and energy between water and land (Bai et al., 2009; Wang et al., 2017). Heavy metals in the

* Corresponding author at: Yunnan Key Laboratory of International Rivers and Trans-boundary Eco-security, Kunming 650091, China.
E-mail address: dmhe@ynu.edu.cn (D. He).
[1] The authors contributed equally to this work.

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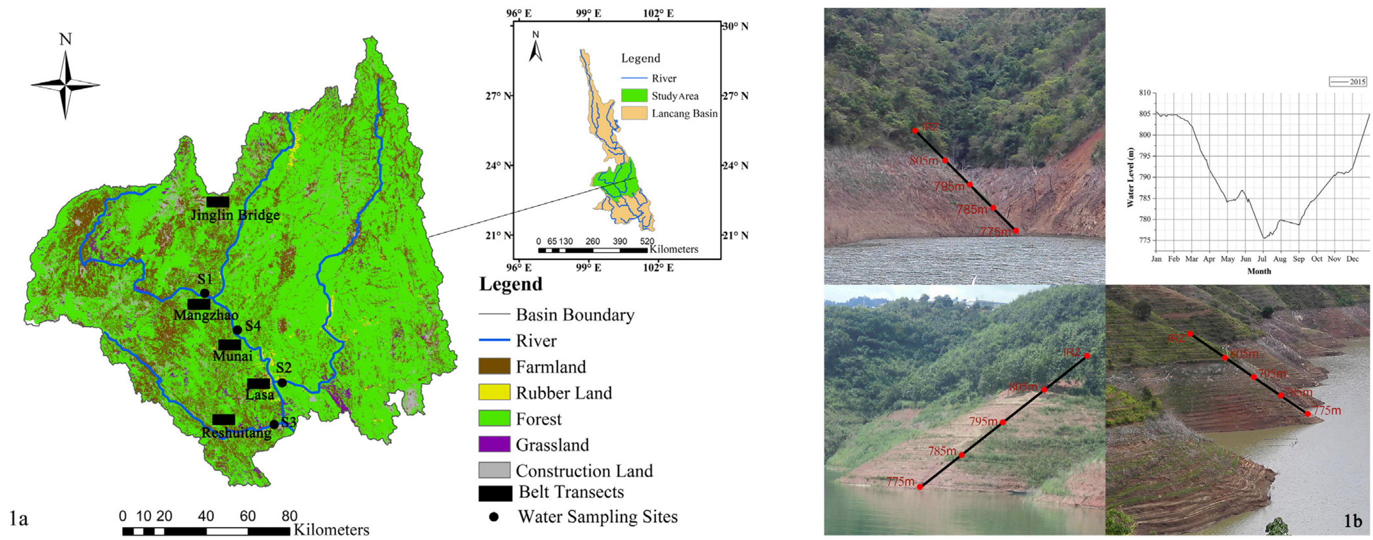

Fig. 1. Sampling sites and variations in the water level within the study area. (1a - the study area, five soil sampling transects, and four water sampling sites; 1b - the vertical sampling lines in each land-use type and the fluctuations in the water level in 2015).

soil of a WLFZ typically enter the reservoir and river system by dissolution, exchange, and diffusion after the soil become inundated, creating potential ecological risks to water quality (Smart et al., 2001; Huang et al., 2017). Conversely, heavy metals in river systems migrate to the soil of a WLFZ via sedimentation and adsorption, thus changing the properties and functions of the soil in the WLFZ (Cheng et al., 2009; Ye et al., 2012; Miao et al., 2016). Furthermore, the interactions between water and soil change the pathways and rate of redistribution of heavy metals by altering soil moisture conditions (Han et al., 2001). In addition, soil moisture affects the pH, Eh, and content of organic matter and $CaCO_3$ in the soil. Han et al. (2001) reported that soil in both saturated paste and wetting-drying cycle moisture regimes display comparatively high redistribution rates of metals into more stable fractions. Accordingly, soil moisture may indirectly influence the transformation and repartitioning of heavy metals in soil.

Inundation time is an important factor in the accumulation and redistribution of heavy metals because it alters the physical and chemical properties of soil at different elevations (Ye et al., 2011). Several studies have reported that the heavy metals in the soil of a WLFZ undergo a process of longitudinal redistribution (Liu et al., 2014; Tang et al., 2015). Tang et al. (2015) identified progressive decreases in heavy metal content with increasing elevation. The differing mobility of various heavy metals has been observed in inundated soil (Mukwaturi and Lin, 2015). Zhu et al. (2014) reported that soil properties and the degree of activation of Fe showed vertical differences caused by repeated inundation and exposure. However, Wang et al. (2012) found no significant difference in the content of heavy metals under different water levels, consistent with the results of Wang et al. (2010).

Different types of land use also affect the functions of contaminants in soil (Gao et al., 2010) and soil properties and play an important role in determining the concentrations of heavy metals (Liu et al., 2016b; Wang et al., 2017). Cutillas-Barreiro et al. (2016) indicated that forest soil have higher concentrations of Hg than prairie soil. Arable land is more likely to be polluted by Cd, Zn, Pb, and Cu than non-arable land due to irrigation with sewage (Liu et al., 2016b). Change in land use and land cover also affect the erosion and redistribution of soil (Wang et al., 2016) and thus influence the redistribution of heavy metals in soil. Meng et al. (2001) showed that the losses of nutrients (N, P, and K) from orchard plots via runoff and erosion were < 20%, whereas these losses ranged from 50% to 99% in arable plots near the Three Gorge Reservoir (TGR). The soil within the WLFZ and its land use patterns are disturbed by the construction and operation of dams (Zhao et al., 2010); thus, the erosion of these soils is generally serious during the initial impoundment (Bao et al., 2015a). The erosion of soil in a WLFZ promotes the deposition of sediment or soil at lower elevations (Wang et al., 2016), which causes nutrient losses and material transportation in soil in the WLFZ (Cui et al., 2011). Previous studies have focused on the distribution of heavy metals in the WLFZ and IRZ (Ye et al., 2011; Liu et al., 2014; Tang et al., 2014), but few have focused on the impact of land use before dam construction on the concentration of heavy metals in the WLFZ.

The upper Mekong River, which is called the Lancang River in China, its six mainstream dams have been completed (He et al., 2014; Räsänen et al., 2017). Nuozhadu dam is the second mega dam with the largest storage capacity among the six cascade dams, and the last huge reservoir flowing into the lower Mekong (He et al., 2014; Fan et al., 2015). Its upstream area, the largest mineral resource of lead and zinc, has been exploring. The water quality change of the reservoir, such as heavy pollution, would result in transboundary water security issues. As operating started, a riparian zone with a steep slope and over 30 m water level change was formed in Nuozhadu reservoir. This riparian height is even higher than that of Three Gorge Reservoir (Ye et al., 2012; Shu et al., 2017). Nuozhadu reservoir has operated over three years, however, little is known about the vertical distribution of heavy metals in the unique alpine canyon WLFZ of this reservoir. This paper takes the Nuozhadu reservoir as a case study to (1) explore the accumulation and redistribution of heavy metals in the WLFZ and IRZ; (2) to analyze possible relationships between heavy metals and different land use types, soil properties, and elevations; and (3) to characterize the factors that control heavy metals accumulation and redistribution processes in WLFZ.

2. Materials and methods

2.1. Study area

The Nuozhadu reservoir is located in the lower portion of the main stream of the upper Mekong River Basin in southwestern China (Fig. 1a). Construction of the dam began in 2004, and it was completed in 2014. The dam is 261.5 m high, the normal water level is 812 m, and the dead water level is 765 m. The total capacity of the reservoir is $23.73 \times 10^8\ m^3$, and its adjustable storage capacity is $113.35 \times 10^8\ m^3$ (Xiao et al., 2016). The region has a southwest subtropical monsoon climate. The annual mean temperature ranges from 17.8 °C to 20.2 °C, and the annual precipitation ranges from 912 to 1546 mm. The land use types around the Nuozhadu reservoir are divided into five categories: