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Soil degradation associated with water-level fluctuations in the Manwan Reservoir, Lancang River Basin

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ABSTRACT

This study was conducted to understand the impacts of dam-induced water-level fluctuations (WLFs) on soil properties. The redundancy analysis (RDA) and two soil degradation indices were used to analyse soil degradation under different land uses and at different soil depths. In addition, the relationships among soil degradation and topographical and geographical parameters were determined. The sampling sites were located in two zones along the Manwan Reservoir, which is a section of the Lancang River in Southwestern China. These zones included a water-level-fluctuation zone (WLFZ) and an infralittoral reference zone (IRZ), which included forestlands, scrublands, and farmlands. The results indicated that WLFs increased soil pH, total phosphorus (TP) concentrations, and total potassium (TK) concentrations, and decreased soil total carbon (TC) and total nitrogen (TN) concentrations. Meanwhile, the WLFs increased the soil C/N ratio, which indicated that the WLFs had a stronger effect on TN than on TC. The degree of soil degradation based on the soil degradation index and the changes in the soil quality index indicated that WLFs significantly affected topsoil quality (0–5 cm), especially in the scrubland, which had the highest degradation level. The results from the RDA indicated that soil degradation significantly increased with decreasing distance along the river upstream of the dam ($P < 0.05$; $F = 3.05$). Our results identified soil degradation in the WLFZ along the Manwan Reservoir. However, further research is needed to determine the mechanisms of degradation in this zone.

1. Introduction

Water-level fluctuations (WLFs) occur in nearly all rivers, reservoirs, and lakes worldwide. These fluctuations dominantly control the structure and function of aquatic ecosystems (Leira and Cantonati, 2008; Wang et al., 2011). In addition, WLFs play an important role in the littoral and aquatic processes that change a water body (especially its extent, frequency, and duration). Furthermore, WLFs affect the ecological processes and patterns (Leira and Cantonati, 2008; Wantzen et al., 2008) by altering littoral sediments, biogeochemical characteristics (Furey et al., 2004; Leira and Cantonati, 2008), the littoral food web (Brauns et al., 2008), biomass allocations (Peintinger et al., 2007), and habitat qualities (Riis and Hawes, 2002; Wang and Yin, 2008).

The generation of WLFs is related to two major factors, including climatic changes and anthropogenic disturbances. As one of the most influencing factors, climatic change is expected to cause significant changes in the hydrological regime of rivers, reservoirs, and lakes, which can result in an unbalanced water budget with seasonal variations in precipitation, air temperature, and evaporation (Hofmann et al., 2008). However, WLFs induced by climatic changes are usually regarded as natural WLFs and are characterised by smaller fluctuation amplitudes and a more regular seasonal pattern (Brauns et al., 2008). Similarly, anthropogenic disturbances are expected to generate WLFs. In addition, the impacts of these WLFs are likely enhanced by climatic changes (Brauns et al., 2008; Leira and Cantonati, 2008). In the past, increasing anthropogenic disturbances have altered the magnitude and temporal distribution of floods (Nilsson et al., 2005) and increased concern regarding the effects of human-altered WLFs (Coops et al., 2003; Leira and Cantonati, 2008). These changes may negatively influence the entire littoral zone (Peintinger et al., 2007).

Most knowledge regarding the effects of humans on WLFs is based on research related to the construction of dams and reservoirs for hydropower production, flood control, agriculture irrigation, and drinking water supply (Aroviita and Hämäläinen, 2008; Brauns et al., 2008). Due to the reservoir operation pattern of water release and storage during and after the flood season, drastic WLFs have been caused (Wang et al., 2011). These drastic WLFs are large enough to move the systems (both aquatic and terrestrial) out of their homeostatic plateau, especially at the boundary zones between the terrestrial and aquatic ecosystems, which is called the water-level-fluctuation zone (WLFZ) (Riis and Hawes, 2002; Wang and Yin, 2008). Abnormal timing and the frequency of WLFs that are induced by dam and reservoir operation affect the vegetation distribution, species diversity, reservoir morphology, littoral sediments, and biogeochemical characteristics (Furey et al., 2004;

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Leira and Cantonati, 2008; Wang and Yin, 2008). Meanwhile, any changes in the soil and water interactions in the WLFZ likely affect the soil nutrient dynamics (Abrahams, 2008; de Vicente et al., 2010; Hofmann et al., 2008). Abrahams (2008) indicated that the substrate in the WLFZ is often sandy or stony with low nutrient levels because the exposure of soils to WLFs affects the organic matter, nutrient, and fine particle concentrations in the substrate. Meanwhile, Hofmann et al. (2008) indicated that strong turbulence and high current velocities associated with WLFs enhance solute diffusion across the sediment-water interface. In contrast, Ye et al. (2012), who studied soil nitrogen dynamics in the water level fluctuation zone of the Three Gorges Reservoir in China, found that WLFs significantly influenced the nitrification process in the WLFZ soil. In addition, the soil inorganic N concentration declined after a WLF. Furthermore, de Vicente et al. (2010) studied the sediment nutrient dynamics in an oligotrophic high mountain lake and found that WLFs potentially decreased the phosphate adsorption capacity of the sediment, which increased the availability of P in the oligotrophic water column.

Soil nutrients in the WLFZ are important for many ecological processes. These ecological processes affect the distribution and diversity of macrophytes (Brauns et al., 2008; Liang et al., 2010; Peintinger et al., 2007; Wilcox and Nichols, 2008), phytoplankton (Brauns et al., 2008), and benthic communities (e.g., fish species and invertebrates) that use the littoral zone as a habitat for reproduction (Brauns et al., 2008; Peintinger et al., 2007; Richardson et al., 2002). Therefore, WLF-induced soil degradation directly determines the habitat quality of the reservoir area, especially in the highly dynamic cascade reservoir system. The Lancang River in Yunnan Province of Southwestern China is used as an example. Here, 14 dams have been planned since the 1980s. Once all of the planned dams have been completed, thousands of kilometres of eulittoral habitat will be submerged. In addition, the infralittoral habitats will be transformed into new eulittoral habitats under the highly dynamic WLFs. Since the first dam of the Lancang (located in the Yunnan Province) was completed in Manwan in 1993, the Lancang River Basin has become the most controversial area in which ecological and socioeconomic issues have been focused (He et al., 2006; Zhao et al., 2012a). It is reported that the shrub and grass communities in the riparian habitats are the most endangered vegetation communities (Li et al., 2012) due to large dams increase the water levels in the river and cause the inundation of the riparian habitats along the river, and Wang and Zhang (2000) and Wu and Zhu (1987) indicated that the landmark riparian shrub community was dominated by a typical riparian (*Homonoia riparia Lour*) plant in southwestern Asia before it disappeared due to the inundation of the Manwan Reservoir. Therefore, it is practical and very important to investigate the response of soil properties to WLFs.

We examined the effects of WLFs on soil properties of three soil depths for three land use types along the Manwan Reservoir. First, we compared soil nutrients in the WLFZ with those in the infralittoral reference zone (IRZ, non-submerged, above the WLFZ), which was along the Manwan Reservoir. Second, we calculated the degree of soil degradation using soil quality and the soil degradation indices, respectively. Ultimately, we analysed the correlations between the degrees of soil degradation and the topographical and geographical parameters (such as, slope, aspect, and distance from dam).

2. Materials and methods

2.1. Study area

The study area is located in the middle reach of the Lancang River (Fig. 1). The Lancang River in Yunnan Province forms the upper reach of the Mekong River. The river channel is 1170 km long and decreases in elevation by 1780 m with an average gradient of 0.15% (Zhao et al., 2012a, 2013). From north to the south, the Lancang River crosses several different geographic environments. The geomorphology of the river varies from high mountains and deep valleys to medium/low mountains and wide valleys (He et al., 2005, 2006). Most of the mountain peaks near the reservoir are more than 2200 m above sea level. Among these mountains, the highest on the west bank is the Heilongtan Mountain, which is in Fengqing County (2863 m). The lowest valley occurs near the damsite (891 m) and the highest mountain on the east bank is the Wuliang Mountain (3291 m) (Zhao et al., 2010). The study area is characterized by complicated geologic structures, including fold structure, fault structure, and magmatic activity (Fang and Tang, 1993), wherein, the first two of them are the dominating factors. Geological substrate of the study area is dominated by clastic rock (quartz sandstone) with fractured aquifer (Wang and Qiangbazhaxi Peng, 2008) and relatively thin fault gouge. The aquifer mainly consists of the quaternary slope and diluvium which are more than 2 m in depth and rich in pore water. Ground water in this area is mainly recharged by atmospheric water and surface flow, with a balanced water table via discharging into the river. The rock weathering is dominated by homogeneous surface weathering which decreases from peak to river bed in depth (Fang and Tang, 1993). Moreover, land use of the study area primarily consists of forestland and scrubland (Zhao et al., 2013). Trees and shrubs are the dominant type of vegetation on the uplands. In contrast, grass and shrub vegetation are dominant vegetations in the riparian areas (Li et al., 2012). In the study area, the dominating soil group and soil type are red soil and sandy soil respectively, and sandy soil is characterized by loose and good air and water permeability of soil conditions with organic matter about 2%, pH values fall in the range of 6.2–7.3, and thickness of tillage layer more than 30 cm. Further, soils in the study area are influenced by natural factors and anthropogenic activities, such as parent material, excessive utilisation of farmland with less maintenance in sustainable development, and hydropower development.

Unique geographic features and plentiful hydraulic resources within the basin provide multiple opportunities for developing hydropower (He et al., 2005, 2006). Previously, only 4 dams (Manwan, Dachaoshan, Jinghong, and Xiaowan) have been constructed and completed in the main stream. The first dam that was constructed, the Manwan Dam, was completed in 1993. The Manwan Dam has a crest length of 418 m, a height of 132 m, and a total installed capacity of 150×10^4 kW (Zhao et al., 2010). After impoundment, a reservoir and an area of 23.6 km^2, an average width and length of 37.1 m and 70 km, respectively, was formed. With a typical water level of 994 m, the reservoir area is 2.8 times greater than that of the natural channel before constructing the dam. The total capacity of the reservoir reaches 1060×10^6 m^3 with an effective capacity of 257×10^6 m^3, which depends on the regulation of seasonal discharge (He et al., 2005, 2006; Zhao et al., 2012b).

Because the reservoir is operated to provide flood control and generate power in different seasons, the amplitude of the WLFs was altered (Fig. 2). For example, before dam construction in 1991, the WLFs at the Gajiu station (2 km downstream from the Manwan Dam) were characterised by a summer flood that was caused by precipitation in August (Zhao et al., 2012b), which resulted in lower water levels in the winter and spring. Following dam construction in 1997 and due to the high demands for energy and flood control, bimodal flood distributions occurred in the summer (July) and autumn (October). These results indicated that the peak of the flood decreased due to reservoir operations and that the duration of the flood was extended because the timing of the flood was delayed.

2.2. Soil sampling and chemical analysis

To investigate the soil nutrient concentrations in the water-level-fluctuation zone (WLFZ) and the infralittoral reference zone (IRZ), field surveys were conducted in June 2011 when the WLFZ was exposed to air after submergence. Soil samples were collected at depths of 0 to 5, 5 to 15, and 15 to 25 cm at 28 locations (12 forestlands, 10 scrublands, and 6 farmlands) in the WLFZ and the IRZ along the reservoir (Fig. 1) (for a total of 168 soil samples, 2 zones × 28 locations × 3 depths). At