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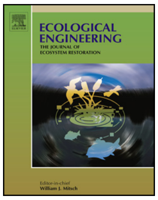

Spatial variations of sedimentary organic carbon associated with soil loss influenced by cascading dams in the middle Lancang River

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ABSTRACT

Construction and operation of cascading dams can pose drastic effects on sediment transport and deposition, thus affecting sedimentary carbon concentrations in the riverine ecosystem. This paper examines the spatial variations of sedimentary organic carbon (OC_{sed}) and its potential relationship with terrestrial soil loss in two cascade reservoirs (Manwan and Dachaoshan) along the mainstream of Lancang River. During both wet and dry seasons in 2013 and 2014, 25 sampling sections were chosen to evaluate the spatial variations of sedimentary organic carbon. Generally, the contents of OC_{sed} in the upper 5 cm of the bottom sediment in wet seasons were higher than those in dry seasons in both reservoirs. Spatially, lower reservoir (Dachaoshan) preserved higher OC_{sed} content than the upper reservoir (Manwan), at 36.1 kg m^{-2} and 27.8 kg m^{-2}, respectively. Additionally, the contents of OC_{sed} in the reservoir heads were higher than those in the reservoir centres and tails, this trend was also observed for terrestrial organic carbon (OC_{ter}) and liable organic carbon (LOC). Hillslope delivery ratio (HSDR) method are used to estimate the incoming sediment yields from the river basin. The results indicated that Dachaoshan catchment generated higher sediment stream deposits than the Manwan catchment with the high sediment loading (>40 t/ha/year) areas located within 3 km buffers encompassing a higher accumulation of farmlands. The cumulative effects of sediment transport on OC_{sed} along the river channel were further investigated by setting sequential riverine sediment delivery ratios (0–0.55) to explore potential relationships between OC_{sed} and total sediment delivered to stream. The results showed that in the Dachaoshan Reservoir the OC_{sed} contents correlated with the total sediment delivered to streams when the ratios ranged from 0.10 to 0.55, in particular in delivery ratios ranging from 0.50 to 0.55. These findings emphasized the importance of direct and indirect connections between the terrestrial and riverine ecosystems, and also provided a preferable view to understand the cumulative effects of sediment transport on OC_{sed} distributions in the reservoirs generated by cascading dams.

1. Introduction

Dams have many functions beyond the typical application in energy crisis mitigation, with practical uses spanning, to flood control and global climate change risk reduction (Zhai et al., 2010; Rood et al., 2016). Nevertheless, such substantial hydraulic dam structures and their adjacent reservoirs, pose significant negative effects on a river's hydrodynamic conditions, including water disturbance, water level fluctuation and velocity decrease (Zhang et al., 1999; Klaver et al., 2007; Wei et al., 2008). Subsequent to the reservoir impoundment, such changes of hydrologic and hydrodynamic conditions significantly affect the compositions, spatio-temporal distributions, and transport fluxes of organic carbon in the reservoir area and downstream river (Dynesius and Nilsson, 1994; Klaver et al., 2007). The delivery of organic carbon from the terrestrial environment to the riverine ecosystem and sediment is a key process of carbon flux, which has significant importance on global carbon sequestration (Aufdenkampe et al., 2011).

In South-western China, the Manwan dam was first completed in 1995 in the middle Lancang River, since then studies stated that the total water storage capacity of the Manwan Reservoir has been significantly decreasing (Fu et al., 2008). These reservoirs have trapped a portion of the incoming sediment from terrestrial landscape and upstream river basin (Fu and He, 2007). Also, sediment trapped by the upstream reservoirs can reduce the amount

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of sediment reaching floodplain and deltas (Mueller et al., 2016). Previous literature further demonstrated that the estimated potential trapping efficiency of the eight reservoirs in the mainstream of Lancang River could reach 78–81% in the future (Kummu et al., 2010). However, less evidence has been found for spatial distributions of sedimentary organic carbon (OC_{sed}) and loss of soil quantity, especially in the mountainous regions of the reservoir basins.

Many factors, including hilly topography, soil property, land use types and climate factors, are associated with soil erosion in the mountainous regions (Park et al., 2010; Sidle et al., 2006). At a local scale, investigating the land use changes and soil erosion are essential for understanding the organic carbon from terrestrial land to riverine ecosystems(Bianchi et al., 2015). It is well established that the forests on the sloping land can reduce hillslope surface runoff and soil loss, whereas farmland can improve the runoff and sediment yield (Ouyang et al., 2010; Haregeweyn et al., 2017). The most widely applied method to estimate the amount of soil erosion is the Revised Universal Soil Loss Equation (RUSLE), which incorporates the dominant factors including erosivity, erodibility, hill length and vegetation cover (Renard et al., 1997). River modification and dam operation will affect vegetation regimes in watershed and thus the soil erosion level (Benjankar et al., 2012). However, there are still limited understandings of total sediment delivered to stream from the terrestrial ecosystem associated with soil loss in the middle Lancang River (Li and Bush, 2015a; Oeurng et al., 2016).

In the canyon reservoirs along this international river, intense soil erosion and high sediment trapping efficiency caused an increasing concern on the effects of soil erosion on carbon concentrations. Most of the sediment in the mainstream Lancang River could be stored inside the channel according to Gupta et al. (2002). Assessing the relationship between soil erosion and organic carbon can deepen the understanding on the cumulative effects of carbon flows and sediment in the catchments (Li and Bush, 2015b).

To date, many researchers have investigated soil erosion and the sediment yield process, but few researchers have investigated the carbon flows affected by soil erosion in the dammed river. In this context, this study aims to: (a) identify the spatio-temporal distributions of OC_{sed}; (b) investigate the soil loss and sediment loading to river channel in the cascading reservoir region; and (c) explore the cumulative effects of soil loss on OC_{sed} in the river channel.

2. Methodology

2.1. Study area

The Lancang River, located in the south-eastern corner of Asia, originates from the Guyong-Pudigao Creek at the foot of Jifu Mountain on the Qinghai-Tibetan Plateau (Kummu and Varis, 2007). The upper reaches flow through the Chinas' and Myanmars' watersheds, with the lower reaches flowing through Laos, Thailand, Vietnam and Cambodia. Deep mountain valleys surround the cascading dams constructed in the middle Lancang River. The study area is located in the upper Lancang River valley, which covers the Manwan Reservoir and Dachaoshan Reservoir (Fig. 1). Manwan Dam is the first multimillion kilowatt hydropower station in Yunnan Province, the reservoir covers an area of 23.6 km^2 with a height of 132 m and a crest length of 418 m. The Dachaoshan Dam, completed in 2003, is situated downstream of the Manwan Dam with a distance of 91.25 km. In the study area, Cambisols is the dominating soil type, which is characterized by good air and water permeability conditions with an organic matter content of about 2% (Zhao et al., 2014). The annual average temperature ranges from 18 °C to 20 °C and rainfall is abundant (1000–1150 mm yr^{-1}). The study area has a typical continental climate with a hot rainy season (May to November) and cool dry season (December to April).

2.2. Sample collection and analytical methods

Twelve cross-sections in Manwan Reservoir and 13 cross-sections in Dachaoshan Reservoir were selected to investigate the spatial distributions of OC_{sed} in May and December of 2013 and 2014. Surface sediment samples (0–5 cm) were collected using a gravitational bottom sediment sampler. In each cross-section, we collected one sample in the middle of the river and two samples 3–5 m away from the bank. All three samples from the same section were mixed together in equal amounts to avoid the variations of samples from different sites before laboratory analysis. Moreover, 25 surface soil samples (0–5 cm) were collected at the shoresides of Manwan and Dachaoshan catchment and the location are in line with the sediment samplings horizontally. The OC_{sed} and OC_{ter} were measured using a Total Organic Carbon Analyser (Shimadzu, Inc., Japan). 350 mg of air-dried soil samples were removed inorganic carbon by adding acid, then OC were tested using TOC analyzer after rotating freeze-drying. Soil samples were added to 333 mmol L^{-1} of potassium permanganate solution and they were diluted 250 times after 1 h at room temperature oscillation and centrifugal separation. And the labile organic carbon (LOC) content was measured using an ultraviolet spectrophotometer under the wave length of 565 nm (Baham and Sposito, 1983).

In order to analyze spatial distribution characteristics of OC_{sed} in Manwan and Dachaoshan Reservoir, the first four cross-sectional sites (sites M9–M12 and sites N10–N13) were catalogued as 'reservoir tail'. The next four cross-sectional sites (sites M5–M8 and sites N6–N9) were defined as 'reservoir centre' and the last cross-sectional sites (sites M1–M4 and sites N1–N5) as 'reservoir head' near Manwan and Dachaoshan Dam, respectively (Wang et al., 2012).

2.3. Subbasin delineation

The study catchments encompassed the entire reservoir and the direct convergent areas of the main river channel with approximately 20 km buffers. The boundaries of the catchments were modified by the ridgelines of the subbasins generated by DEM data (1:50000). Twelve subbasins were delineated in the Manwan catchment and 13 subbasins in the Dachaoshan catchment. Soil loss was calculated and summarized within each subbasin.

2.4. Simulation the spatial distribution of OC_{sed}

The organic carbon pool was calculated as follows (Tue et al., 2014):

$$\text{Organic Carbon Storage}(\text{kg m}^{-2}) = \text{Bulk Density } (\text{g cm}^{-3}) \times \text{OC}(\text{g kg}^{-1}) \times 5\text{ cm} \times 10 \quad (1)$$

Spatial distributions of OC_{sed} in the river channel were simulated using the Kriging interpolation method based on the measured data in each sampling section and interpolated to the reservoir boundary in ArcGIS 10.2. Kriging interpolation, as a popular geostatistical method, is used to interpolate into a continuous surface from sample points considering their spatial autocorrelation. This method uses variation function theory and structural analysis to regionalize variables in a limited area in an unbiased and optimal manner. Kriging is based on unknown samples in finite neighborhoods and takes into account the shape, size, and spatial position in the sample areas along with the relationship between unknown sample spaces. The variation function provides the structure of the information, which is used to estimate the spatial distributions of soil properties. It is a moderate interpolation approach comparing with other interpola-