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The sediment delivery ratio in a small catchment in the black soil region of Northeast China

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Abstract

The black soil region of northeast China, which covers the Provinces of Heilongjiang, Jilin and the Inner Mongolia autonomous region with black soil, chernozem and meadow soil, has experienced soil erosion since intense agricultural reclamation began approximately 100 years ago. However, the sediment delivery ratio, defined as the fraction of gross erosion that is transported from a given area in a given time interval, is still unclear. In this study, we calculated the delivery ratio and analysed changes in erosive processes within Hebei catchment from 1977 to 2007 based on an analysis of sediments of the Liudui reservoir. The original vegetation layer clearly identified the bottom of the reservoir when it was constructed in 1977; thus, the reservoir sediments could be precisely dated. The delivery ratio, calculated by comparing the sediment deposition in the reservoir with the total soil erosion in the upstream catchment, was found to be exponentially correlated (r^2 = 0.95, P < 0.01) with decreasing grain size, except for the fraction <0.002 mm. The delivery ratio for the clays (<0.002 mm) was low, averaging 0.10 during the study period, which indicated partial removal of clays from the reservoir. The changes in the reservoir deposition rate reflected the temporal changes in the erosion processes. The exceptionally high rainfall in 1998 was confirmed by the distributions of ^{137}Cs, ^{210}Pb, and the grain-size of the sediments. Beginning from the position of the original grass layer, we defined three periods from 1977 to 2007 based on deposition rates: 2.40 cm year^{-1} from 1977 to 1997, 5.60 cm year^{-1} in 1998 due to unusually high rainfall, and 1.55 cm year^{-1} from 1999 to 2007. The overall average deposition rate for the entire period was 2.26 cm year^{-1}. Precipitation was found to be the main factor affecting the soil erosion of the study area.

Key Words: Sediment delivery ratio, Reservoir sediments, Black soils, China

1 Introduction

Soil erosion, which results in the sedimentation of rivers and other bodies of water, is a major land degradation process that can lead to environmental pollution and decrease crop productivity (Hudson, 1995). The sediment yield from a catchment is often much lower than the gross erosion in the catchment (Wasson et al., 1996), suggesting that a proportion of the eroded soil is deposited before being transported out of the catchment. The sediment delivery ratio is a measure of sediment transport efficiency, defined as the fraction of gross erosion that is transported from a given catchment in a given time interval, and can therefore be used to represent the degree of sediment deposition. The delivery ratio changes on both temporal and spatial scales, and it generally decreases with increasing drainage area (Walling, 1983).

Reservoir sediments often preserve the chronological order of deposition because of the stagnation of water; this preserved chronology could be used to reconstruct the history of erosion in a catchment (Eriksson and Sandgren, 1999). Some sedimentary evidence, such as the grain-size distribution, varve records, and presence of dead vegetation layers, has been used to analyse the age of sediments (Christiansen et al., 1981; Zhang et al., 2006; You et al., 2007). In recent years, radiometric dating based on ^{137}Cs and ^{210}Pb has become an important method. The isotope ^{137}Cs (half-life 30.17

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years) was produced by the testing of nuclear weapons in the 1950s and early 1960s, with the maximum fallout occurring in 1963 (Zapata, 2003; Estrany et al., 2010). The isotope ^{210}Pb (half-life 22.3 years) is a member of the U series and is produced by a series of short-lived radionuclides from the decay of ^{222}Rn, the daughter of ^{226}Ra. The proportion of total ^{210}Pb that is not in equilibrium with its parent ^{226}Ra has been called excess ^{210}Pb (Zapata, 2003; Li et al., 2003; Ruiz-Fernandez et al., 2004). The isotope ^{210}Pb is often used to date sediments at different depths using the constant rate of supply (CRS) and constant initial concentration (CIC) models (Walling et al., 2003; Sombrito et al., 2004). Both ^{137}Cs and ^{210}Pb are strongly adsorbed by fine soil particles (He and Walling, 1996).

The contiguous areas of northeast China with black soil, chernozem and meadow soil are called the north-eastern black soil region, an important agricultural area of China (Liu et al., 2008). This region has experienced soil erosion since intense reclamation for agriculture began approximately 100 years ago (Wu et al., 2008), but the history of the erosion rate is still unclear. Another question regarding this region is the nature of the sediment delivery process. Although the soil erosion in this region is severe, the river sediment load remains low. It is necessary to better understand the sediment delivery ratio at the catchment scale to understand the sediment transport processes in this region, but little research has been performed on this subject. In this study, we obtained sediment cores from the Liudui reservoir in the study region for the following purposes: (1) to determine the average delivery ratio for the catchment from 1977 to 2007; and (2) to detect changes in the deposition rate at a medium-term scale and discuss the historical erosion processes of the study area.

2 Study area

The Hebei catchment (48°59′03.37″N to 49°02′35.07″N, 125°15′45.71″E to 125°20′46.79″E) is located northeast of Heshan Farm (Fig. 1) in the upper reaches of the Songhua River basin in Heilongjiang Province, China. The area of the catchment is 27.29 km^2, and its elevation ranges from 312.0 to 388.5 m above sea level. The average slope is approximately 3.5°, and the lengths of the hill slopes range from 500 to 4,000 m (Wu et al., 2008). The main land use in the catchment is cropland, which covers approximately 70% of the catchment area. The land use has not changed significantly in the past 30 years.

The climate of the region is continental-semi humid, with mean temperatures of -21 and 21°C in January and July, respectively. The average annual precipitation from 1972 to 2007 was approximately 534 mm. The topsoil is classified as Udic Argiboroll in the USDA Soil Taxonomy or as Luvic Phaeozem in the FAO/Unesco system. The dry bulk density ranges from 1.0 to 1.6 g cm^{-3} and averages approximately 1.27 g cm^{-3} (Hu et al., 2007; Zhang et al., 2007; Wu et al., 2008).

Construction of the Liudui Reservoir was completed by October 1976. The reservoir now covers an area of 0.25 km^2 with a capacity of approximately 2,775,000 m^3. There is a sluice gate at the outlet of the reservoir, which would open when the water level was above the warning line.

3 Materials and methods

3.1 Field sampling and laboratory measurements

We chose three sites for obtaining core samples in the reservoir (Fig. 1): near the entrance (RK), in the centre (ZX), and at the outlet (CK). Two cores (Table 1) were taken at each site to provide replication and serve as a backup sample. The cores were obtained in December 2007 after the ice was thick enough for samples to be safely obtained.

We used the depth of penetration into the sediment as the real length of the cores and calculated a compression ratio equal to the depth of penetration divided by the length of the core (Table 1). The average dry bulk density of the reservoir sediment was 0.67 g cm^{-3}. The cores were divided into 1-cm vertical intervals for analysis. A layer of the original vegetation (the surface vegetation, primarily grass, which existed when the reservoir was constructed) was found at the bottom of each core (Table 1), indicating the bottom of the reservoir in 1977.

All of the samples were air-dried, weighed, and then passed through a 2-mm sieve. Sample ZX2 was chosen to test the ^{137}Cs and ^{210}Pb activities because the sediments at the centre of the reservoir tended to have sustained less hydrodynamic disturbance than the other sediments. We took one sample per 4-cm interval to test for ^{210}Pb at the Laboratory of U-Series Chronology of the Institute of Geology and Geophysics, Chinese Academy of Sciences, using the α-spectroscopy method with 24 hours of counting and a 4% precision. We combined 4 contiguous 1-cm layers as one sample for ^{137}Cs testing at the Environmental Radionuclide Lab of Beijing Normal University using the γ-spectrometry method. The average weight of each ^{137}Cs sample was 7.03 g, and the counting time was more than 16 hours with a precision of 10%.

The grain-size distribution of the ZX2, RK2 and CK2 samples was tested using the pipette–sieve method. We also analysed 15 topsoil samples (0 to 10 cm) collected randomly from the Hebei catchment. All of the samples were tested to determine the fractions falling within the seven size ranges: >0.063 mm, 0.031 to 0.063 mm, 0.016 to 0.031 mm, 0.008 to 0.016 mm, 0.004 to 0.008 mm, 0.002 to 0.004 mm, and <0.002 mm.