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Sediment yield and sources in dam-controlled watersheds on the northern Loess Plateau

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ABSTRACT

An improved understanding of the temporal variations in soil erosion rates and sediment sources is necessary to identify the main areas prone to soil erosion and to effectively implement soil and water conservation measures. In this study, we selected two dam-controlled watersheds (Xiaoshilata and Yangjiagou) on the northern Loess Plateau, China, and determined the temporal variations in the sediment yield. The sedimentation upstream of the dams showed that there were 31 and 9 flood couplets in the Xiaoshilata (1958–1972) and Yangjiagou watersheds (2007–2011), respectively, which have trapped 16.5×10^4 t and 3.38×10^4 t of sediment, respectively. The estimated specific sediment yield was approximately 173.6 t/ha/a and 106.1 t/ha/a in the Xiaoshilata and Yangjiagou watersheds, respectively. A multivariate mixed model was applied to identify the different sediment sources. The results indicated that weathered sandstone contributed approximately 61.52% of the total sediment, and the remaining sediment loss was from bare loess soil (32.54%) and grassland (5.94%) in the Xiaoshilata watershed. In the Yangjiagou watershed, approximately 66.8% of the sediment originated from weathered sandstone, whereas bare loess and grassland accounted for 17.5% and 15.7% of the sediment yield, respectively. Based on these findings, we recommend that comprehensive soil conservation measures are needed to soil erosion control for the permanent steep gullies due to high sediment contribution. The sedimentation behind the check dams provides an indirect method for estimating the sediment yield in ungauged basins.

1. Introduction

Accelerated soil erosion and increased sediment yields lead to loss of surface soil and result in soil quality degradation and agricultural production reduction (Lal, 2003; Fleskens and Stringer, 2014). Severe soil erosion poses a serious threat to land management sustainability and water resource utilization in many areas of the world (Cerdà et al., 2009; Collins et al., 2001; Mukundan et al., 2010). Climate changes and intensive human activities could increase the rates of soil erosion induced by water over the next few decades (Guzman et al., 2013). Thus, obtaining reliable soil erosion rates and sediment sources is important to better understand the processes and the primary controlling factors of water erosion, and to provide a useful reference for scientifically sound land use and conservation measures (Zhao et al., 2016).

The use of traditional techniques such as erosion plots and predictive models to monitor and assess soil loss effectively addresses certain management requirements (Borrelli et al., 2015; Zhao et al., 2015). However, the data obtained have limitations at different temporal and spatial resolution (Fang et al., 2012). For example, extending the finding from plot data to large-scale watersheds is challenging. Furthermore, the measurements are time consuming and expensive. At the catchment scale, hydrological gauge measurements reveal the long-term sediment transport of the entire catchment; however, these observations only represent a fraction of the sediment yield in many river systems due to sediment trapping by dams, reservoirs and other soil and water conservation measures (Valero-Garces et al., 1999; Mekonnen et al., 2015a; Zhao et al., 2015). To avoid these limitations, many studies have focused on the sedimentation behind dams or in ponds as an indirect approach to estimate the real sediment yield (i.e. sediment that has not been trapped by the dams/reservoirs or other soil erosion conservation measures) at regional scales (Bussi et al., 2013; Grauso et al., 2008; Mekonnen et al., 2015b; Romero-Díaz et al., 2007; Verstraeten and Prosser, 2008; Zhang et al., 2006; Zhang et al., 2009). Verstraeten et al. (2007) estimated the sediment yield based on 26 small farm dams in SE Australia, and the data were used for model calibration. Alatorre et al. (2010) assessed the sediment yield and sources based on the depositional record at the Barasona reservoir (NE Spain) and found that the agricultural land and badlands were the dominant contributors to the sediment in the watershed. Zhang et al. (2006) investigated a sediment

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profile in a small dam-controlled catchment of the Yanhe River on the Loess Plateau and estimated an average annual sediment yield of 127 t/ha/a. These studies provide strong support that sedimentation behind dams or in reservoirs provide a valuable tool for estimating sediment yields.

Sediment yields provide quantitative information on the soil loss induced by water or wind, whereas sediment sources indicate where most of the soil erosion occurs in the watershed. Identifying sediment sources is essential to establish a catchment sediment budget, develop models and implement soil conservation strategies (Fang, 2015; Porto et al., 2016; Sougnez et al., 2011). Therefore, in recent decades, studies have focused on identifying sediment sources using fingerprinting methods. An increasing number of investigations focusing on identifying sediment sources have been conducted in many regions throughout the world, such as the UK, the USA, Australia, Brazil, and different parts of China (Collins and Walling, 2002; Guzman et al., 2013; Kim et al., 2013; Lamba et al., 2015; Stevens and Quinton, 2008; Walling, 2005; Walling et al., 2008; Zhang et al., 1989).

Previous studies addressed numerous types of fingerprinting properties, such as soil physical characteristics, stable isotopes, mineral magnetic properties and fallout radionuclides (Chen et al., 2016; Collins and Walling, 2002; Fang, 2015; Guzman et al., 2013; Zhang et al., 2016). Various tracers are used because a single tracer does not fulfill all the requirements to identify the sediment sources (Guzman et al., 2013; Lamba et al., 2015; Stevens and Quinton, 2008). The ideal tracer should have the following characteristics (Zhang et al., 2001): the tracers/fingerprinting properties should strongly bind to soil particles, are easy to quantify and sufficiently sensitive for analysis; the tracers should not be altered during sediment transport, have low plant uptake, be environmentally benign, and available in variants with similar but distinguishable physicochemical properties for multiple tracking.

The Chinese Loess Plateau is the most severe soil erosion region in the world (Hessel, 2006; Zheng, 2006). Since the 1950s, a series of soil and water conservation measures have been implemented on the Loess Plateau, including >90,000 check dams (Wang et al., 2015; Zhao et al., 2014). A large number of studies have reported that gauge-observed sediment loads (which are measured at the hydrological stations in the catchment) have decreased significantly over the past six decades (Mu et al., 2012; Tian et al., 2016; Wang et al., 2015; Xu, 2009; Yue et al., 2014). However, the real sediment yields remain unknown because the gauge-observed data have been greatly altered by dams, terraces, and other conservation measures. Thus, reliable information on sediment yields and sources is needed to provide a useful reference for implementing soil conservation measures and sustainable ecological restoration in the future.

The objectives of this paper are as follows:

1) to quantify the sediment yield in two dam-controlled watersheds on the northern Loess Plateau, where limited previous studies have been conducted;
2) to examine the potential sediment sources using a fingerprinting method in the small watersheds.

2. Study area

The Huangfuchuan catchment (39°10′–40°N and 110°20′–111°15′ E) is located in the middle reaches of the Yellow River basin and covers an area of 3246 km^2. The catchment is within a region where both wind and water are important drivers of erosion on the northern Loess Plateau (Fig. 1a). The main soil types in the catchment include aeolian sandy soil, fine loess soil and weathered sandstone with local name of Pisha sandstone (Zhao et al., 2015), which is a type of loose inter-bedded sandstone, and is easily eroded because of its physical and chemical characteristics. The average annual precipitation (1954–2010) is 380 mm, which is concentrated between June and September in the form of heavy storms, leading to severe soil erosion and high sediment yields during the rainy season.

According to the observed sediment load at the Huangfu gauging station (the controlled area is 3199 km^2), the average annual sediment yield was 125 t/ha/a between 1955 and 2009. Due to severe soil erosion, a series of soil and water conservation measures have been implemented since the 1950s. Particularly, a number of check dams were built to control gully erosion and floods. In total, 507 check dams were built in the Huangfuchuan catchment as of 2010 (Tian et al., 2013).

In this study, we selected two check dam-controlled watersheds to estimate the sediment yields and sources based on the sedimentation behind the dams in the Huangfuchuan catchment. Neither dam has sluicing gates or pumps that are generally used to avoid flood damage risk, allowing all the upstream sediment to be trapped behind the dams. The Yangjiagou and Xiaoshilata watersheds are located in the lower reaches of the Huangfuchuan catchment. The Yangjiagou watershed was approximately 10 km upstream of the town of Huangfu (Fig. 1b), and the Xiaoshilata watershed is located approximately 1 km west of the town of Gucheng. The drainage areas are 0.64 km^2 in the Yangjiagou and 0.68 km^2 in the Xiaoshilata watershed. A dam was built in 1974 and has trapped a large amount of sediment (Fig. 2a and c). A small silt dam was built in 1958 and was damaged by an extreme flood in 1972 (Fig. 1c) in the Xiaoshilata watershed (Fig. 2b and d).

The dominant soil types are fine silt loess and coarse weathered sandstone. The surface of the hilly plateau is covered by fine loess with gentle slopes <15°, and sheet and rill erosion are very common. The steep gullies in the weathered sandstone are widespread (Fig. 2b), and occur where the area has very steep slopes with gradients >25°. The main land cover consists of bare land and sparse grassland (Fig. 2a, b and d), which mostly distributed on the gentle plateau surface covered by loess soil. The weathered sandstone (without vegetation cover, Fig. 2c) is distributed on the steep slopes of the gullies, and the sediment deposits upstream of the dam that fill the river channel (Fig. 3). The relative flat river sediment was partly covered by grass or used for arable land near the dam (Fig. 2a and d), and characterized of sandy sediment in the upstream branches (Fig. 2c).

3. Field sampling and measurement

3.1. Field sampling

Field sampling in the Yangjiagou watershed was undertaken in April 2012, and May 2013 in the Xiaoshilata watershed. In each watershed, we selected three sites to obtain the sediment samples (Fig. 1c and d). Points A and D were considered as the main profiles of the watersheds, and the other two sites were used to check the flood couplets layers and estimate the volume of sediment. As shown in Fig. 1c, a sediment profile with a vertical length of 9.90 m was obtained at point A from the base of the deposit to the surface. In the Yangjiagou watershed, the sedimentation behind the dam was estimated to be approximately 11 m deep from the base to the present-day surface, according to the history and height of the dam. However, the sediment profile was only 1.98 m because the water stored in the sediment leaked out from the bottom and sidewall of the profile. All the profiles were carefully sectioned to reflect the cyclic flood couplets/units (Fig. 2e and f).

We obtained 31 couplets in the Xiaoshilata watershed and 9 couplets in the Yangjiagou watershed. The couplets were characterized by fine soil at the top and coarse sand at the base (Fig. 2e); thus, the boundaries of the couplets were clearly identified. A total of 65 and 21 sediment samples were collected from the profile in the Xiaoshilata and Yangjiagou watersheds, respectively (Table 1).

The sediment samples were collected using a cylindrical core to obtain the soil bulk density, and additional sediment was sampled to measure the physical and chemical properties. The sediment source samples were collected 2 cm from the topsoil. At each sampling point, at least four samples were taken and combined in the field to form a