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Sediment yield estimation in a small watershed on the northern Loess Plateau, China

Guangju Zhao [a,b,c], Andreas Klik [c], Xingmin Mu [a,b,*], Fei Wang [a,b], Peng Gao [a,b], Wenyi Sun [a,b]

[a] Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China
[b] Institute of Soil and Water Conservation, Chinese Academy of Sciences & Ministry of Water Resources, 26 Xinong Road, Yangling 712100, Shaanxi Province, China
[c] Institute of Hydraulics and Rural Water Management, Department of Water Atmosphere & Environment, University of Natural Resources & Life Sciences, Vienna, Muthgasse 18, A-1190 Vienna, Austria

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ABSTRACT

Soil erosion is a major form of land degradation throughout the world and the key environmental problem that threatens the ecosystem of the Chinese Loess Plateau. In this study, we determined the sediment yield from a small dam-controlled watershed in the Huangfuchuan watershed, northern Loess Plateau, with a drainage area of 0.64 km^2. The dam infill sediment provided evidence of at least 31 flood couplets, which corresponded to rain storms during 1958–1972. In total, 1.65×10^5 t sediment was accumulated within the whole check dams in this period. The annual sediment yield ranged from null in 1965 to 59,990 t in 1959. We used the modified WATEM/SEDEM model to simulate soil erosion and the sediment yield in the watershed and the sedimentation records were used for model verification. The model produced satisfactory results; the total soil erosion and sediment delivery ratio were estimated to be 1.97×10^5 t and 83.6%, respectively. Bare weathered stone in the steep gullies contributed >90% of the sediment yield, while the remainder was derived mainly from bare loess slopes and the alluvial plain. This study suggests that analyzing sedimentation behind check dams and applying the WATEM/SEDEM model are useful for the quantitative analysis of sediment dynamics in ungauged basins on the Loess Plateau.

1. Introduction

Soil erosion is one of the most significant forms of land degradation throughout the world and it is influenced greatly by land use/cover, soil types, climate, and lithology. Severe soil erosion leads to the loss of surface soil, thereby resulting in soil quality degradation and reduced agricultural production, which threatens food and environmental security throughout the world (Lal, 2003). Sediment transport in rivers and lakes delivers large amounts of nutrients from the land surface to the sea, which threatens aquatic ecosystems, as well as yielding infertile farmland and the eutrophication of freshwater (Zhao et al., 2013a). Each year, soil erosion leads to the loss of about ten million hectares of cropland, which reduces the limited amount of arable land available for food production, thereby contributing to malnourishment in millions of people (Pimentel, 2006). In addition, the accumulation of large volumes of sediment can cause severe sedimentation in reservoirs and channel beds, resulting in the loss of various functions in these hydraulic projects. Thus, it is very important to determine the sediment yield rates and sediment sources in watersheds, which can provide a good basis to facilitate soil erosion control and river basin management.

Numerous studies have indicated that the sediment load in many large rivers is reduced significantly by land use changes as well as the construction of reservoirs, farm dams, flood-control ponds, water diversions, and other water stores (Syvitski et al., 2005; Kondolf et al., 2014; Yue et al., 2014; Zhao et al., 2014). These results suggest that landscape features have direct and major impacts on the sediment dynamics by storing sediment, but the sediment load observed at gauging stations is only a fraction of the sediment yield in many river systems that are highly affected by reservoirs and dams. Thus, estimating the actual sediment yield rates at a regional scale would be helpful for identifying the causes of sediment load reduction in dam-controlled areas. Traditional soil erosion plot measurement can provide valuable results, but it is expensive and time consuming. In addition, extrapolating these results to watershed scale is highly problematic. Thus, the majority of studies have used the sediment volume accumulated in lakes and reservoirs as an indirect approach to sediment yield estimation (Zhang et al., 2006, 2009; Grauso et al., 2008; Bussi et al., 2013). For example, Zhang et al. (2006) investigated the sediment profile in a small dam-controlled watershed of the Yanhe River on the Loess Plateau and estimated an average annual sediment yield of 12,700 t km^{-2} yr^{-1}. Romero-Díaz et al. (2007) compared several methods for obtaining sediment yield rates, and showed that the bathymetric survey method (mapping the basin of the reservoirs and

* Corresponding author at: Institute of Soil and Water Conservation, Northwest A&F University, 26 Xinong Road, Yangling 712100, Shaanxi Province, China. Tel: +86 2987082210.
E-mail address: xmmiswc@gmail.com (X. Mu).

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determining the bulk density of the sediment) provided satisfactory accuracy for sediment yield rate estimation. These previous studies suggested that analyzing the sedimentation in dams or reservoirs can provide valuable information that facilitates estimation of the overall sediment yields.

Recently, many studies have attempted to use the sedimentation rates in reservoirs to validate sediment yield modeling methods (Romero-Díaz et al., 2007; Verstraeten and Prosser, 2008). In particular, Verstraeten et al. (2007) used 26 small farm dams in SE Australia to calibrate a spatially distributed soil erosion and sediment delivery model (WATEM/SEDEM). The model performed satisfactorily with high model efficiencies, and the sediment transport capacity for cropland was two times higher than that for degraded pasture. De Vente et al. (2008) compared the sedimentation rates obtained with three different models: WATEM/SEDEM (Van Rompaey et al., 2001), PESERA (Kirkby et al., 2008) and SPADS (De Vente et al., 2008), and showed that the SPADS and WATEM/SEDEM models provided the best results after being calibrated separately, whereas the PESERA model represented a promising alternative to the use of empirical models that can be applied to highly diverse environments with little calibration. Bussi et al. (2013) coupled a distributed conceptual hydrological and sediment model (TETIS model) with the Sediment Trap Efficiency for Small Ponds (STEP) model and applied it to a small Spanish watershed with a drainage area of 12.9 km^2. The results demonstrated satisfactory agreement between the measured and simulated data, although the estimated sediment yield was relatively lower than that of other Mediterranean watersheds. Alatorre et al. (2010) used the deposition record of the Barasona reservoir (NE Spain) to calibrate the WATEM/SEDEM model and found that the sediments were derived mainly from the lower reaches of agricultural land and the badlands in the middle part of the watershed. These studies suggest that sediment yield estimation based on dam's deposition is a very useful tool, although Bussi et al. (2013) showed that this method has limitations in relation to the storage capacity estimates of reservoirs and the historical dynamics of sediment yield assessments. Thus, sediment coring and paleolimnological techniques are needed to provide accurate information to facilitate sediment rate estimation (Zhang et al., 2009; Alatorre et al., 2012).

On the Chinese Loess Plateau, more than 50,000 check dams have been built during the past six decades. Observations suggested that there has been a significant decline in the sediment load due to soil and water conservation measures (Mu et al., 2012; Zhao et al., 2013b). Although the sediment yields are often unknown, sedimentation in the check dams may provide a great opportunity for sediment yield estimation. Thus, the objectives of the present study are: (1) to quantify the sediment yield in a dam-controlled watershed on the northern Loess Plateau; and (2) to test the possibility of model calibration and/or validation based on check dam sedimentation rates.

2. Study area

The Huangfuchuan watershed (39°10′–40°N and 110°20′–111°15′E) is located in the middle reaches of the Yellow River basin, where it belongs to the "coarse sandy hilly area" on the Loess Plateau, China (Fig. 1a) (Zhao et al., 2013a). The watershed is characterized by a semiarid continental climate with average annual rainfall of 380 mm and a mean annual temperature of 7.5 °C. The annual rainfall exhibits high intensity, where ca. 80% occurs between June and September, mainly in the form of storms. The frequent occurrence of storms has led to severe soil erosion and an extraordinarily high sediment yield in the summer (Tian et al., 2013). The average annual sediment load at the Huangfu station was 4.0×10^7 t (125 t ha^{-1} yr^{-1}) between 1955 and 2009 (Fig. 1b, the upstream area is 3199 km^2) (YRCC, 2011).

The Xiaoshilata watershed is located within the lower reaches of the Huangfuchuan watershed, at nearly 1 km apart away from Gucheng Town (the triangle point in Fig. 1b). The Xiaoshilata watershed has a drainage area of 0.64 km^2, with the highest altitude of 1110 m and the lowest altitude of 962 m. In the 1950s and 1960s, small check dams were built mostly by farmers for flood control on the Loess Plateau. According to local farmers, a small silt dam was built in the watershed in 1958 (Fig. 1c), which was damaged by an extreme flood in 1972.

The land surface is characterized by dense gullies with poor vegetation cover. The dominant soil types are very fine silt loess and coarse weathered bedrock (locally called *pisha* stone). The watershed can be subdivided into two geomorphological units: hilly plateau surfaces and deeply dissected gullies. The rolling plateau areas of the hilly plateau surfaces (inter-gully area) are relatively gentle with gradients <15° and sheet and rill erosion processes are widespread on the gentle slopes. The gully area comprises steep gully slopes with gradients >25°, except for flatter gully bottoms. The rolling plateau surface is mostly covered by loess, and the steep gullies are underlain by heavily weathered stone (*pisha*), where gully erosion is very active.

3. Field sampling and measurement

Sediment samples were collected for ^{137}Cs analysis in May, 2013. We selected a sediment depositional profile (point A in Fig. 1c) with a height of 9.90 m from the bottom of the deposition layer. The other two sites (points B and C in Fig. 1c) were used to check the flood couplet layers and to estimate the sedimentation volume. The sampling site (point A) was located 30 m upstream of the failed dam (Fig. 1c). The upper part of the profile, with a thickness of 7 m, was exposed because the dam was destroyed by the flood in 1972 (local investigation). Thus, this part of the sediment could be sampled directly. The remaining 2.90 m was accessed by digging. The profile was sectioned carefully to reflect the cyclic flood couplets (Fig. 2). In total, 31 couplets corresponded to individual flood events. The boundaries of the couplets could be identified clearly because the top part of the sediment was fine and the bottom layer of a couplet was coarse (Fig. 2). The thickness of a couplet varied from a few centimeters to hundreds of centimeters. In total, 65 sediment samples were collected from the profile. According to the depth of the couplet, we divided each into three samples, although a few couplets were divided into two or four samples. For each sediment layer, a soil cylinder with a volume of 100 cm^3 was used for sampling to calculate the soil bulk density.

The width, length, and thickness of the sediment behind the check dam were measured in situ, and three sampling points (Fig. 1) were selected to determine the variation in the sediment thickness along the valley. A topography map (1:10,000) obtained from the Shaanxi Geodata Center was used to produce a digital elevation model (DEM). We estimated the total volume of the sediment using the "3D Analyst Tool" of ArcGIS 10.1 (http://www.esri.com). All of the sediment samples were air-dried, disaggregated and passed through a 2-mm sieve, before analyzing their ^{137}Cs activity levels by gamma spectrometry using a hyperpure coaxial germanium detector collected to a multi-channel digital analyzer system (ORTEC). All of the sample weights exceeded 400 g and ^{137}Cs was measured at 661.6 keV with a counting time of about 288,000 s, thereby providing a measurement precision of ca $\pm$ 6% at the 95% confidence level.

4. Soil erosion model

4.1. Model concept

In order to estimate the watershed sediment yield, we employed a spatially distributed soil erosion and sediment delivery model, WATEM/SEDEM, with a modified slope factor due to steep slopes of the well-developed gullies in our study area (Van Rompaey et al., 2001, 2005; Verstraeten and Prosser, 2008). The model comprises three main components: soil loss assessment, sediment transport capacity calculation and sediment routing. The mean annual soil loss was estimated using the Revised Universal Soil Loss Equation (RUSLE; Renard et al., 1997):

$$E = R \cdot K \cdot L \cdot S \cdot C \cdot P \quad (1)$$