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Fractal features of soil particle size distribution in layered sediments behind two check dams: Implications for the Loess Plateau, China

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ABSTRACT

The layered sediment deposited behind a check dam can provide useful information about soil erosion processes in the dam-controlled area. This study aims to evaluate the possible fractal nature of layered sediments behind check dams, assessing whether fractal dimension can serve as a feasible index for evaluating the impact of land use types on the area controlled by the check dam. Fractal dimension measurement was employed to analyze the features of soil particle size distribution (PSD) for different layered sediments of the Shipanmao and Zhangshan check dams in the Dalihe River Basin of the Loess Plateau, China. Results show that the predominant soil particle sizes of the sediment layers behind the Shipanmao and Zhangshan dams are silt–clay (<0.05 mm) and fine sand (0.25–0.05 mm). The overall gradients of the trends for silt–clay and fine sand are 0.0622 (slight increase) and -0.0618 (slight decrease), respectively, for Shipanmao, and -0.8415 (decrease) and 0.8448 (increase), respectively, for Zhangshan. There are considerable differences in the PSDs among different layers, especially in the coarse and fine sand fractions. The coefficient of variation (*CV*) for the coarse sand fraction is highest, followed by the fine sand and the silt–clay size fractions. Larger soil particle sizes coincide with larger *CV* values. The fractal dimension (D_m) of the PSD ranges from 2.111 to 2.219, and 2.144 to 2.447 for Shipanmao and Zhangshan, respectively. The D_m values tend to increase and decrease for the layered sediments from top to bottom with some turning points. The turning points of D_m are related to the trends of the soil PSDs in the adjacent sediment layers. Although D_m has significant positive and negative correlations with the silt–clay and the fine sand size fractions, respectively, no correlation with the coarse sand fraction was observed. Soil PSD is a more dominant factor affecting D_m than the time lag between soil erosion and sediment deposition. Overall, D_m decreased for Shipanmao during the deposition period (1972–1979). The total increment of the *C* factor in the universal soil loss equation and the soil erosion amount per rainfall erosivity were applied to analyze land use changes between 1972 and 1979 for the dam-controlled area of the Shipanmao dam. The total increment of *C* during 1972–1979 was 0.021 and the soil erosion amount per rainfall erosivity was smaller in 1972 than in 1979, indicating desertification in the dam-controlled area. In addition, the land use types prevalent in 1979 were more prone to soil loss than those in 1972. D_m is a useful parameter to assess land use types and soil degradation processes in dam-controlled areas of the Loess Plateau.

1. Introduction

Soil erosion is one of the most serious environmental issues in China (Shi and Shao, 2000; Zheng, 2006; Li et al., 2011; Li and Wei, 2014). It affects an area of 3.6 million km^2, equal to about 37% of the country's total land area (MWR, 2002). Water, wind, and freeze-thaw erosion of soils are widely distributed in China, causing soil deterioration (Marques et al., 2008; Fu et al., 2011; Jebari et al., 2012), decline in land productivity (Pimentel and Kounang, 1998; Lantican et al., 2003; Fu et al., 2011), and degradation of streams, lakes, and estuaries through transportation and settling of sediments and pollutants (Li and Wei, 2014). The Chinese Loess Plateau in particular has suffered from serious soil erosion in recent decades (Zhang et al., 1998; Shi and Shao, 2000; Li and Wei, 2014) due to intensive human disturbance and the presence of thick erodible soil (Shi and Shao, 2000; He et al., 2004). Erosion from the Loess Plateau, which is the main source area of sediment discharging into the Yellow River (Ren and Shi, 1986; Shi and Shao, 2000; Xu, 2003), contributes about 30% of the total soil loss in China (MWR, 2002). Soil loss is also a major environmental problem threatening the sustainable development of the Loess Plateau (Ni et al., 2008; Feng et al., 2010; Liu et al., 2012).

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To mitigate the severe soil erosion in this region, a number of soil and water conservation measures have been adopted such as revegetation, tillage management, enclosures, terracing, and check dams (Creamer et al., 1997; Valentin et al., 2005; Lu et al., 2012). Among these measures, check dams, manmade structures built across a channel to reduce stream speed and trap sediment (Hudson, 1981; Creamer et al., 1997; Chanson, 2004; Zeng et al., 2009), are often the most efficient engineering approaches toward sediment retention (Creamer et al., 1997; Xu and Sun, 2004; Ran et al., 2008; Li and Wei, 2011; Lu et al., 2012; du Plessis et al., 2015; Sylvain et al., 2015). They are popular on the Chinese Loess Plateau and have a long history of construction and use (Fang et al., 1998; Hu et al., 2002; Jiao et al., 2003; Li, 2003; Zeng et al., 2009). The speed and magnitude of check dam development on the Loess Plateau has been accelerated in the last 50 years with the support of the Chinese government (Li and Wei, 2011; du Plessis et al., 2015), leading to a reduction in sediment yield, soil and water conservation (Foncin, 1996; MartiFabregas, 1996; Magiera, 1997; Jiao et al., 2001, 2003; Ran et al., 2004; Xu and Sun, 2006), and increased stability of dam systems (Coppens and Kato, 1997).

Sediments behind a dam are soils eroded in the dam-controlled area, including top and deeper soils depending on land use types such as sloping farmland and abandoned grazing land subject to rainfall and runoff. On the Loess Plateau, the area of sediment deposition behind a check dam (hereafter referred to as dam land, following the terminology of local farmers) is often formed by several rainfall events causing erosion in the dam-controlled area. The area of sediment deposition in a dam land is often flat and more fertile compared with the sloping land. Local farmers prefer to plant corps there and obtain 8- to 10-times more yield than on the sloping land (Fang, 1996; Xu et al., 2006).

The peak of sediment deposition and the flood peak tend to be synchronized in this region at the watershed scale (Chen et al., 1988; UMYRBYRCC, 2000; Tang, 2004; Wei et al., 2006b; Li and Wei, 2014), with larger floods producing more sediment, although a time lag between eroded soil sources and final sediment destination may exist, triggered by rainstorms with high intensity and short duration (Shi et al., 2012). Overall, however, sediment deposition behind the check dam reflects erosion in the upstream area (Zhang et al., 2007; Zhao et al., 2010a, 2010b; Romero-Diaz et al., 2012; Hsieh et al., 2013). The problem of water and soil loss in the upstream area of a check dam, resulting from human influences such as land use, can be analyzed quantitatively using system theory (Li and Wei, 2011). However, there are few studies on the evaluation of land use types in areas controlled by check dams on the Loess Plateau.

Soil particle size distribution (PSD) is commonly used in the estimation of various related soil properties and for soil classification (Hillel, 1980). The PSD is one of the most important physical soil attributes (Prosperini and Perugini, 2008) due to its strong influence on movement and retention of water, solutes, heat, and air (Su et al., 2004). During soil erosion, a decrease in water-holding capacity, loss of soil nutrients, and depletion of soil structure are accompanied by selective removal of the fine particle size fractions (Lobe et al., 2001; Zalibekov, 2002; Su and Zhao, 2003; Su et al., 2004; Xu et al., 2013) by rainfall and runoff (Wang et al., 2008; Xu et al., 2013). Thus, identifying changes in PSD may provide useful insight into soil degradation caused by land use (Wang et al., 2008; Liu et al., 2009). Fractal theory has been applied to various geological phenomena that display large, scale-invariant, and self-similar characteristics since the 1980s (Mandelbrot, 1982; Katz and Thompson, 1985; Turcotte, 1986; Su et al., 2004; Wang et al., 2008; Liu et al., 2009; Xu et al., 2013). In addition, the possibility of characterizing PSD using fractal theory has been explored by several researchers (Tyler and Wheatcraft, 1992; Su et al., 2004; Xu et al., 2013; Yu et al., 2015). Fractal dimension becomes a useful measurement to quantitatively describe soil structure, soil erodibility, water permeability, and related soil properties (Perfect and Kay, 1995; Perfect, 1997; Su et al., 2004; Xia et al., 2015; Yu et al., 2015). Soil science has successfully utilized fractal methods to shed new light on soil degradation/desertification and complex dynamics of soil forming processes by studying PSD (Pachepsky et al., 1995; Su et al., 2004; Prosperini and Perugini, 2007; Xu et al., 2013). Fractal information may reveal sediment deposition processes and facilitate the choice of soil and water conservation measures and land use types in dam-controlled areas of the Loess Plateau (Wang et al., 2008; Liu et al., 2009). However, so far, there are only few reports on the application of fractal theory to analyze soil PSD of layered sediments in the dam land behind check dams and to determine the effects of human activities on soil erosion from the dam-controlled area. In fact, whether the PSD of layered sediment in dam lands has fractal characteristics is still unknown.

This study aims to evaluate the fractal nature of layered sediments in the dam lands of the Shipanmao and Zhangshan check dams, located in the Xiaohegou and Hongheze watersheds of China's Loess Plateau. Fractal dimension (D_m) was measured and the relationship between PSD of layered sediment and D_m was evaluated to assess the desertification trend of the dam-controlled area. Then the applicability of D_m to analyze the impact of land use types in the dam-controlled area was evaluated.

2. Materials and methods

2.1. Study area

The Xiaohegou and Hongheze watersheds are located at N37°36′17″ to N37°43′34″ and E109°47′42″ to E109°56′10″, and N36°42′23″ to N36°45′20″ and E108°53′30″ to E109°02′00″, respectively (Fig. 1). They are situated along tributaries of the Dalihe River, whose water flows into the Yellow River. The Xiaohegou and Hongheze watersheds cover an area of 63.5 and 76.2 km^2 with average gradients of 1.42% and 3.60%, respectively (SWCB, 2003; Li et al., 2007). The topography of both watersheds is characterized by low mountains and hills. The elevation ranges from 921 m above sea level (a.s.l.) in the southwest to 1249 m a.s.l. in the northeast for the Xiaohegou watershed and from 1233 m a.s.l. in the southeast to 1606 m a.s.l. in the northwest for the Hongheze watershed. They are characterized by an arid to semiarid monsoon climate. According to the nearest Caoping hydrological station, the average annual temperature and precipitation are 9.79 °C and 421 mm, respectively (Fig. 2), with 69.8% of rainfall occurring between June and September. Typical loess soils are commonly found, and the annual average erosion modulus and sediment discharge from the watershed are 15,000 t km^{-2} yr^{-1} and 922,500 t, respectively, for the Xiaohegou watershed (SWCB, 2003), and 13,500 t km^{-2} yr^{-1} and 739,000 t, respectively, for the Hongheze watershed (Wei et al., 2006a). The two watersheds are located in sub-region I of soil erosion regions of the Loess Plateau as defined by Meng (1996), corresponding to the area of severest soil erosion.

2.2. Soil sampling

The Shipanmao and Zhangshan check dams were built in 1972 and 1974, and damaged by rainstorms in 1979 and 1989, respectively. The sampling locations were positioned in the dam land about 5 m upstream from the two dams. Soil sampling sites were dug with a shovel. The total thicknesses of the deposited sediments are 6.28 m for the Shipanmao check dam covering the period of 1972–1979 and 7.89 m for the Zhangshan check dam for 1974–1989. The number and thickness of sediment layers formed by rainstorms and floods are mainly influenced by storm intensity, rainfall amount, basin topography, land cover, soil texture, and degree of land use. A layer from a single rainstorm and flood can be identified based on the layer structure of the sediment (Fig. 3). We divided the 6.28-m thick soil profile from the Shipanmao dam land into 21 layers and the 7.89-m thick soil profile from the Zhangshan dam land into 17 layers. We only linked the sediment layers from Shipanmao to rainstorm events recorded during 1972–1979 at Caoping station (Table 1). For the Zhangshan dam, we did not link the sediment layers to the rainstorm events because