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Assessing sedimentological connectivity using WATEM/SEDEM model in a hilly and gully watershed of the Loess Plateau, China

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ABSTRACT

Sedimentological connectivity is an important issue in soil erosion and sediment transport. Landscape patterns, in combination with the rainfall regime, are known to shape such sedimentological connectivity. The quantification of sedimentological connectivity provides a link between sediment delivery and landscape pattern. There are two categories of connectivity: structural connectivity, which describes the physical coupling of landscape units, and functional connectivity, which delineates the linkage among landscape elements maintained by material transport. To quantify sedimentological connectivity, both the physical coupling of, and material transfer between, the various landscape components need to be assessed. This study quantifies the sedimentological connectivity of a headwater catchment in the Loess Plateau of China using the soil erosion and sediment delivery model (WATEM/SEDEM). Based on the model, two indicators of connectivity were developed: the area of sedimentologically effective catchment area (SEA) that contributes sediment to the sinks, and the minimum sediment output of locations on the flow path that link sources and sinks. This approach effectively represents the annual status of catchment-scale sedimentological connectivity and, furthermore, the simple structure and readily available input data make it highly practicable. However, for larger river systems in which sediment transport between sources and sinks occur over longer time scales and larger spatial scales, we suggest different techniques for quantifying the sediment flux and parameters delineating the physical coupling of landscape units.

1. Introduction

In hydrologically controlled systems, sediment transport is heavily influenced by landscape patterns, such as the spatial arrangement of sediment sources, delivery pathways, and sediment sinks. Sedimentological connectivity is an effective concept to study the interrelationships between sediment transport and these factors in such a system (Brierley et al., 2006; Fryirs et al., 2007a,b; Borselli et al., 2008; Chiverrell et al., 2009).

Sedimentological connectivity refers to sediment transport from source to a sink via sediment detachment and sediment transport (Bracken and Croke, 2007; Bracken et al., 2013, 2015), and is controlled by how the sediment moves between all geomorphic zones in a landscape (Bracken et al., 2015). Sedimentological connectivity can be quantified by describing physical adjacency of landscape units (structural connectivity) or sediment transport across landscapes (functional connectivity) (Lexartza-Artza and Wainwright, 2009; Wainwright et al., 2011). While structural connectivity delineates the contiguity or physical linkage of landscape elements (With et al., 1997; Tischendorf and Fahrig, 2000), functional connectivity is indicative of the sediment flow between landscape compartments. Therefore, the physical contact status and sediment transfer among landscape compartments are some of the criteria used to categorize sedimentological connectivity (Jain and Tandon, 2010) and are the basis for measuring connectivity (Borselli et al., 2008; Heckman and Schwanghart, 2013).

Spatial arrangement of check dams, ponds and vegetation barriers effectively shapes sedimentological connectivity within a catchment, and between the catchment and the river trunks. For this reason, measuring sedimentological connectivity is used to assess the effect of landscape patterns on sediment transport. The two main approaches for quantifying connectivity include models and connectivity indices (Bracken et al., 2013). Connectivity indices are simple and easy-to-use for quantifying sedimentological

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connectivity (Imeson and Prinsen, 2004; Fryirs et al., 2007b; Borselli et al., 2008; Mayor et al., 2008). For example, the effective catchment area (EA), as defined by Fryirs et al. (2007b), is an explicit indicator of catchment connectivity. It quantifies the proportion of a catchment that potentially contributes sediment to the sinks (i.e. the river network). The identification of EA incorporates the distribution of natural or anthropogenic landscape barrier components that impede sediment movement both to and within river channels.

Based on landscape information such as land use and topographic characteristics, Borselli et al. (2008) developed the distributed index of sedimentological connectivity (*IC*) to quantify the probability of sedimentological linkages between sources and sinks. *IC* combines the probability of sediment input from upslope areas and the probability of sediment export to downward sinks. Field validation has shown that *IC* results in a realistic spatial arrangement of sedimentological connectivity, and agrees well with field observations of sediment transfer (Borselli et al., 2008; Cavalli et al., 2013). Graph theory is also effective in assessing sedimentological connectivity and Heckman and Schwanghart (2013) explored the network structure of sediment pathways and the upslope (contributing area) and downslope (source to sink) functional connectivity. Although these quantifications of sedimentological connectivity were found to be independent of the volume of sediment flux, they represent sediment delivery risks or probability.

Physical coupling and the amount of sediment transfer between sources and sinks are the two key aspects of sedimentological connectivity (Jain and Tandon, 2010). However, the connectivity indices are mostly not involved in sediment flux quantification, and may therefore omit some meaningful information, such as the dynamic response of a system (Wainwright et al., 2011). For instance, the effective catchment area identified by Fryirs et al. (2007b) may not actually contribute runoff, and therefore sediment, to the outlet (Ambroise, 2004). Ideally, both the degree of physical coupling and the intensity of sediment transfer between a source and a sink need to be combined when measuring sedimentological connectivity. A simple and robust approach that incorporates sediment flux may provide a more realistic result. With distributed soil erosion models, such as the WATEM/SEDEM model (Van Rompaey et al., 2001), the sediment balance of each location and the sediment routing over a catchment can be quantitatively modeled. Thus, the spatially distributed models are powerful tools for the quantification of sedimentological connectivity (Jordan et al., 2005; Lesschen et al., 2009; Medeiros et al., 2010). In this approach, physical adjacency and sediment flow are combined, and structural simplicity and sediment routing capacity makes the WaTEM/SEDEM well-suited to sedimentological connectivity assessment.

In this study, we aim to develop a simple, practicable and model-based approach to measure sedimentological connectivity on an annual average basis. According to the principles of Bracken et al. (2015), the catchment of interest (Nianzhuang of the Loess Plateau, China) is hydrologically controlled. Using WATEM/SEDEM (Van Rompaey et al., 2001; Verstraeten et al., 2002) as a foundation, two indicators are developed. These are the area of sedimentologically effective catchment area (SEA) and the minimum sediment output of sites on the flow path between source and sink (switch value, *SW*). Additionally, the sedimentological connectivity between hillslopes and sinks (including river channels, dam farmland and reservoirs) in a catchment in the Yellow River basin are assessed.

2. Environmental setting

The Nianzhuang catchment is located in the northern part of the Loess Plateau of China (36°37′–36°45′ N, 109°26′–109°37′ E, Fig. 1). The catchment typically comprises hills and gullies with intense anthropogenic disturbance that has modified both the vegetation cover and the local landforms significantly (Fu et al., 2011; Xin et al., 2008). This catchment is a headwater of the Yellow River and has a short stream connecting it to the Yan River, a first-order tributary of the Yellow River, that covers an area of 54.2 km^2. This catchment has a mean annual precipitation of 527 mm and has elevation ranges from 926 to 1278 m above mean sea level. The catchment is covered with soils of thick calcareous Cambisols (chalk loess) that evolved from loess parent material. These soils are uniformly textured, weakly structured and highly erodible by water (Li et al., 2003). Well-formed gullies occur widely in Nianzhuang catchment, with a gully density of 2.74 km km^{-2}.

In the incised valleys, check dams have been constructed to trap sediment for farming (dam farmland) or store water (reservoirs) for irrigation and fisheries (Figs. 1 and 2). More than 180 check dams have been built (Li and Bai, 2003). Cropland with a slope gradient >25° has been abandoned for revegetation. The dominant planted forest species is *Robinia pseudoacacia* and, elsewise, a few patches of *Populus tremula* and *Salix alba* appear in the valleys. Most shrub species are native, such as *Spiraea pubescens Turcz*, *Rosa xanthina Lindl* and *Syringa oblata Lindl*, and cover the northward slopes that receive relatively low solar radiation and have relatively high soil water content. Bare soil is mainly found in areas with slope gradients >25°. The residential and otherwise developed areas have expanded in the valleys, especially near the catchment outlet.

Dam building and revegetation have been the main soil-loss controls in the Nianzhuang catchment. Before the 1980s, dam construction in the valleys was the primary countermeasure to reduce soil-loss (Fig. 3) and, consequently, physical coupling between hill slopes and reservoirs and dam farmland became dominant mode of landscape connectivity. Since then, revegetation has dramatically reduced sediment export from hillslopes (Liu et al., 2012). Investigation of sediment deposition in the reservoirs revealed that the soil erosion rate from 1950 to 1960 rose to 401.02 t ha^{-1} yr^{-1} on average, and then decreased to 90.50 t ha^{-1} yr^{-1} from 1980 to 1990 (Li and Bai, 2003).

The average soil erosion rate in rural residential areas within this catchment was 22.23 t ha^{-1} yr^{-1} in 2005, but was nearly double at 41.43 t ha^{-1} yr^{-1} at the catchment-scale (Yue and Dong, 2010). The field experiment of Liu et al. (2012) on a well-vegetated hill slope inclined at 22° in the Nianzhuang catchment showed that the average sediment loss was <16 t ha^{-1} during the rainy season of 2008–2009. However, the current soil erosion rate still exceeds the regional tolerance rate of approximately 10 t ha^{-1} yr^{-1} (Ministry of Water Resources of PR China, 2008).

3. Methods

3.1. Model and model calibration

In this study, the WATEM/SEDEM model is applied to model the sediment budget and consists of three components: (1) estimation of annual gross soil erosion; (2) calculation of annual transport capacity (*TC*); and (3) determination of sediment routing to sinks (rivers, dam farmland, reservoirs). The annual gross soil erosion (*E*) was estimated using the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) as follows:

$$E = R \times K \times LS \times C \times P \quad (1)$$

where *E* is the annual gross soil loss (kg m^{-2} yr^{-1}), *R* is the rainfall erosivity factor (MJ mm m^{-2} h^{-1} yr^{-1}), *K* is the soil erodibility factor (kg h MJ^{-1} mm^{-1}), *L* is the slope length factor (dimensionless), *S* is the topographic slope factor (dimensionless), *C* is the crop and management factor (dimensionless), and *P* is the factor of erosion