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Research papers

Using the comprehensive governance degree to calibrate a piecewise sediment delivery ratio algorithm for dynamic sediment predictions: A case study in an ecological restoration watershed of northwest China

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ABSTRACT

The sediment delivery ratio (SDR) is a bond of slope erosion and channel sediment transport but exhibits poor dynamic applicability, which makes it difficult to accurately identify the spatio-temporal evolutions of sediment yield in an ecological restoration watershed with different governance degrees. i) An innovative piecewise SDR algorithm considering the multi-stage effects of the comprehensive governance degree from 1991 to 2013 was embedded in a dynamic sediment yield model to solve the complex dynamic applicability problem of the SDR in sediment yield predictions. ii) The main advantages of the improved SDR algorithm over the existing models are small data requirements, dynamic mechanism, wide application range, reduced complexity, ease of use and better accuracy. iii) The erosion intensities of sloping farmland and orchards in the Yangou River watershed were both intensive at the early stage of governance in 1997. The trends in erosion and sediment yield were closely related to the watershed management measures. The soil erosion modulus in this watershed decreased from 5657 t/km^2 in 1997 to 906.2 t/km^2 in 2012, a total decrease rate of 84%. The sediment yield modulus decreased from 4500 t/km^2 in 1997 to 51.9 t/km^2 in 2012, a total reduction rate of 98.8%. iv) The annual dynamics of the SDR values were not completely affected by the random fluctuations in rainfall erosivity but showed an obvious decreasing trend from 0.932 in 1992 to 0.057 in 2012 due to the soil conservation measures. The annual average SDR in 1991–2013 was approximately 0.38, indicating that the average sediment yield after ecological restoration was significantly less than the average soil erosion in the Yangou River watershed. The results of this study may provide a better understanding of dynamic SDR studies and reveal the profound insights needed to guide watershed soil conservation planning.

1. Introduction

Quantifying the sediment transport flux remains a severe challenge in landscape evolution studies (Xie and Li, 2012; Tsai et al., 2012). The sediment delivery ratio (SDR), a ratio of the sediment yield from a region to the gross erosion of that same region, is a bond of slope erosion and channel sediment transport and plays a key role in various projects involving the sediment yield prediction and soil conservation planning (Wu et al., 2012a, 2016a). Generally, the development of the SDR algorithm was mainly based on the definition and main influencing factors of the SDR (Gao et al., 2007). Previous studies have shown that the SDR algorithm can be summarized as three categories: i) a single-factor SDR algorithm considering the basin area; ii) a two-factor SDR algorithm, primarily considering the rainfall and runoff depth, followed by gully density; iii) a multi-factor SDR algorithm, primarily including rainfall, gully density, runoff depth, channel slope and basin area (Xie and Li, 2012; Tao and Chen, 2015; Wu et al., 2018a).

Although most of the existing SDR algorithms are legitimate and applicable for the individual research object in specific regions (Wu et al., 2018a), they were only statistically empirical equations, it is

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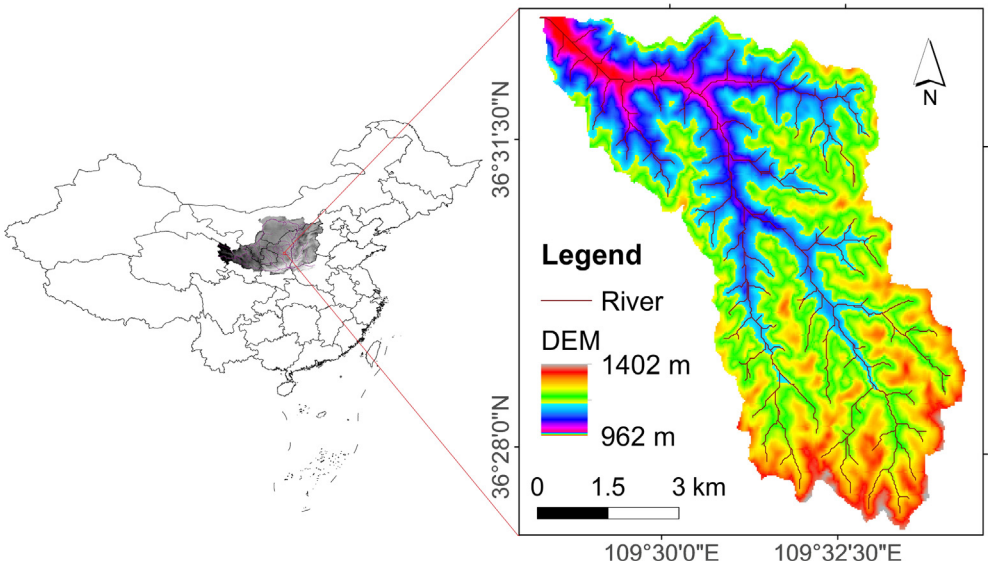

Fig. 1. Study region: the relative location of the Loess Plateau and China, DEM (digital elevation model), river system, and latitude and longitude coordinates of the Yangou River watershed.

difficult to obtain the general statements on interactions between different catchments because each study takes a rather narrow and specific perspective (Rogger et al., 2017). Moreover, the existing SDR studies were primarily focused on the long-term average value by the limited hydrological observations of a particular watershed (Chen et al., 2001; Xu, 2010), there have been few reports on the dynamic SDR algorithms, especially for the impacts of human activities such as soil and water conservation measures (Ali and De Boer, 2010; Sang et al., 2015). The difficulty in producing a widely applicable SDR algorithm was partly due to the complexity of sediment delivery processes and their interactions, and partly due to the lack of definitive assessments of the natural and anthropogenic influencing factors (Didoné et al., 2015). The Loess Plateau in China is one of the most fragile soil erosion regions in the world (Ouyang et al., 2010). Soil erosion in this region is mainly caused by several heavy rainstorms during 6–9 months, and the amount of erosion by heavy rains accounts for > 60% of total annual erosion (Wu et al., 2018b). However, the ecological environments on the Loess Plateau have been significantly improved since the effective implementation of large-scale soil and water conservation measures (e.g. returning farmland to forest/grass, conservation tillage, contour farming, terracing, construction of warp land dams, hillside ditches, and contour buffer strips) (Wu et al., 2016b). How to accurately quantify the dynamic changes associated with the hydrometeorological parameters and anthropogenic land management activities is the main challenge of the SDR, which is also the critical knowledge gap between slope erosion and sediment yield in an ecological restoration watershed (Liu et al., 2007; Wu et al., 2018a). Therefore, the comprehensive governance degree, a percentage index used for quantifying the dynamic governance level in a watershed, was innovatively introduced to address the issue of the quantification accuracy in dynamic sediment yield predictions.

The existing SDR studies on the Loess Plateau are primarily focused on the Wuding River, Dali River, Chabagou River, Quanjiagou River, Yangdaogou River, Jiuyuangou River, Yangou River, Nanxiaohegou River and Yanhe River (Chen 2000; Cao et al., 1993; Sun and Li, 2004; Xie and Li, 2012). Through statistical analysis, it was definitely found that all the above watersheds had experienced different governance backgrounds. Among them the governance of the Yangou River watershed was the most typical and representative case on the Loess Plateau (Ju et al., 2003). The corresponding large-scale comprehensive governance project in this watershed was implemented in 1997 and basically reached a stable governance state in 2009 (Liu et al., 2011; Wu et al., 2016e). This project went through four periods in which the governance degree increased from 27% to 83%: the first period in 1991–1997 with a governance degree < 27%, the second period in 1998–2002 with a governance degree < 52%, the third period in 2003–2008 with a governance degree < 73%, and the fourth period in 2009–2013 with a governance degree < 83% (Xu et al., 2012a,b). Therefore, the Yangou River watershed in northern Shaanxi Province was selected as a study case to explore and develop a dynamic SDR algorithm, which is critical later to test hypotheses regarding the effects of the comprehensive governance degree on sediment yield dynamics.

This study aims to: i) develop a piecewise SDR algorithm coordinatively considering the main natural factors and the multi-stage comprehensive governance degree in an ecological restoration watershed; ii) verify the applicability of the improved SDR algorithm in different watersheds; and iii) evaluate the effectiveness of the piecewise SDR algorithm on the spatio-temporal dynamics response of sediment yield in the Yangou River watershed. The results may provide new understanding not only for the quantitative estimation of spatio-temporal sediment yield evolutions but also for the reasonable soil conservation planning at different ecological restoration regions.

2. Materials and methods

2.1. Study region and data sources

The Yangou River watershed (109°20′E-109°35′E, 36°20′N-36°32′N), which belongs to the hilly and gully region of the Loess Plateau (Fig. 1), is located 5 km southeast of Yan'an City, Shaanxi Province, China. The catchment area is 47.68 km^2, the elevation of this watershed is 962–1402 m with an average of 1198 m. The maximum height difference between the upper and lower reaches is 439 m, and the terrain in this watershed is dominated by steep slopes (Liang et al., 2003). The Yangou River, a second grade tributary of the Yanhe River, has an 8.6 km main river channel, a longitudinal bottom slope of 2.41‰, and a gully density of 4.8 km/km^2. The watershed is located at the transitional zone from semi-arid to semi-humid climate regions, where the average annual temperature is 9.4 °C; the average temperatures in January and July are -6.7 °C and 22.9 °C, respectively; the extreme maximum temperature is 39.7 °C; and the extreme minimum temperature is -25.4 °C. The average annual precipitation is 558.4 mm, the inter-annual variability of precipitation is large and the seasonal distribution is uneven, so approximately 70% of the rainfall is