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Assessment of wind and water erosion risk in the watershed of the Ningxia-Inner Mongolia Reach of the Yellow River, China

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ABSTRACT

The watershed of the Ningxia-Inner Mongolia Reach of the Yellow River (NIMRYR) suffers from soil erosion by wind and water because of the wide distribution of deserts and arsenic sandstones in this region. The sediment generated by erosion fed into the Yellow River directly or by its tributaries, silting up the Yellow River and raising the elevation of the river bed. The silting of the Yellow River result in serious flood disasters in this watershed. Therefore, it is urgent to implement soil conservation projects to control wind and water soil erosion. To reach this objective, understanding the spatial and temporal variations of soil erosion in this watershed is very important. In this study, an assessment of soil erosion risk by wind and water was performed based on soil erosion models. The Integrated Wind Erosion Modeling System (IWEMS) and the Revised Wind Erosion Equation (RWEQ) were used to estimate the wind erosion modulus in this watershed, and the water erosion modulus was estimated by the Revised Universal Soil Loss Equation (RUSLE). The results show that during 2000s, the wind erosion modulus ranged from 0 to 31,440.4 t/km^2/a, and the water erosion modulus was from 0 to 24,048.5 t/km^2/a. Moreover, the total soil erosion modulus by wind and water has ranged from 0 to 32,792.7 t/km^2/a. Due to the influence of regional weather and geomorphology, occurrences of wind and water erosion in this watershed are not identical in their spatial and temporal patterns. Based on the calculated soil erosion modulus, soil erosion risk was assessed according to the “Classification criteria for soil-erosion intensities” (SL190-2007). It was assumed that the areas with erosion intensity higher than slight were at risk of erosion; by this criterion, more than 34% of the total area of the watershed of the NIMRYR would be at erosion risk. Based on this estimation, it was also found that the NIMRYR watershed is not a region of wind–water erosion crisscross and that land-use conversions have a significant impact on soil erosion.

1. Introduction

Soil erosion is the detachment, entrainment, transport, and deposition of soil particles caused by one or more natural or anthropogenic erosive forces (rain, runoff, wind, gravity, tillage, etc.). In arid or semi-arid zones, rivers crossing deserts usually suffer from complex soil erosion by wind and water. Soil erosion by wind and water is a threat to sustainable agriculture and environmental quality. It causes damage to agricultural lands and water or air pollution through soil particles and chemicals, mudflows which may affect urban areas, and desertification of vulnerable ecosystems. According to the survey report published by the World Meteorological Organization and the United Nations Environment Program (WMO-UNEP), more than 17.5% of the total land area of the Earth is undergoing soil erosion by wind and water. These areas are mainly distributed in the Eyre Lake and Murray Darling River regions of Australia, the Sahel region, Namib Desert, and Kalahari Desert in Africa, the Great Basin region in the western part of North America, the regions between the Andes and the Brazilian Plateau, Pakistan in South Asia, Central Asia, and the inland regions of China (McIntosh, 1983; Teller and Lancaster, 1986; Knighton and Nanson, 1994; Jones and Blakey, 1997; Mason et al., 1997; Bourke and Pickup, 1999; Tooth, 1999; Bullard and McTainsh, 2003). China is one of the countries suffering the most severe soil erosion by wind and water, with a total area simultaneously suffering soil erosion by wind and water of up to 2.6×10^5 km^2 (Ministry of Water Resources of the People's Republic of China, 2001).

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Soil erosion risk assessment and prognosis maps, which are a common method for determining the course of action in soil conservation, are usually generated using soil erosion models. Many water erosion assessment and mapping methods have been developed, and various approaches or equations for risk assessment and prediction are available in the literature (Yang, 1990; Yoder and Lown, 1995; De Jong et al., 1999; Grimm et al., 2003; Cantón et al., 2011; Xu et al., 2012). The models used range from empirically to physically based and the spatial extent from micro-plots to national scales (Yang, 1990; Yoder and Lown, 1995; De Jong et al., 1999; Cantón et al., 2011; Xu et al., 2012). However, studies of wind erosion risk assessment are relatively rare, and the assessment methods are mainly involved some intrinsic (mainly are soil characters) and extrinsic factors (such as topography, meteorological conditions, etc.) (Hoffmann et al., 2011; Martínez-Graña et al., 2012); and the models are essentially or the Revised Wind Erosion Equation (RWEQ) or the Wind Erosion Prediction System (WEPS) (Mezosi and Szatmari, 1998; Zobeck et al., 2000; Coen et al., 2004; Hagen, 2004; Mendez and Buschiazzo, 2010; Du et al., 2015).

Previous studies have mainly focused on one of the stresses that drive the erosion process (Yang, 1990; Yoder and Lown, 1995; Mezosi and Szatmari, 1998; De Jong et al., 1999; Zobeck et al., 2000; Grimm et al., 2003; Coen et al., 2004; Hagen, 2004; Webb et al., 2006, 2009; Mendez and Buschiazzo, 2010; Cantón et al., 2011; Martínez-Graña et al., 2012; Xu et al., 2012; Du et al., 2015). Generally, a particular type of soil erosion was related to a specific climate zone: wind erosion to more arid regions, and water (rainfall) erosion to more humid zones. However, in some arid or semi-arid regions, both erosion processes contribute significantly to total soil erosion and sometimes occur almost simultaneously. An assessment of soil erosion that focused on only one stress might therefore provide incomplete recommendations to the local soil conservation department, especially in regions crossed by rivers. However, so far, studies of the assessment of wind and water erosion are very few (Martín-Fernández and Martínez-Núñez, 2011; Zhang et al., 2011; Martínez-Graña et al., 2014).

In recent decades, GIS technology has a significant development, which made the erosion risk estimation in large regions can be realized through linking erosion predicted models (methods) and GIS databases. Meanwhile, many literatures about erosion estimation in large scale came forth (Yang, 1990; Yoder and Lown, 1995; Mezosi and Szatmari, 1998; De Jong et al., 1999; Zobeck et al., 2000; Webb et al., 2006, 2009; Mendez and Buschiazzo, 2010; Hoffmann et al., 2011; Martínez-Graña et al., 2012; Du et al., 2015), and these researches impelled soil erosion science having great development. In this study, using the Integrated Wind Erosion Modelling System (IWEMS), the RWEQ, and the Revised Universal Soil Loss Equation (RUSLE), the wind and water (rainfall) erosion risk in the watershed of the Ningxia-Inner Mongolia Reach of the Yellow River (NIMRYR), China, was mapped and assessed. These models were selected because they having some common advantages, such as simple modeling processes, fewer input parameters, and easily integrates with GIS database.

The NIMRYR extends from Xiaheyan, Ningxia Province to Toudaoguai, Inner Mongolia, with a total length of 1200 km (Fig. 1). The total area of the watershed is about 1.5×10^6 km^2. The Hedong Sandy Land, the Ulanbuh Desert, and the Kubuqi Desert all locates in this watershed (Fig. 1), and a wide desert valley has developed in this region and can be as wide as 60 km. Various tributaries of the Qingshui River, Kushui Rivers, and the Ten Tributaries feed into the Yellow River in this watershed. Serious wind and water erosion hazard occurred in this watershed (Ta et al., 2003, 2013; Fan et al., 2012). According to the previous estimation, there are 5.56×10^7 t of aeolian sediment have been blown into the Yellow River from the Ulanbuh Desert from 2000 to 2010 (Du et al., 2014a), and the annual erosion modulus caused by runoff can be as high as 12,000 t/km^2 in the Ten Tributaries watershed alone (Conservancy Annals of Dalad Banner in 1989, unpublished data).

Because of severe soil erosion in this region, a mass of sediment is fed into the Yellow River by winds and tributary inflows and has silted up the main channel, besides a relatively flat gradient (0.2‰) in this reach, the silting condition is getting worse. Even with the joint operation of Liujiaxia and Longyangxia Reservoirs in the upstream basin, the river bed has still shown a tendency to rise (Hou, 1996; Zhao et al., 1999). The elevated bed of the Yellow River results in frequent flood disasters in the watershed of the NIMRYR. In this situation, construction of soil conservation projects in this region is badly needed.

The main objectives of this paper are to identify the spatial and temporal distribution of soil erosion and to assess soil erosion risk in the NIMRYR watershed, and to investigate the relationship between the land use and erosion risk. Herein, the soil erosion risk maps and relationship between erosion risk and land use could provide valuable information for management and planning of ecology and environment such as the soil conservation installations arrangement, ecomigration, erosion hazards prevention, land use conversion planning, etc. In addition, the methods evaluated and the map of potential erosion risk is also expected to be interesting for environmental and ecological scientists.

2. Methods and materials

In this study, the IWEMS and the RWEQ models were used to assess wind erosion risk, whereas water (rainfall) erosion in this watershed was assessed using the RUSLE model.

2.1. Methods

2.1.1. Wind erosion risk assessment

In this study, the IWEMS model proposed by Shao (2001) and the RWEQ model issued by United States Department of Agriculture (USDA) (Fryrear et al., 1998) were used to predict the wind erosion modulus for non-arable land and arable lands respectively in the watershed of the NIMRYR.

2.1.1.1. The IWEMS model. The IWEMS model is a physically based model, and it easily coupling with other physically based model such as soil moisture models. It was designed to predict wind erosion processes at regional and national scales. Lu and Shao (2001) has applied this model to simulate the dust-storm event in the Australian continent in the period of February, 1996, and obtained satisfactory simulated results. In this research, two key parameters were needed: the saltation threshold friction velocity, u_{*t}, m/s; and the streamwise saltation flux, Q, kg/m/s. Considering the effect of vegetation and soil moisture, the threshold friction velocity u_{*t} can be expressed as:

$$u_{*t}(d_s; \lambda, \theta) = u_{*t}(d_s) f_\lambda(\lambda) f_w(\theta), \tag{1}$$

where $u_{*t}(d_s; \lambda, \theta)$ denotes the threshold friction velocity of sand particles with diameter d_s in the presence of vegetation and soil moisture, m/s; λ is the frontal area of the roughness element, m^2; $f_\lambda(\lambda)$ is a function that modifies the threshold friction velocity to reflect the roughness elements; θ is the volumetric soil moisture, m^3/m^3; $f_w(\theta)$ is a function which corrects threshold friction velocity for soil moisture; and $u_{*t}(d_s)$ is the threshold friction velocity under the ideal condition that the surface is covered by loose sand particles of uniform and spherical shape. The threshold friction velocity