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Assessment of soil erosion characteristics in response to temperature and precipitation in a freeze-thaw watershed

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ABSTRACT

Precipitation and temperature are important factors affecting soil erosion especially in mid-high latitude areas. The effects of climatic factors on soil erosion have been observed in many studies. However, watershed soil erosion and its links between the contributors under climatic impacts display unique characteristics due to the freeze-thaw process, which are not fully understood. Therefore, the approaches of meteorological data monitoring, hydrological modelling (Soil and Water Assessment Tool) and multivariate statistical analysis of long-term data were integrated. Based on the cluster analysis, four categories of years (C1-C4) were classified as high precipitation, freezing with sufficient precipitation, dry hot, and normal years, respectively. The soil erosion loads from C1 to C4 were 2.03 $t\,ha^{-1}\,a^{-1}$, 1.27 $t\,ha^{-1}\,a^{-1}$, 2.12 $t\,ha^{-1}\,a^{-1}$, and 1.61 $t\,ha^{-1}\,a^{-1}$, respectively. The results demonstrated that soil erosion tended to increase in years observed with high precipitation and in years observed with cold temperature but sufficient precipitation, with the erosion loads under these two categories respectively 26% and 32% higher than the load in normal years. Low temperature combined with adequate precipitation may cause higher soil loss in the freeze-thaw areas. Furthermore, runoff and precipitation were the dominate factors affecting soil erosion, with high correlations with erosion load (0.920, $p = 0.01$ and 0.768, $p = 0.01$, respectively). Nonetheless, snowmelt runoff and R_s played more substantial roles than precipitation in the snowmelt period. Temperature was also related to soil erosion, but not for the snowmelt period. The weakest relationships between erosion and dominate contributors were observed in C1 under all conditions, but the strongest relationships were found in C4 except that between R_s in the snowmelt period. These findings of the study provide important implications for soil erosion control in freeze-thaw areas, which can help decision makers conserve soil and water resources with high efficiency in the event of adverse weather conditions.

1. Introduction

Soil erosion leads to land degradation, which damages soil productivity and ecosystem services (Ouyang et al., 2017). As the most fertile, productive and suitable soil for farming, the black soil plays a key role in food production and the black soil area in northeastern China has become one of the major grain bases in China (Deng et al., 2015). However, due to agricultural development and climatic influence during freeze-thaw processes, soil erosion is severe in this area. A study by Yu et al. (1992) reported that 37.9% of the total farmland in this region was facing significant water erosion. Due to distinct seasonal climatic changes (Zhao et al., 2012), the soil was eroded by rainfall water and meanwhile by snowmelt water in early spring. Thus, special consideration should be given to the impacts of precipitation and temperature on soil erosion owing to the freeze-thawing process.

Precipitation and temperature influence soil erosion greatly in freeze-thaw areas. Especially in agricultural areas, the soils can be eroded by rainfall easily (Cerda et al., 2017). Rainfall is the main cause of most water erosion because it detaches soil particles and creates surface runoff (Moore, 1979). Previous research reported that an increase of 4–18% in precipitation can cause an increase of 21–167% in soil loss and 49–112% in surface runoff (Zhang, 2007). Hence, rainfall erosivity (R), the potential of soil erosion by rainfall is considered when evaluating the effect of rainfall on soil erosion in the Universal Soil Loss Equation (USLE) and the revised version (RUSLE) (Xie et al., 2016). Many studies have estimated R from observed precipitation in spatial distribution and temporal trends (Mello et al., 2013; Fiener et al., 2013; Qin et al., 2016). Temperature is another important factor influencing soil erosion from water in regional water cycles. Runoff affects the transportation of soil particles (Nunes et al., 2013), while the

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temperature factor contributes to variations in runoff by changing the evapotranspiration. In addition, the freeze and thaw cycles decrease the stability of aggregates of soils (Edwards, 1991), making it easier for soil particles to be carried away by surface flow.

The hydrological processes related to erosion rate under effects of precipitation and temperature have been investigated in previous studies (Comino et al., 2016), many of which found a highly positive correlation among runoff, soil loss, and sediment yield (Safari et al., 2016; Mandal et al., 2008). Tuset et al. (2016) pointed out that sediment load was related to direct runoff, but the suspension was predictable from rainfall and runoff data in the Mediterranean mountainous area. Nonetheless, Li and Fang (2016) showed that the impact of raindrops was 3.6–19.8 times higher than that of runoff detachment on soil loss. Moreover, temperature characteristics also modify runoff and soil erosion process. Mhazo et al. (2016) indicated that the variations in soil losses and runoff were different in temperate zones (lower than 10 °C) but not in tropical areas (above 10 °C) worldwide under tillage abandonments. Hence, a deeper understanding of the synergic effects of climatic factors on runoff and soil erosion is needed to support water and soil management.

Snowmelt runoff and its induced soil loss occupy a large fraction of total annual runoff and soil erosion in cold areas (Wu et al., 2018). With the variation in snowfall during winter, soil loss differs. Data from 1969 to 2007 for Siberia indicated that soil loss in low (or very low) snow years was below 2 t ha^{-1} and in high (or very high) snow years ranged from 4.8–15.8 t ha^{-1}, and 1 mm of runoff could transport soil material at amounts of up to 150 kg ha^{-1} (Tanasienko et al., 2011). The research from Matonse et al. (2011) demonstrated that the higher air temperatures in winter and earlier snowmelt led to more runoff and heavier soil erosion. Although intensive work was done on soil erosion by snow melt (Ollesch et al., 2006; Rodzik et al., 2009; Su et al., 2011), the improved investigation of the links between runoff and soil erosion under climatic impacts requires long-term and continuous data. This can be achieved by hydrological modelling, and the Soil and Water Assessment Tool (SWAT) is one of the widely used methods to interpret the temporal-spatial hydrological processes of watersheds (Arnold et al., 1998).

Numerous studies have focused on the mechanisms of runoff and erosion during the freeze-thaw process, however, there is still a gap in our understanding of soil erosion and its links between the major drivers under climatic impacts in the freeze-thaw watersheds. In this research, we combined hydrological modelling and multivariate statistical analysis of long-term data to study climate factor impacts on soil erosion in a freeze-thaw watershed. Specifically, the main objectives were to (1) assess watershed surface runoff and soil erosion characteristics in response to temperature and precipitation; (2) investigate soil erosion contributors during the snowmelt period and throughout the year; and (3) clarify the roles of precipitation and runoff in affecting soil erosion under climatic impacts.

2. Data and methodology

2.1. Study sites

The study area is the Abujiao River Basin, which lies in Heilongjiang Province in the northeastern China and has an area of 142.9 km^2 (Fig. 1). This area is a typical watershed located in one of the black soil areas worldwide, which plays an extremely important role in crop production in China (Hao et al., 2012). This typical freeze-thaw watershed has a temperate continental climate with cold and long winters and cool summers. The mean daily temperature ranges from −2.66 °C to 7.92 °C in a year. The mean annual precipitation is about 583 mm, and the precipitation occurs mainly in the form of snow fall from November through April. The mean snowfall is approximately 109 mm, accounting for 18.7% of the total precipitation. The study area is located in a highly agricultural area, developed for the reclamation of farmlands from wetlands (Ouyang et al., 2018).

2.2. Potential of soil erosion by rainfall and snowfall

The observed daily precipitation and air temperature data in this study were gathered from Bawujiu Farm Meteorological Station and Raohe County Meteorological Station in the local area, covering the period from 1970 to 2014. These meteorological data were consistent and continuous for estimating the potential of soil erosion by precipitation. R reflects the function of rainfall physical characteristics and weather effects on water-related soil erosion. In USLE and RUSLE, R is applied extensively in empirical soil loss prediction, however, due to the special climate of this study area, the potential of erosion by snowfall is also an important consideration for precipitation erosivity assessment. Thus, the effect of snowmelt runoff from snowfall on soil erosion was considered here. In this study, precipitation erosivity reflected soil erodibility under the influence of rainfall and snowfall, which was composed of two parts: rainfall erosivity and snowmelt runoff erosivity. Based on climate characteristics, the twelve months in a year during the study period were divided into two categories: rainfall period (from May to October) and freeze-thaw period (from November to April).

The equation below has been widely used in China to calculate rainfall erosivity based on daily rainfall during the rainfall period (Zhang et al., 2002; Zhang and Fu, 2003):

$$Ri = \alpha \sum_{j=1}^{K} (Pj)^{\beta} \tag{1}$$

where R_i is the ith half month rainfall erosivity for the year, MJ mm ha^{-1} h^{-1} a^{-1}; K is the number of days within the corresponding half month, d; and P_j is the erosive rainfall for the jth day in the half month, mm. Daily rainfall higher than 12 mm is considered erosive rainfall. α and β are model parameters that were calculated as follows:

$$\beta = 0.8363 + 18.144Pd12^{-1} + 24.455Py12^{-1} \tag{2}$$

$$\alpha = 21.586\beta^{-7.1891} \tag{3}$$

where P_{d12} is the daily average rainfall of the days with rainfall higher than 12 mm during the rainfall period, mm; and P_{y12} is the annual average rainfall of the days with rainfall higher than 12 mm during the rainfall period, mm.

According to precipitation data from 234 meteorological stations and runoff and sediment data from 21 typical watershed hydrology stations in Heilongjiang Province, snowmelt runoff erosivity was calculated based on the empirical equation (Jiao et al., 2009):

$$R_s = 33.124P_s^{0.5845} \tag{4}$$

where R_s is snowmelt runoff erosivity, MJ mm ha^{-1} h^{-1} a^{-1}; and P_s is the annual average precipitation during the freeze-thaw period, mm. The total precipitation erosivity was:

$$R_T = R + R_s \tag{5}$$

where R_T is precipitation erosivity for the year, MJ mm ha^{-1} h^{-1} a^{-1}; and R is rainfall erosivity, which was obtained from the half month rainfall erosivity for the year. Rainfall erosivity, also known as precipitation erosivity in this study, is normally acquired using high temporal resolution rainfall data from long periods, which may not be readily available in many areas. This study applied the consistent meteorological data, therefore the accuracy and reliability of the results were expected robust.

2.3. Runoff and soil erosion calculation

Soil and Water Assessment Tool (SWAT) is one of the most suitable models to predict spatial effects of land or soil on water, sediment, and nutrient transport in watersheds (Parajuli et al., 2008). It is an effective