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Snowmelt water drives higher soil erosion than rainfall water in a mid-high latitude upland watershed

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ABSTRACT

The impacts of precipitation and temperature on soil erosion are pronounced in mid-high latitude areas, which lead to seasonal variations in soil erosion. Determining the critical erosion periods and the reasons behind the increased erosion loads are essential for soil management decisions. Hence, integrated approaches combining experiments and modelling based on field investigations were applied to investigate watershed soil erosion characteristics and the dynamics of water movement through soils. Long-term and continuous data for surface runoff and soil erosion variation characteristics of uplands in a watershed were observed via five simulations by the Soil and Water Assessment Tool (SWAT). In addition, laboratory experiments were performed to quantify the actual soil infiltrabilities in snowmelt seasons (thawed treatment) and rainy seasons (non-frozen treatment). The results showed that over the course of a year, average surface runoff and soil erosion reached peak values of 31.38 mm and 1.46 t ha^{-1} a^{-1}, respectively, in the month of April. They also ranked high in July and August, falling in the ranges of 23.73 mm to 24.91 mm and 0.55 t ha^{-1} a^{-1} to 0.59 t ha^{-1} a^{-1}, respectively. With the infiltration time extended, thawed soils showed lower infiltrabilities than non-frozen soils, and the differences in soil infiltration amounts between these two were considerable. These results highlighted that soil erosion was very closely and positively correlated with surface runoff. Soil loss was higher in snowmelt periods than in rainy periods due to the higher surface runoff in early spring, and the decreased soil infiltrability in snowmelt periods contributed much to this higher surface runoff. These findings are helpful for identification of critical soil erosion periods when making soil management before critical months, especially those before snowmelt periods.

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1. Introduction

Soil erosion, a hazardous form of land degradation that threatens soil quality and field productivity, is caused mainly by water detachment and transport (Alexandridis et al., 2015; Mao et al., 2010). Soil erosion is clearly affected by precipitation amounts and intensities (Li and Fang, 2016). Particularly, in mid-high latitude and cold areas, such as the northern parts of North America and Europe and northeast China, soil erosion depends greatly on the climatic state (Edwards et al., 1998), and is characterized by seasonal variations due to the increasing surface runoff led by snowmelt in early spring and intense rainfall in summer (Ouyang et al., 2017). Seasonal variations in air and soil temperatures coupled not only with rainfall, but also snow and glacier melting, influence soil erosion considerably (Kurylyk et al., 2014). A previous study has shown that melt-induced soil losses can reach 15.8 t ha^{-1} in southern West Siberia (Tanasienko et al., 2011). Hence, it is essential to identify seasonal soil erosion features, especially the critical erosion periods in such areas because erosion rates in the melt period may be even higher than those in the rainy period (Edwards et al., 1998; Ollesch et al., 2005).

Surface runoff is always accompanied by soil erosion and sediment yield (Abrol et al., 2016), with the flow carrying soil materials away. In addition to surface flow velocity, surface runoff affects soil erosion mainly in the variations of runoff volume. In rainy seasons with high precipitation intensity, increasing runoff discharge was the dominant factor influencing soil erosion in a study reported by Vaezi et al. (2017). While in early spring, runoff led by snowmelt will also aggravate the erosion of surface soils (Zuzel et al., 1982). As mentioned above, although surface runoff exhibits a growing trend in both rainy and snowmelt periods due to concentrated rainfall and snowmelt water, the annual runoff feature has not always been the same as the seasonal runoff feature (Luo et al., 2017). For this reason, detection of runoff variations on the

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seasonal scale in response to precipitation and temperature variations is necessary.

Soil infiltration is an indicator of soil erosion and plays a significant role in the transformation between precipitation, surface runoff and soil water. With higher infiltrability, the surface runoff and soil loss will be low. Moreover, as a dynamic process (Wang et al., 2014), soil erodibility will decrease when the soil final infiltration rate increases (Wang et al., 2015). In most cases, soil loss often occurs due to runoff detachment when infiltrability is less than rainfall intensity in rainy seasons. But in snowmelt periods in cold areas, the varying soil infiltrability plays an important role, and great quantities of melt water will cause erosion (Stähli et al., 1999). Cerda (2001) showed that soil erosion rates became 39 times higher when the steady infiltration rate decreased from 44.5 mm h^{-1} to 27.5 mm h^{-1}. Soil infiltrability was affected by soil type, bulk density and soil moisture. Previous studies have shown that for frozen or unfrozen soils, infiltrability decreased as soil moisture grew, but the influence of moisture on the infiltration rate declined with time (Bodman and Colman, 1944; Zheng and Fan, 2000). Overall, enhancing infiltrability is an effective strategy to control soil loss (García-Ruiz et al., 2017), and thereby studying soil infiltration characteristics under the influence of seasonal precipitation and temperature remains a critical issue in soil erosion research.

The mollisol region of northeast China in the mid-high latitude region has contributed significantly to grain production (Liu et al., 2011), but is facing severe soil erosion issues due to long-term agricultural exploitation (Zhang et al., 2007) and special climatic conditions. Large areas of natural cover lands have been cultivated into croplands, and paddy field areas have expanded with the development of pond water irrigation in recent years (Ouyang et al., 2014). The terrain of this area is marked by gentle and long slopes that lead to extensive topsoil erosion (Xin et al., 2016), and excess infiltration runoff takes the dominant place in runoff generation (Zhang et al., 2006). Therefore, surface runoff and soil infiltrability are closely related to soil erosion in this region. Fan et al. (2011) reported that melt runoff was the primary factor governing soil loss, and the erosion amount when runoff is under 300 mm h^{-1} is markedly higher than the erosion that occurs when runoff varies from 60 to 240 mm h^{-1}. In addition, freeze-thaw cycles affect soil erosion by altering soil structures and the shape of rills (Gatto, 2000). Due to the impacts of freeze-thaw cycles, snowmelt and rainfall, the cyclic process of soil erosion exists in the mollisol region (Hu et al., 2009). Soil infiltrability, surface runoff and soil erosion of the watershed thereby exhibit seasonal characteristics.

Many field investigations, laboratory experiments and modelling analyses have been conducted in studies of runoff and soil erosion processes (Anache et al., 2017; Rodrigo Comino et al., 2016; Wu et al., 2017). Field and laboratory experiments are traditional methods, which aim to investigate soil erosion mechanisms at small scales, but they can hardly be used to describe results for watershed-scale hydrological processes. In recent decades, runoff and soil erosion estimations in watersheds with the aid of hydrology models has developed rapidly. The Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998) is one of the most widely used models for watershed hydrological processes and soil erosion assessment, which has been applied successfully in both rainfall-based (Kumar and Mishra, 2015; Serpa et al., 2015) and snowmelt-based processes (Kang and Lee, 2014; Wang and Melesse, 2005). Modelling is helpful for analyses, which cover long-term soil erosion data. Nonetheless, such methods barely utilize detailed soil erosion processes. Therefore, a method that integrates experiments and modelling is vital for understanding watershed soil erosion characteristic and the detailed processes that are involved.

Deeper insight into seasonal variations in watershed-scale soil erosion processes and the reason behind the growing erosion loads in critical periods in mid-high latitude areas are needed to help with soil management and soil erosion control. Specifically, this study integrates approaches of experiments and modelling, which aims to: (i) assess seasonal surface runoff and soil erosion features of the upland under the influence of precipitation and temperature variations in the watershed, (ii) investigate the differences in soil infiltration capacity in rainy and snowmelt periods, and (iii) clarify the water-driven forces behind the rises in surface runoff and soil erosion in critical soil loss periods.

2. Materials and methods

2.1. Study area

Abujiao River Basin, which plays an important role in grain production in China (Yin et al., 2016), is located on the Bawujiu Farm in the Sanjiang Plain in the northeast of China (Fig. 1). Abujiao River is a seasonal river with a basin area of 142.9 km^2, which is characterized by a typical cold temperate monsoon continental climate with a mean annual temperature of 2.94 °C. The rainy season with concentrated rainfall events extends from July to August, and the freeze-thaw season with abundant snowfall is from November to March (or April) in the next year. The mean annual precipitation is 583 mm. During the snowfall period, the mean snow water equivalent is approximately 109 mm and the snow depth on the ground ranges from 20 cm to 50 cm. The depth of the frozen soil is approximately 141 cm in winter. This basin has gentle gradients, and six types of soil with high soil organic content (4.48%) were observed there (Ouyang et al., 2016). The soil in the upland area is mainly meadow albic soil (Glossoboralf in Soil Taxonomy). The upland (dry farmland), where soybeans have been grown, was first cultivated in the 1950s, and the area of upland continuously expanded in the following decades. In the 1990s, the upland area started to shrink and was gradually largely replaced by paddy fields (Fig. 1).

2.2. Upland surface runoff and soil erosion modelling

To evaluate seasonal surface runoff and soil erosion loads over the whole basin, the physically based and distributed Soil Water Assessment Tool Model (SWAT) was adopted in this study. SWAT (within ArcGIS 10.2.2) can quantify variations in the watershed hydrological cycle, sediments, and nutrients in response to climate and watershed management activities on a daily time scale (Rossi et al., 2012) while taking snow cover effects into consideration. Therefore, this model is an effective tool to assess and predict surface runoff and soil erosion of the upland in the Abujiao River Basin. In the model, the watershed is divided into hydrologic response units (HRUs) with a single soil type, land-use type and slope type in each unit. Surface runoff and soil erosion were extracted from the HRUs of the uplands. The Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975a,b) was used to calculate soil erosion according to climatic, soil, topographic, and cover characteristics, and management and support practices in the study area.

2.3. Model preparation, calibration and validation

Data from the Digital Elevation Model (DEM), land use, meteorology, soil, watershed cropping tillage and management are required to run the SWAT model. DEM data (30 m × 30 m) were downloaded from the Geospatial Data Cloud (http://www.gscloud.cn/). After decades of agriculture development, types of

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