Seasonal Dynamics of Runoff-Sediment Relationship and Its Controlling Factors in Black Soil Region of Northeast China

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Abstract: Seasonal runoff-sediment dynamics and its controlling factors were studied in an agricultural watershed in the black soil region of Northeast China. Daily sediment and discharge data from 1957 to 1989 (except for 1961 and 1962) was used to investigate runoff-sediment dynamics, and the observed data shows that the discharge patterns are dominated by runoff from July to September, which accounted for about 64.7% of annual discharge; fluctuations in suspended sediment concentration (SSC) are markedly different from discharge fluctuations; and SSC in the snowmelt season (April) and late June to July is conspicuously higher than at other periods of the year. One concept was proposed to isolate the individual effect of each controlling factor on SSC from their joint effects and the preliminary analysis shows that: (1) high SSC in April is mainly dominated by freeze-thaw, and high SSC in July is dominated by intensive rainfall erosivity rather than volume of discharge; (2) an increase in rainfall erosivity increases SSC whether or not a field is covered by crops; (3) the effect of rainfall erosivity with increasing SSC in July is larger than the reduction effect from crop cover. The results reveal that the concept of isolating an individual effect from the joint effect played by multiple controlling factors on SSC provides potentially an efficient and effective way for evaluating land use and management practices in a new area with limited data.

Key words: black soil region; runoff-sediment relationship; seasonal dynamics; controlling factors of sediment yield

1 Introduction

The continuous monitoring of discharge (Q) and suspended sediment concentrations (SSC) in streams allows an improved estimation of sediment yield (Walling and Webb 1988) and provides help in understanding the runoff and sediment production processes active in a catchment area (Soler et al. 2008). In some places such as the Loess Plateau in north China, the runoff-sediment relationship is usually strong and can be represented as a linear or power function in many cases (Zheng et al. 2008). However, the runoff-sediment relationship is normally not homogenous neither within nor between events in many other places (Eder et al. 2010; Rodriguez-Blanco et al. 2010), which can often be explained by hysteresis effects (Williams 1989). Reasons for the runoff-sediment relationship variations should be attributed to changes in the interactions of the natural and anthropogenic factors that control sediment production and delivery (Zabaleta et al. 2007). Therefore, analysis of the seasonal runoff-sediment relationship dynamics in a watershed exhibits the possibility to assess the effects of human activities on...
The black soil region in northeast China was originally characterized by a deep, dark A-horizon, and has been the major base for marketable grain production. However, more than half a century of intensified use has degraded its productivity, mainly with the loss of the dark-coloured A-horizon through rainfall erosion (Yang et al. 2003; Zhang et al. 2007). Degradation of farmland in the black soil region is a growing threat to food security in China; thus, effective conservation practices are urgently needed.

Effects of conservation practices on reducing sediment have been widely studied in many places by comparing sediment yields before and after practices using observed data or simulated results (Beasley et al. 1985; Das et al. 2004; Faucette et al. 2008; Hazel et al. 2008; Kuhnle et al. 2008; Minella et al. 2009; Potter and Hiatt 2009; Zeimen et al. 2006). However, paired data for comparisons to evaluate effects of practices are scarce in this area. Moreover, models may have limitations in simulating different field management conditions (Boardman 2006; Maski et al. 2008) due to the lack of understanding of the related processes and features, especially the unique topographic relief, soils, and climate of such a gentle hilly region with cold winters.

In the black soil region, where seasonal variations in erosion processes are controlled by floods generated by both spring snowmelt and summer storms, seasonal variation in sediment yield may mask the relationship with discharge (Walling 1988). This has been verified in previous studies through the weak relationship between discharge and sediment in this region (Cui 2007; Fang et al. 2009). Previous findings indicate that not only discharge, but also variation in other factors (such as snowmelt, rainfall erosivity, crop cover, and tillage practices) also play important roles in determining sediment. However, knowledge about the effect of each individual factor on runoff-sediment relationship in this region is scarce. Thus, building the relationship between SSC and its contributing factors, lacking at present, should be especially helpful to understanding erosion patterns in this area.

The aim of this paper is threefold: (i) to investigate the dynamics of the runoff-sediment relationship over seasons based on the long-term daily discharge and sediment data of an agricultural watershed in the black soil region in northeast China; (ii) to analyze the controlling factors affecting the runoff-sediment relationship; and (iii) to qualitatively assess the relative contribution of each factor with the intent to improve the understanding of the processes that control runoff-sediment patterns in an agricultural watershed characterized by snowmelt and rainstorms.

2 The study area

The study area, located in the upper stream of the Wuyuer River Watershed (Fig. 1), is a typical rolling-hill black soil region with a land area of approximately 7423 km². The Wuyuer River originates in the low hilly areas on the western side of the Xiao Hinggan Mountains and east of Bei’an City in Heilongjiang Province in the northeast of China, and finally winds into the wetland of Zhalong National Nature Reserve. The climate of the region can be characterized as an East Asian monsoon climate, with a long, cold winter; a dry, windy spring; a hot, humid summer; and a short autumn. Annual precipitation is about 490 mm, about 80% of which is received from June to

![Fig. 1 Location of upstream Wuyuer River watershed.](image-url)
September. The area has a mean annual temperature of about 1.5 °C, and the average daily temperature is below 0 °C for more than 5 months of the year (from November to the following March) (Fig. 2). This area is a typical zone of seasonal frozen soil, with the frozen depth about 2–2.5 m. Soil for agricultural purposes is mainly black soil, which is loose in structure and easily eroded by rainfall and snowmelt runoff. This area has been listed as a national critical erosion control areas since 1996.

Land use type in the study area is dominated by rain-fed agricultural practices (66.84%), and also includes marshland (12.58%), forests (11.86%), grassland (3.98%), and other (4.74%). As rain-fed farmland dominates the watershed, agricultural management practices have a crucial influence on runoff and sediment in this area.

3 Materials and methods
3.1 Data collection and measurements
Discharge and sediment data: To collect data for the purposes of engineering design and scientific research with respect to flooding and soil loss in northeast China, hydrometric stations have been established by the Songliao Water Resources Commission since the 1950s. Water discharge and suspended sediment concentrations are regularly measured and reported by the faculties of these stations. All measurements of discharge as well as suspended sediment concentrations have adhered to national standards issued by Ministry of Water Resources of China. Strict checks on complying with the standards have been performed. The procedures used for hydrological survey, sampling, and laboratory analyses at hydrometric stations in China are basically the same as those used internationally (For a detailed introduction, please refer to the work of Yan (1984)).

The water level was observed at a streamflow gauge, and the flow discharge was obtained using previously established water-discharge level curves. The curves were calibrated according to the measurements of flow discharge obtained using current meters installed in the river. Samples of water and suspended sediment were taken using horizontal samplers, and the sediment samples were then analyzed in the laboratory to determine sediment concentration of the samples and finally the sediment concentration of the cross section. Based on the observed water discharge and suspended sediment concentrations, monthly sediment concentrations were calculated by dividing the total sediment yield by the total volume of discharge for that time period.

For this study, 31 years of daily discharge and sediment data from 1957 to 1989 (except for 1961 and 1962) were collected from the Yi’an Hydrometric Station, where long-term sediment data have been observed and well-documented.

Leaf Area Index (LAI): An LAI curve of soybeans during the growing season was derived from Song et al. (2005), who in 2003 manually measured leaf areas of individual soybean plants during 8 growing stages and finally calculated the corresponding LAI. In order to measure total leaf areas, they cut the sample plants and unfolded all of their leaves on a black background, then took photos of all the leaves and measured their total area in a computer with the help of image-processing software. As the growing season of soybeans is approximately the same from year to year, the observed LAI curve by Song et al. in 2005 was used as a surrogate for yearly average conditions in this study.

Rainfall erosivity: Monthly rainfall erosivity was collected from literature as presented in Zhang et al. (1992). After examination of the relationships of soil loss with different combinations of kinetic energy (E) and rainfall intensity (I) in Heilongjiang Province which occupies large part of black soil regions in northeast China, Zhang et al. (1992) found that the combination of 60 min maximum rainfall kinetic energy (E60) with 30 min maximum rainfall intensity (I30) mostly correlated with soil loss, and that this combination was different from ∑EI30 proposed by Wischmeier and Smith (1978). Zhang et al. then calculated the monthly rainfall erosivity for key stations in Heilongjiang Province using data from rainfall autorecord meters based on E60I30. Monthly average rainfall erosivity of the Keshan Meteorological Station within the study area from 1957 to 1989 was among the stations they calculated and presented. Therefore, results in their paper (Zhang et al. 1992) were directly used for this study.

3.2 Data analysis
To facilitate analysis and presentation, variations of SSC are shown at both daily and monthly temporal scales and investigated by plotting against time or controlling factors (e.g. rainfall erosivity). Effect of each controlling factor on the change of SSC is evaluated by relating change of SSC to the variation of controlling factors at the time.

Seasonal dynamics of SSC is a complex phenomenon mainly resulting from the combined effects of freeze-thaw, rainfall erosivity, crop cover, and tillage practices.
The relative magnitude and importance of these factors are difficult to discern due to the fact that effects of several factors are always jointly exerted. One concept proposed here was to isolate the individual effect of each factor on SSC from the joint effects through inter-month comparison of SSC and then link the changes of SSC with the presence or absence of a controlling factor. For this, a careful but qualitative approach was used: the presence or absence of freeze-thaw, crop cover, and tillage practices were examined to describe the surface conditions and the corresponding SSC variation of the related time; magnitude changes in rainfall erosivity were used to correlate with SSC.

4 Results and discussion

4.1 Seasonal dynamics of runoff-sediment relationship

There are two peaks for both runoff and sediment yield during a year according to the monthly averaged data (Fig.3), but the months for peaks of sediment yield to appear differ from those of runoff. Sediment yield peaks appear in April and July, the snowmelt and the rainfall flood seasons, respectively, with sediment yield in July notably higher than other months. However, runoff peaks appear in May and August, with discharge volume in August noticeably higher than in other months. Runoff in April is only about 7% of the annual total, but during which the sediment yield exceeds 15% of the annual total. Contribution in August to annual runoff is about 27%, but only 20% for sediment yield. Fluctuation of the runoff-sediment relationship from month to month during a year can be clearly seen in Figure 3, which implicates the seasonal transformation of controlling factors for soil erosion.

Average daily SSC for the 31 years is shown in Figure 4. SSC is high in April and late June to July and then decreases gradually after July. Reasons for the fluctuation of SSC are discussed from aspects of freeze-thaw effect, crop cover, tillage practices, and rainfall erosivity in the following sections.

4.2 The freeze-thaw effect

The study area is located in a typical zone of seasonal frozen soil, with the depth of the soil frozen in winter of about 2–2.5 m (Wang and Cheng 2001). The layer of surface soil becomes more erodible after the cycle of freeze-thaw process in the spring season. Concurrently, the frozen soil in the lower layer impedes percolation of melted snow water from the top layer; thus, surface soil water content increases until saturation. Surface soil in this condition is easily dispersed, transported, and prone to collapse (Kok and McCool 1990; Liu et al. 2001; Zhang et al. 2007). Rainfall at this time, if any, accelerates the thaw rate of the frozen layers and generates a more erosive runoff than in other periods. Moreover, the farmland is totally bare from winter to April or May, when erosion is further facilitated by snowmelt (Zhang et al. 2008). Observations also show that freeze-thaw cycles have a strong influence on ephemeral gully erosion in spring (Zhang et al. 2007). The special effect of freeze-thaw on soil and the bareness of soil surface in spring cause average SSC to maximize in April (Fig. 3).

4.3 The rainfall erosivity effect

Rainfall is the driving force of soil erosion in seasons of intensive rain. In order to investigate the effect of rainfall erosivity on SSC, the monthly sediment yields and SSC were plotted against rainfall erosivity derived from Zhang et al. (1992) (Fig. 5).

Figure 5 shows that rainfall erosivity in July is dramatically high and contributes to approximately 56% of the total annual amount and that the sediment yield and SSC also reach their maximum values accordingly in July (except for the freeze-thaw season). The overall linear relationship between sediment yield and rainfall erosivity...
is strong, with $R^2 = 0.91$, but the linear relationship between SSC and rainfall erosivity is weak, as the $R^2$ is merely 0.27. SSC in May and June is high, although their respective rainfall erosivity is small. This indicates that a variation of factors in May and June from that in August and September also plays an important role in influencing the SSC.

4.4 The crop cover effect

Soybeans, with a growing season from early May to September, are the main agricultural crop in the study area. LAI of soybeans across the year is shown in Figure 4. LAI increases gradually from June to July and reaches its peak in August; after that, LAI drops quickly from the end of August to September. Most of the soybean leaves fall at the end of September when soybeans reach maturity, and, thus, LAI becomes very small at this time.

Comparing the SSC curve with the changes in LAI, it can be generally observed that SSC drops from the end of July to mid-August when LAI increases; however, SSC continues to drop when LAI decreases from mid-August to the end of September. Furthermore, though LAI is high in July, SSC during this period is higher than that of May and June which has lower LAI. This reveals the limited effect of LAI on SSC. It would seem that the influences of other factors lead to the high SSC from the end of June to the beginning of July and the decrease in SSC in the autumn.

4.5 The management practices effect

Routine management practices are mainly conducted at several specific periods of the year. Sowing time is usually from the end of April to the beginning of May; tillage for cultivation and weeding is conducted 2 to 3 times in June to July; and harvest is usually conducted at the end of September.

The relationship between SSC and management practices is shown in Figure 4. SSC drops significantly after the sowing period, but rises during the period of tillage for cultivation and weeding, and then decreases gradually from August to mid-September when there are no tillage practices. Finally, SSC fluctuates a little during harvest at the end of September.

Frequent tillage practices in June and July loosen the soil surface and reform the soil structure, thereby increasing soil erodibility. Soil erosion may more easily occur just after tillage, but less likely after a long period when soil surface again becomes compacted under the effects of rainfall (Zhang et al. 2001). Therefore, tillage for cultivation appears to promote high SSC in June and July. After July, crop leaves entirely cover the furrows in the fields and tillage practices cease, and the soil surface is gradually compacted under the effects of rainfall, all contributing to a decrease in SSC.

The effect of tillage practices on SSC deduced above can be verified through various studies. For example, after field observations in the black soil regions, Zhang et al. (2007) found that the depths of gullies in spring were larger in fields with deep tillage after autumn harvests than in fields that were not cultivated. Plot scale experiments in Hailun Agroecological Experimental Station of the Chinese Academy of Sciences in Heilongjiang Province have revealed that no-till farming could lead to markedly less sediment than conventional tillage (Liu 2010). Results from Revised Universal Soil Loss Equation (RUSLE) simulations also demonstrated that no-till practices could reduce soil loss by up to 90 percent a year compared to conventional tillage (Yang et al. 2003). Studies in other places have revealed that no-tillage was an efficient practice in sediment reduction (Beasley et al. 1985; Lafond et al. 2009; Truman et al. 2005; Zeimen et al. 2006; Zhou et al. 2009) and has been widely adopted on the American and the Canadian prairies.
Hence, no-till would be very useful for sustainability, productivity, and portability in the black soil regions in Northeast China.

### 4.6 Relative importance of each factor

To assess the contribution of each controlling factor to variations in SSC, the temporal distributions of these factors are examined and listed in Table 1. As LAIs of crops are low in June (Fig. 4), it is assumed that the field is bare at that time. For September, although LAI is decreasing, defoliation covers the soil surface, so the field is classified as covered in September.

After examination of the distribution of the controlling factors throughout the year as shown in Table 1, changes in SSC can be attributed to corresponding controlling factors at the turning points of the SSC-Time curve:

1. A decrease in SSC from April to May is mainly due to a change in the cause of erosion, that is to say, from snowmelt erosion after freeze-thaw to rainfall erosion;
2. An increase in SSC from June to July is mainly caused by joint effects from an increase in rainfall erosivity and the presence of crop cover, as tillage practices persist during these two months;
3. A decrease in SSC from July to August is mainly caused by a decrease in rainfall erosivity and cessation of tillage activities.

Based on the above observations and analysis, change in SSC can be related to its controlling factors from April to September (Fig. 6), and the contribution of controlling factors during the year can be drawn as follow:

1. Soil erosion in April is largely promoted by freeze-thaw process as SSC in April is significantly higher than in other months;
2. Tillage practices and crop cover largely influence SSC. For the period the fields are tilled and have no crop cover (from May to June), SSC is observably higher than in August and September when the fields are covered by crops and no tillage practices occur, in spite of the fact that rainfall erosivity in August and September is higher than that in June and May, respectively;
3. A rise in rainfall erosivity increases SSC if field conditions are similar. Even though fields are covered by crops in July, intensive rainfall erosivity at this time results in a higher SSC than that in other months of the year (except for April). A clear pattern can be seen in the change in SSC from May to June and from August to September when an increase in rainfall erosivity increases SSC in spite of the existence of crop cover or tillage practices;
4. An increasing, but much slower, rate of SSC against rainfall erosivity occurs from June to July than from May to June, indicating that the presence of crop cover partially cancels the effect of an increase in rainfall erosivity. SSC in July is higher than June, indicating that the amount of SSC potentially reduced by crop cover is smaller than the amount increased by rainfall erosivity;
5. Cessation of tillage practices and the presence of crop cover markedly reduce erosion, as revealed by the clearly lower SSC in August and September compared to other months.

These findings reveal the importance of conducting conservation tillage in this area to control soil erosion, especially that conservation tillage has not been widely implemented in the black soil region to date (Xu et al. 2010).

The established linkage between variations in SSC and its controlling factors can be useful for seeking an appropriate agricultural land use and management system. Moreover, the concept of isolating individual controlling effects from the joint effects played by multiple controlling factors provides an efficient and effective way for investigating areas with little previous data and few changes in land use, practice, and management.

### 5 Conclusions

This study investigated the seasonal dynamics of runoff-sediment relationship and its controlling factors in black soil region of northeast China based on long-term daily discharge and sediment data. The results show that:

1. Under seasonal effects of freeze-thaw, rainfall erosivity, crop cover, and tillage practices, the runoff-sediment relationship varies significantly between seasons;
2. High SSC in April and July can be mainly attributed to the freeze-thaw process and intensive rainfall erosivity, respectively, but the bareness of land and tillage practices significantly increase SSC. An increase in rainfall erosivity increases SSC whether or not fields are covered, and the effect of rainfall erosivity in increasing SSC in July is larger than the reduction effect from crop cover;
3. The isolation effect of individual factors on SSC from the joint effects is practical and promising for the evaluation of management practices in a new area with limited data.

### Table 1 Emergence and magnitude of the controlling factors from April to September*

<table>
<thead>
<tr>
<th>Month</th>
<th>Freeze-thaw</th>
<th>Crop cover</th>
<th>Tillage</th>
<th>Rainfall erosivity E$<em>{10}$J$</em>{10}$</th>
<th>SSC</th>
</tr>
</thead>
<tbody>
<tr>
<td>4</td>
<td>√</td>
<td></td>
<td></td>
<td>0</td>
<td>0.679</td>
</tr>
<tr>
<td>5</td>
<td>√</td>
<td></td>
<td></td>
<td>1.504</td>
<td>0.376</td>
</tr>
<tr>
<td>6</td>
<td>√</td>
<td></td>
<td></td>
<td>16.155</td>
<td>0.435</td>
</tr>
<tr>
<td>7</td>
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<td>√</td>
<td></td>
<td>70.751</td>
<td>0.497</td>
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<tr>
<td>8</td>
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<td>√</td>
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<tr>
<td>9</td>
<td>√</td>
<td>√</td>
<td></td>
<td>7.483</td>
<td>0.120</td>
</tr>
</tbody>
</table>

* Freeze-thaw, crop cover, and tillage practices are classified as present or absent, with √ for present.

**Rainfall erosivity is derived from Zhang et al. (1992); Table 3: Keshan Station.**
This preliminary study was conducted to qualitatively discern the contribution of each factor from the joint effects they imposed on seasonal dynamics of runoff-sediment relationship. Quantification of their effects requires further investigation and research.

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References


东北典型黑土区流域水沙关系季节动态特征及原因分析

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摘要：以位于东北典型黑土区的黑龙江省乌裕尔河流域中上游为研究区，利用依安站31年的日水沙观测资料，对流域水沙的季节性动态特征进行了分析，对影响水沙关系的自然及人为因素进行了探讨。观测数据表明，7–9月的径流量占全年的64.7%，对本区的产流起主导作用；径流平均含沙量在4月融雪期和6月底到7月中旬明显高于其他时段，含沙量的季节变化与径流的变化明显不同。为描述各影响因素对含沙量变化的贡献，本文通过将含沙量的季节变化与其影响因素的变化进行关联，提出了一种从多因素联合影响中分离出单因素影响的思路，分析表明：冻融作用对裸地的径流含沙量影响强烈，明显增加土壤侵蚀；在地表有无植被及耕作措施情况下，降雨侵蚀力的增加都将增加径流含沙量；植被的出现可以削弱降雨侵蚀力增大时的增沙效应，但7月降雨侵蚀力的增沙作用超过了作物覆盖的减沙作用。所提方法可方便地用于缺少对比观测实验地区的土地利用和管理措施水保效益评价。

关键词：典型黑土区；水沙关系；季节性；产沙影响因素