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A New Method for Computing the Sediment Delivery Ratio for the Hyper-Concentrated Flow Areas of the Loess Plateau, China

T. H. Li[1, 2 *] and W. C. Xie[2]

[1] *College of Environmental Sciences and Engineering, Peking University; Key Laboratory of Water and Sediment Sciences, Ministry of Education, Beijing 100871, China*
[2] *Shenzhen Graduate School of Peking University, Shenzhen, Guangdong 518055, China*

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ABSTRACT. The sediment delivery ratio (SDR) is an important index for understanding sediment erosion, transportation and deposition features in a river basin. Based on the commonly accepted definition of SDR and the characteristics of the sediment delivery process in hyper-concentrated flow areas of the Loess Plateau, China, a new model for computing the SDR is proposed. The model is a functional relation of fractional form, in which the denominator is the surface runoff of the basin, and the numerator is the water volume needed for saturated sediment discharge in the controlling hydrological station at the exit of the basin when the saturated sediment load is equal to the measured sediment load. Using the proposed SDR equation, the long-term series of SDRs in the Yanhe River basin, a typical hyper-concentrated flow basin in the Loess Plateau, were calculated from 1952 to 2010. The results show that the long-term annual average SDR in the Yanhe River basin was 0.92, which is consistent with the results of previous studies; this finding confirms the validity and effectiveness of the method. The proposed method only requires gauge data of sediment concentration, sediment delivery rate, sediment delivery volume, and runoff ratio from hydrological stations, which makes it easy to use, and it can be used to easily estimate soil erosion in the basin.

Keywords: Loess Plateau, sediment delivery ratio (SDR), sediment yield, soil erosion, Yanhe River basin

1. Introduction

The sediment delivery ratio (SDR) is typically defined as the fraction of gross erosion that is transported from a given catchment during a given time interval (Walling and Kleo, 1979; Walling, 1983; Lu et al., 2006), and it is commonly used to explain spatial and temporal changes in sediment transport through a catchment (Walling, 1983; Burt and Allison, 2010). In practice, the SDR can be used to evaluate the benefit of sediment reduction due to soil and water conservation, to evaluate the effects of erosion and sediment production on the increase in siltation levels of the downstream rivers (Jing, 2002), to forecast the amount of soil erosion and the river's sediment discharge (Zhang, 1993; Brath et al., 2002; Lim et al., 2005; Syvitski et al., 2005; Pak and Lee, 2012), and even to improve capability in modeling the sources of sediment affecting stream water quality and in prioritizing natural resource management investments (Lenhart et al., 2005; De Vente et al., 2008). Sediment transport is a complicated process. It is not only related to the location, temporal scale, and geological, geomorphological, meteorological, and hydrological conditions of the basin but also to soil/sediment that is being eroded and the sediment production process (sediment particles), the properties of the interface where the erosion and sediment production process occurs (soil quality), and external factors (e.g., human activities) (Walling, 1983; Richards, 1993; Fraser et al., 1998; Diodato and Grauso, 2009; Borrelli et al., 2015; Marchamalo et al., 2016; Zhao et al., 2016). SDR conceptualizes the erosion-transport-deposition cycle (White, 2005) and reflects the capacity of the flow of a drainage basin to transport sediment.

However, it is difficult to measure the amount of erosion in a basin, which is required to directly calculate the SDR. Models have been used to estimate the amount of soil erosion. In addition to the widely used empirical models, such as the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965), the Modified Universal Soil Loss Equation (MUSLE) (Williams, 1975), the Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1991), and the rapid soil assessment model (Ni et al., 2014), some physical process based models, such as the ANSWERS (Beasley et al., 1980), WEPP (Nearing et al., 1989), KINEROS (Woolhiser et al., 1990), EUROSEM (Morgan et al., 1998), SWAT (Arnold et al., 1996), HowLeaky2008 (McClymont et al., 2008), and EROSION 3D (Stumpf et al., 2017) have also been developed (Bhattarai and Dutta D, 2007; Zhou et al., 2008; Vigiak et al., 2012; Lee and Kang, 2013; Woznicki and Nejadhashemi, 2013). Although important progress in these models had been achieved, the considerable data requirements and the inability

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[*] Corresponding author. Tel.: 86-10-62753351; fax: 86-10-62753351.
E-mail address: lth@pku.edu.cn (T. H. Li).

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to include all relevant erosion processes still hamper these models to accurately predict the erosion amount on the basin scales (Merritt et al., 2003; De Vente et al., 2007; Vaezi et al., 2017).

To overcome the difficulties in determining the erosion amount that is required for computing SDR, many empirical models have been proposed to directly calculate SDR through the regression analysis of a large amount of data for each factor that affects the SDR of a basin. The formulae for computing SDR can be classified into three types, based on the influencing factors that they consider: single-factor-based formulae, such as those proposed by Ebisemiju (1990), Ferro and Minacapilli (1995), Maner (1958), Mutchler et al. (1976), Roehl (1962), and Zhao et al. (2002); double-factor-based formulae, such as those proposed by Arnold (1996), Chen et al. (2001), Mutchler and Bowie (1976), Tang et al. (2001), and Yuan et al. (2008); and multi-factor-based formulae, such as those proposed by Kasai et al. (2001), Liu (2007), Williams (1994), and Xu (2010). The area of the drainage basin is the most frequently used factor in the single-factor-based formulae, although recent studies, such as De Vente et al. (2007) and Worrall et al. (2014), questioned the relationship of SDR to the catchment area and noted that area is a poor predictor of the variation in the sediment transfer processes. Precipitation and runoff are typically the most important factors in double-factor-based formulae, followed by the runoff depth and the gully density. Among the factors considered in multi-factor-based formulae are the drainage basin area, runoff volume, runoff coefficient, runoff depth, precipitation, precipitation intensity, precipitation duration, and gully depth. A few researchers, including Morgan et al. (1998) and Van Rompaey et al. (2001), have proposed methods based on an improved physical understanding of sediment transport processes to predict sediment delivery and deposition. Lu et al. (2004, 2006) noted that these models are restricted by the availability of model inputs and parameters, especially for large-scale applications, and they proposed an SDR model that incorporates the key elements of the catchment storm response and sediment delivery processes, based on a simple linear model of catchment response (Sivapalan et al., 2002).

Primarily induced by concentrated sediment flows in concentrated periods, the Loess Plateau has suffered the most severe soil erosion and is also the main source of sediment for the Yellow River (Gao et al., 2015). Previous studies in this region focused upon spatiotemporal changes in runoff and sediment (Zhao et al., 2017; Zheng et al., 2017) and the effects of human activities on runoff and sediment regime (Zhao et al., 2013; Gao et al., 2015; Mekonnen et al., 2015; Wei et al., 2017; Zhao et al., 2017), while few studied SDR. The SDR studies, such as those by Chen (2000), Liu (2007), and Xu (2010), used empirical models. Fu et al. (2010) developed a sediment rating curve-based formulation of SDR on the flood-event scale in the Lower Yellow River. So far, there are not any formulae for SDR calculation based upon an understanding of sediment transport processes from slopes and the river network in hyper-concentrated flow area.

This study aimed to develop a new model for SDR calculation that considered physical processes of sediment transport on the slope and river networks. With the proposed model, we revealed the variations of sediment transport over the past 60 years in the Yanhe River Basin in the Loess Plateau, China, a typical basin where hyper-concentrated flows occur.

2. Methodology

2.1. Study Area

The location of the Yanhe River is illustrated in Figure 1. The Yanhe River Basin, located between 108°45'E and 110° 28'E and 36°23'N and 37°17'N, has an area of 7,689 km^2 and is a typical highly erodible basin in the Loess Plateau (Wang et al., 2015), which is the best-known area in the world that suffers from serious soil erosion (Zhao et al., 2013). The Yanhe River Basin contains rolling hills and intersecting gullies and has elevations of 504 m to 1,731 m and slopes of 0 ~ 60°. The Yanhe River is a primary branch of the Yellow River. It is located on the right bank of the main stream of the Yellow River and originates in the Xiangzhou Mountains at the village of Tianciwan in Jingbian County. The Yanhe River flows through the counties of Jingbian, Zhidan, and Ansai and the Baota District of the city of Yan'an and into the Yellow River near the village of Liangshui'an, in the town of Nanhegou in Yanchang County. The main stream of the Yanhe River is 286.9 km long.

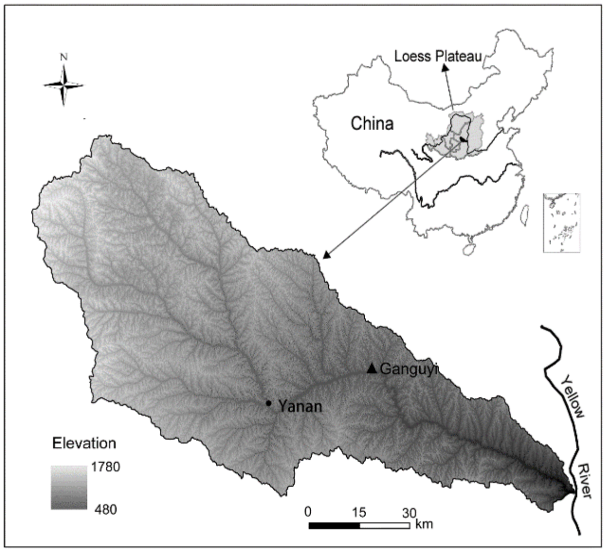

Figure 1. Location of the study area.

The Yanhe River Basin has a continental monsoon climate, an average annual temperature of approximately 9.2 °C and an average annual precipitation of 516 mm. The annual precipitation in the basin is extremely unevenly distributed, and most precipitation occurs during the summer in the form of rainstorms. Therefore, the annual runoff volume in the basin is also extremely uneven and has a large inter-annual variation. The Yanhe River Basin has a multi-year mean evaporation of 897.7 ~ 1,067.8 mm and a drought index that ranges from 1.57 to 1.92. The basin contains four main soil types, specifically, loessal soil, black soil, red soil, and silty soil. The vegetation in the basin forms a forest-steppe transition zone. The original forests have been destroyed, and the basin is now mostly covered by secondary vegetation.

The soil and water loss in the Yanhe River Basin is severe, due to the high density of gullies and flows with high sediment concentration when rainfalls occur. The Yanhe River Basin has an annual soil and water loss modulus of 9,000 ~ 15,000 t/km^2, which indicates that the erosion in the Yanhe River Basin is intense to extremely intense. The Yanhe River has very high sediment content, due to the severe soil and water loss in the basin. The adverse geomorphology of the gullies, the scouring of rainstorms during the summer, and the unfavorable land use types are the main causes of the soil and water loss. The Yanhe River Basin has a population of approximately 500,000 and a population density of approximately 65 people/ km^2. In recent decades, various soil and water conservation measures had been undertaken in the basin. As a result, the vegetation coverage in the basin steadily increased, and the sediment and water noticeably reduced.

The Ganguyi hydrological station, the control hydrological station at the outlet of the Yanhe River Basin, controls an area of 5,891 km^2 (Zhao et al., 2016). Hereinafter, the "Yanhe River Basin" in this paper refers to the control area of the Ganguyi hydrological station.

2.2. Data Preparation

Table 1 lists the descriptions of the data used in the present study.

Table 1. Data from the Ganguyi Hydrological Station in the Yanhe River Basin

Data item	Time period of data	Content of data	Data source
Discharge (m^3/s)	1952 ~ 1989, 1952 ~ 1997	Daily discharge, monthly mean discharge, maximum monthly discharge, and minimum monthly discharge	The Loess Plateau Region Data Sharing and Operational Service Center
Runoff volume (m^3)	1954 ~ 1989, 1990 ~ 2010	Monthly runoff volume	The Yellow River Sediment Bulletin; Wang and Fan, 2002
Sediment content (kg/m^3)	1952 ~ 1989, 1960 ~ 1997	Daily sediment content, monthly mean sediment content, maximum monthly sediment content, and minimum sediment content	The Loess Plateau Region Data Sharing and Operational Service Center
Sediment transport rate (kg/s)	1980 ~ 1997	Daily sediment transport rate	The Yellow River Conservancy Commission
Sediment discharge (10,000 t)	1954 ~ 1989, 1990 ~ 2010	Monthly sediment discharge and annual sediment discharge	The Yellow River Sediment Bulletin; Wang and Fan, 2002
Basin surface precipitation (mm)	1954 ~ 1989	Monthly surface precipitation	Wang and Fan, 2002

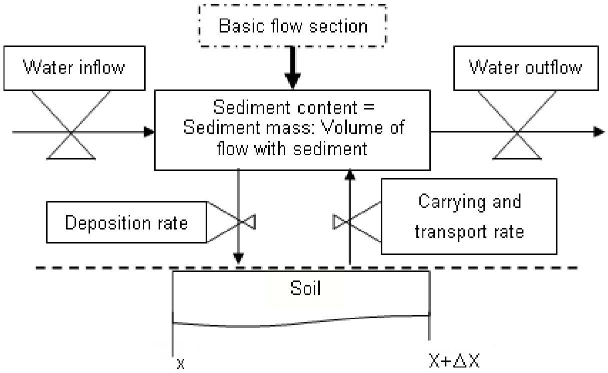

Figure 2. Flow chart of the basic cross section of sediment erosion, deposition, and transport from Rose (1983).

2.3. Basic Concepts Underpinning the Construction of the SDR Model for Hyper-Concentrated Flow Areas in the Loess Plateau

Runoff is the carrier and direct driving force of sediments. Rose (1983) investigated sediment erosion-transport and concluded that there is no significant difference in the erosion processes between rills, that sediment transport can occur within a rill, between two rills, or as slope flow and that the process by which surface flow carries sediment is similar to the bed load transport process in a river. Griffin et al. (1988) studied soil erosion, sediment production, and sediment discharge and noted that sediment transport is induced by runoff, and it is closely related to the total runoff volume and the discharge of the largest runoff.

According to the law of mass conservation, if it is assumed that there is a sediment transport unit whose total mass remains constant regardless of whether the sediment transport occurs on a surface slope or in a gully/river, the sediment transport process can be expressed as shown in Figure 2.

In Figure 2, the surface water unit is above the soil, and the sediment exchange between the flow and the soil is clearly expressed. The directions of the arrows indicate the movements of the flows, and the dotted line indicates the soil interface. Water inflow (outflow) can either be water inflow (outflow) from the slope surface or water inflow (outflow) from a river channel in the gully. Figure 2 also shows that in addition to the separate effects of landslide, gully, and precipitation processes on the soil, the sediment content in a flow is mainly influenced by the sediment deposition rate and the carrying and transport rate.

2.4. Assumptions in Construction of SDR Model for Hyper-Concentrated Flow Areas in the Loess Plateau

The model was developed based on the following three assumptions.

I. Assuming that the sediment particles have the same diameter and the same depositing rate, the ratio of the water contents of saturated water-sediment mixtures A and B is equal to the ratio of sediment contents of A and B. According to the theory of relative movement, water-sediment mixtures A and B that have the same flow velocities are static relative to each other. Therefore, the ratio of the water content of saturated water-sediment mixture A to B is the same as that of the sediment content of saturated water-sediment mixture A to B.

II. In hyper-concentrated flow areas of the Loess Plateau, water-sediment mixture flows along the slopes can be regarded as saturated during a rainfall occurrence. The study area is covered with very thick loess that is vulnerable to erosion by water. The very thick loess provided enough sediment sources for erosion. Flows with high sediment contents often occurred during rainfall, and the phenomenon that erosion, deposition, re-erosion and re-deposition occurs in the slopes were verified by many researchers (Wang et al., 1982; Zhang et al., 1994; Yang et al., 1997; Wu et al., 1997; Xu, 2004; Wu et al., 2005; Wang et al., 2006; Ma et al., 2008; Li et al., 2009a, 2009b; Xu, 2009; Li et al., 2011). This implies that water-sediment mixture flows along the slopes can be regarded as saturated.

III. The flow at the hydrological station with the maximum monthly sediment content is assumed to be of high sediment content. Research has shown that the sediment content of flows has an upper limit (Qian, 1979), which is called the saturated sediment content. Therefore, when the flow at the hydrological station has the maximum monthly sediment content, the flow is assumed to be saturated, and the water discharge that is measured at the hydrological station is the volume of water that is required for saturated sediment transport.

2.5. Construction of the SDR Model for Hyper-Concentrated Flow Area of the Loess Plateau

Based on the three assumptions stated above, the sediment content in the water-sediment mixture at location B is measured by sediment discharge (W) (units: kg or t). The water content in the water-sediment mixture at location B is the runoff volume during saturated sediment transport (Q_w) (units: m^3). The sediment content in the water-sediment mixture at conceptualized location A is the total amount of sediment yield of the slope (E) (units: kg or t). The water content in the water-sediment mixture at location A is the total runoff volume on the slope (Q_S) (units: m^3). This relation is described by Equation (1):

$$\frac{W}{E}=\frac{Q_w}{Q_s} \tag{1}$$

A basin with a certain area contains many slopes that are similar to slope A ($A_1, A_2, A_3, \ldots, A_n$). The sum of the erosion amounts (E_i) of all of the slopes is the total amount of erosion of the slopes (E), which is the total erosion of the basin. Similarly, the sum of the runoff volumes (Q_{si}) of all of the slopes is the total runoff volume of the slopes (Q_s) or the surface runoff volume of the basin. Thus, we have the following:

$$E=\sum_{i=1}^{n}E_i\ ,\ \ Qs=\sum_{i=1}^{n}Qs_i \tag{2}$$

According to the definition of the SDR, we have the following:

$$SDR=\frac{Y}{S}=\frac{W}{E}=\frac{Q_w}{Q_s} \tag{3}$$

where SDR represents the sediment delivery ratio, Y represents the sediment discharge that is measured at the section of the hydrological station, and S represents the amount of erosion of the basin. Thus, Equation (4) is obtained:

$$SDR=\frac{Q_w}{Q_s} \tag{4}$$

A sediment-transporting flow past a hydrological station can be divided into surface runoff and base flow. The base discharge can be calculated based on the multi-year mean value of the minimum runoff volumes. The surface runoff volume of a basin (i.e., the total runoff volume of the slopes in the basin) is the difference between the runoff volume that is gauged at the control hydrological station at the outlet of the basin and the base discharge that is measured at the hydrological station, which can be calculated by Equation (5):

$$Q_s=Q-Q_b \tag{5}$$

By substituting Equation (5) into Equation (4), Equation (6) is obtained:

$$SDR=\frac{Q_w}{Q-Q_b} \tag{6}$$

where Q_w represents the required volume of water when the saturated sediment discharge is measured at the control hydrological station at the outlet of the basin (units: m^3), Q represents the runoff volume that is measured at the hydrological station (i.e., the total runoff volume of the basin; units: m^3), and Q_b represents the base discharge (units: m^3), which can be obtained by various base flow separation methods (Arnold et al., 1995; Eckhardt, 2008; Longobardi and Villani, 2008; Partington et al., 2012) from long time series of daily runoff records.

2.6. Method for Calculating the SDR of the Yanhe River Basin

According to the analysis procedure described in the previous section, to calculate the SDR of the Yanhe Basin, it is necessary to calculate the total runoff volume and the base discharge of the basin, as well as the saturated water volume when the saturated sediment discharge is observed at Ganguyi hydrological station.

2.6.1. Runoff Volume

The runoff volume for each month is calculated based on the known monthly mean runoff volume (Q_m). The sum of the runoff volumes of all of the months within a year is the annual runoff volume, which is given by Equation (7):

$$Q = \sum_{i=1}^{12} (Q_m \times \Delta T_1) \tag{7}$$

where $i = 1 \sim 12$, Q represents the annual runoff volume at Ganguyi Hydrological Station (units: m^3), Q_m represents the monthly mean discharge at Ganguyi Hydrological Station (units: m^3/s), and ΔT_1 represents the time (ΔT_1 = 30 or 31 or 28 or 29 days × 24 hours/day × 3,600 s/hour).

2.6.2. Base Discharge

The minimum runoff volume for each month is calculated based on the known minimum monthly runoff volume (Q_{min}). The sum of the minimum runoff volumes of all of the months in a year is the annual minimum runoff volume. The multi-year minimum runoff volumes are then averaged to obtain the multi-year mean minimum runoff volume, which can be regarded as the base discharge (Q_b). Based on the measured data from 1952 to 1989, the value of the base discharge (Q_b) is 5,726.25 × 10^4 m^3.

2.6.3. Calculation of the Required Volume of Water for Saturated Sediment Discharge

The required volume of water for saturated sediment discharge is calculated in the following four steps.

(1) Calculating the discharge during saturated sediment transport

The flow past Ganguyi Hydrological Station during the maximum sediment content each month is considered to be sediment-saturated flow. The monthly runoff volume at Ganguyi Hydrological Station during saturated sediment transport is calculated based on the saturated sediment discharge. The annual saturated runoff volume at Ganguyi hydrological station is the sum of the saturated runoff volumes of the 12 months in the year. The annual saturated discharge can be calculated by dividing the annual saturated runoff volume by time using Equation (8):

$$Q_{y-max} = \frac{1}{\Delta T_2} \sum_{i=1}^{12} (Q_{max} \times \Delta T_1) \tag{8}$$

where $i = 1 \sim 12$, Q_{y-max} represents the annual runoff volume at Ganguyi Hydrological Station during saturated sediment transport (units: m^3/s), Q_{max} represents the discharge on the day that the maximum sediment content occurs each month (units: m^3/s), ΔT_1 represents the time (ΔT_1 = 30 or 31 or 28 or 29 days × 24 hours/day × 3,600 s/hour), and ΔT_2 represents the time (ΔT_2 = 365 days × 24 hours/day × 3,600 s/hour).

(2) Calculating the sediment discharge during saturated sediment transport

Without considering the chemical reactions in a water flow, the total volume of the saturated water-sediment mixture should be equal to the sum of volume of water and sediment. Based on the relationship between the monthly volume of saturated water (Q_{s-max}), the monthly saturated sediment discharge (W_s), the density of the sediment particles (ρ), and the monthly maximum sediment content during saturated sediment transport (S_{max}), the following relations can be obtained: 1) the volume of saturated water is equal to the runoff volume when flow is saturated with the sediment Q_{s-max}; 2) the volume of saturated sediment is equal to the fraction of saturated sediment discharge (W_s) and density of sediment particles (ρ); and the total volume of the saturated water-sediment mixture is equal to the fraction of the saturated sediment discharge (W_s) and saturated sediment content (S_{max}). Equation (9) describes the relationship of these variables:

$$Q_{s-max} + \frac{W_s}{\rho} = \frac{W_s}{S_{max}} \tag{9}$$

Algebraic operations are performed on Equation (9) to obtain Equation (10) for calculating the saturated sediment discharge (W_s):

$$W_s = Q_{s-max} \times \left(\frac{\rho \times S_{max}}{\rho - S_{max}}\right) \tag{10}$$

Then, the annual saturated sediment transport rate (G_{y-s}) can be calculated using Equation (11):

$$G_{y-s} = \frac{1}{(\Delta T_2 \times 1000)} \sum_{i=1}^{12} \left[(Q_{max} \times \Delta T_1) \times \left(\frac{\rho \times S_{max}}{\rho - S_{max}}\right)\right] \tag{11}$$

where $i = 1 \sim 12$, G_{y-s} represents the annual saturated sediment transport rate (units: t/s), and ρ represents the density of the sediment particles with a uniform diameter (ρ = 2.65 × 10^3 kg/m^3).

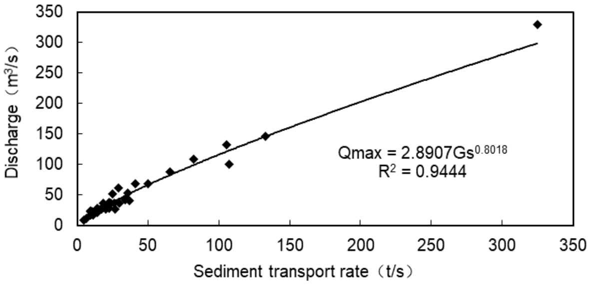

Figure 3. Relationship between discharge and sediment transport rate during saturated sediment transport at the Ganguyi Hydrological Station in the Yanhe River Basin.

(3) Constructing the relationship between the sediment transport rate and the discharge during saturated sediment transport

The annual saturated discharge during saturated sediment transport (Q_{y-max}) (units: m^3/s) can be calculated from Equation (9), and the annual saturated sediment transport rate during saturated sediment transport ($G_{y\text{-}s}$) (units: t/s) can be calculated from Equation (11). $Q_{y\text{-}max}$ and $G_{y\text{-}s}$ are calculated based on the data from 1952 to 1989 at Ganguyi Hydrological Station, and the relationship between $Q_{y\text{-}max}$ and $G_{y\text{-}s}$ can be constructed (Figure 3 and Equation (12)):

$$Q_{y-max} = 2.8907 G_{y-s}{}^{0.8018},\ \left(R^2 \ =\ 0.9444\right) \tag{12}$$

Equation (12) is also consistent with the results of previous studies on sediment transport rates and discharges of flows (Jing et al., 1993).

(4) Calculating the required water volume for saturated sediment discharge

Based on the assumptions described above, the saturated sediment discharge at Ganguyi Hydrological Station is the measured sediment discharge, and the water volume that is requisred for saturated sediment transport is the water volume that is required for the measured sediment discharge (i.e., the corresponding saturated runoff volume Q_w). The saturated sediment transport rate during saturated sediment discharge can be deduced based on the measured sediment discharge (W). Equation (13) can be obtained:

$$G_{w\text{-}s} = W / \Delta T_2 \tag{13}$$

where $G_{w\text{-}s}$ represents the saturated sediment transport rate during saturated sediment discharge (units: t/s), and W represents the saturated sediment discharge (units: t).

The saturated discharge during saturated sediment discharge can be calculated based on the known saturated sediment transport rate ($G_{w\text{-}s}$) and Equation (12), using the following equation:

$$Q_{w\text{-}max} = 2.8907(W / \Delta T_2)^{0.8018} \tag{14}$$

where $Q_{w\text{-}max}$ represents the saturated discharge (units: m^3/s).

The runoff volume during saturated sediment discharge ($Q_{w\text{-}max}$) is obtained, and then, the runoff volume during saturated sediment discharge (Q_w) can be calculated by Equation (15):

$$Q_w = 2.8907(W / \Delta T_2)^{0.8018} \times \Delta T_2 \tag{15}$$

2.6.4. The SDR Calculation in the Yanhe River Basin

According to Equations (6) and (15), the SDR calculating formula of the Yanhe River Basin can be expressed by Equation (16):

$$SDR = \frac{2.8907 \times (W / \Delta T_2)^{0.8018} \times \Delta T_2}{Q - Q_b} \tag{16}$$

where W represents the annual sediment discharge measured at the Ganguyi Hydrological Station (units: t), ΔT_2 represents the time interval (ΔT_2 = 365 days × 24 hours/day × 3,600 s/hour), Q represents the annual runoff volume measured at the Ganguyi Hydrological Station (units: m^3), and Q_b represents the base discharge of the Ganguyi Hydrological Station (units: m^3). Equation (16) can be used to calculate the SDR in the Yanhe River Basin or in a basin with properties that are similar to those of the Yanhe River Basin.

3. Results and Discussion

3.1. Variations of the SDR of the Yanhe River Basin

The values of the SDR of the Yanhe River Basin from 1952 to 2010 were calcSulated with the proposed SDR calculating formula with the data from the Yanhe River Basin from 1952 to 2010 (Figure 4).

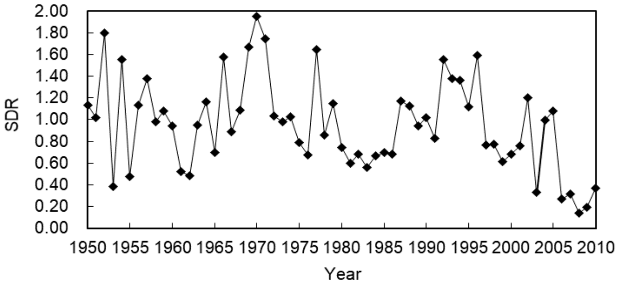

Figure 4. Variation of the annual average SDR in the Yanhe River Basin from 1952 to 2010.

Figure 4 shows that the SDR of the Yanhe River Basin from 1952 to 2010 exhibits a decreasing trend. Before 2000, the values of the SDR varied relatively smoothly and fluctuated around 1. After 2000, the SDR significantly decreased. The highest and second-highest values of the SDR between 1952 and 2010 were 1.96 (1970) and 1.75 (1971), respectively. The lowest value of the SDR between 1952 and 2010 was 0.14 (2008). Figure 5 shows a histogram of the annual mean values of the SDR in the basin for groups of decades between 1952 and 2010. The average SDR before the 1970s was 0.96, and the mean SDR between the 1970s and the 1990s was 0.99. The mean value of the SDR after the 1990s was 0.82. The mean values of the SDR for the 1950s, 1960s, 1970s, 1980s, 1990s, and the early 2000s were 0.99, 0.93, 1.19, 0.79, 1.10, and 0.57, respectively.

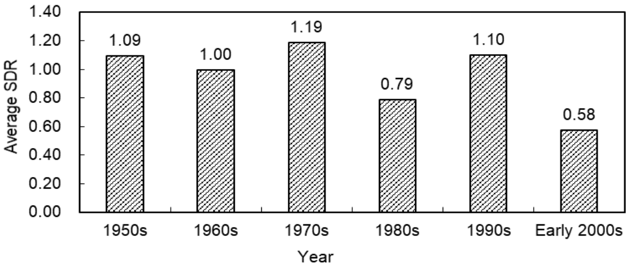

Figure 5. Variation of the annual average SDR values in the Yanhe River Basin for different periods from 1952 to 2010.

3.2. Discussion

3.2.1. Validation of the Results of the SDRs

The results of Figures 4 and 5 are consistent with the flow-sediment relationships in the region revealed by previous studies (Zhao et al., 2013; Wang et al., 2015; Gao et al., 2016). The conclusion that the SDR in the Loess Plateau is close to 1 has been widely recognized (Zheng, 2017). Jing et al. (1993) argued that, based on the characteristics of the gullies and riverbeds, the SDRs of areas on the Loess Plateau can be classified into two types: class I (SDR ≥ 0.95) and class II (SDR < 0.95). The SDRs of most areas belong to class I, and most areas at the end of the river have SDRs belonging to class II. The Yanhe River Basin is located in the core area of the Loess Plateau, and it normally belongs to Class I. Thus, the SDR in the Yanhe River Basin should be above 0.95. In this study, the average SDR in the 1950s, 1960s and 1970s is 1.03, and this is consistent with the results of Jing et al. (1993). After the 1970s, large water conservation practices were carried out in this basin, and the SDR should be reduced. The average SDR in the 1980s, 1990s and 2000s is 0.82, and this is also reasonable.

Figures 4 and 5 also show that the mean values of the SDR of the Yanhe River Basin between 1952 and 2010 fluctuate around a value of approximately 1 but exhibit an overall decreasing trend. The SDRs of the Yanhe River Basin exhibit a significant decreasing trend after the 1970s and a slightly increasing trend in the 1990s. Other studies also showed that runoff and sediment discharge had decreased significantly since the 1980s because of the implementation of soil and water conservation measures (Zhao et al., 2013; Wang et al., 2015). These trends indicated that the soil and water conservation measures that were implemented after the 1970s resulted in a decrease in the sediment transport capacity of the basin, which in turn resulted in a decreasing trend of the SDRs. Engineering projects that cause sediment impounding, such as check dams, were extensively developed in the 1980s and resulted in less sediment discharge (Gao et al., 2017; Wei et al., 2017), which in turn resulted in relatively low SDRs during this period. Most of the check dams were full in the 1990s, which resulted in a slight increase in the sediment transport capacity of the basin during this period and in turn resulted in an increase in the SDRs in the 1990s. Since the 1990s, the World Bank has carried out several projects of soil conservation in the Yanhe River Basin. These projects have resulted in a significant decrease in the SDR values after the 1990s.

As mentioned in the introduction section, the SDR is influenced by many factors of the basin. By considering the physical processes of sediment transport on the slope and river networks, the proposed SDR calculating formula only requires gauge data of sediment concentration, sediment delivery rate, sediment delivery volume, and runoff ratio from hydrological stations, which makes it easy to use.

3.2.2. Erosion Verification of the Basin

The amount of erosion in the Yanhe River Basin can also be conveniently estimated by the SDR of the basin and the measured sediment discharge at the basin outlet. The values of the erosion modulus of the river basin were compared with the results of previous studies to verify the reasonability of the results of the new SDR model. Statistical data on the annual erosion modulus for the control area of the Ganguyi hydrological station from 1952 to 1984 were obtained from the Loess Plateau Region Database of the Thematic Database for Human-Earth Systems of the Institute of Geographic Sciences and Natural Resources Research of the Chinese Academy of Sciences. A total of 33 sets of data for the SDR-calculated erosion modulus of the Yanhe River Basin from 1952 to 1984 and statistical data from the database are plotted in Figure 6.

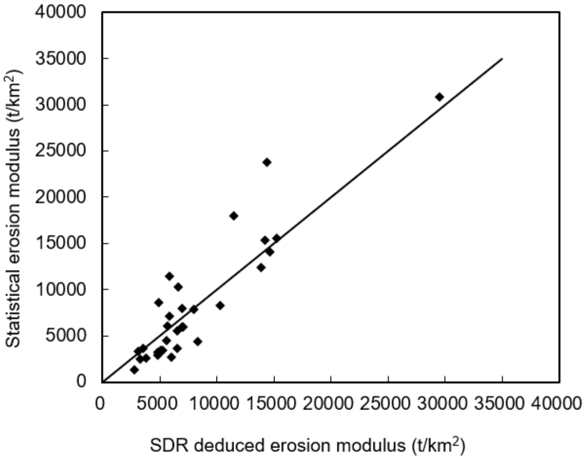

Figure 6. Comparison of erosion modulus data for the Yanhe River Basin from 1952 to 1984 from the statistical database and deduced by SDR results in this study.

In Figure 6, the scattered points are obviously distributed near the $y = x$ line, and the correlation coefficient is as high as 0.91, which indicates that the SDR-deduced erosion values are relatively consistent with the statistical values from the database. Therefore, the values of the erosion modulus of the Yanhe River Basin that were calculated using the new SDR model are considered quite accurate. This suggests that if the SDR is known, just with the observed sediment yield data at a basin outlet, the erosion in the river basin can be easily estimated.

4. Conclusions

A new SDR calculation formula was constructed by analyzing the physical process of sediment transport in the hyperconcentrated flow area of the Loess Plateau, China. Based on data measured from 1952 to 2010 at the Ganguyi hydrological station, which is a control hydrological station in the Yanhe River Basin, the SDR calculating formula is obtained. The new SDR formula is a function in the form of a fraction. The numerator of the formula is a power function relationship between the sediment transport rate and the discharge obtained by fitting the known data, while the denominator is the difference between the measured runoff volume and the base discharge.

With the SDR calculating formula, the SDRs of the Yanhe River Basin between 1952 and 2010 were computed. The multi-year (1952 ~ 2010) mean value of SDRs of the Yanhe River

Basin is 0.92, which is consistent with the results of previous studies. The erosion modulus of the Yanhe River Basin between 1952 and 1984 were also estimated by SDR, and the results are close to those that were calculated from existing statistical data with a correlation coefficient of 0.91, which also suggested the reasonability and accuracy of the proposed SDR calculating formula.

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