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Linking watershed geomorphic characteristics to sediment yield: Evidence from the Loess Plateau of China

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The geomorphic characteristics of a watershed affect the energy fluxes, mass movement, and water and sediment dispersion within the watershed. This paper examines how watershed complexity affects sediment yield in terms of rainfall and geomorphic characteristics. The geomorphic characteristics include primary, secondary and compound topographic attributes; watershed shape characteristics; relief parameters; and stream network characteristics. Because of the high co-dependence among these characteristics, partial least-squares regression (PLSR) was used to identify the relationships between the sediment yield and 29 selected watershed characteristics. The PLSR combines the features of a principal component analysis and multiple linear regression and is a robust multivariate regression method that is appropriate when the predictors exhibit multiple co-linearity. The first-order factors were determined by calculating the variable importance for the projection (VIP). Those variables with high VIP values are the most relevant for explaining the dependent variable. The results showed that the watershed shape and relief parameters have large influences on the sediment yield. The VIP values revealed that the sediment yield is primarily controlled by the plan curvature (VIP = 1.87) and the highest order channel length (VIP = 1.53), followed by the hypsometric integral (VIP = 1.49), rainfall (VIP = 1.44), basin relief (VIP = 1.19), slope (VIP = 1.15), sediment transport capacity index (VIP = 1.13), length ratio (VIP = 1.06), profile curvature (VIP = 1.01) and divide average relief (VIP = 1.00). This paper quantified the effects and relative importance of different geomorphic attributes on sediment yield. The insight provided by these results can be used in the selection of appropriate geomorphic variables for watershed erosion and hydrological models. Thus, this study is intended to elucidate the internal dynamics of sediment transport and storage in a watershed and provide a guide for watershed management.

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1. Introduction

Soil erosion is the dominant geomorphic process on much of the Earth's land surface (Toy et al., 2002) and includes the detachment, transport and storage of soil particles. Sediment is detached from the soil surface by raindrop impacts and by the shearing force of runoff (Jain and Kothyari, 2000). If the sediment that is available for transport is greater than the transport capacity, storage results in the accumulation of sediment on the soil surface (Trimble, 1975; Toy et al., 2002). The amount of sediment that passes through the outlet of a watershed comprises the sediment yield of the watershed (Glymph, 1954; Parsons et al., 2006; Fryirs, 2013; Vanmaercke et al., 2014). This yield is determined by the environmental conditions of the watershed, such as climate, soil, topography, land use, and various forms of human disturbance, which can affect the sediment supply, transport, storage, residence time, as well as the connectivity of sediment sources to the watershed outlet (Trimble, 1983; Zheng et al., 2008; Fryirs, 2013; Shi et al., 2013; Yan et al., 2013). Providing reliable tools for determining and quantifying sediment yield and its determinant factors is of essential importance for sustainable catchment management (Parsons et al., 2006).

In a study of global sediment yields and their controlling factors, Walling and Fang (2003) found that sediment yields are sensitive to many factors, including reservoir construction, land clearance and land-use change as well as other forms of land disturbance, such as mining activity, soil and water conservation measures, sediment control programs, and climate change. Human activities and climate change have a profound impact on watershed geomorphic characteristics and connectivity (Fryirs, 2013). Watershed longitudinal linkages are weakened with the construction of dams and reservoirs, which causes the sediment yield to decrease, whereas natural vegetation clearance and mining activity reduce the resistance of land surfaces and enhance the effectiveness of flow on sediments, thus increasing sediment yield (Renschler and Harbor, 2002; Gobin et al., 2003). The importance of

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land cover in preventing soil erosion is well known (Walling and Fang, 2003; Gyssels et al., 2005; Rey and Burylo, 2014). Land cover is considered to be a major factor that reduces soil erosion because land cover can improve soil structure, increase the surface roughness and infiltration rate, trap and retain sediment and break landscape connectivity (Burylo et al., 2007; Hudek et al., 2010; Ouyang et al., 2010; Preti et al., 2011; Lü et al., 2012; Rey and Burylo, 2014). Watershed management for soil and water conservation is primarily designed to increase water retention and reduce the on-site effects of soil erosion (Walling and Fang, 2003; Chen et al., 2007). Watershed management for soil and water conservation also reduces sediment transfer to river channels and sediment loads in rivers by increasing sediment storage and reducing sediment mobilization and watershed connectivity (Walling and Fang, 2003; Chen et al., 2007). Connectivity in geomorphic system was defined as the water-mediated transfer of sediment between two different compartments of the watershed sediment cascade (Fryirs, 2013). Watershed connectivity can be used to examine watershed internal structures and quantify the sediment cascade over a range of

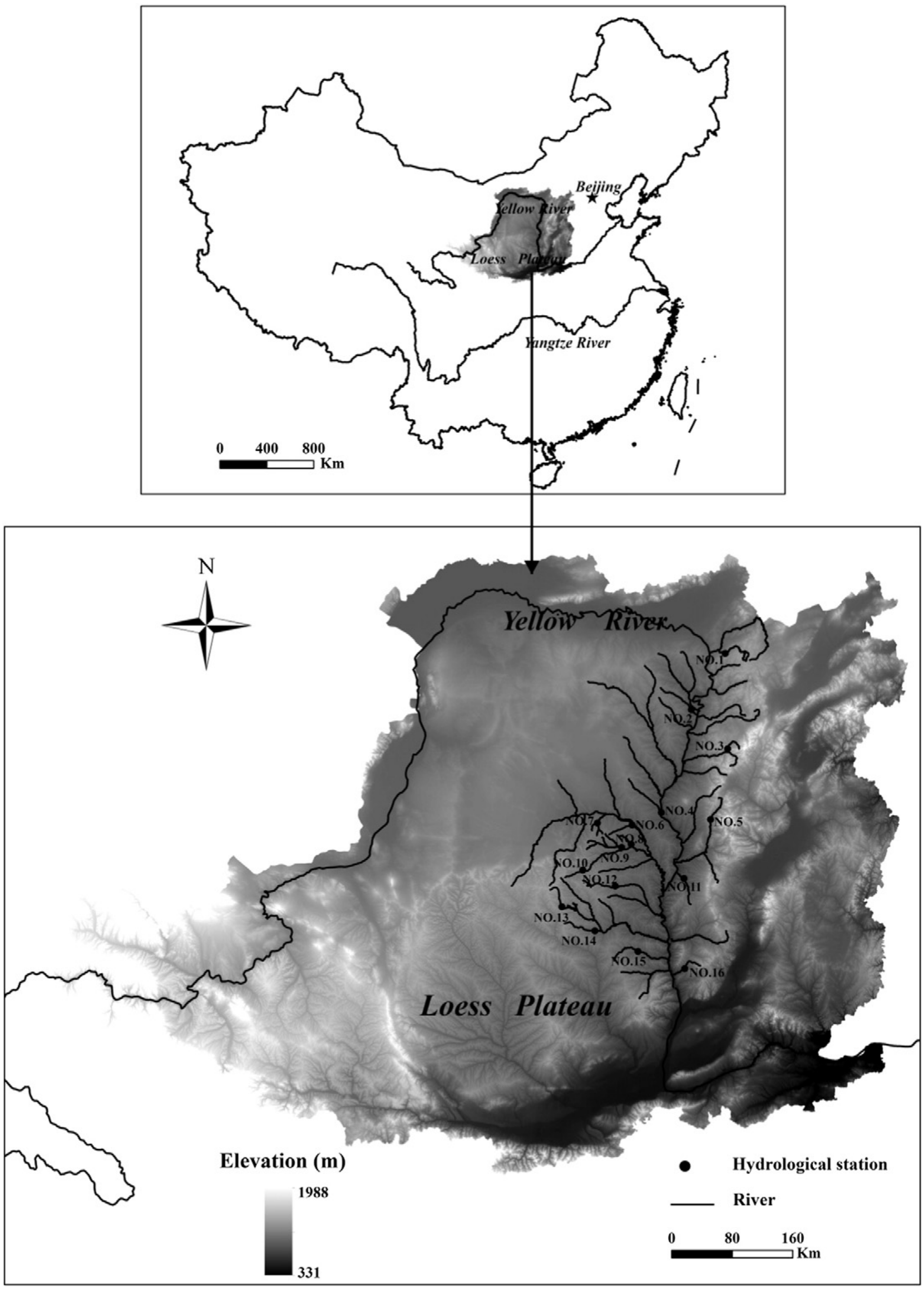

Fig. 1. Locations of the watersheds and hydrological stations used in this study.

Table 1
Locations and basic characteristics of the hydrological stations in this study.

Station no.	Station name	Latitude (N)	Longitude (E)	Controlled area (km^2)	Average sediment yield (t/ha)
1	Qingshuihe	39°54′	111°41′	541	31.2
2	Qingshui	39°15′	111°03′	735	97.9
3	Kelan	38°42′	111°34′	476	2.5
4	Shenjiawan	38°02′	110°29′	1121	40.6
5	Gedong	37°53′	111°14′	749	5.1
6	Mahuyu	37°53′	110°01′	371	17.6
7	Dianshi	37°56′	109°29′	327	31.5
8	Caoping	37°39′	109°59′	187	41.9
9	Lijiahe	37°37′	109°50′	807	22.7
10	Qingyangcha	37°22′	109°13′	662	26.4
11	Peigou	36°11′	110°45′	1023	49.9
12	Zichang	37°09′	109°42′	913	49.2
13	Xinghe	36°56′	108°52′	479	94.3
14	Zaoyuan	36°38′	109°20′	719	63.3
15	Linzhen	36°20′	109°59′	1121	3.8
16	Jixian	36°05′	110°40′	436	18.6

spatial and temporal scales. Analyses of watershed connectivity can help determine the dynamics of sediment yield in watersheds (Hooke, 2003; Fryirs, 2013). However, limitations of geomorphic knowledge are a key challenge to analyses of watershed connectivity and changes in sediment yield (Hooke, 2003; Fryirs, 2013).

Geomorphology affects soil thickness and water-thermal conditions that can lead to various spatial patterns of land cover (Cantón et al., 2004; Bertoldi et al., 2006). Therefore, geomorphic characteristics are important for restoring ecosystems and developing regulatory land management policies (Newson, 2002; Cantón et al., 2004; Poff et al., 2006; Xu et al., 2008). Moreover, geomorphic characteristics are important land surface properties that affect the energy fluxes, mass movement, and sediment and water dispersion within a watershed (Holmes et al., 2000; Bertoldi et al., 2006). All of these factors can affect watershed soil erosion. Geomorphological research can play an important role in the development and implementation of soil erosion assessment tools and soil conservation measures (Renschler and Harbor, 2002). However, many studies have overlooked the role of watershed geomorphic characteristics when determining the watershed sediment yield (Stocking, 1995; Poesen et al., 2003; Poff et al., 2006; Abu Salim, 2014).

In recent decades, emphasis has been placed on the development of quantitative physiographic methods to describe the evolution and behavior of surface drainage networks (Pareta and Pareta, 2011). In previous studies of watershed soil erosion and sediment yield, geomorphologists have focused on controlling soil erosion processes and assessing soil erosion risks by developing physical parameters and models (Renschler and Harbor, 2002). Moreover, the influence of watershed geomorphic attributes on soil erosion has generally been accounted for by the slope angle, slope length, and catchment area. These geomorphic parameters have been used extensively, such as in the Revised Universal Soil Loss Equation (RUSLE) and Soil and Water Assessment Tool (SWAT) (Wolock and McCabe, 2000; Renschler and Harbor, 2002). Using geographical information system (GIS) and digital elevation data, it is easy to quantitatively describe and compute geomorphic characteristics, such as the specific catchment area and the wetness index (Jain and Kothyari, 2000; Wolock and McCabe, 2000). Several studies have assessed the role of certain morphometric properties in increased regional debris flow susceptibility and landslide susceptibility, including the profile curvature, plan curvature, stream

Table 2
Abbreviations and descriptions of the selected topographic and geomorphologic attributes of the monitored watersheds.

Variable	Abbr.	Description or formula	References
Elevation	E	Average elevation of the subarea.	Speight (1980); Moore et al. (1991)
Slope	S	Average slope of the subarea.	Speight (1980); Moore et al. (1991)
Aspect	A	Average aspect of the subarea.	Speight (1980); Moore et al. (1991)
Plan curvature	Pl_c	Curvature in the contour line direction.	Moore and Thornes (1976)
Profile curvature	Pr_c	Curvature in the vertical plane parallel to the slope direction.	Moore and Thornes (1976)
Sediment transport capacity index	LS	$LS = (m + 1)(A_s/22.13)^m \times (\sin\beta/0.0896)^n$, where A_s is the specific catchment area ($m^2\ m^{-1}$), β is the slope gradient in degrees, m is 0.4, and n is 1.3.	Moore et al. (1991)
Topographic wetness index	TWI	$TWI = \ln(A_s/\tan\beta)$, where A_s is the specific catchment area ($m^2\ m^{-1}$), and β is the slope gradient in radians.	Moore et al. (1991)
Stream power index	SPI	$SPI = A_s \times \tan\beta$, where A_s is the specific catchment area ($m^2\ m^{-1}$), and β is the slope gradient in radians.	Moore et al. (1991)
Basin length	L	$L = 1.4 \times Area^{0.6}$, where Area is the area of the subarea.	Speight (1980); Moore et al. (1991); Sharma and Tiwari (2009a,b))
Form factor	F_f	$F_f = Area/L^2$, where Area is the area of the subarea.	Horton (1945); Sharma and Tiwari (2009a,b)
Basin shape	B_s	$B_s = L^2/Area$, where Area is the area of the subarea.	Schumm (1954); Sharma and Tiwari (2009a,b)
Circularity ratio	C_r	$C_r = (4\pi Area)/P^2$, where Area is the area of the subarea, and P is the perimeter of the subarea.	Miller (1953); Sharma and Tiwari (2009a,b)
Elongation ratio	E_r	$E_r = 2(Area/\pi)^{0.5}/L$, where Area is the area of the subarea.	Schumm (1956); Sharma and Tiwari (2009a,b)
Lemniscate ratio	L_r	$L_r = L^2/4Area$, where Area is the area of the subarea.	Chorley et al. (1957); Sharma and Tiwari (2009a,b)
Basin relief	BF	$BF = E_{max} - E_{min}$, where E_{max} and E_{min} are the highest and lowest elevations of the subarea, respectively.	Schumm (1954); Hadley and Schumm (1961); Sharma and Tiwari (2009a,b)
Divide average relief	D_f	$D_f = E_{da} - E_o$, where E_{da} and E_o are the average divide elevation of the subarea and the outlet elevation, respectively.	Farvolden (1963); Sharma and Tiwari (2009a,b)
Stream length	L_s	Average length of the streams in the subarea.	Horton (1945)
Relief ratio	R_r	$R_r = BF/L_{smax}$, where L_{smax} is the highest stream length.	Schumm (1954); Schumm (1956); Sharma and Tiwari (2009a,b)
Relative relief	R_{re}	$R_{re} = BF/P$, where P is the perimeter of the subarea.	Dury (1951); Sharma and Tiwari (2009a,b)
Hypsometric integral	H_i	$H_i = (E_{mean} - E_{min})/(E_{max} - E_{min})$, where E_{mean} is the mean elevation of the subarea.	Strahler (1957); Sharma and Tiwari (2009a,b)
Drainage density	D_d	$D_d = L_{st}/Area$, where L_{st} is the total length of the streams in the subarea, and Area is the area of the subarea.	Horton (1945); Sharma and Tiwari (2009a,b)
Strahler order	S_o	Ordered stream network based on the Strahler method.	Strahler (1964)
Shreve magnitude	S_m	Ordered stream network based on the Shreve method.	Shreve (1966)
Length ratio	R_l	$R_l = L_{s(i)}/L_{s(i-1)}$, where $L_{s(i)}$ and $L_{s(i-1)}$ are the average lengths of streams of order i and order i − 1, respectively.	Horton (1945); Sharma and Tiwari (2009a,b)
Slope ratio	R_s	$R_s = S_i/S_{i+1}$, where S_i and S_{i+1} are the average slopes of streams of order i and order i + 1, respectively.	Sharma and Tiwari (2009a,b); Sreedevi et al. (2009)
Highest order channel length	L_h	Average length of the highest order stream.	Horton (1945)

Table 3
Basic statistics for the selected watershed characteristics.

Variable	Units	Minimum	Maximum	Mean	Standard deviation
Sediment yield	t/ha	0.2	213.4	38.6	43.4
Rainfall	mm	250.9	774.4	443.0	113.6
Area	km^2	187	1121	666.2	275.0
Perimeter	km	71.1	193.1	137.7	34.0
E	km	1.1	1.6	1.3	0.2
S	°	9.3	17.1	13.2	2.4
A	°	172.0	185.7	177.8	4.2
Pl_c	rad/km	1.7	17.7	9.0	4.7
Pr_c	rad/km	3.7	18.6	9.9	4.2
LS	None	12.5	32.6	22.8	6.1
TWI	None	3.1	4.7	4.2	0.5
SPI	None	8.2	87.5	20.8	20.0
L	$km^{6/5}$	61.1	94.6	67.7	17.7
F_f	None	0.1	0.2	0.1	0.01
B_s	None	5.6	8.0	7.1	0.7
C_r	None	0.3	0.6	0.4	0.1
E_r	None	0.4	0.5	0.4	0.02
L_r	None	1.4	2.0	1.8	0.2
BF	m	40.2	76.4	57.8	11.2
D_f	m	155.6	466.7	267.5	95.4
L_s	km	12.7	42.2	25.0	8.4
R_r	None	0.6	41.8	14.1	10.4
R_{re}	None	0.2	0.7	0.5	0.1
H_i	None	0.2	0.6	0.5	0.1
D_d	km/km^2	1.1	4.4	2.1	0.9
S_o	None	3	5	3.7	0.7
S_m	None	15	95	51.1	24.1
R_l	None	0.4	0.9	0.7	0.1
R_s	None	0.9	2.0	1.4	0.3
L_h	km	1.1	26.4	8.3	6.7

power index and topographic wetness index (Tunusluoglu et al., 2007; Chen and Yu, 2011; Abu Salim, 2014). However, few studies have compared the influence and importance of these geomorphic attributes on sediment yield within a watershed.

This paper contributes to understanding the effects of geomorphic attributes on sediment yield by examining the role of geomorphic attributes in determining watershed sediment yield. Specifically, the objectives of this study were to: (1) quantify and analyze the differences in the geomorphic attributes and sediment yields of contrasting watersheds; (2) infer the influence of geomorphic characteristics on watershed sediment yield; and (3) compare the relative importance of different geomorphic attributes to sediment yield. Addressing these objectives will increase the understanding of how geomorphic attributes affect soil erosion and can be used to help select appropriate geomorphic variables of watershed erosion for use in hydrological models.

2. Regional setting

The Loess Plateau in China is located in the upper and middle reaches of the Yellow River between 33°43′ and 42°13′N latitude and between 100°54′ and 114°33′E longitude and covers an area of 630,000 km^2 (Fig. 1). This region is characterized by a continental monsoon climate with a mean annual temperature of 4.3 °C in the northwest and 14.3 °C in the southeast.

Sixteen monitored watersheds of less than 1500 km^2 each were selected as the case study area (Fig. 1 and Table 1). The 16 studied hydrological stations are located in the middle of the Loess Plateau within the sediment-rich region of the Yellow River Basin (Fig. 1 and Table 1). The average annual precipitation in the study area is 456 mm (Gao et al., 2012). Approximately 78% of the annual rainfall occurs between May and September (Gao et al., 2012). The soil in this region is primarily developed from loess parent materials and has a silty loam texture.

3. Materials and methods

3.1. Data collection

Daily rainfall and sediment yield data recorded at the 16 hydrological stations were obtained from the Loess Plateau Data Sharing Service Center (http://loess.geodata.cn/Portal/?). The annual data were derived from higher resolution daily data. The study extended from 1980 to 1989; this time period was selected because limited human activities occurred during the study period (Chen et al., 2007). A digital elevation model (DEM) with a resolution of 30 m × 30 m was downloaded from the Geospatial Data Cloud. Based on the locations of the 16 hydrological stations and the DEM data, the boundaries of the watersheds monitored by the hydrological stations were extracted by hydrologic modeling using ArcGIS (Fig. 1).

3.2. Topographic attributes

The primary topographic attributes were directly calculated from the DEM data and consist of elevation (E), slope (S) and aspect (A) (Speight, 1980; Moore et al., 1991). The secondary topographic attributes were derived from the primary attributes and comprise profile curvature (Pr_c) and plan curvature (Pl_c) (Moore and Thornes, 1976; Moore et al., 1991). The sediment transport capacity index (LS), topographic wetness index (TWI) and stream power index (SPI) are compound topographic attributes that include combinations of the primary attributes and describe or characterize the spatial variability of specific processes that occur in the landscape (Moore et al., 1991). Table 2 describes these topographic attributes and lists their abbreviations, which are used in the subsequent text.

3.3. Geomorphic attributes

The watershed shape characteristics, relief parameters, and stream network characteristics were derived using the boundaries of the watersheds and DEM data. The watershed shape parameters include the form factor (F_f), basin shape (B_s), basin length (L), circularity ratio (C_r), elongation ratio (E_r) and lemniscate ratio (L_r) (Sharma and Tiwari, 2009a,b). The relief parameters include the basin relief (BF), divide average relief (D_f), relief ratio (R_r), relative relief (R_{re}) and hypsometric integral (H_i) (Sharma and Tiwari, 2009a,b). The stream network

Table 4
Values of the intercorrelation coefficients between selected watershed characteristics (independent variables or predictors).

	Area	L	F_f	B_s	L_s	C_r	E_r	L_r
Area	1							
L	0.995**	1						
F_f	−0.950**	−0.975**	1					
B_s	0.979**	0.994**	−0.993**	1				
L_s	0.742**	0.748**	−0.732**	0.745**	1			
C_r	−0.165*	−0.196*	0.241**	−0.221**	−0.434**	1		
E_r	−0.958**	−0.981**	1.000**	−0.996**	−0.736**	0.237**	1	
L_r	0.979**	0.994**	−0.993**	1.000**	0.745**	−0.221**	−0.996**	1

** Significant at $\alpha = 0.01$.
* Significant at $\alpha = 0.05$.

Table 5
Summary of the PLSR model for specific sediment yield (R^2: the fraction of the total variation of dependent variables explained by the optimal PLSR model; Q^2: the fraction of the total variation of dependent variables that can be predicted by the optimal PLSR model according to the cross-validation; Component: the number of components in PLSR model; Explained variability in Y (%): the fraction of the variation of dependent variables explained by a component in PLSR model; RMSECV: the root-mean-square error of cross-validation; Q^2_{cum}: the cumulative fraction of the variation of dependent variables that can be predicted by overall PLSR components according to the cross-validation.).

Response variable Y	R^2	Q^2	Component	Explained variability in Y (%)	Cumulative explained variability in Y (%)	RMSECV (t/ha)	Q^2_{cum}
Sediment yield	0.627	0.550	1	25.8	25.8	35.4	0.202
			2	21.6	47.4	29.9	0.414
			3	10.3	57.7	26.9	0.518
			4	4.98	62.7	24.8	0.550
			5	1.99	64.6	25.4	0.541

characteristics include the drainage density (D_d), length ratio (R_l), slope ratio (R_s), Strahler order (S_o), Shreve magnitude (S_m) and highest order channel length (L_h) (Sharma and Tiwari, 2009a,b). Table 2 describes all the selected geomorphic parameters and lists their abbreviations, which are used in the subsequent text.

3.4. Partial least-squares regression (PLSR)

PLSR is an alternative method to ordinary regression for problems with partly or highly collinear predictor variables and is also particularly suitable for multivariate problems in which the number of observations is less than the number of possible predictors (Carrascal et al., 2009; Nash and Chaloud, 2011; Onderka et al., 2012). Using PLSR, the relationships between the predictors and the response variables can be inferred from the weights and the regression coefficients of the individual predictors in the group comprising the most explanatory components. The influence of a predictor on a dependent variable and thus the importance of the predictor are indicated by the variable importance for the projection (VIP). Those terms with high VIP values are the most relevant for explaining the dependent variable. The regression coefficients of the PLSR model were used to determine the direction of the relationship between each of the individual predictors and the dependent variable. To overcome the problem of over-fitting, the appropriate number of components to include in the PLSR model was determined by cross-validation to find an optimal balance between the explained variation in the response (R^2) and the predictive ability of the model (goodness of prediction, Q^2) (Onderka et al., 2012; Shi et al., 2013; Yan et al., 2013). All of the predictors must be normally distributed. If not, the predictors were logarithmically transformed to achieve a normal distribution.

4. Results

4.1. Sediment yield characteristics

The mean annual sediment yield of each watershed varies widely for the period from 1980 to 1989 (Table 1). The No. 2 subarea has the highest mean sediment yield of the 16 watersheds at 97.9 t ha^{-1}. The lowest mean annual sediment yield is 2.5 t ha^{-1} and occurs in the No. 3 watershed. The No. 4 and No. 15 watersheds both have an area of 1121 km^2, but the sediment yields are 40.6 and 3.8 t ha^{-1}, respectively. The No. 8 watershed is the smallest in this study (187 km^2), but the sediment yield is 41.9 t ha^{-1}. The annual sediment yield for the 16 watersheds varies widely from 0.2 to 213.4 t ha^{-1} (Table 3). The mean annual sediment yield of the 16 watersheds is 38.6 t ha^{-1}.

4.2. Geomorphic characteristics

The statistics for the geomorphic characteristics of the watersheds are shown in Table 3. The area and annual rainfall of the 16 watersheds also vary widely from 187 to 1121 km^2 and from 250.9 to 774.4 mm, respectively. The E, TWI, F_f, B_s, C_r, E_r, L_r, R_{re}, H_i, D_d, S_o, R_l and R_s parameters all have standard deviations less than 1. The mean H_i value is 0.5, which indicates that the hydrological station-controlled watersheds are between the monadnock and inequilibrium stages. The S values vary less, from 9.3 to 17.1°, and the A values range from 172.0 to 185.7°. The mean Pl_c and Pr_c values are 9.0 rad/km and 9.9 rad/km, respectively. All of the Pl_c and Pr_c values of the 16 watersheds are positive, which indicates a surface that is convex upward across and concave upward along the direction of maximum slope. The LS ranges from 12.5 to 32.6, and the SPI varies greatly from 8.2 to 87.5. The mean R_r, S_m and L_h values are 14.1, 51.1 and 8.3 km, respectively. Nine variables were randomly chosen from among all of the variables to perform a preliminary correlation analysis (Table 4). The results show that there is no significant relationship between annual rainfall and L_s, but for the remaining pairs of different variables there is significant correlation at the 0.01 or the 0.05 probability level between the variables.

4.3. Relating the geomorphic characteristics to sediment yield

Table 5 summarizes the PLSR model for the specific sediment yield. The prediction error decreases with an increasing number of components and has a minimum root-mean-square error of cross-validation (RMSECV) with four components. A further increase in the number of components leads to larger prediction errors, which suggests that the subsequent components are not strongly correlated with the residuals of the predicted variable. In the model, the first component explains 25.8% of the variance in the sediment yield dataset (Table 5). The addition of the second component can cumulatively explain 47.4% of the total variance in the sediment yield. By adding the third and fourth components, the PLSR model can cumulatively explain 57.7% and 62.7% of the total variance in the sediment yield, respectively. Adding more components to the PLSR model does not substantially improve the explained variance.

The weights of the predictors in the first and second components are presented in Fig. 2. The first component of the sediment model is

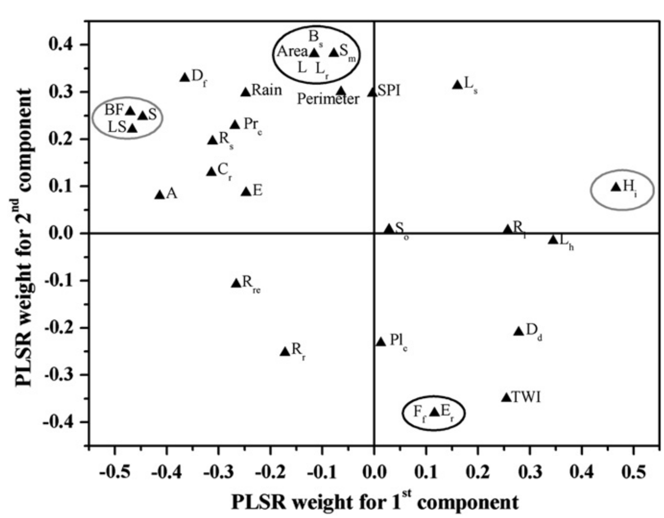

Fig. 2. Weight plot for the first and second PLSR components of sediment yield. The predictors with the highest weights for the individual components are highlighted in circles.

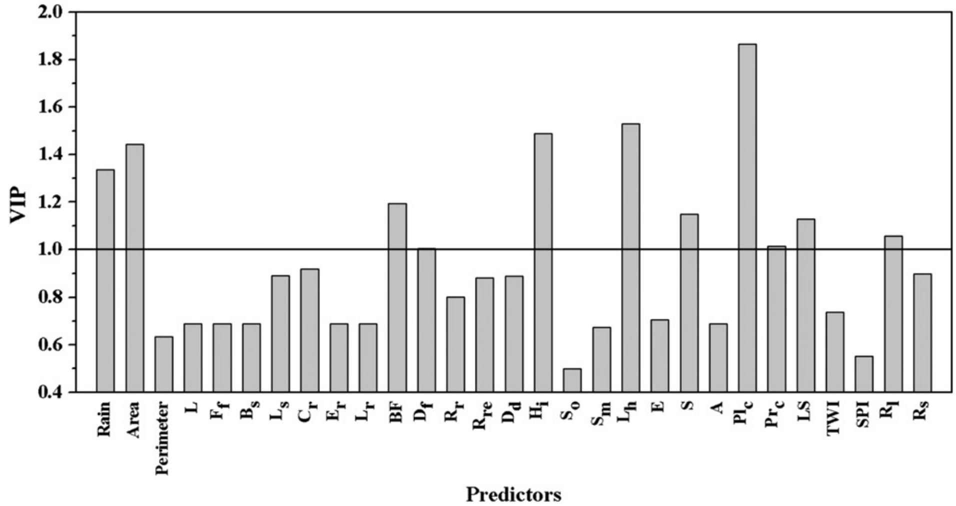

Fig. 3. Variable importance of the projection (VIP) of each predictor of sediment yield.

dominated by H_i on the positive side, and BF, LS and S on the negative side. The S_m, L_r, B_s, L and area parameters dominate the second component on the positive side, whereas F_f and E_r dominate this component on the negative side.

Figs. 3 and 4 show the VIP value and regression coefficient, respectively, of each watershed characteristic of the sediment yield. The highest VIP values are for Pl_c (VIP = 1.87, b = −0.54) and L_h (VIP = 1.53, b = 0.38). However, higher Pl_c and L_h values are correlated with lower and higher sediment yields, respectively (as indicated by the negative and positive regression coefficients, respectively). The highest VIP values are observed for H_i (VIP = 1.49, b = 0.20), area (VIP = 1.44, b = −0.38), rainfall (VIP = 1.34, b = 0.31), BF (VIP = 1.19, b = 0.10), S (VIP = 1.15, b = 0.11), LS (VIP = 1.13, b = 0.06), R_l (VIP = 1.06, b = 0.12), Pr_c (VIP = 1.01, b = −0.25), and D_f (VIP = 1.00, b = −0.16). The regression coefficients indicate that the sediment yield would be lower for higher area, Pr_c and D_f values and higher for higher H_i, rainfall, BF, S, LS and R_l values. The VIP values of the other predictors are less than 1. Therefore, these predictors are considered to be of minor importance for sediment yield prediction.

5. Discussion

Geomorphic characteristics can influence soil water distribution within a watershed and are important for determining changes in sediment yield (Stocking, 1995; Renschler and Harbor, 2002; Chen and Yu, 2011). The Chinese Loess Plateau, which is located in the middle reaches of the Yellow River Basin, suffers serious soil erosion and has a mean annual soil loss rate of 5000–10,000 t km^{-2} $year^{-1}$ in most areas and higher than 20,000 t km^{-2} $year^{-1}$ in certain areas (Fu et al., 2005; Wang et al., 2006; Li et al., 2010). Taking 16 watersheds monitored by hydrological stations in the Chinese Loess Plateau as a case, this study assessed the relative importance of watershed characteristics on sediment yield. The results of the correlation analysis showed that many of the predictors are co-linear (Table 4). The PLSR methodology offers a novel approach to interpreting watershed geomorphic characteristics that is considered to be advantageous because it can eliminate some of the co-dependencies of the variables and provide an unbiased view of the relationships between the predictors and the response variables (Onderka et al., 2012; Shi et al., 2013; Yan et al., 2013). Therefore, the PLSR methodology was used to measure the effects of the watershed features on the sediment yield. Initially, a PLSR model with four components was extracted. The weight plot shows that the watershed shape parameters and the relief parameters dominate the first and second components (Fig. 2). The watershed shape affects the dynamics of the river tributaries on the formation of the surface morphology and determines the volume of the watershed sediment yields. The relief characteristics of a watershed can determine the erosion stage that the tributaries reach during the formation of their surface morphologies

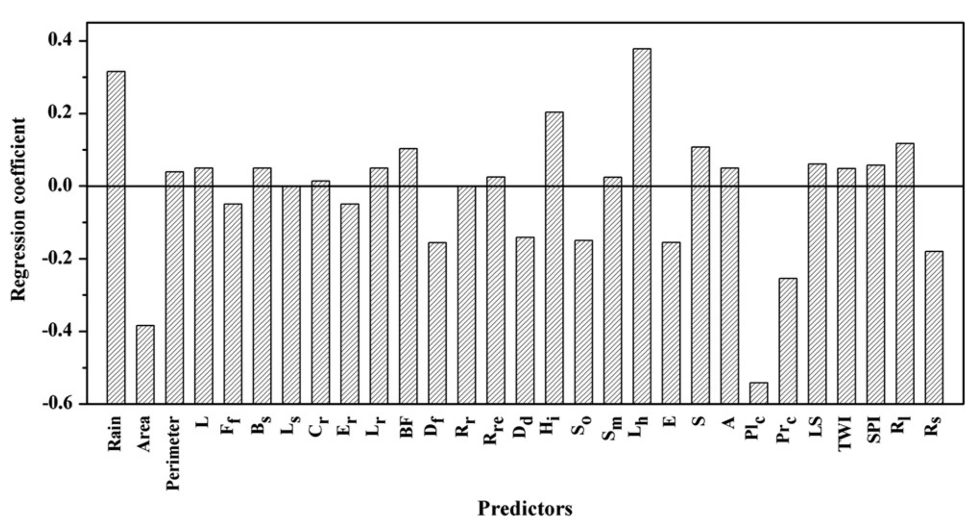

Fig. 4. Regression coefficients of each predictor of sediment yield.

and storage capacity that can be produced at this stage for a given topography (Abu Salim, 2014).

Although the weight plot indicates the importance of individual watershed characteristics for the observed sediment yield, a more convenient and comprehensive expression of the importance of the predictors can be obtained from their VIP values (Fig. 3) and regression coefficients (Fig. 4). Note that all of the variables considered are related to the specific sediment yield, but only some of them have VIP values that are greater than 1. The predictors with VIP values less than 1 are considered to be of minor importance for prediction purposes (Onderka et al., 2012); thus, the discussion is restricted to only those variables with VIP values greater than 1 in this study. Plan curvature displays first-order control on the sediment yield and has a negative regression coefficient, which indicates that plan curvature is the main controlling factor for sediment yield and suggests that the amount of sediment increases with decreases in plan curvature. Plan curvature is the curvature of a contour line that is formed by the intersection of a horizontal plane with the ground surface, and it influences erosion by controlling the convergence or divergence of water that flows downhill (Nefeslioglu et al., 2008). A positive plan curvature value indicates a convex upward surface across the direction of maximum slope, which tends to diverge the flow of water, whereas a negative plan curvature indicates a concave upward surface, which tends to converge with runoff, and a value of zero indicates a flat surface (Chang et al., 2007; Nefeslioglu et al., 2008). Thus, higher plan curvature values lead to lower sediment yields (Pennock, 2003). Nefeslioglu et al. (2008) also found that higher plan curvature values had lower soil erosion susceptibility (Table 6). However, Tunusluoglu et al. (2007) obtained opposite results (Table 6) because lithologic variables were considered in their study.

In addition to plan curvature values, the regression coefficients for the basin area, profile curvature and divide average relief also suggest negative correlations with sediment yield. Table 7 shows the negative relationship between sediment yield and drainage basin area in different regions (Walling, 1983; De Vente and Poesen, 2005), which is similar to the results of our study. The sediment yield decreased with increases in basin area. There are several reasons for this negative correlation: (1) small watersheds have large relief ratios, which lead to high erosion intensity; (2) a single rainstorm can easily cover a small watershed but not a large watershed (Abu Salim, 2014); and (3) increases in watershed area increase the opportunities for sediment storage on floodplains (Walling, 1983). According to Nefeslioglu et al. (2008) and Tunusluoglu et al. (2007), a negative relationship occurs between profile curvature and soil erosion susceptibility (Table 6), which is similar to the results found in our study. Profile curvature is the curvature in the vertical plane parallel to the slope direction; this curvature is a measure of the rate of change of the slope gradient. Thus, this parameter directly controls the velocity of the water flow and slope erosion (Nefeslioglu et al., 2008). A negative profile curvature value indicates a convex upward surface in the direction of maximum slope, which can accelerate the runoff and increase the erosion rate; a positive profile curvature value indicates a concave upward surface, which can reduce the flow velocity and increase runoff storage; and a value of zero indicates a flat surface (Chang et al., 2007). Higher profile curvature values predict a lower sediment yield.

Table 6
Overview of the beta coefficients between watershed characteristics and soil erosion susceptibility in the published literature.

Variable	Beta coefficients[a]	References
Pl_c	−0.064	Nefeslioglu et al. (2008)
	1.148	Tunusluoglu et al. (2007)
Pr_c	−0.079	Nefeslioglu et al. (2008)
	−3.294	Tunusluoglu et al. (2007)
LS	0.022	Nefeslioglu et al. (2008)
	12.287	Tunusluoglu et al. (2007)

[a] Beta coefficient: the regression coefficient of linear regression.

Table 7
Overview of the relationships between specific sediment yield (SSY) and drainage basin area (A) in the published literature.

Location	Equation	References
Israel	$SSY = 753.7A^{-0.41}$ ($R^2 = 0.22$, n = 17, p = 0.6)	Inbar (1992)
Tunisia 1	$SSY = 11954A^{-0.37}$ ($R^2 = 0.58$, n = 14, p = 0.002)	Lahlou (1996)
Tunisia 2	$SSY = 2027A^{-064}$ ($R^2 = 0.20$, n = 23, p = 0.03)	Albergel et al. (2000)
Morocco	$SSY = 19193A^{-0.43}$ ($R^2 = 0.59$, n = 17, p < 0.001)	(Lahlou, 1996; Fox et al., 1997)
Spain	$SSY = 4139A^{-0.44}$ ($R^2 = 0.17$, n = 60, p < 0.001)	Avendaño Salas and Cobo Rayán (1997)

The second most important variable is the highest-order channel length, which shows a positive regression coefficient. There is also a positive relationship between the length ratio and sediment yield. The watershed size increases with increases in Strahler order, and an exponential relationship occurs between channel length and watershed size (Hughes et al., 2011). Therefore, the length of the highest-order channel is indicative of the area that contributes to watershed soil erosion (Magesh et al., 2011). The value of the length ratio between successive stream orders of a watershed varies because of differences in the slope and topographic conditions (Sreedevi et al., 2009) and has an important relationship with the surface flow discharge and erosional stage of the watershed. Higher length ratio values indicate a high relief and low-permeability rocks (Sreedevi et al., 2009). Therefore, the sediment yield increases with increasing highest-order channel length and length ratio values.

In addition to the highest-order channel length, there are positive relationships between sediment yield and hypsometric integral, rainfall, basin relief, slope, and sediment transport capacity index. The hypsometric integral can be interpreted as the percentage of the volume of the original watershed that has not been eroded (Strahler, 1957; Bishop et al., 2002; Singh et al., 2008; Prasannakumar et al., 2011). High hypsometric integral values generally indicate that there is relatively limited erosion in the watershed and that the watershed is highly susceptible to erosion (hypsometric integral ≥0.60, inequilibrium stage). With values of 0.3 ≤ hypsometric integral ≤0.60, the cycle of erosion is in equilibrium and transforms from the inequilibrium stage to the monadnock stage; when the hypsometric integral is ≤30%, the cycle of erosion is in the monadnock stage, which indicates a fully stabilized watershed (Strahler, 1957; Bishop et al., 2002; Singh et al., 2008; Prasannakumar et al., 2011). In monadnock valleys, the drainage system becomes extremely broad, and most of the landscape relief has been denuded and eroded. In addition, high hypsometric integral values indicate that the speed of forming water flows is high and that soil particles travel short distances, which significantly increase soil erosion and sediment yield (Abu Salim, 2014). In our study, there is a positive relationship between sediment yield and rainfall (b = 0.31), which is most likely a result of high rainfall increasing runoff (Abu Salim, 2014; Huang et al., 2014).

The relief characteristics of watersheds have an important influence on drainage development, surface and subsurface water flow, permeability, landform development and associated features of the terrain (Biswas et al., 1999; Magesh et al., 2011; Prasannakumar et al., 2011; Abu Salim, 2014). Basin relief is an important factor for understanding the denudational characteristics of watersheds. Higher basin relief values indicate low infiltration and high runoff of drainage. Schumm (1954) also found a strong positive correlation between basin relief and sediment yield. As expected, a steeper watershed can produce a higher sediment yield, which is indicated by the positive slope regression coefficient. The slope attribute plays a significant role in determining the relationship between infiltration and runoff. Infiltration is inversely related to the incline; i.e., gentler slopes result in higher infiltration and less runoff (Sreedevi et al., 2009). An increase in slope increases the amount and speed of the runoff, which increases the erosion and sediment load. The sediment transport capacity index is derived from unit stream power theory and equivalent to the length-slope factor in RUSLE (Nefeslioglu et al., 2008). In the present study, the relationship between the sediment yield and sediment transport capacity index is positive. These results are consistent with the findings of Nefeslioglu et al. (2008) and Tunusluoglu et al. (2007) (Table 6), who found that soil erosion susceptibility is proportional to the sediment transport capacity index.

6. Conclusions

The aim of this study was to identify the relative importance of different watershed geomorphic characteristics for sediment yield. Using PLSR, which is relatively insensitive to co-dependencies among the predictor variables, it was found that the watershed shape parameters and relief parameters were the major factors that affected sediment yield in the Chinese Loess Plateau. The results of this study indicate that sediment yield is primarily controlled by the plan curvature and highest-order channel length, followed by the hypsometric integral, rainfall, basin relief, slope, sediment transport capacity index, length ratio, profile curvature and divide average relief. However, the highest-order channel length, hypsometric integral, rainfall, basin relief, slope, sediment transport capacity index, and length ratio determined the amount and formational speed of runoff and the capacity of sediment transport, and these values had positive impacts on the sediment yield. However, the plan curvature, area, profile curvature and divide average relief were negatively correlated with sediment yield because of controls on storage and the timeframe of sediment storage. This study also analyzed the relative importance of different watershed geomorphic characteristics for sediment yield. When developing soil erosion models and regulatory policies, geomorphic variables can be selected based on their contributions and importance to sediment yield. Thus, this study provides useful information on the internal dynamics of sediment transport and storage in watersheds and can be used to guide watershed management.

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