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The relationship between sediment yield and catchment characteristics in the middle Yellow River basin of China

LU JINFA[1] **& HUANG XIUHUA**[2]

1 *Institute of Geographical Sciences and Natural Resources, Chinese Academy of Sciences, Beijing 100101, China*
lujf@igsnrr.ac.cn
2 *Institute of Remote Sensing Application, Chinese Academy of Sciences, Beijing 100101, China*

Abstract Nearly 100 drainage basins with gauging stations were chosen to investigate relationships between sediment yield and catchment characteristics in the Middle Yellow River basin. The size of the catchments ranged from 50 to 25 000 km^2 and they were grouped into seven categories according to their different physiographic characteristics. A database comprising information on sediment yield and catchment characteristics, including vegetation cover, surface material and morphology, was assembled for these basins using remote sensing combined with ground truthing and desk analysis. Based on this information, an index of basin characteristics *VSD* was produced to relate to specific sediment yield and a significant positive relationship was obtained for the study catchments. Multiple regression analysis was also employed to demonstrate that the most important variable influencing specific sediment yield was vegetation coverage, followed by basin morphology and surface material.

Key words catchment characteristics; China; Middle Yellow River basin; sediment yield

INTRODUCTION

The relationship between sediment yield and catchment characteristics has long attracted the interest of geomorphologists and hydrologists (e.g. Gregory & Walling, 1973; Schumm, 1977; Hadley *et al.*, 1985; Chien *et al.*, 1987; Walling & Webb, 1996; Chen *et al.*, 1988). However, uncertainties still remain in our understanding of this important topic. For example, the relative importance of different controlling variables is difficult to establish in an environmentally complex region, such as the Middle Yellow River basin, where rainfall, vegetation, surface material, and morphology exhibit considerable local variability. Against this background, Hadley *et al.* (1985) and Walling & Webb (1996) pointed to the need for more detailed analysis of sediment yield data from different regions of the world and from different environments, in order to explore general relationships between sediment yield and catchment characteristics.

The Middle Yellow River basin of China is well known for the severe soil erosion that occurs over much of its area. From north to south, the basin extends across the arid and desert steppe zone, the semiarid steppe zone, and the warm temperate semihumid forest-steppe zone and its morphology is characterized by hills and mountains alternating with intermountain basins (Fig. 1). The landscape of the region therefore ranges from rocky mountains through rock-loess mountains and hills to gullied loess hills and loess tablelands, resulting in considerable diversity of catchment characteristics and sediment yields in the tributary drainage basins.

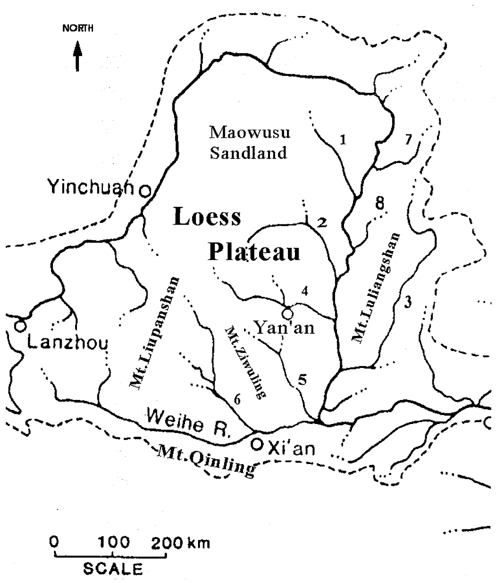

Fig. 1 A sketch map of the Yellow River basin. The dotted line shows the watershed of the river basin. The numbers refer to some of the main tributaries: (1) Kuyehe River; (2) Wudinghe River; (3) Fenhe River; (4) Yanhe River; (5) Beiluohe River; (6) Jinghe River; (7) Zhujiachuan River; (8) Qiushuihe River.

Nearly 100 tributary basins within the main Middle Yellow River basin for which sediment yield data were available were selected for this study. With catchment areas ranging from 50 to 25 000 km^2, these basins were classified into seven categories according to their physiographic characteristics. Using the database of basin characteristics, which was assembled using remote sensing, morphometric analysis and field investigation, an integrated study was undertaken to explore the relationships between sediment production and catchment characteristics.

DATA SOURCES

All the specific sediment yield data used in this study represent mean annual values. The sediment yield records extend back to the establishment of the measuring stations and cover periods ranging from 10 to 32 years. The data were abstracted from the hydrological yearbooks prepared by the Yellow River Conservancy Commission for internal use.

Vegetation cover density, surface material and drainage density were selected as key catchment characteristics for this study. The procedure for assembling these data was as follows. Firstly, each river basin was subdivided into a number of terrain units, and the vegetation cover and surface material were determined for each terrain unit by visual interpretation of Thematic Mapper (TM) images, combined with thematic maps and field investigations. Secondly, morphometric data were obtained from topographic maps (1:50 000) for each terrain unit by sampling. Finally, the value of each index for each basin was obtained by area-weighting all terrain units within the basin.

Table 1 Relative erodibility values for different types of surface material.

Type of surface material	Loess			Easily erodible material					Hard rock
	Sandy loess	Loess	Clayey loess	Siltstone/ mudstone	Red earth1	Red earth2*	Sandstone/ shale	Weathered granite	
Values	6.0–9.0	4.0–6.0	<4.0	9.0–10.0	2.5–5.0	2.5–3.0	2.0–2.7	1.5–2.0	0.5–1.0

* Red Earth 1 and 2 are both Late Tertiary strata. The former is widespread in western part of the Middle Yellow River Basin and the latter in north part of the basin. The latter is rich in illite and montmorillonite and is easily weathered.

Five classes of vegetation cover density were delimited viz. (1) >70%, (2) 50–70%, (3) 30–50%, (4) 10–30%, and (5) <10%, and five types and 11 subtypes of surface material were identified. Information on vegetation cover density was obtained primarily by interpretation of TM images, based on the percentage of red patches and exposed bedrock as well as the clarity of the gully pattern. For the purpose of this investigation, surface material was primarily an expression of geology and thus the incidence of loess and bedrock with associated weathering horizons. The relative erodibility was used as an index to characterize the resistance of surface materials to erosion and was determined using a rating procedure based on both expert knowledge of the erosion features associated with each type of surface material in the field and data on specific sediment yield for small catchments dominated by a particular surface material. Some laboratory measurements, including tests for resistance to erosion and scour, were also used to establish the relative erodibilities of sandy loess, loess, clayey loess and red earth. The relative erodibility rating values for each type of surface material are listed in Table 1.

In order to establish how different sets of physiographic conditions can influence the relationship between sediment yield and catchment characteristics, seven types of river basin with different physiographic conditions were identified as follows: (a) semiarid sandy loess and siltstone and mudstone basins; (b) semiarid hilly gullied loess basins; (c) semiarid and sub-humid hilly loess basins with some rocky mountains; (d) thin loess hilly basins; (e) sub-humid rocky mountain basins with some areas of gullied loess hills; (f) sub-humid loess plateau basins; and (g) sub-humid rocky mountain basins.

RESULTS

The relationship between specific sediment yield and an index of catchment characteristics, *VSD*

Due to the complex physiographic background of the study catchments, the mean annual values of specific sediment yield of the individual tributary basins within the Middle Yellow River basin varied from 25 t km^{-2} $year^{-1}$ to 20000 t km^{-2} $year^{-1}$ (Table 2). Highest values of specific sediment yield are associated with river basins underlain by sandy loess and Pishayan strata (Permian siltstones and mudstones) and with a low vegetation cover density, followed successively by loess and mixed loess-rock basins. The basins underlain primarily by hard rocks and with a good vegetation cover have the lowest values of specific sediment yield.

Table 2 The range of specific sediment yields for different types of river basin.

Basin types	Semiarid sandy loess and siltstone–mudstone basin	Semiarid loess gullied hilly basin	Semiarid and sub-humid loess hilly basin partly with rocky mountain	Thin layered loess hilly basin	Sub-humid loess tableland basin	Sub-humid rocky mountain basin partly with loess gullied hills	Sub-humid rocky mountain basin
Specific sediment yield (t km^{-2} year^{-1})	12500–21000	7500–14000	3100–8300	2000–2800	1500–2000	400–1800	<400

In this paper *VSD* was introduced in an attempt to provide an integrated index of basin characteristics to relate to specific sediment yield. It was defined as follows:

$$VSD = (1 - V_c) + S_m + D_d \qquad (1)$$

in which V_c (%) is the vegetation cover density, S_m is the relative erodibility of the surface material, and D_d is the drainage density. All values of V_c, S_m and D_d were standardized to lie within the range 0–1 before they were summed. Since specific sediment yield was positively related to surface material and drainage density, but negatively related to vegetation cover the vegetation index was expressed as $(1 - V_c)$, in order to maintain a common positive relationship (Lu, 2001, 2002; Lu & Huang, 2003). *VSD* therefore reflects the capacity of a river basin to resist erosion. As *VSD* increases, the resistance of the river basin to erosion reduces and sediment production increases for a given energy condition and *vice versa.*

Figure 2 shows that there is a well-defined positive relationship between specific sediment yield and *VSD*, with the correlation coefficient reaching 0.93. The different types

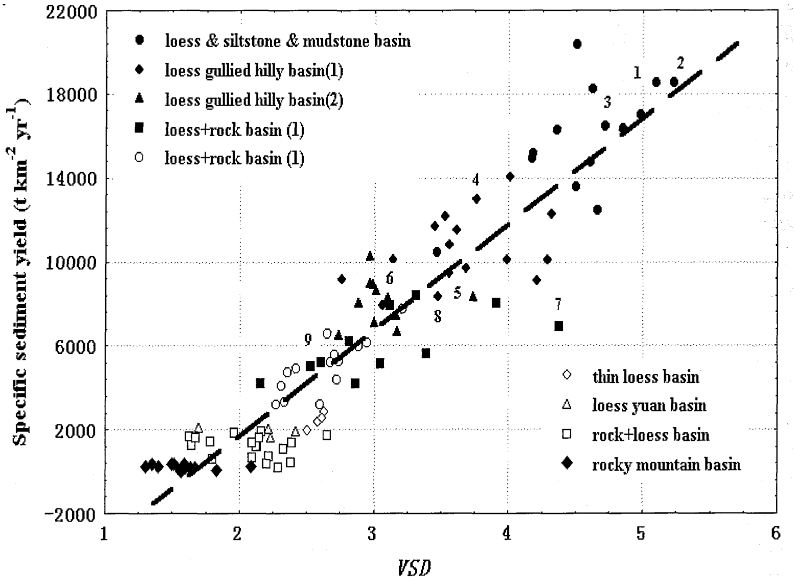

Fig. 2 The relationship between specific sediment yield and the index *VSD* for catchments in the Middle Yellow River basin. The numbers refer to specific rivers: (1) Huangpuchuan; (2) Gushanchuan; (3) Jialuhe; (4) Kuyehe (above Shenmu); (5) Kuyehe (above Wenjiachuan); (6) Wulanmulun; (7) Tuweihe; (8) Pianguanhe; (9) Lanyihe.

of river basin have been distinguished on Fig. 2 using different symbols and it can be seen that the different types of basin fall on different parts of the line, according to the resistance of the river basin to erosion. For example, the Huangpuchuan River, the Jialuhe River and the Gushanchuan River in North Shaanxi Province, which are mostly underlain by sandy loess and Pishayan strata and are poorly vegetated and highly dissected, are all located in the upper part of the plot. These are followed in turn by loess basins and loess-rocky basins, more resistant rocky-loess basins and resistant rocky basins, respectively. This sequence clearly demonstrates the influence of catchment characteristics on sediment production. The Wulamulun River, the Kuyehe River above Shenmu County and the Upper Tuweihe River are found lower in the plot than the above rivers, because they are situated in the transitional zone between the Loess Plateau and the Erdos High Plain and the Maowusu Sandland, and are characterized by an undulating morphology and an intermittent coverage of sand.

Basin morphology can also exert an important influence on specific sediment yield. For example, although they are located at a similar latitude to the above basins, the Pianguanhe and Lanyihe Rivers in Western Shanxi Province are also found in the lower part of the plot, because 60–70% of their catchment area is composed of less dissected rocky mountains or loess-covered rocky mountains with vegetation coverage as high as 50%, and 10–50% of their catchment area lies on the Tertiary peneplain.

Multivariate analysis of the relationship between specific sediment yield and catchment characteristics

It has been shown above that in the Middle Yellow River basin specific sediment yield is inversely related to vegetation cover and positively related to the erodibility of the surface material and the drainage density. In order to explore further the relative importance of these three variables and also catchment area, multiple regression analysis was employed. All variables were standardized to the range 0–1 before the regression analysis was undertaken. The final regression equation (R = 0.96) took the form:

$$Qs = -9119.89 - 0.695 \times \ln V_c + 0.343 \times D_d + 0.10 \times S_m + 0.030 \times S_a \qquad (2)$$

Where: V_c, D_d, S_m and S_a are vegetation cover density, drainage density, the relative erodibility of surface material and catchment area respectively, and Qs is the specific sediment yield. The correlation coefficient for the multiple regressions was 0.96, and the variance analysis for the relationship is presented in Table 3.

Table 3 Variance analyses for the stepwise regression between sediment yield and basin characteristics for catchments in the Middle Yellow River basin.

	SUMS OF	DF	MEAN_SQU	F	P_LEVEL
Regress.	2.77E + 09	4	6.93E + 08	320.2516	0
Residual	2.19E + 08	101	2164867		
Total	2.99E + 09				

SUMS OF, Sums of Squares;
DF, Degree of Freedom Mean;
SQU, Mean Squares;
F, F-test values;
P-Level, Significance level.

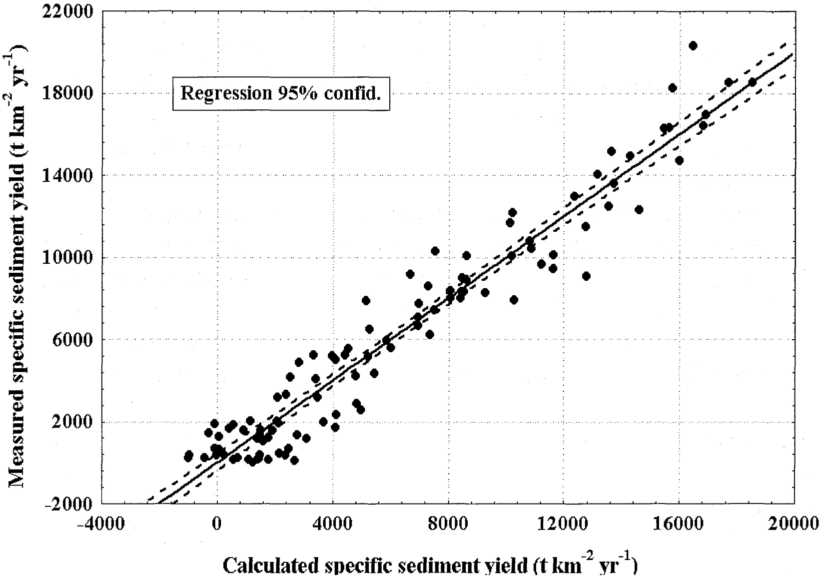

Fig. 3 The relationship between estimated and measured specific sediment yield for catchments in the Middle Yellow River basin.

Table 4 Partial correlations between sediment yield and basin characteristics for catchments in the Middle Yellow River basin.

	BETA_IN	PARTIAL COR.	SEMIPART COR.	TOLERNCE	R_SQUARE	T_103_	P_LEVEL
lnV_c	0.695	0.807	0.370	0.283	0.717	13.741	7.43E-25
D_d	0.343	0.703	0.267	0.606	0.395	9.930	1.28E-16
S_m	0.100	0.171	0.047	0.217	0.783	1.741	0.084771
S_a	0.030	0.107	0.029	0.952	0.048	1.083	0.281231

BETA_IN, The beta in (standard regression coefficient for the respective variable if it were to enter into the regression equation as an independent variable);

PARTIAL COR, The partial correlation (between the respective variable and the dependent variable, after controlling for all other independent variables in the equation);

SEMIPART COR, The semi-partial (part) correlation (the correlation between the unadjusted dependent variable with the respective variable after controllingfor all independent variables in the equation);

TOLERNCE, The tolerance for the respective variable (defined as 1 minus the squared multiple correlation between the respective variable and all independent variables in the regression equation);

R_SQUARE, The minimum tolerance (the smallest tolerance among all independent variables in the equation if the respective variable were to be entered as an additional independent variable);

T_103_, The t-value associated with these statistics for the respective variable;

P_LEVEL, The statistical significance of the t-value.

A comparison between observed sediment yields and those estimated for the same catchments using the multiple regression equation is presented in Fig. 3, on which the 95%confidence limits for the relationship, have also been plotted. The partial correlation coefficients and beta coefficients for the multiple regressions have been calculated and these are listed in Table 4. The partial correlation coefficients and the beta coefficients indicate that vegetation cover density exerts the strongest influence on specific sediment yield, followed by drainage density, the relative erodibility of the surface material and catchment

Table 5 The result for a simple regression between the relative erodibility of surface material and drainage density for catchments in the Middle Yellow River basin.

	BETA	ST. ERR.	B	ST. ERR.	T_103_	P_LEVEL
Intercept			–2.261	0.989	–2.286	0.024
D_d	0.562	0.081	1.743	0.251	6.937	3.51E-10

BETA, the standardized regression coefficients;
B, non-standardized regression coefficients;
ST. ERR., standard error.

area. The relationship between specific sediment yield and basin area is relatively weak and the positive trend differs from the negative relationship between specific sediment yield and catchment area commonly reported in the literature (cf. Walling, 1983).

The above results indicate that in an environmentally complex area, such as the Middle Yellow River basin, the influence of surface material and drainage area on specific sediment yield is secondary to the control on specific sediment yield exerted by the vegetation cover and the morphology of a catchment, and only becomes clear when vegetation cover and morphology show limited variation. In addition to the above, the relatively weak relationship between specific sediment yield and surface material is probably attributed to the fact that relative erodibility of surface material is closely related to drainage density, i.e. surface material does not act as an independent variable in the multiple regression (Table 5).

CONCLUSIONS

In an environmentally complex region such as the Middle Yellow River basin, where rainfall, vegetation, surface material, and morphology exhibit considerable spatial variability, a good relationship was obtained between specific sediment yield and basin characteristics by introducing an index of basin characteristics *VSD*. A multiple regression analysis was also carried out and this indicated that the best correlation occurs between specific sediment yield and vegetation cover, followed in turn by drainage density and surface material. Therefore, within the study area in the Middle Yellow River basin, vegetation cover must be seen as the most important factor affecting sediment production, compared with morphology and surface material.

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