Sediment sources and yield from small drainage basin

MOU JINZE
Division of Soil and Water Conservation
Yellow River Conservancy Commission
Zhengzhou, People's Republic of China

ABSTRACT The spatial distribution of sediment sources in small basin is discussed, and erosion processes on the entire slope and variation of scour or fill on the gully bed are illustrated based on the observed data from the plots located at the different erosion zones and sections of scour or fill on the gully bed in the Tuanshangou small basin. Finally the formulas of sediment yield in small basin have been developed.

INTRODUCTION

The gullied-hilly loess area, where the loss of soil and water is most severe, is one of the main regions of sediment sources in the Yellow River Basin. In order to study sediment delivery processes from upland slopes through the gullies to the stream channels and rainfall runoff relationship, the Zizhou runoff experimental station at the Chaba gully, the first order of tributaries of the Dali River in north Shaanxi, was built by the Yellow River Conservancy Commission, and the Tuanshangou gully, the third order of tributaries, was selected as one of typical small experimental drainage basin.

The basin has a catchment area of 0.18 km^2 with length of 0.63 km, mean width of 0.286 km and 135 percent of average gradient of main gully bed. Twelve runoff plots from 150 to 17,200 m^2 in the area with slope of 158-1,730 percent have been set up, the purposes of which are to study the effects of slope, length and soil types on soil erosion as well as the sediment sources on the different geomorphological parts (Mou, 1981), 15 sections observed scour or fill with total length of 395.3 m have also been built on the gully bed in order to investigate characteristics of scour or fill variation there (Fig. 1).

Spatial distribution of basin sediment sources

The gullied-hilly loess area is mainly made up of small gully watersheds which have catchment area of 10-200 km^2 and essentially similar characteristics in soil composition, geomorphy, erosion process and features of sediment production and transport. The typical cross section of Tuanshangou small watershed for the aforementioned area is shown in Figure 2. According to the eroded geomorphy the gully rim line (rim line of present gully) can be deemed as a boundary to divide a small gully watershed into two vertical zones, namely, the ridge land above this line and the gullied land below it, the former including the crown of ridge and ridge slope, the latter the gullied bank and the gully bed. The ridge land is sloping farmland with gentle gradient of 10-15 degrees. The gully bank involves the escarpments steeper than 60 degrees, the wild lands of 40-60 degrees and some sloping farmlands of 25-35 degrees.

Based on observed data from the plots, scour or fill sections of gully bed and the section of outlet, soil erosion from the different

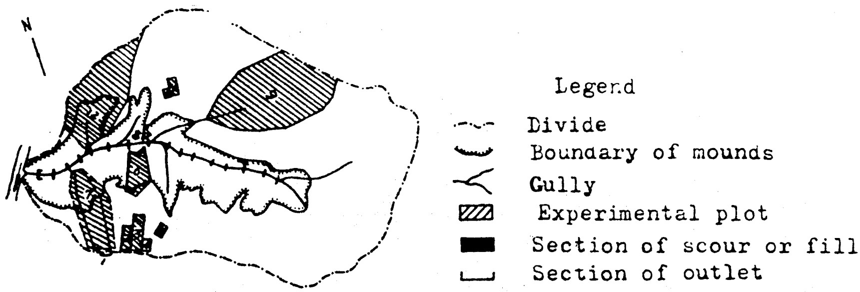

Figure 1 Layout of plots and scour or fill sections in Tuanshangou small drainage basin

parts of eroded zones has been estimated and spatial distribution of sediment sources in Tuanshangou small drainage basin has been obtained in Table 1.

By analyzing the Table 1 the results could be gained as follows:

(a) In above-mentioned basin 33298 t/km^2 of erosion rate might be on the gullied land, 19030 t/km^2 of that on the ridge land, erosion rate on the former being 75 percent greater than that on the latter. Soil erosion on the gullied land might be more severe than that on the ridge land.

(b) Owing to 74 percent of catchment area being on the ridge land and only 26 percent of that on the gullied land in aforementioned basin, the sediment load in this basin mainly might come from the ridge land, and spatial distribution of basin sediment sources might be respectively 61.8 percent of basin sediment load on the ridge land, 27.4 percent of that on the gully bank and 10.8 percent of that on the gully bed.

Characteristics of scour or fill variation on the gully bed

As stated above, the gullied land including the gully bed in the gullied-hilly loess area is the most serious zones of soil erosion. The

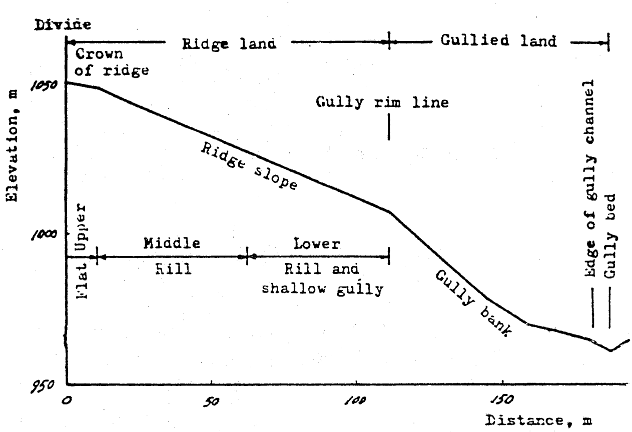

Figure 2 Sketch of cross section on the left of Tuanshangou basin

Table 1 Spatial distribution of sediment sources in Tuanshangou basin

Area of vertical zones

Catchment Area (km^2)	Ridge land		Gullied land	
	Area (km^2)	% of the catchment area (%)	Area (km^2)	% of the catchment area (%)
0.18	0.133	74	0.047	26

Sediment sources*

Ridge land			Gullied land							Whole basin	
			Gully bank		Gully bed		Total				
Soil erosion (t)	% of the total sed. load (%)	Erosion rate (t/km^2)	Soil erosion (t)	% of the total sed. load (%)	Soil erosion (t)	% of the total sed. load (%)	Soil erosion (t)	% of the total sed. load (%)	Erosion rate (t/km^2)	Total sed. load (t)	Sed. yield (t/km^2)
2531	61.8	19030	1124	27.4	441	10.8	1565	38.2	33298	4096	22756

*Based on the data recorded from 1963-1967.

Table 2 Annal volume of scour or fill in Tuanshangou gully bed

Years of obser-vation	Length of observed reach (m)	Volume of scour (-) or fill (+) in the reach (t)	Section of outlet		Percent of scour or fill volume against annual sediment load (%)
			Annual runoff depth (mm)	Annual sed. load (t)	
1963	392.0	- 804.2	12.6	1490.2	- 54.0
1964	395.3	- 1012.1	31.7	3514.7	- 28.8
1965	395.3	+ 83.7	0.9	38.7	+ 216.3
1966	395.3	- 455.3	102.1	12986.4	- 3.5
1967	395.3	- 17.5	23.2	2448.0	- 0.7
Total		- 2205.4	170.5	20478.0	- 10.8

Tuanshangou gully bed made up of soil material, where soil erosion is actively under way and scour or fill variation is obvious, becomes one of basin eroded material sources zones.

(a) Yearly variation of scour or fill on the gully bed. According to analysis scour or fill variation data recorded from 1963-1967 in Tuanshangou gully bed, the results could be seen as follows:

(i) Scour predominantly occurred on the gully bed from year to year, while slight fill only finding out in 1965 (Table 2, Fig. 3). The scour

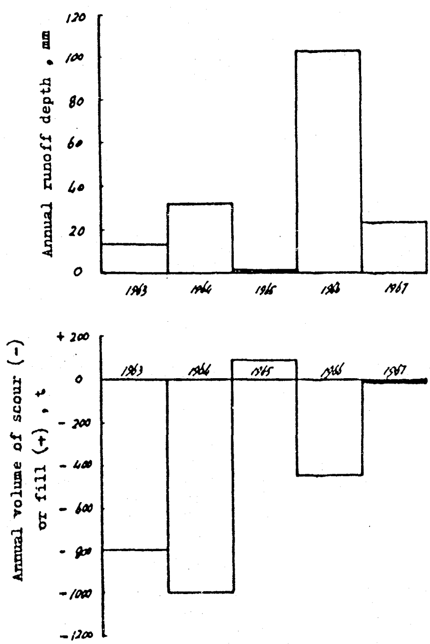

Figure 3 Yearly variation of scour or fill and runoff depth in Tuanshangou basin

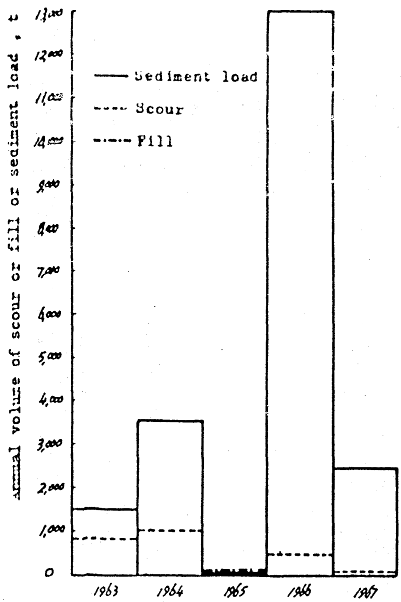

Figure 4 Comparison of scour or fill volume on gully bed with sediment load in Tuanshangou basin

phenomenon on the gully bed showed that surface flow with high sediment-carrying capacity might be not only able to transport material eroded from upland slopes, deliver sediment aggregated on the gully bed by gravity erosion from the gully bank, but also undercut the gully bed itself. That would mean the main gully bed in the Tuanshangou watershed might be either sediment transport channel or one of sediment source zones. The reason for the slight deposition in 1965 was that average annual runoff depth in this year was too small (0.9 mm) to deliver all eroded material aggregated on the gully bed by gravity erosion.

(ii) By comparing annual volume of scour or fill on the gully bed with annual sediment load at the section of outlet (Fig. 4), it can be shown that the former may occupy 0.7-54 percent of the latter, and annual average 10.8 percent.

(iii) Although the absolute magnitude of fill volume on the gully bed in 1965 was not so large, but the relative magnitude could be equal to 216 percent of annual basin sediment load of this year.

In a word, owing to the fact that the main gully bed in Tuanshangou basin lies in erosion development stage with scouring and undercutting in addition to the steep gradient, fine particles, hyperconcentration of sediment and high sediment-carrying capacity, as a result, the sediment

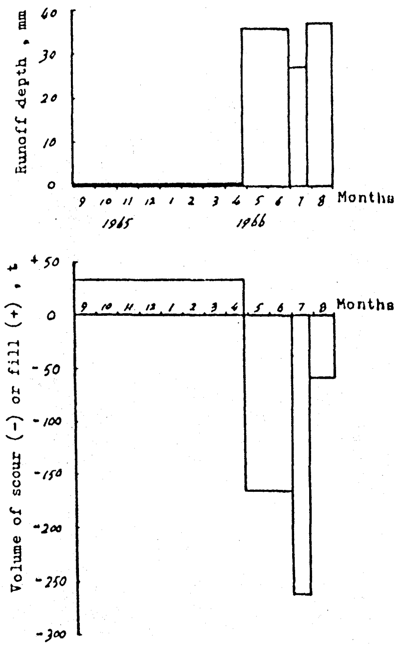

Figure 5 Seasonal variation of scour or fill on gully bed and depth of runoff in Tuanshangou basin

delivery ratio may be nearly equal to unity (Mou et al.). The crux of the matter, that the sediment delivery ratio for small drainage basin in gullied-hilly loess area keeps to high value, is once again demonstrated on the other hand.

(b) Seasonal variation of scour or fill on the gully bed. By analyzing the data of the seasonal variation of scour or fill in Tuanshangou gully bed (Fig. 5), the results could be seen as follows:

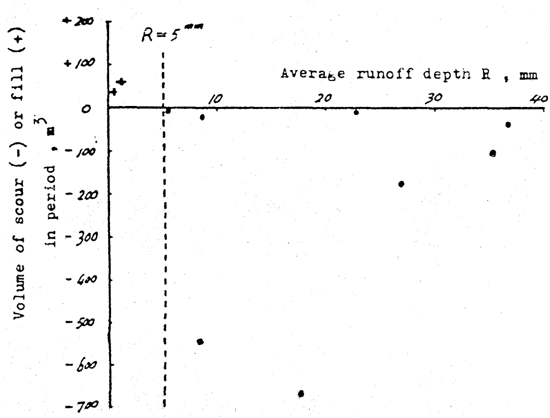

Figure 6 Changes of scour or fill on gully bed with average runoff depth

Table 3 Scour or fill on the gully bed in period with corresponding average runoff depth in Tuanshangou basin

Period (month-day-year)	Scour (-) or fill (+) on the gully bed (m^3)	Average runoff depth (mm)
6-25-1963 to 8-30-1963	- 547.1	8.3
5- 6-1964 to 7-10-1964	- 20.99	8.6
7-10-1964 to 8-28-1964	- 665.7	17.7
8-28-1964 to 9-28-1964	- 1.793	5.4
4-16-1965 to 9-21-1965	+ 57.30	0.9
9-21-1965 to 4-26-1966	+ 25.10	0
4-26-1966 to 6-30-1966	- 107	35.3
6-30-1966 to 7-22-1966	- 175	26.7
7-22-1966 to 8-18-1966	- 38.7	36.7
6-14-1967 to 9- 9-1967	- 11.92	22.7

(i) Scour on the gully bed might be predominant in flood season, while slight fill being in non-flood season. Ratio of scour volume in flood season to fill volume in non-flood season is 14.3.

(ii) In non-flood season even though no runoff might be formed in the basin, the fill still takes place in the gully bed. This phenomenon shows that the sediment deposition on the gully bed might be not because the surface flow has not enough sediment-carrying capacity to deliver the material eroded from upland slopes and gully bank, it is because the eroded material caused by gravity erosion such as landslide, slip, and slumping aggregates on the gully bed.

(c) Relation of scour or fill on the gully bed to runoff. Surface flow in the watershed as a power of erosion and delivery on the gully bed would play a decisive effect on its variation of scour or fill. By comparing the scour or fill volume on the gully bed in the period with corresponding runoff depth in Tuanshangou basin (Fig. 6, Table 3), it can be discovered that as the runoff varies there is a dividing line between scour and fill on the gully bed. When the average runoff depth was less than 5 mm, the fill on the gully bed occurred, otherwise the scour would be done. According to the comparison of scour or fill with corresponding runoff depth in Figure 3 and Figure 5 there were no relationships between the two.

Basin erosion processes and sediment yield

(a) Basin erosion processes. Erosion processes in Tuanshangou small drainage basin can be divided into the two parts, namely, erosion process on the ridge land and erosion process on the gullied land.

(i) Erosion process on the ridge land. Erosion forces within the ridge land are mainly the raindrop impact and surface flow. Splash erosion takes place predominantly on the crown of ridge, while surface flow scour occurs mainly on the ridge slope. The effects of raindrop impact on the soil manifest not only breaking its structure and detaching its aggregate, but increasing turbulence of surface flow and raising its silt-carrying capacity. Maximum sediment concentration of about 600 kg/m^3 had been caused by splash erosion based on analyzing the data from the plots in 1966. Scouring action caused by surface flow forms the rills and shallow gullies on the gully slope in the main. In the process of forming them sediment concentration further increases with the increasing sediment supply in surface flow. According to analyzing the data from plots Number 2, 3 and 4, maximum sediment concentration through the surface flow scouring on the gully slope will increase to about 900 kg/m^3, that is about 30 percent larger than the limited sediment concentration caused by splash erosion (Wang et al., 1982).

(ii) Erosion process on the gullied land. Undercutting of gully bed, enlargement of gully bank and progress of gully head are concentrically manifested in this process. This erosion process is accompanied by gravity erosion including considerable landslide, slip and slumping as well as hydraulic erosion. Hydraulic erosion added to severe gravity erosion makes the gully bank the most serious zone of soil erosion in the drainage baisn, while overland discharge entering into the gully bank from the ridge land is important for aggravating soil erosion in this zone. Surface flow from the ridge land, passing through the gully bank, obtains new sediment supply from hydraulic and gravitational erosion. On the basis of analysis of the data observed from entire slope plots Number 7 and 9, maximum sediment concentration has reached 1000 kg/m^3 or so after running through the gully bank (Wang et al., 1982).

The basin erosion processes are also quite obviously reflected in the quantitative relationship between erosion and runoff. From Figure 7, it can be seen that under the same annual depth of runoff the annual erosion modulus of plot Number 4 near to the crown of ridge might be the lowest, that of plots Number 2 and 3 increases with increasing their length towards the ridge slope, and finally that of entire slope plot Number 7 including the gully bank might be the highest.

(b) Calculation of basin sediment yield. The material eroded from different zones of basin (including the ridge land, the gully bank and the gully bed), carried and delivered to the section of outlet, becomes the basin sediment yield. On the

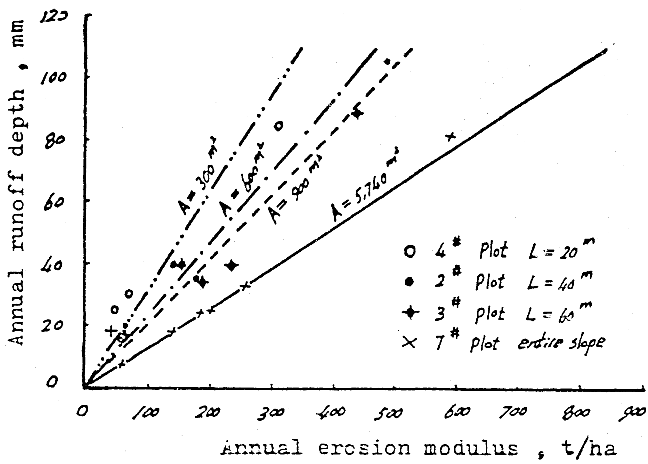

Figure 7 Relationship between erosion and runoff for plots of different vertical zones

certain conditions of surface feature in the watershed the basin sediment yield is dominated by runoff. For the sediment yield during a flood the total volume of flood runoff is predominant, that is because the total flood volume not only represents influence of the total precipitation itself, but also marks the concentrical degree of storm and runoff which reflects effect of flood peak discharge in certain measure. If effect of flood peak discharge itself is considered and the composite factor of total flood volume plus flood peak discharge is adopted as surface flow factor, the more close relationship would be obtained. For annual sediment yield, surface flow condition having an influence on annual sediment yield would be only depended on annual runoff volume, while flood peak discharge itself does not take effect as factor alone. So the modulus of annual runoff is only used as surface flow factor.

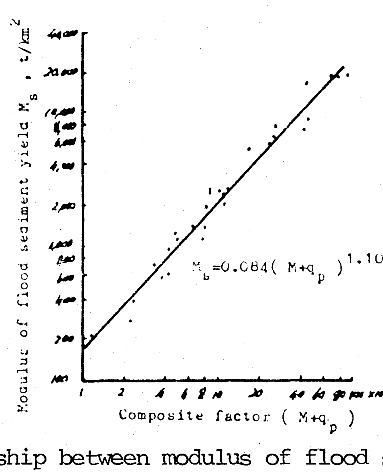

Figure 8 Relationship between modulus of flood sediment yield and composite factor in Tuanshangou basin

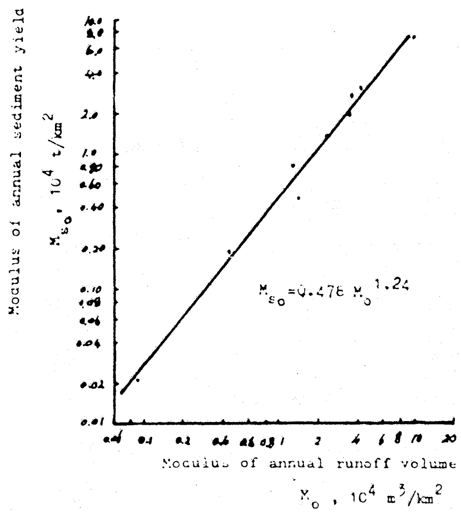

Figure 9 Relationship between modulus of annual sediment yield and modulus of annual runoff volume in Tuanshangou basin

According to the data observed on section of outlet in Tuanshangou small watershed, relationships between basin sediment yield and surface flow factor are obtained in Figure 8 and Figure 9, the computing formulas are as follows:

For flood sediment yield

$$M_s = 0.084\ (M+q_p)^{1.10} \qquad (1)$$

in which M_s = modulus of sediment yield during a single flood (t/km^2); M = modulus of total flood runoff volume (m^3/km^2); q_p = modulus of flood peak discharge (dm^3/sec-km^2). The correlation coefficient r = 0.984, and the average relative error is 20.4 percent in equation (1).

For annual sediment yield

$$M_{so} = 0.478\ M_o^{1.24} \qquad (2)$$

in which M_{so} = modulus of annual sediment yield (10^4 t/km^2); M_o = modulus of annual runoff volume (10^4 m^3/km^2). The correlation coefficient r = 0.993, and the average relative error is 16.2 percent in equation (2).

CONCLUDING REMARKS

By way of the aforementioned analysis, the following are presented as we realize it:

(a) The soil erosion in small drainage basin is dominated by gully erosion on the gullied-hilly loess area in the Yellow River Basin. On the ridge land erosive forces would be mainly created from the raindrop impact and surface flow, and on the gullied land the gravity erosion including landslide, slip and slumping might be very severe as well as the hydraulic erosion.

(b) The most serious zone of soil erosion lies in gullied land in small drainage basin. Owing to the fact that the area of ridge land in Tuanshangou basin is greater than that of gullied land, sediment yield in this small basin would mainly come from the ridge land. Spatial distribution of basin sediment sources might be respectively 61.8 percent of basin sediment yield on the ridge land, 27.4 percent of that on the gully bank and 10.8 percent of that on the gully bed.

(c) The main gully bed in Tuanshangou basin lies in erosion development stage with the scouring and undercutting. As viewed from scour or fill variation either yearly or seasonal in the gully bed, scouring occurs predominantly in both cases. The main gully bed might be not only a sediment transport channel, but one of zones of eroded material sources. From upland slopes to gully bank in whole small basin, sediment concentration and soil loss per unit area increase continuously along the path. Sediment delivery ratio is nearly equal to unity.

(d) On the certain conditions of surface feature in the watershed the basin sediment yield might be dominated by surface flow factor. According to the existing close relation of sediment load to surface flow in a watershed, basin sediment yield could be estimated from runoff.

REFERENCES

Jinze, M. (1981) The establishment of experimental plots for studying runoff and soil loss in the rolling loess regions of China. IAHS Publ. No. 133.

Jinze, M. & Qinmei, M. (1981) Sediment delivery ratio as used in the computation of watershed sediment yield. Journal of Hydrology, New Zealand, v. 20, no. 1.

Xinkui, W., Ning, Q. & Weide, H. (1982) The formation and process of confluence of the flow with hyperconcentration in the gullied-hilly loess areas of the Yellow River Basin. Journal of Hydraulic Engineering, no. 7, Beijing (in Chinese).