SEDIMENT DELIVERY RATIO AS USED IN THE COMPUTATION OF WATERSHED SEDIMENT YIELD

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ABSTRACT

Sediment delivered from gullied, hilly loess areas on the middle reaches of the Yellow River is essentially the product of gully erosion. In estimating the sediment delivery ratio of this area the total material eroded from the entire watershed is taken as the sum of the quantities yielded by way of sheet, gully and channel erosion.

Analyses and calculations for typical watersheds in the aforementioned area show that wash load comprises over 95% of the total sediment load during most floods, with the result that the floods are frequently of hyper-concentration (average sediment content during a flood being no less than 500 kg/m^3). This is due to the mechanism of particle suspension, and is the basic reason why the sediment delivery ratio is nearly equal to unity.

Finally, a formula for computing a modified sediment delivery ratio in the study areas, obtained through correlation analyses and considered to be acceptable, is presented.

INTRODUCTION

With the swift development of planning for comprehensive control of medium and small watersheds, and the widespread building of dams and reservoirs of medium and small size, we urgently need data on sediment yield from watersheds. The estimation of sediment yield of watersheds of medium or small sizes, in areas lacking adequate data on sediment regime, by using the sediment delivery ratio is one method used in Europe and America at present. In the Dali River watershed in N. Shaanxi, in the gullied, hilly loess on the middle reaches of the Yellow River, the problems of calculating the sediment delivery ratio are dealt with using observed data on the regime of streamflow and sediment discharge at control sections at the mouths of ravines and gullies.

THE DEFINITION OF SEDIMENT DELIVERY RATIO

In general, the sediment eroded from a watershed undergoes either deposition or scouring along the path of transport before reaching a certain cross-section of the stream. The ratio between the observed sediment yield at a cross-section of a stream and the total quantity of soil eroded in the catchment above that section is the sediment delivery ratio, or:

$$DR = Y/T \quad (1)$$

in which: DR = sediment delivery ratio;
Y = observed sediment yield at the control section at the mouth of the river basin;
T = total quantity of soil eroded from the watershed above the control section at the mouth.

At present, in using the sediment delivery ratio defined by (1), there are two different methods of estimating T. The first is by using the "Universal Soil Loss Equation" (Wischmeier and Smith, 1965):

$$T = RKLSCP \quad (2)$$

in which R = factor of rainfall energy;
K = factor of soil erodibility;
L = factor of length of slope;
S = slope factor;
C = factor of cultivation and management;
P = factor of soil conservation measures.

The second method is by adopting the sum of the products of sheet, gully and channel erosion (UP, GU and CH respectively) as the total quantity of soil eroded in the watershed (Mutchler and Bowie, 1975):

$$T = UP + GU + CH \quad (3)$$

These two methods of estimating the total quantity of soil eroded in the watershed can both be used when erosion rates for the slopes and gullies are approximately the same. In case of a wide difference between the two, and for regions or catchments in which the total area of the gullies comprises a considerable percentage of the total area of watershed, the two methods give different results. We consider the second method as a more reasonable way of computation.

In the Dali River watershed in N. Shaanxi, China, gullies and slopes comprise about one half of each of the area of the region or watershed (with the top of ridges and mounds as divides), and the erosion rate of gullies is often larger than the erosion rate of slopes (Mou Jinze and Xiong Guishu, 1980).

Using data on sediment regime taken simultaneously at three observation points (Fig. 1 and Table 1) at the cross-sections in small runoff plots (Tuanshangou No. 3 and No. 7) and at the mouth of Tuanshangou in the Zizhou Runoff Experimental Station, curves have been plotted to show the relationship between the annual rate of soil erosion (Fig. 2a) and average annual erosion rate through the years 1965–1969 (Fig. 2b) for small plots of slopes (representing sheet erosion), for small runoff plots extending over the whole length of slope (representing sheet erosion plus gully erosion) and for a complete element of watershed (representing sheet erosion plus gully erosion plus channel erosion).

It can be seen from Table 2 and Fig. 2 that the erosion rate for the cross-section at the mouth of the gully is larger than that of Runoff Plot No. 7, and the latter is larger than that of Runoff Plot No. 3, both in average values for a single year and in variation of erosion rate from year to year. The erosion rate in the gullies is highest, that of the gully slopes the second, and that as result of sheet erosion the lowest. Factors such as precipitation, soil, vegetative cover and landform affect the erosion of soil in a watershed. During each rain, the amount of rainfall may be considered to be essentially the same for a small watershed such as Tuanshangou, particularly for two neighbouring runoff plots. It can also be seen from Table 1 that the soil, vegetative cover and land slope of the three plots under comparison are similar. Hence, the main difference lies only in the geomorphic elements, or in other words, whether there are gully slopes and gullies or not, as well as the

Table 1. Basic Features of the Tuanshangou Watershed and Small Runoff Plots No. 3 and 7 on Tuanshangou

Name	Catchment m^2	Locality	Soil	Gradient ‰			Main crops on land in the catchment in different years				
				Slopes	Gullies	Watershed	1965	1966	1967	1968	1969
Runoff plot No. 3	900	slope on left bank	loess	404	—	—	intercropping of millet & mung bean	potato	intercropping of millet & mung bean	intercropping of broom corn millet & mung bean	alfalfa
Runoff plot No. 7	5,740	Slope surface & gully slope	loess	445	1,750	—	millet, black soya bean & alfalfa	potato, alfalfa	intercropping of millet and mung bean, alfalfa	intercropping of broom corn millet and mungbean, alfalfa	potato
Section at mouth of gully	180,000	gully mouth	loess	—	—	579	millet, pea, alfalfa	potato, alfalfa, wheat	millet, pea, wheat	broom corn millet, millet (foxtail), wheat	alfalfa, potato, wheat

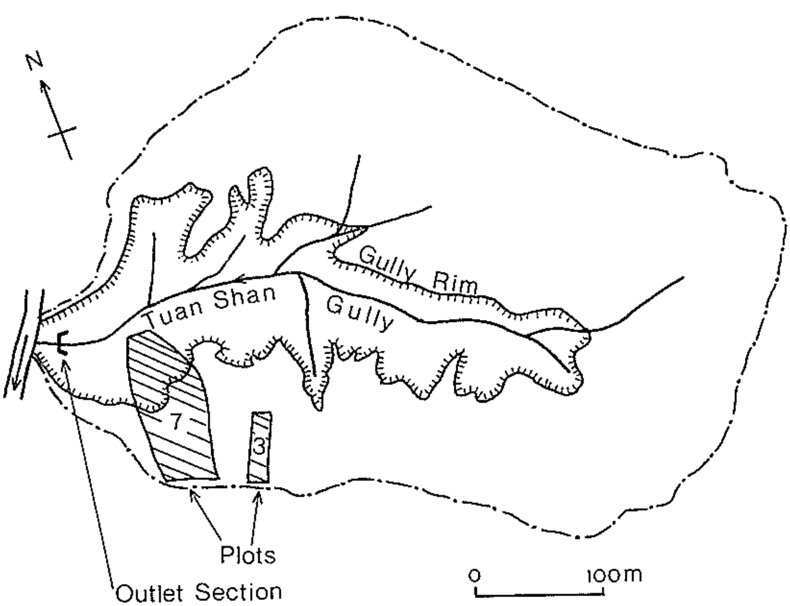

FIGURE 1—Layout of Tuan Shan Gully and runoff plots.

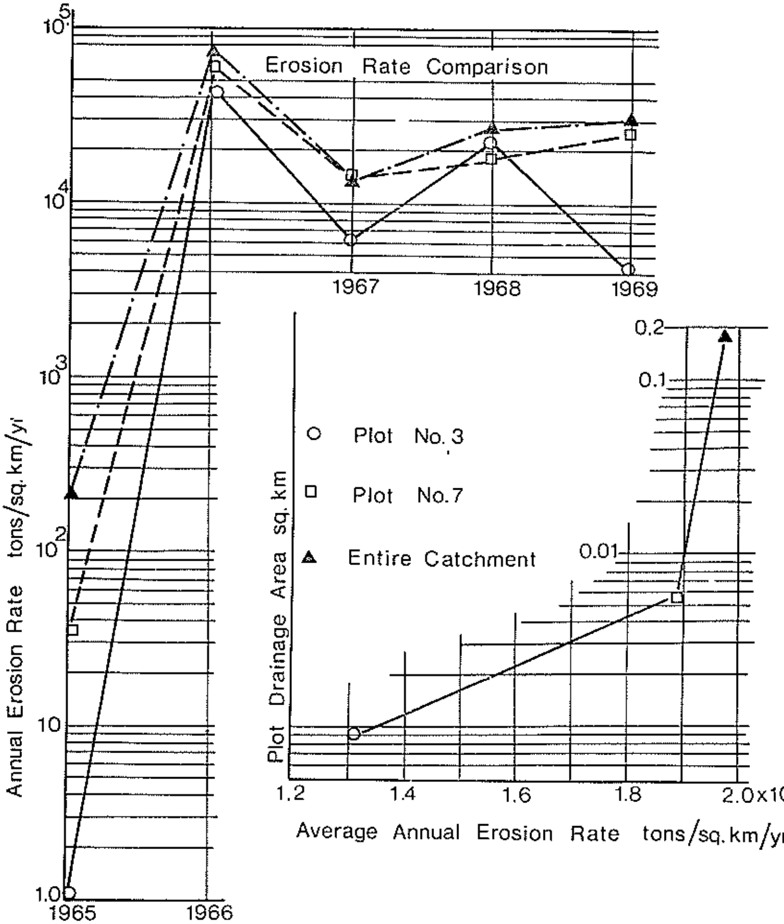

FIGURE 2—Comparison of erosion rate of ridge slope, gully slope and gully in the Tuan Shan gully of Chaba Gully in north Shaanxi.

quantitative disparity in erosion rates. This was also proven through field investigations made in 1966, when the erosion rate as a result of sheet erosion was relatively large, but that for the entire watershed was still higher. This is caused, according to the findings of the investigation, by the abundant rainfall in that year, with plenty of runoff and a sudden increase in scouring, and particularly severe gravitational erosion of the gullies extending over the entire watershed, with widespread undercutting, caving-in and slipping. In estimating the sediment delivery ratio for the Dali River basin in N. Shaanxi and similar areas in China, it is better to take the total quantity eroded from the watershed as the sum of the products of sheet, gully and channel erosion.

Table 2. Comparison of Erosion Rates as Result of Sheet, Gully and Channel Erosion in Tuanshangou Catchment of the Chabagou Basin in N. Shaanxi.

Year	Annual Erosion Rate of Small Runoff Plot No. 3, Tuanshangou (t/km^2)	Annual Erosion Rate of Small Runoff Plot No. 7, Tuanshangou (t/km^2)	Annual Erosion Rate for the control section at the mouth of Tuanshangou (t/km^2)
1965	0.1	33.5	215
1966	43,904	59,151	72,102
1967	6,248	14,018	13,600
1968	23,393	18,491	27,069
1969	4,363	25,605	30,380
mean value 1965-1969	13,148	18,934	19,751

One of the most appreciable difficulties in estimating the sediment yield of a watershed using the sediment delivery ratio lies in the lack of a practical formula for calculating the total quantity of soil eroded from the catchment by either of the two aforementioned methods. An attempt has been made to achieve this purpose on the basis of the foregoing analyses. In China there exist quite a number of elementary watersheds with adequate observed data on the regimes of streamflow and sediment. By elementary watershed is meant areas under study with similar types of soil erosion characteristics, of drainage area under 1.0 km^2, including all three landform elements of slopes, gully slopes and gullies, which form a complete watershed. Such a watershed is regarded as the source zone of sediment. The ratio of the sediment delivery rate of another medium-sized or small watershed, to that of the elementary watershed is defined as a modified sediment delivery ratio. Thus the sediment yield of a medium or small watershed in an area lacking observed data on sediment regime can be evaluated by using the observed data in elementary watersheds.

DECISIVE FACTORS AFFECTING THE VALUES OF SEDIMENT DELIVERY RATIO

Sediment delivery ratio is one of the key problems in the computation of sediment yield of a watershed. At present, specialists abroad (e.g. Roehl, 1962; Williams and Berndt, 1972; Vanoni, 1975) are generally of the opinion that the sediment delivery ratio decreases rapidly with an increase in drainage area (see Table 3), and that the delivery ratio may be assumed to be unity only in the case of very small cultivated plots.

The findings of Chinese research workers (Gong Shiyang and Xiong Guishu, 1980), however, revealed that the sediment delivery ratio of gullied rolling loess regions on the middle reaches of the Yellow River is always nearly unity, no matter whether the watershed is large or small. The high values of the sediment yield ratio for these regions were originally explained from the point of view of geology and geomorphology. Here we shall attempt to interpret them further by way of the principles of fluvial dynamics.

Table 3. Sediment Delivery Ratio versus Drainage Area

Data of Roehl (1962)		Data of Williams and Berndt (1972)		Vanoni data (1975)	
D.A. (km²)	Delivery ratio	D.A. (km²)	Delivery ratio	D.A. (km²)	Delivery ratio
5.7	0.17	0.5	0.67	0.1	0.53
161	0.12	0.7	0.63	0.5	0.39
78.5	0.21	1.3	0.66	1.0	0.35
19.5	0.13	4.5	0.48	5.0	0.27
272	0.04	17.7	0.42	10.0	0.24
41.3	0.13			50.0	0.15
24.2	0.10			100.0	0.13
45.9	0.18			200.0	0.11
11.8	0.29			500.0	0.09
17.2	0.13				
36.0	0.15				
433	0.09				
17.9	0.59				
1.6	0.55				
190	0.09				

The sediment of a river may be divided into two parts, the wash load and the bed load. Wash load is often the main constituent of the sediment transported, and can play a decisive role in the magnitude of the sediment yield of a watershed (or the sediment delivery ratio). Therefore, the causes of variation of the values of the delivery ratio should be examined in the light of the variation of the quantities of wash load in the sediment of a stream.

At present, one method of differentiating wash load and bed material is by applying the theory of "spontaneous suspension" of Bagnold (1962) and Wang Shangyi (1979), from which the maximum critical settling velocity of the wash load is expressed as follows:

$$Wk' = V.J \qquad (4)$$

Taking into consideration corrections for sediment content, the maximum critical settling velocity of the wash is:

$$Wk = VJ/[1-c/(0.755 + 0.222 \log d_{50})]^{2.5} \qquad (5)$$

in which: Wk, Wk^1 = maximum critical settling velocity (in cm/s) of the wash load, considering and without considering corrections for sediment content;

V = mean velocity of flow in the section (m/s);

J = hydraulic gradient (fraction);

c = mean sediment content in the section (ratio, by volume);

d_{50} = median diameter of suspended sediment (mm).

We have computed, by means of (5), the quantity of wash load, using data on sediment transport during 27 floods obtained at the control section at the mouth of the gully at Caoping, in the Chabagou watershed in N. Shaanxi. The results are shown in Table 4.

Table 4. Computation of Wash Load as a Part of the Sediment Delivery by Floods Observed at Caoping Station in Chabagou Watershed in N. Shaanxi.

Date of Occurrence of flood		Average discharge through the cross-section (m³/s)	Average velocity of flow in the cross-section (m/s)	Hydraulic gradient (o/oo)	Wk = V.J. (cm/s)	Wash load as percentage of the total delivery corresponding to V.J (%)	Mean sediment content		Median diameter of suspended sediment (mm)	Maximum critical settling velocity in still water Eq.(5) (cm/s)	Percentage of wash load against total delivery (%)
							in kg/m³	ratio, by volume			
Apr 29,	1964	5.03	0.68	2.91	0.198	47.0	897	0.339	0.056	4.45	99.6
Aug 2,		12.7	1.09	3.15	0.343	54.5	679	0.256	0.058	2.30	99.8
Dec 17,		2.75	0.62	2.89	0.179	37.8	665	0.251	0.055	1.18	96.3
Aug 1,	1965	9.44	1.06	3.12	0.331	49.5	676	0.255	0.061	2.12	98.1
Aug 4,		3.89	0.80	2.99	0.239	29.5	500	0.189	0.069	0.79	76.0
Aug 9,		1.21	0.50	2.79	0.140	26.0	594	0.224	0.068	0.63	62.0
June 26,	1966	9.19	0.96	3.07	0.295	62.5	811	0.306	0.053	4.04	99.8
June 27,		31.5	1.39	3.27	0.455	64.0	738	0.278	0.054	4.17	99.8
July 17,		47.4	1.49	3.30	0.492	76.5	776	0.293	0.045	6.39	99.9
Aug 9,		6.85	0.78	2.97	0.232	45.0	801	0.302	0.053	2.98	99.0
Aug 15,		48.1	1.50	3.30	0.495	66.5	776	0.293	0.052	5.69	99.9
Aug 28,		26.2	1.25	3.22	0.403	62.0	744	0.281	0.057	3.70	99.0
May 21—22,	1967	2.54	0.60	2.87	0.172	39.5	793	0.299	0.054	2.08	96.0
July 17—18,		9.97	0.95	3.07	0.292	56.5	783	0.296	0.048	3.72	99.5
Aug 22,		4.44	0.76	2.96	0.225	48.5	548	0.207	0.049	0.99	81.0
Aug 26,		14.9	1.01	3.10	0.313	48.0	766	0.289	0.057	3.17	97.8
Sept 1,		5.73	0.81	2.99	0.242	51.0	674	0.254	0.048	1.77	98.2
Sept 13,		2.00	0.64	2.89	0.185	48.5	546	0.206	0.050	0.80	96.0
July 15,	1968	6.63	0.82	3.00	0.246	50.0	798	0.301	0.053	3.11	99.4
July 18,		2.91	0.60	2.87	0.172	43.0	721	0.272	0.048	1.56	95.0
July 25—26,		6.74	0.84	3.01	0.253	57.0	584	0.220	0.045	1.31	99.1
Aug 13,		5.30	0.74	2.95	0.218	50.5	812	0.306	0.048	3.25	98.5
Aug 22,		14.3	1.14	3.18	0.363	64.5	779	0.294	0.050	4.40	98.2
May 11,	1969	34.5	1.30	3.25	0.423	52.0	805	0.304	0.071	4.39	99.1
July 26,		12.2	1.10	3.15	0.347	53.0	645	0.243	0.057	2.04	97.0
Aug 9—10,		12.9	1.01	3.10	0.313	69.0	500	0.189	0.050	1.15	96.2
Aug 20—21,		36.9	1.47	3.30	0.485	79.0	763	0.288	0.054	5.04	99.5

It can be seen from Table 4 that, in most floods, wash load comprises over 95% of the total delivery. In other words, the sediment delivery of each flood is essentially wash load. The carrying capacity for wash load is so large that, however high the yield of wash load from a watershed may be, it can generally be transported down the stream by the flowing water. Hence the wash load or the sediment yield of a watershed is mainly dependent upon the water yield of the watershed, and obviously the sediment delivery ratio in these watersheds is exceedingly high.

The reason for the predominance of wash load in the total delivery by each flood in these catchments lies in the hyper-concentration of sediment during floods. The average sediment content is over 500 kg/m^3 for all floods in watersheds of medium or small size in the gullied rolling loess regions on the middle reaches of the Yellow River.

It can be shown by comparing the results computed by using formulas (4) and (5), as seen in Table 4, that if the correction for sediment content is not taken into consideration, the wash load is no more than 50–60%. The percentage of wash load increases to over 95% after introducing the correction. Floods with hyper-concentration of sediment tend to reduce the settling velocity of the particles, so that the transporting capacity rapidly increases. The same has been pointed out by Williams and Berndt (1972) in an analysis of the cause for the high values of delivery ratio in Brushy Creek watershed; the soil in the watershed has a high content of clay particles which, once suspended, do not settle readily. The basis of the observation, that the sediment delivery ratio for medium or small watersheds in gullied rolling loess regions on the middle reaches of the Yellow River keeps to 1.0 or so, lies in the hyper-concentration of sediment during floods.

ESTIMATION OF THE SEDIMENT DELIVERY RATIO

Many factors affect the sediment delivery ratio, and the findings of research workers have varied. Roehl (1962) stated that the delivery ratio is only a function of the characteristic values of the watershed in question, irrespective of the conditions of flow. Williams and Berndt (1972) further pointed out that the delivery ratio can be computed as an exponential function of the mean gradient of the gullies or of the area of watershed. It has also been found through polynomial regression analysis that the mean gradient of gullies is significant. Li and Simons (1973) were of the opinion that, under similar hydrological and geological conditions, the sediment delivery ratio may be an exponential function of both the average gradient of the gullies and the area of watershed. It is because of the very complexity of the problem of delivery ratio that an equation for delivery ratio which is universally applicable to all instances is at present still lacking. Formulae have been derived by a number of research workers for computing the delivery ratio corresponding to particular regions.

From the studies made in rolling red-earth areas in S. Kansas and other places, Maner (1958) obtained the following equation for delivery ratio (see Vanoni, 1975):

$$\log DR = 2.943 - 0.824 \log L/R \qquad (6)$$

Using data collected through field investigations carried out in foothill regions in southeastern United States, Roehl (1962) derived the following equation:

$$\log DR = 4.5 - 0.23 \log 10A - 0.51 \log L/R - 2.79 \log B \quad (7)$$

The equation derived by Williams and Berndt (1972) in studying the sediment delivery ratio in the small watershed of Brushy Creek is:

$$DR = 0.627\, SLP^{0.403} \quad (8)$$

The formula for delivery ratio by Mutchler and Bowie (1975) is:

$$DR = 0.488 - 0.00064A + 0.0099RO \quad (9)$$

where: DR = sediment delivery ratio (%);

A = drainage area, in square miles in equation (7) and in hectares in eq. (9);

L/R = dimensionless ratio of length versus height of the watershed (i.e. the length of watershed measured along the main gully divided by the difference in elevation of the divide and the mouth of the gully);

B = ratio of branches (weighted mean);

SLP = gradient of main gully, in %;

RO = runoff, in cm.

Analyses have been made by the authors on their modified delivery ratio for varying watershed areas in the Dali River basin study area. It can be seen from the dashed line in Fig. 3 that, other conditions being identical, there is a tendency for a decrease in the modified delivery ratio with an increase in the area of watershed, though at a much slower rate. The relatively large deviation of a few points from the overall trend is due to the fact that the gully density of these watersheds is larger than that of the elementary watersheds.

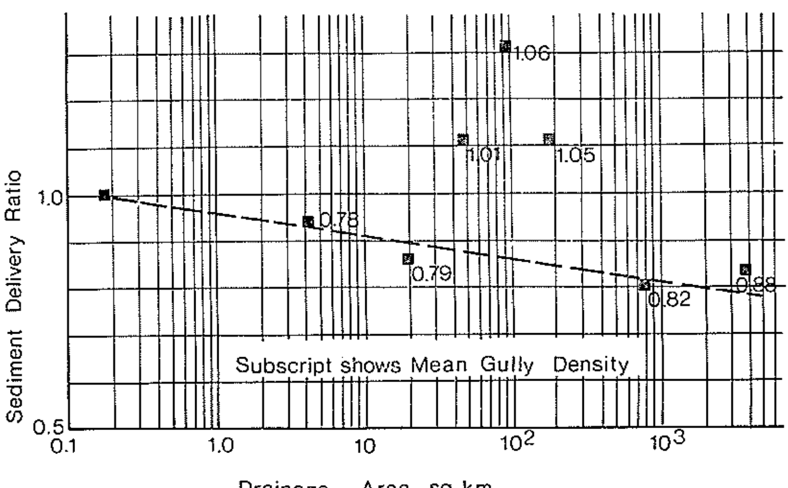

FIGURE 3—Delivery ratio (DR) of the watershed of Dali River versus drainage area (A).

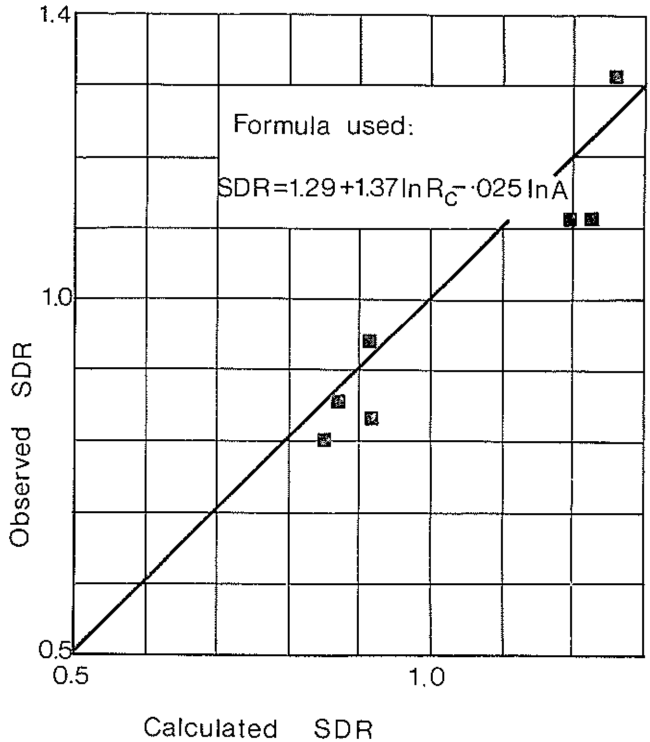

FIGURE 4—Comparison of computed and observed values of delivery ratio in the Dali River basin.

Thus, the rate of soil erosion in gullies and ravines is much higher than that due to sheet erosion in the areas, as stated above. The delivery ratios of these watersheds may therefore be larger than that of an elementary watershed.

From the previous analyses, it can also be seen that there is but weak correlation between the delivery ratio of the Dali River basin study area and the regime of flow. The former is only a function of particular characteristic values of a certain watershed. Taking into consideration factors such as area of watershed and gully density, we arrive through correlation analyses, at the following formula for computing delivery ratio:

$$DR = 1.29 + 1.37 \ln Rc - 0.025 \ln A \qquad (10)$$

in which: DR = modified sediment delivery ratio (fraction);
Rc = gully density (total length of gullies measured on topographic map of the scale 1 : 100,000, divided by the area of watershed), expressed in km/km^2;
A = area of watershed (km^2).

It is manifest from Eq. (10) that the delivery ratio does decrease with an increase in area of watershed, and increases with an increase in gully density. This finding agrees with the foregoing analyses in the main. A comparison of the computed and observed values of delivery ratio is given in Fig. 4. The relative error of the computed values is below 11% so that Eq. (10) will satisfy precision requirements for practical purposes.

CONCLUDING REMARKS

1. In the gullied rolling loess regions on the middle reaches of the Yellow River, the area occupied by gullies is relatively large, gravitational erosion is severe, and the erosion rate of gullies is higher than that of the slope surfaces. The total quantity of soil eroded from the watershed in the formula for computing the delivery ratio should thus not be simply taken as the global sum of the erosion of soil from the land surface of the watershed, but as the combined erosion rates of slope surfaces and gullies.

2. As a practical formula for estimating the total quantity of soil eroded from a watershed is still lacking, the sediment yield of medium and small watersheds may be determined by means of observed data on sediment regime in elementary watersheds. A modified sediment delivery ratio may be defined as the ratio between the delivery rate of a medium or small watershed and the erosion rate of an elementary watershed.

3. As wash load comprises over 95% of the total quantity of soil eroded from a watershed, in gullied rolling loess regions on the middle reaches of the Yellow River, it constitutes the main part of the delivery. The delivery ratio is therefore particularly large. The basic cause of this phenomenon is the frequent occurrence of rainstorm floods with hyper-concentration of sediment in medium and small watersheds in this area.

4. As the delivery ratio for the Dali River basin is a function of the characteristic values of a watershed and has little to do with the conditions of stream flow, it can be computed directly by using Eq. 10 from the known gully density and area of watershed. For other regions and watersheds, however, owing to the lack of a formula for computing delivery ratio which is universally applicable, its evaluation should be closely related to the local conditions, reference being made to the available findings of research work.

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