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Effect of Runoff and Sediment from Hillslope on Gully Slope In the Hilly Loess Region, North China**

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ABSTRACT

In the hilly loess region, due to variation in geomorphological characteristics and to a lesser extent difference in soil characteristics, the relative significance of erosion processes and sub-processes varies with slope zone (upper hillslope, middle hillslope, lower hillslope, gully slope). Thus empirical relations established as well as parameters selected in these relations vary with slope zone. In addition, contributions of runoff and sediment from the hillslope have a significant effect on the gully slope. Data available show that if appropriate soil conservation measures are established to prevent the input of runoff, then the contribution of runoff and sediment by gully slope will be reduced by 29% and 64% respectively during an average storm, and by 61% and 84% respectively during the maximum storm.

INTRODUCTION

Some people have recognized the spatial variation of landforms and geomorphic processes in the hilly loess region, North China (Chen et al., 1988). Such variations have been linked to the vertical zonation of soil erosion and sediment production in this area (Cai et al., 1994). However, none of the studies approach the problem in a quantitative manner. Nor were the relations between soil erosion processes on the one hand, and hydrologic and pedagogical characteristics of the various slope zones on the other, clearly established. In addition, recent studies in the area have provided data to show the importance of spatial process interaction (e.g. Zeng, 1980; Luk, 1991). This is an important aspect of the vertical zonation of soil erosion because of its implications for effective soil conservation.

In this paper, our objectives are to elucidate the vertical zonation of soil erosion and sediment production in the hilly loess region based on quantitative process data, which have been collected; and to discuss the effect of upper slope contribution to lower slope runoff generation and sediment production.

Study Area

The Loess Plateau region in North China is well known for its extremely high rates of soil erosion. Every year, an average thickness of more than one centimetre of loess is removed from this region. The hilly loess region, where the study area is located, is one of the most severely eroded regions of the Loess Plateau. In part, this is related to the steep slope present and the thick Quaternary loess deposits, which have an average depth of over 100m. Furthermore, about two-thirds of the annual precipitation of some 500 mm occurs in July to September, mostly as short intensive storms. In addition, large areas were cleared for cultivation and as a consequence, soil erosion was accelerated.

In the hilly loess region, wide ranges of erosional processes are present. Generally speaking, these processes are differentiated according to slope zone and slope gradient, in the area hillslope can be conveniently divided into four zones (Luk, 1991). On the upper slope (zone 1 and 2), the slope gradient increases from a few degrees in zone 1 to 35° towards the base of zone 2. These slopes are underlain by Malan Loess and Lishi Loess of Upper and Middle Pleistocene Under the auspices of the National Natural Science Foundation of China

Age respective surfaces are usually cultivated and in part (zone 1) terraced, and the dominant processes are rain splash, sheet erosion, and rill erosion. The lower slope (zone 3) is marked by a sharp break in slope at its upper end (Fig. 1), and is characterised by a substantial increase in gradient to exceeding 40°. The underlying material is Lishi Loess and red Earth, a clayey deposit of late Tertiary age. The slope surfaces are covered by shrubs such as Caragana Koshinskii and the dominant land use is grazing of sheep and goats, and mass wasting as well as gully erosion are the most significant erosional processes. Furthermore, subsurface erosion in the form of tunnels typically develop inlets in zone 2 and upper zone 3 while outlets occur in the lower part of zone 3, often where the Lishi Loess is in contact with the Tertiary Red Earth. At the base of the lower slope, a valley floor (zone 4) with gentle gradient is present which directs runoff and sediment away from the slope base and towards the mouth of the drainage basin. Detailed field monitoring and additional field experiments were conducted in the Wangjiagou Experimental Basin located in Lishi City, Shanxi Province since 1956. Based experience of working in various parts of the hilly loess region, we believe that this experimental basin is typical of condition generally found in the region.

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Variation in runoff and sediment production

During 1963-1968, detailed field data were collected by local researchers in the Yangdaogou small basin, which has a basin area of 0.206 km^2 (SISWC, 1982). This remains the single most detailed source of information on runoff and sediment production in the entire region. Here, is suffices to provide a summary of experimental design. In the Yangdaogou basin, experimental runoff plots spanning the entire length of hillslope (zone 1 to zone 3) as well as for

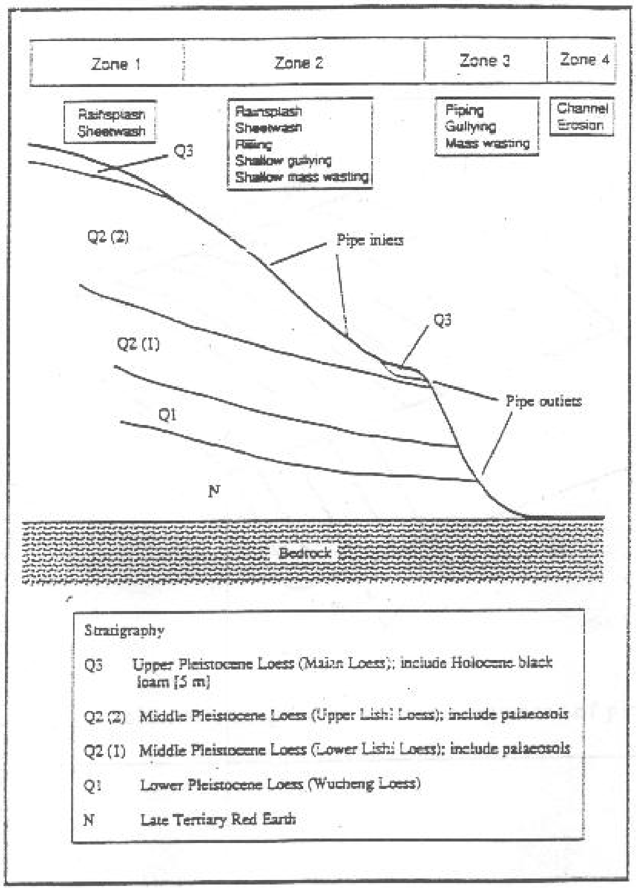

Figure 1. Slope zone and dominate erosional processes in the Yangdaogou Basin

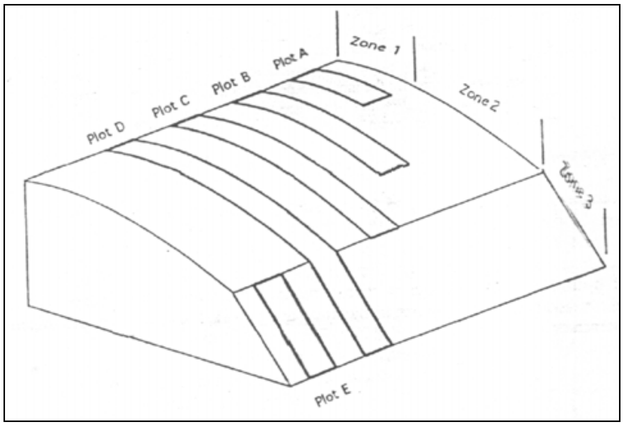

Figure 2. Schematic diagram to show arrangement of plots.

Table 1. Description of runoff plots.

Plot	Topographic position	Slope (°)	Length (m)	Area (m^2)	Slope zones included	Monitoring Method
A	Ridge top	0-8	40	200	zone 1	Flow divisors
B	Upper valley slope	13	70	600	zone 1 + upper zone 2	Flow divisors
C	Entire valley slope	17	105	1855	zone 1 +zone 2	Parshall flume
D	Entire hillslope	29	185	4167	zone 1 +zone 2 + zone 3	Parshall flume
E	Gully slope	36	90	1655	zone 3	Parshall flume

Table 2. Mean storm runoff depth, soil loss, and sediment concentration.

Plot*	Slope zones included	Runoff depth (mm)	Soil erosion (t/km^2)	Sediment Concentration (kg/m^3)	Number of Storms
A	Zone 1	4.59	109	35.7	28
B	Zone 1+upper zone 2	3.11	331	96.1	27
B1	Upper zone 2	3.94	606	151.7	27
C	Zone 1+zone 2	3.07	1312	377.7	34
C1	Lower zone 2	4.87	2749	530.0	34
D	Zone 1+zone 2+zone 3	3.55	2433	614.5	40
D1	Zone 3	4.77	4131	927.5	40

* Plot B1 = Plot B - Plot A; Plot C1 = Plot C - Plot B; Plot D1 = Plot D - Plot C

Table 3. Mean annual runoff depth and soil loss

Plot	Runoff depth (mm)	Soil loss (t/km^2)
A	21.4	509
B	14.1	1500
C	17.4	7433
D	23.7	16221
E	34.1	26615

different slope zones were established (Fig. 1). Details of plot dimensions and general characteristics of each plot are shown in Table 1.

Runoff and sediment concentration was monitored at the outlet of the basin during the same period. In total, 40 storms were monitored during 1963-1968. Mean storm runoff, soil loss, and sediment concentration for each plot is shown in Table 2. In this table, it can be seen that variations in average storm runoff depth are small. However, it should be noted that the number of storms, which generated runoff, is significantly different between plots. This is because runoff occurred much more frequently on the lower slope. Another way of evaluating runoff is to consider mean annual runoff of each plot. A summary of these data is given in table 3. Here, it can be seen that mean annual runoff depth (1963-1968) increased significantly in the downslope direction. The only exception is a somewhat higher runoff of rate from plot A (zone 1). It is most likely that this is related to the high frequency of occurrence of surface sealing and crusting on the gentler slopes (Luk et al., 1993).

For soil loss and sediment concentration, There is a progressive increase as the plot is extended in length to the base of the entire slope. The trend is similar for both the average event (table 2) and the average annual data (Table 3). Using data from table 2, if plot A (zone 1) is taken as unity, then unit area soil loss will increase to 3, 12 and 22 times for plot B, C and D respectively. Similarly, average sediment concentration will increase to 2.7, 10.6 and 17.2 times respectively. These variations in soil loss and sediment concentration are related to the dominant erosion processes operating in each slope zone. They will be discussed in the following section.

Variation in runoff and soil loss relation

In addition to runoff and soil loss rates, information on variation in runoff-soil loss relations provide insight to the vertical zonation of soil erosion and sediment production in the hilly loess region. In the following discussion, such variations are discussed with respect to the power function relation:

$$S = a\,Q^{b} \qquad (1)$$

where S is soil loss rate (t/km^2), Q is runoff depth (mm), ‘a’ and ‘b’ are empirical coefficients.

It should be noted also that the exponent of this power function relation in the Loess Plateau is known to be considerably lower than has been found in most other parts of the world. The main erosion is that because of the high erodibility of the loess soil (Luk et al., 1989), as well as the high frequency of occurrence of hyper concentrated flow (Hamilton, 1990), consistently high sediment concentration is associated with medium to runoff events. Hence, sediment concentration ‘C’ has values hovering around 0 for the relation:

$$C = a'\,Q^{b'} \qquad (2)$$

and a value of close to 1.0 is often observed for the exponent in equation (1).

In zone 1 (plot A), because of its topographic position and relatively gentle gradient (0-8°), erosion is strongly influenced by rain splash detachment and transport by interrill flow. Flow detachment is ineffective. As a result, the exponent for the S-Q relation is only 0.69 (table 4), indicating that as runoff increases, soil loss is not increases in proportion. An additional factor is the high frequency of occurrence of surface sealing and crusting on shallow slope (Luk et al., 1993). The crusted surface typically has high soil strength and thus is more resistant to stresses by raindrop impact or interrill flow.

For plot B that extends to the upper part of plot zone 2, runoff and soil loss rate is considerably higher due to input from zone 1. It is noteworthy that runoff depth is especially high in zone 1 due to surface sealing and because of the higher soil resistance there, transport capacity of the interrill flow was not attained. However, in the upper part of zone 2, flow concentration occurs frequently. Thus, rill development, aided to some extent by the under-capacity of runoff contributed from upslope, becomes much more frequent. As a result, the observed exponent of the S-Q relation is raised to 0.88 (table 4). To determine net contribution of the upper part of zone 2, the difference between plot A and plot B for each storm was determined and the results are referred to as plot B1. Regression analysis shows that the exponent for plot B1 is 0.84, which is not significantly different from in plot B.

In the plot extending to the lower part of zone 2 (plot C), the frequency of rill development is much higher, flow detachment becomes more significant, and hyper concentration was often observed. The maximum concentration recorded was 669 kg/m^3. Because of the high frequency of rill flow and the occurrence of hyper concentration, the exponent for the S-Q relation reached 1.08. Where the net concentration of the lower part of zone 2 is considered (plot C - Plot B, plot C1), the exponent for the S-Q relation is 0.99.

For plot D that extends from zone 1 to zone 3, rill and shallow gully development is often observed. Because of the deeper flows attained in the rills and shallow gullies as a result of runoff input from upslope, flow detachment is the dominant mechanism for sediment entrainment. In contrast, splash detachment is the insignificant. Also because of the steeper slope gradient, transport capacity of the surface flow is further enhanced. Maximum sediment concentration exceeding 900 kg/m^3 was observed. The exponent for the S-Q relation was found to be 1.25, which is slightly higher than the value of 1.08 observed when the net influence of zone 3 (plot D – plot C, or plot D1) is considered.

Thus, on the whole, there is a systematic increase in the exponent for the S-Q relation from zone 1 to zone 3, indicating the changing characteristic of the erosion processes in response to varying topographic conditions and increase in input of runoff and sediment from the upper zones.

Variations in infiltration and soil characteristics

Apart from the variation in the dominance of erosion processes, there are several other factors, which may explain increases in soil erosion and sediment concentration from zone 1 to zone 3. Clearly, one important factor is soil infiltration characteristics. Existing data derived from field-testing using a small portable rainfall simulator (Li 1992) show final infiltration rates, which generally decrease in the downslope direction (table 5). In part, the downslope decrease in infiltration capacity is a result of different types of surface material distributed in the different slope zones.

Table 5. Final infiltration rates for a range of slope zones.

Slope zone	Infiltration rate (mm/min.)
zone 1	0.97 - 1.02
zone 2	0.78 - 0.87
zone 3	0.55 - 0.71
zone 4	0.33 - 0.44

In zone 1 and zone 2, the slope surface is typified by mixed Malan and Lishi Loess, which have been cultivated for an extended period of time. The surface is either "plowed" and hence in a loose state, with bulk densities in the range of 1.02-1.15 g/cm^3 (Luk et al., 1989), or "cultivated" which is plowed soil subjected to a period of compaction by natural rainfall and consolidation, resulting in bulk densities of 1.10-1.22 g/cm^3. In zone 3, it is mostly soil derived from Lishi Loess and Red Earth, which were not cultivated. The range of bulk densities observed was 1.40-1.67 g/cm^3.

In addition, infiltration characteristics are influenced by soil moisture condition. Soil moisture content in the different slope zones was not monitored. However, some data published in Luk et al. (1989) show trends of increasing moisture content in the downslope direction. This trend is consistent with the observed downslope increase in runoff depth.

Effect of upslope contribution to gully slope runoff and sediment load

It is obvious from the above discussion that unit area soil loss from gully slope (zone 3) is substantially greater than the upper zones. However, previous studies (e.g. Zeng, 1980) have suggested that soil loss from these gully slopes be influenced by the upslope contribution of runoff and sediment. In fact, it was shown that in the same area, where runoff from the upper zone were prevented from reaching the gully slope, runoff and soil loss from these gully slope was reduced by 59% and 78% respectively (Zeng 1980). Similarly, in the hilly loess region, soil loss from the gully slope was increased by 126-140% when runoff was allowed to reach the gully slope (XSCES 1978). Here, the problems of the influence of upslope runoff and sediment concentration are evaluated based on data available from the Yangdaogou presented above.

Taking Q_D as runoff depth from plot D which span zone 1, 2 and 3, Q_{D1} as runoff from the gully slope (zone 3) with upslope runoff contribution (Q_D-Q_C), and Q_E as runoff from the gully slope with no upslope contribution, we can establish the following power function relations:

$$Q_{D1} = 1.30Q_D^{0.97} \quad (3)$$

with r=0.92 and n=35, and

$$Q_E = 1.47Q_D^{0.60} \quad (4)$$

with r = 0.67 and n=39.

Both relations are significant at the 0.01 level. By combining equation (3) and (4), we can establish the following:

$$Q_{D1}/Q_E = 0.88Q_D^{0.37} \quad (5)$$

Where Q_{D1}/Q_E represents the ratio of runoff derived from the gully slope with upslope contribution to runoff from the same slope with no upslope contribution (or runoff ratio). The resultant relation implies that when Q_D =1mm, Q_{D1}/Q_E =0.88, which means that where total runoff is small, or during the early period of runoff production, the runoff ratio is close to 1, and upslope runoff contribution has little influence. However, when total runoff ratio will greatly exceed unity. For instance, average and maximum storm runoff depth during 1963-68 is 3.55 mm and 2.17 mm respectively. The corresponding runoff ratios are 1.44 and 2.75 respectively.

By following the same procedure for soil loss, the following relation can be established:

$$S_{D1} = 6.77\, Q_{D1}^{1.08} \quad (6)$$

Where $r = 0.91$ and $n = 35$, and

$$S_E = 254.2\, Q_E^{1.17} \quad (7)$$

Where $r = 0.93$ and $n = 39$.

The notations for soil loss S are similar to runoff Q. both relations are significant at the 0.01 level. Combining equations (6) and (7) yield:

$$S_{D1} / S_E = 2.66\, (Q_{D1}^{1.08} / Q_E^{1.17}) \quad (8)$$

And substituting from equation (5) yields

$$S_{D1} / S_E = 2.25\, Q_D^{0.34} (9)$$

Where S_{D1}/S_E represents the ratio of sediment load derived from the gully slope with upslope runoff and sediment contribution, to sediment load from the same slope with no upslope contribution (or sediment ratio). This relation suggests that when $Q_D > 0.1$ mm, the sediment ratio will exceed 1.0. This can be explained by the fact that with upslope contribution of runoff and sediment, some sediment is available on the gully slope due to deposition towards the later stages of a previous storm. Hence, any significant amount of runoff will yield higher sediment load from the gully slope with upslope runoff contribution. When runoff increases during moderate to heavy storms, the sediment ratio will recorded during 1963-68 is 3.46 and 6.39 respectively.

From the above discussion, it is clear that while gully slopes contribute a large proportion of total basin sediment load, a significant part of the sediment contribution is induces by the upslope input of runoff. If appropriate soil conservation measures are established to prevent the input of runoff, then the contribution of runoff and sediment by gully slope will be reduced by 29% and 64% respectively during an average storm, and by 61% and 84% respectively during the maximum storm.

CONCLUSIONS

Due to variation in topographic, soil, and land use conditions, there is clearly a vertical zonation of soil erosion processes, which give rise to zonations of runoff rates and soil loss rates. These spatial variations of soil erosion and sediment production are shown by actually monitored runoff and soil loss data, as well as runoff-soil loss relations. Furthermore, there is significant spatial interaction of processes. Contribution of runoff from upslope (zone 1 and zone 2) has a very significant effect on runoff and sediment production on the lower slope or gully slope (zone 3). If appropriate soil conservation measures are established to prevent the input of upslope runoff to gully slopes, then the contribution of runoff and sediment by gully slopes can be significantly reduced.

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