DEVELOPMENT AND APPLICATION OF THE RUNOFF EROSIVITY FOR SEDIMENT YIELD PREDICTION ON WATERSHED SCALE

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Abstract

Based on runoff power theory, the relation between runoff power and sediment yield module from single rainfall on a watershed scale was setup using field observation data from 4 watersheds on the Loess Plateau. Results indicated that there was a good power relation ($y=ax^b$) between runoff erosivity and sediment module, with its correlated coefficient over 0.9. The exponential constant in the relation was ranged from 0.4~0.65, with its average value 0.52, and it was bigger in the watershed with proper management. While the constant "a" decreased with the increase of watershed area, and it was smaller in the watershed with proper management. Preliminary experimental verification indicated that the precision of sediment yield from watersheds has been greatly improved by replacing rainfall erosivity and runoff with runoff erosivity, which proved to be a key parameter in soil erosion sediment yield prediction of single rainfall events in loess areas.

Introduction

In the last decades, studies on the physical mechanism and development processes of rill erosion have drawn great attentions all over the world (Foster and Meyer, 1975; Govers, 1990; Knisel, 1980; Nearing *et al*, 1989; Laflen *et al.*, 1991). Numerous equations describing the relationships between the soil detachment rate and the average hydraulic shear stress of flow have been proposed (Meyer, 1964; Foster and Meyer, 1975; Nearing *et al.* 1989; Laflen *et al.*, 1991; Foster *et al.* 1977; Foster, 1982, 1990; Foster and lane, 1983; Lei Alin, 1998). Meyer (1964), Foster *et al.* (1984), Knisel(1980), Laflen *et al.*(1991), Meyer *et al.* (1985) and Foster and Myer (1975) proposed that soil detachment from a rill perimeter was primarily a function of the average shear stress of flowing water. However, Foster *et al.* (1984), Lei and Nearing (1998) indicated that flow in the rills is very inconsistent because of non-uniformities of both channel cross-section and bottom profile along the rill. Hence, the shear stress from roughness in the rill varies spatially. Use of constant average hydraulic shear stress as an overall parameter for rill detachment is not reasonable because of the spatial and temporal variations of shear stress in the rills.

It is well known that the process of soil detachment by flowing water in the rill is a process of flow energy. The higher flow energy is, the more soil particles are detached. Zhanbin Li (2001) discussed the rationality of replacing runoff shear stress with runoff power for calculating the runoff detachment ratio, and the quantitative relation between runoff power and sediment yield on slope is setup. Results indicated that unit runoff power increased with the increase of slope gradient under the same runoff discharge. In this paper, based on the definition and mechanism of energy consumption, runoff power theory is used for the sediment yield on watershed scale.

Theory of the model

In USLE, rainfall erosivity was defined as the total storm energy (E) timing the maximum 30-min intensity (I_{30}), which reflected the amount and intensive degree of each rainfall. But there also existed irrationality in this model. For example, soil erosion seldom occurs when the vegetative cover was over 70% on forestry sites. In addition, in China, especially on the Loess Plateau, concentrated floe erosion was the main form of soil erosion, and sediment yield from raindrop splash accounted for only small proportion of the total sediment yield. Thus for the research of sediment yield on watershed scale, it is important to develop a new index based on runoff erosion to replace rainfall erosivity.

Flood characters of the watershed are the complex interactions between rainfall and surface characters in the watershed. Runoff from the watershed surface is not only the essential drive of the erosion from slope and gully, but also the main carrier for sediment transportation. Thus flood characters at the exit of the watershed is the cooperative results of rainfall, soil, vegetation, topography, and human activity, which reflected indirectly the influence of rainfall and surface characters in the watershed. That is also the reason why most researchers built erosion-sediment yield model by determining the relation between runoff and sediment transport based on runoff and sediment data from the hydrological station at the exit of the watershed. Runoff and flood peak discharge are the two main parameters for flood character, among which runoff discharge is reflected the amount of flood, and flood peak discharge reflected the intensity of the flood. Analysis had demonstrated that there was no direct relation between

runoff discharge and peak runoff discharge. Although peak runoff discharge affected the amount of runoff discharge, runoff discharge was not determined by the peak runoff discharge. Thus these two parameters can be treated as independent to each other. As the relation between sediment transportation modulus runoff discharge and peak runoff discharge is exponential relation respectively, sediment transportation modulus in each rainfall should be the function of runoff depth and peak runoff discharge modulus:

$$M_S = f(H, Q_m) \tag{1}$$

Among all the factors influencing the sediment yield on watershed scale, water was considered as the most important. It will be better to calculate the sediment yield by runoff and peak runoff discharge modulus when using amount of rainfall and rainfall intensity as the basic variable for input. Thus in this paper, a new conception, runoff erosivity, was put forward by combining runoff depth and peak runoff discharge modulus, which reflected the jointed effect of runoff and peak runoff discharge on sediment yield and transportation. As runoff and peak runoff discharge are all closely related to the watershed area, and sediment transportation modulus was the amount of sediment transportation on unit area, runoff erosivity should be defined to reflect the soil erosion and sediment transportation ability by runoff, which had no relation to watershed area. Based on above consideration, the equation for runoff erosivity was listed as follows:

$$Y = Q_m H \tag{2}$$

$$Y = \frac{W}{A} Q_m \tag{3}$$

where Y — runoff erosivity; Q_m—flood peak discharge, $m^3 s^{-1}$; W—runoff dischage, m^3; A—watershed aream, m^2; H—runoff depth. In equation (2), runoff erosivity can be treated as the results of runoff discharge on unit area (in mass) times peak runoff discharge.

Results and Discussion

Based on the analysis of field observation data, (including rainfall, runoff and sediment yield) in Chabagou watershed, relation between runoff erosivity and sediment transportation modulus was determined by linear and non-linear regressive analysis (Table 1).

Table 1. Regressive analysis of relation between runoff erosivity and sediment transportation modulus.

Watershed	Watershed area (km^2)	Linear regressive model		Non-linear regressive model	
		Equation	Correlative coefficient R^2	Correlative index R^2	Equation	Determining coefficient R^2
Caoping	187	Y=91.888E$^{0.5281}$	0.9532	0.9406	Ms=136.52E$^{0.4729}$	0.9459
Dujiagoucha	96	Y=152.61E$^{0.4801}$	0.9295	0.9282	Ms=158.66E$^{0.4737}$	0.9276
Xizhaung	49	Y=139.02E$^{0.5119}$	0.8029	0.9080	Ms=224.08E$^{0.4312}$	0.9114
Sanchuankou	21	Y=121.14E$^{0.6219}$	0.9418	0.8979	Ms=269.11E$^{0.4710}$	0.9147
Tuo'erxiang	5.74	Y=145.46E$^{0.6520}$	0.9268	0.9879	Ms=241.55E$^{0.5395}$	0.9936
Shejiagou	4.72	Y=342.15E$^{0.5380}$	0.9435	0.9666	Ms=413.45E$^{0.5003}$	0.9680
Heifangou	0.133	Y=1950.4E$^{0.9041}$	0.9577	0.9087	Ms=1233.60E$^{0.5523}$	0.9825
Shuiwanggou	0.107	Y=1080.7E$^{0.8066}$	0.9727	0.8966	Ms=1827.83E$^{0.4730}$	0.9832

It was clear that in different watersheds, sediment transportation modulus increased with the increase of runoff erosivity, which indicated that there existed exponential relation between sediment transportation modulus and runoff erosivity as follows:

$$M_S = aE^b \tag{4}$$

where Ms is the sediment transportation modulus, E is the runoff erosivity, and a and b is the constant in the equation. There also existed differences in the results by the two methods (Table 1). Results by linear analysis indicated that

correlation coefficient in Shuaiwanggou was the biggest, 0.9727, but its correlation index was smallest, 0.8966. Except for Dujiacha, all determining coefficients by nonlinear regressive analysis were bigger than that by linear analysis. To Dujiacha watershed, parameters in the two models were close, and the correlation coefficient; correlation index and determining coefficient index were close too.

Differences also existed in parameters by the two methods. To the exponential index "b" by linear analysis, its value in Dujiacha was the smallest, 0.4312; while it was the biggest in Hefangou, 0.5523. and there was no remarkable changes in this parameter among the watersheds, which was all close to 0.5. To the constant "a" in the equation, except for Tuo'erxiang watershed, its value had and inverse ratio rations to the watershed area, and decreased with the increase of watershed area. Based on the recordings of observation, slope and gully management in Tuo'erxiang watershed was relative higher than those in the other watershed, which was in accordance with the decrease in sediment reduction, may be the reason for the decrease of "a" value.

Conclusion

Based on the above analysis, it was clear that there was close relation between runoff erosivity and sediment transportation modulus. In former researches, it was difficult to reflect the ground characters of watershed when using rainfall erosivity for soil erosion prediction, thus runoff erosivity will be more useful because it was the results between rainfall and ground characters, and it reflected not only soil erosion by runoff, but also sediment transportation ability. As runoff discharge and peak runoff discharge are the two important parameters for the flood, it will be more rational to reflect the soil erosion and sediment transport ability by runoff by united these two parameters into one (that is runoff erosivity).

Results indicated that there existed exponential relation between runoff erosivity and sediment transportation modulus, with regressive correlation coefficient over 0.9. Exponential index "b" was related to the management of the watershed, which was bigger in the watershed with more management, and smaller in the watershed with less management. On the other hand, constant "a" was related both watershed area and management, which decreased with the increase of watershed area and watershed management.

Although there was a similar relation between runoff erosivity and sediment transportation modulus in the watershed of different area, differences in the parameter indicated that different management also had some effects on the sediment yield. Thus future researches should be conducted to study the influence of soil and water conservation measures on sediment yield and transportation based on the concept of runoff erosivity.

References

Calloins,D. and T. Dun, (1970). A salt tracing method for measuring channel velocities in small mountain streams. Journal of Hydrology, 11,379-392

Ellion, W.D (1947). Soil erosion studies, part .*Agricultural Engineering* 28 (4):145-146.

Foster, G.R., and Meyer, L.D. (1972). Transport of soil particles by shallow flow. *Transactions of the ASAE* 15(1):99-102

Foster, G.R., and Meyer, L.D. (1975). Mathematical simulation of upland erosion by fundamental erosion mechanics. In Present and Prospective Technology for Predicting Sediment Yields and Sciences, 190-207, ARS-S-40. Washington DC: USDA-Science and Education Administration.

Foster, G.R., and Meyer, L.D. (1977). An erosion equation derived from basic erosion principles. *Transactions of the ASAE*, 1982, 25(4):678-682.

Foster, G.R., Huggins L.F and Meyer, L.D (1984), A laboratory study of rill hydraulics: I. Velocity relationships. *Transactions of the ASAE* 27(3):797-804.

Foster, G.R. (1982). Modeling the erosion process, in Hydrologic Modeling of small watersheds, edited by C.T. Haan, pp.295-380, Transaction of the ASAE. St. Joseph, Mich.

Foster, G.R., Osterkamp, W.R., Lane L.J. (1982). An erosion equation derived from basic erosion principles. *Transactions of the ASAE*, 25(4):678-682

Govers, G. (1990). Empirical relationships for the transport capacity of overland flow: erosion, transport, and deposition process, IAHS Publ., 189:45-63.

Gilley, J.E., Kottwitz, ER and Simanton. J.R (1990). Hydraulic characteristics of rills. *Transactions of the ASAE* 33(6):1900-1906.

Knisel, W.G., ed. (1980). CREAMS: A field-scale model for chemicals, runoff, and erosion from agricultural management systems. Conservation Research Report NO.26. Washington DC: USDA-Science and Education Administration.

Laflen *et al.*, (1991). WEPP soil erodibility experiments for rangeland and cropland soils, *J. Soil and Water Conservation.*, 46(1):39-44.

Lei Alin, Tang keli. (1998). Kinetic Condition of Rill Erosion on Loess Sloping Face. *Journal of Soil Erosion and soil and water conservation*, 4 (3), pp39-43, 72

Meyer *et al.* (1969). Mathematical simulation of the transport capacity of soil erosion by water. *Transactions of the ASAE* 12(6):754-758

Nearing *et al.*, (1989) A process-based soil erosion model for USDA-water erosion prediction project technology. *Transactions of the ASAE* 32(5), 1587-1593.

Tingwu Lei and Mark A. Nearing, (1998). Rill erosion and morphological evolution: a simulation model. *Water Resource Research*, 34(11):3157-3168

Zhanbin LI, Kexin Lu, Wenfeng Ding. (2001) Study on the dynamic process of rill erosion of Loess slope surface. *International Journal of Sediment Research* 16(2):308-314

Zheng Feili, (1988). Rill erosion and its control in the slopping farmland of the loess plateau. Memoir of Northwestern institute of soil and water conservation academia sinica, Vol.**7**:19-25 June, 1988