Research Progress on Soil Erosion Process and Erosion Prediction Model in the USA

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Abstract: Soil erosion process research produces the knowledge and science used in the development of current process-based erosion prediction model. This presentation will highlight past efforts in developing erosion process concepts that lead to the development of current process—based erosion prediction model, i.e., WEPP. Recent erosion process studies have produced data sets that challenge some of the WEPP model concepts. We hope erosion process and model research in USA could enhance soil erosion research in China.

Keywords: **soil erosion**; **erosion process**; **process-based prediction model**; **United States of America**

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美国土壤侵蚀过程及其预报模型研究进展

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摘 要: 土壤侵蚀过程的研究将为基于物理过程的侵蚀预报模型研发提供重要的理论基础。介绍了美国土壤侵蚀过程研究进展, 叙述了土壤侵蚀过程研究对研发水蚀预报模型(WEPP)的重要贡献, 阐述了近期侵蚀过程研究对 WEPP 模型中侵蚀过程概念模型的挑战, 希望对中国侵蚀过程及其预报模型的研究有借鉴作用。

关键词: 土壤侵蚀; 侵蚀过程; 物理过程模型; 美国

During rainfall process, many physical processes occur simultaneously at the soil surface. Processes affecting hydrologic and sediment regimes are infiltration, runoff, sealing, and erosion. These processes change as the rainfall (and consequently, runoff) intensity and surface conditions change. Many research efforts have been invested in the understanding of erosion process and in the development of erosion prediction model at various scales. This paper is a brief account of the erosion process research and model development in the US.

1 Historic Development of Erosion Process Research

In 1945, Vilensky[1] summarized three methodologies for quantifying soil erosion: (1) direct study of soil erosion under natural conditions on plots of various sizes, (2) study certain physical and chemical properties of soils to determine correlation between these properties and resistance of soil to erosion, and (3) direct study both under field and laboratory conditions of the tenacity of soils by means of methods specifically developed for this purpose.

These three methodologies are essentially different approaches taken in the development of erosion science. In the US erosion science history, step 1 can be exemplified by the extensive natural runoff plot data collection effort from the mid 1930s to the late 1950s that eventually lead to the development of Universal Soil Loss Equation[2,3]. Data from these natural runoff plots under individual storm events can be quite vari-

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able and erratic, even from paired side-by-side plots. Nevertheless, when long-term data were collected, they were still the best source in establishing the baseline soil erodibility and quantifying impacts of cropping and management factors. Despite its usefulness and contribution to the early development of erosion science, the number of long-term natural runoff plots in the US has dwindled in recent years. The natural runoff plot is still used extensively in many regions of the world to demonstrate the effectiveness of soil conservation practices.

The second methodology outlined by Vilensky is essentially the effort of defining soil erodibility relationship as functions of soil properties. This line of work dated back to the 1930s when Middleton and his coworkers identified physical and chemical properties that affect soil's response against erosive forces[4, 5]. Key soil properties identified from early research works were soil texture, aggregate stability, and dispersion index. Many soil properties indeed contribute to soil erodibility, some directly and some indirectly. Since soil composition do not change appreciably in a short time, such as within a year, relationships for soil erodibility and soil property tend to be held better for predicting long-term soil loss but less accurate for seasonal and short-term variation. Although soil erodibility is conceptually a measure of soil's response against erosive forces, in reality, erodibility is often defined as a term in the erosion equation relating to erosive terms on one side and soil loss on the other. Examples of such definition include the soil erodibility K factor in the Universal Soil Loss Equation (USLE)[2, 3] and interrill (K_i) and rill (K_r) erodibility in the WEPP model[6]. Therefore, soil erodibility may vary as the form of the erosion equation is changed. Defining soil erodibility from soil properties becomes difficult when the erosion equation is still being developed.

The third methodology of using specific procedures to examine the tenacity of the soil under erosive forces provides knowledge in erosion processes and builds the foundation for the development of erosion process models. This approach means conducting controlled experiments to quantify specific erosion processes or factors that affect the particular erosion processes. Erosive conditions for the experiment include rainfall simulation ranging from single raindrop to multiple drops for detachment and transport processes under rainfall and water flows for processes under concentrated flow. Early works in this category, although not inclusive, include study of raindrop impact splash erosion by J. O. Laws[7], and W. D. Ellison[8-11] and flow detachment and transport by Ellison and Ellison[12, 13] and the slope and rainfall effects by Neal[14]. Around the same time, efforts to quantify rainfall characteristics that are important for the initiation of erosion were also started.

A major step in the development of controlled rainfall experiment is the identification of rainfall simulator nozzles that can be used both in the field and laboratory. The work of Meyer in the late 1950s that identified the pressurized VeeJet series of nozzles for rainfall simulation and this type of nozzle became the most widely used one in the US[15]. Although several different types of rainfall simulators were developed using the same nozzle, such as the Meyer-McCune Rainulator, Swanson's rotating-boom and the oscillating nozzle-type Purdue programmable simulator, the principle of rainfall generation is basically unchanged. Along with the development of the rainfall simulator is the range of experimental procedures that are used in laboratory and field studies. Different plot size, surface preparation, and rainfall sequence often yield different and incompatible results from one study to another. Erosion researchers have long recognized the variability in experimental results and the need to develop a standard procedure in rainfall simulation. Nevertheless, this variability in procedure can be viewed as a part of the learning process because the erosion science is still at the exploratory stage. Such a variation in procedures would produce diverse data sets that allow us to examine different aspects of the unknowns until the erosion science is better developed.

2 A brief Account of National Soil Erosion Research Program

In 1954, the US Department Agriculture established the National Runoff and Sediment Data Center at West Lafayette, Indiana, where the natural runoff plot data collected from various states, predominately from the US mid-west, since the mid 1930s were compiled and summarized. This work led to development of USLE[2,3]. In the 1950s, parallel to the development of USLE by Wischmeier, Meyer[15] evaluated rainfall simulation technologies, identified the Spraying Systems VeeJet nozzle for artificial rainfall generation and initiated erosion process research at West Lafayette. Rainfall simulation allows collection of erosion data in a controlled fashion in a relatively short time as compared to erosion data derived under natural rainfall conditions. Rainfall simulation studies conducted in the 1960s were mainly focused on providing data sets to support the USLE development. Noted works in this period were those from Meyer, Wischmeier, Manning, Moldenhauer and Romkens on cropping and tillage effects, soil erodibility and the crop residue or mulch factor on soil erosion. Beginning in the early 1970s, rainfall simulation studies gradually shifted toward more process-oriented basic studies, largely due to the work by Meyer and Wischmeier[16] in that separate detachment and transport processes were proposed. In the early 1970s, conceptual developments in erosion processes by Meyer and Foster became the foundation of current US process-based erosion model, i.e., WEPP[6]. As the result of Foster and Meyer's proposition to separate erosion processes to those occurring in rill and interrill areas[17-19], erosion process studies were also diverting into quantifying rainfall-dominated interrill and flow dominated rill erosion processes. Since then, the rill-interrill process separation has dominated the erosion process research up till today. Significant works in the 1970s and 1980s included studies of flow hydraulics and sediment transport capacity by Neibling, Foster and Lu; raindrop impact and detachment, surface soil strength measurement, and interrill erosion by Bradford and his graduate students; and surface sealing and micromorphology research by Norton.

3 Development of Erosion Process Models in the US

A conceptual framework for understanding erosion processes was presented more than 50 years ago when Ellison and his co-worker proposed to divide erosion processes to four sub-processes: detachment by raindrop impact (D_R), transport by rain splash (T_R), detachment by surface flow (D_F) and transport by surface flow (T_F)[8-13]. In their sequence of papers, Ellison and his co-worker discussed separately the detachability and transportability of the soil and erosive agent. Although Ellison laid the foundation for a process-based approach to quantify soil erosion processes, rigorous development of erosion process model did not begin until more than 20 years later when Meyer and Wischmeier[16] proposed the 'rate-limiting concept'. The model concept of Meyer and Wischmeier stated that sediment delivery, q_s, was limited by either the detachment rate (D_R+D_F) or the transport capacity (T_R+T_F) depending on which-ever had a lower value. Meyer and Wischmeier also proposed separate equations for each of the individual processes. This is the first attempt to build a process-based erosion model.

Foster and Meyer[17-19] proposed a first-order detachment and transport coupling model for rill flow. This model relates the detachment or deposition rate, D_r, to the difference between transport capacity, T_c, and sediment load, q_s, or:

$$D_r = \alpha(T_c - q_s) \tag{1}$$

where α is a rate control constant. When $q_s < T_c$, the flow will cause additional sediment detachment and when $q_s > T_c$, the excessive sediment will deposit. The value T_c, a predefined hypothetical number, becomes the key in determining whether detachment or deposition occurs. The combination of conceptual frameworks for rainfall-dominated interrill and runoff-dominated rill erosion processes and the Foster-Meyer detachment-transport coupling model for rill erosion led to principal erosion equations in the process-based Water Erosion Prediction Project (WEPP) model[6].

The WEPP model uses a steady state sediment routing (or mass balance) equation:

$$\frac{\mathrm{d}q_s}{\mathrm{d}x} = D_r + D_i \tag{2}$$

where q_s is the sediment delivery rate per unit width of the rill channel, $M L^{-1} T^{-1}$; x is the length scale in the direction of the rill flow, L; D_r is the rill detachment or deposition rate, $M L^{-2} T^{-1}$; and D_i is the interrill sediment delivery rate per unit area of the rill channel, $M L^{-2} T^{-1}$.

Combining Equations (1) and (2) and defining a detachment capacity term, D_c, where $D_c = \alpha T_c$, Equation (2) becomes:

$$\frac{dq_s}{dx} = D_c\left(1 - \frac{q_s}{T_c}\right) + D_i \quad (3)$$

Equations (1) and (3) imply that $D_r = D_c$ when $q_s = 0$ and D_r decreases as q_s is increased. The sediment detachment-transport coupling concept is also widely known as the sediment feedback relationship in a different form:

$$\frac{D_r}{D_c} + \frac{q_s}{T_c} = 1 \quad (4)$$

In the WEPP model, the rill detachment capacity term is further expanded to incorporate the hydraulic shear detachment concept:

$$D_c = K_r(\tau - \tau_c) \quad (5)$$

where K_r is rill erodibility, and τ and τ_c are hydraulic shear and critical shear stresses. The interrill component is expressed as functions of slope and rainfall factors:

$$D_i = K_i S_f I^2 \quad (6)$$

where K_i is interrill erodibility, S_f is the slope factor and I is the rainfall intensity. Eq. (3) now becomes the erosion equation used in the WEPP model:

$$\frac{dq_s}{dx} = K_r(\tau - \tau_c)\left(1 - \frac{q_s}{T_c}\right) + K_i S_f I^2 \quad (7)$$

Recently, researchers have proposed replacements of the interrill intensity square (I^2) term to include a runoff factor, R, such as IR or $I^a R^b$ where a and b are regression coefficients[20, 21].

When $q_s > T_c$, deposition occurs. The deposition equation has a slightly different form from Equation (3) and is written as:

$$\frac{dq_s}{dx} = \frac{\beta}{q_w}(T_c - q_s) + D_i \quad (8)$$

where β is a deposition rate parameter and q_w is the runoff discharge rate per unit width of the rill. According to Foster and Meyer[17, 19], β is related to the fall velocity of the sediment.

4 Recent Developments in Soil Erosion Process Research

Largely due to the WEPP effort in the US and research works in Europe and Australia during the past 15 years, erosion research community throughout the world has recognized the need to pursue a process-based erosion prediction technology to replace the empirically-based USLE-type technology. Advantages of a process-based erosion prediction model are that the model can be universally applied and many areas in the world in need of an erosion prediction tool for conservation planning do not have the long-term databases needed for developing an USLE-type empirical model. Take the WEPP project as an example, there have been a proliferating amount of studies conducted and procedures proposed either to derive the parameters, particularly the rill and interrill erodibilities for the model or by using some sort of computational procedure to validate the model. Nevertheless, very few studies are designed to test the model concept or equation structure imbedded in the model. Literature search yielded no experimental evidence of evaluating the erosion process model concepts in the WEPP model, proposed hypothetically in the early 1970s. This creates a contradictory but amusing phenomenon: a supposedly validated model without any scientific evidence of the model concepts or formulations.

Our recent studies of surface hydrologic effects erosion process and sediment regime and the development of a multiple-box system show[22—26]: (1) sediment regime from the multiple-box system can be categorized into 5 different sediment scenarios ranging from deposition-dominated to detachment and transport-dominated processes; (2) the dominant erosion process depends on slope gradient, rainfall intensity and soil erodibility; (3) an increase in soil erodibility from the artesian seepage condition triggers a transport-dominated regime while a decrease in soil erodibility from profile drainage limits sediment detachment and enhances sediment deposition. These findings may change future directions of erosion process research and prediction model development, as some of current model concepts have already been challenged.

References

[1] Vilensky D G. Methodology for soil tenacity and soil erosion studies[J]. Agricultural Engineering, 1945, 26: 465—467.

[2] Wischmeier W H, Smith D D. A universal soil loss equation to guide conservation farm planning[J]. Trans. 7th International Cong. Soil Sci., I: 418—425, 196.

[3] Wischmeier W H, Smith D D. Predicting rainfall erosion losses—a guide to conservation planning[Z]. USDA

Agricultural Handbook, No. 537, 1978

[4] Middleton H E. Properties of soils which influence soil erosion[J]. USDA Technical Bulletin, No. 178, 1930.

[5] Middleton H E, Slater C F, Byers H G. Physical and chemical characteristics of soils from the erosion experiment stations[J]. USDA Technical Bulletin, No. 216, 1932. Also USDA Technical Bulletin, No. 430, 1934.

[6] Nearing M A, Foster G R, Lane L J, Finkner S C. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology[J]. Trans. ASAE. 1989, 32: 1587—1593.

[7] Laws J O. Recent studies in raindrop and erosion[J]. Agricultural Engineering, 1940, 21: 431—433.

[8] Ellison W D. Studies of raindrop erosion[J]. Agricul-tural Engineering, 1944, 25: 131—136, 181—182.

[9] Ellison W D. Soil erosion studies—Part I[J]. Agricultural Engineering, 1947a, 28: 145—146.

[10] Ellison W D. Soil erosion studies—Part II: Soil detachment hazard by raindrop splash[J]. Agricultural Engineering, 1947b, 28: 197—201.

[11] Ellison W D. Soil erosion studies—Part V: Soil transportation in the splash process[J]. Agricultural Engineering, 1947c, 28: 349—353.

[12] Ellison W D, Ellison O T. Soil erosion studies—Part VI: Soil detachment by surface flow[J]. Agricultural Engineering. 1947a, 28: 402—408.

[13] Ellison W D, Ellison O T. Soil erosion studies—Part VII: Soil transportation by surface flow[J]. Agricul-tural Engineering. 1947b, 28: 442—444, 450.

[14] Neal J H. Effect of degree of slope and rainfall characteristics on runoff and soil erosion[J]. Agricultural Engineering. 1938, 19: 213—217.

[15] Foster G R, Eppert F P, Meyer L D. A programmable rainfall simulator for field plots[M]. Agric. Rev. and Manuals ARM—W—10. USDA—ARS. Western Region. Oakland. CA. 1979. 45—49.

[16] Meyer L D, and Wischmeier W H. Mathematical simulation of the process of soil erosion by water[J]. Trans. ASAE, 1969, 12: 754—758, 762.

[17] Meyer L D, Foster G R, Romkens M J M. Source of soil eroded by water from upland slopes[M]. In: Present and prospective technology for predicting sediment yields and sources, US Department of Agriculture, Agricultural Research Service, Southern Region, New Orleans, Louisiana, ARS—S—40, 177—189. 1975.

[18] Foster G R, Meyer L D. A closed-form soil erosion equation for upland areas[M]. In: Shen, H. W. (ed.) Sedimentation. Colorado State Univ., Ft. Collins, Colorado, 1—19, 1972.

[19] Foster G R, Meyer L D. Mathematical simulation of upland erosion by fundamental erosion mechanics[M]. In: Present and prospective technology for predicting sediment yields and sources, US Department of Agriculture, Agricultural Research Service, Southern Region, New Orleans, Louisiana, ARS—S—40, 1975. 190—207.

[20] Kinnell P I A. Runoff as a factor influencing experimentally determined interrill Erodibility[J]. Australian Journal Soil Research. 1993, 31: 333—342.

[21] Zhang X C, Nearing M A, Miller W P et al. Modeling interrill sediment delivery[J]. Soil Sci. Soc. Am. J. 1998, 62: 438—444.

[22] Huang C, Laflen J M. Artesian seepage and soil erosion for a clay loam soil[J]. Soil Sci. Soc. Am. J. 1996, 60: 408—416.

[23] Gabbard D S, Huang C, Norton L D et al. Landscape position, surface hydraulic gradients and erosion processes [J]. Earth Surface Processes and Landforms. 1998, 23: 83—93.

[24] Huang C, Wells L K, Norton L D. Sediment transport capacity and erosion processes: Concepts and reality[J]. Earth Surface Processes and Landforms. 1999, 24: 503—516.

[25] Zheng F, Huang C, Norton L D. Vertical Hydraulic gradients and Run-on water and sediment effects on erosion processes and sediment regimes[J]. Soil Sci. Soc. Am. J. 2000, 64: 4—11.

[26] Huang C. Sediment regimes under different slope and hydrologic conditions[J]. Soil Sc. Soc. Am. J. 1998, 62: 423—430.

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