doi:10.2489/jswc.68.4.100A

IDEAS & INNOVATIONS

Towards new-generation soil erosion modeling: Building a unified omnivorous model

Liang-Jun Hu and Dennis C. Flanagan

Soil erosion is one of the greatest environmental issues affecting both agricultural and natural lands all over the world (Pimentel et al. 1995). Accordingly, modeling soil erosion is of paramount importance to understanding the processes governing soil degradation and resulting losses (De Vente and Poesen 2005), predicting runoff and soil erosion rates (Foster 1991; Laflen et al. 1991; Boardman 2006), identifying or choosing appropriate measures for erosion control and making decisions and planning in relation to public policy (Renschler and Harbor 2002), as well as coping with projected changes in erosion due to climate change and/or land use (Williams et al. 1996; Lee et al. 1999; Flanagan et al. 2007). As a result, improving the predictive capabilities for soil erosion under global change, by testing and validating several soil erosion models at the field and catchment scale through the Soil Erosion Network (Ingram et al. 1996), has become one of the core tasks in the Global Change and Terrestrial Ecosystem Core Project (GCTE) of the International Geosphere-Biosphere Program (IGBP) (De Roo and Jetten 1999; Jetten et al. 1999).

However, until only recently, soil erosion modeling efforts, together with an understanding of the related soil erosion processes, have been mostly confined to erosion driven by individual agents such as flowing water or wind. These are still studied by certain rather distinct communities (i.e., Aeolian and fluvial) and are often disconnected when multiple erosive agents may be intimately linked with one another, especially in semiarid systems (Williams et al. 1996). Recently, increasing attention has been paid to exploring the hybrid soil erosion processes (Flanagan and Visser 2004; Hu et al. 2009; Hu 2012); however, certain fundamentals in soil erosion science may still be poorly understood. Boardman (2006) stated, "the current generation of erosion models is not particularly successful at predicting rates of erosion," posing an emerging need to timely reexamine the related soil erosion knowledge and modeling purposes. Scaling issues, in space and time, remain a challenge (Kirkby et al. 1996; Imeson and Lavee 1998; De Vente and Poesen 2005; Boix-Fayos et al. 2006). In addition, there are also many other vital issues that require more attention to be paid in future erosion modeling, e.g., how to deal with extreme events that can often cause most of the soil losses in continuous model simulations, etc. "It is clear that there are fundamental limits to our capability for erosion prediction" (Boardman 2006), which may also form the major reason accounting for no or slow arrival of the promised "all-singing, all-dancing" erosion models. Therefore, it is critically important to examine the current gap in both soil erosion knowledge and concomitant modeling experiences so that the soil erosion science can be timely moved forward.

Liang-Jun Hu is an associate professor at the Key Lab for Vegetation Ecology Science, Chinese Ministry of Education, Northeast Normal University, Changchun, Jilin, China. **Dennis C. Flanagan** is a research agricultural engineer with the USDA Agricultural Research Service at the National Soil Erosion Research Laboratory, West Lafayette, Indiana.

By briefly examining the panorama of the discipline so far, we hereby try to give rise to a call for building a new-generation unifying soil erosion model, following Laflen et al. (1991). Despite the suggested view that the future may well be the development of different models for different tasks (Boardman 2006), we believe that building such a unified omnivorous model could not only deal with simultaneous inputs of diversifying erosion forces (i.e., model parameters) to it, but could also reconcile the long-standing scaling predicaments and other major challenges encountered in the simulations. The journey towards such a unification is expected to provide many benefits in deepening a comprehensive systems understanding of soil erosion occurrences and meeting the demands for erosion prediction, soil conservation, and many other applications.

OVERVIEW ON SOIL EROSION MODELING AND THE SUPPORTING SCIENCE BEHIND

Generally speaking, modeling soil erosion can be traced back and attributed to three distinct temporal stages in history: an early erosion experiments stage, an early erosion equations stage, and the real erosion-modeling stage. The first two stages have been described by Meyer (1984), who presented certain keystone events as follows:

- According to Baver (1938), the earliest archived erosion experiments were conducted by a German scientist Ewald Wollny, a pioneer in soil and water conservation research. In contrast, the earliest quantitative measurements of erosion in the United States date back to the work in central Utah in 1912 (Meyer 1984).
- Although erosion plot research was initiated substantially by Miller (1926) and colleagues, there is no doubt that Bennett deserves to be recognized as the "father of soil conservation" in the United States (Meyer 1984).
- The basis for mathematical relationships linking soil erosion and the major variables involved probably began with efforts such as those by Cook (1936). He identified three major factors affecting water erosion (soil erodibility, erosivity of rainfall and runoff, and vegetal cover protection) and further described the subfactors affecting each factor.
- Using equations to calculate field soil loss began when Zingg published his equation in 1940 (Zingg 1940). Soon after that, Smith (1941) added crop (C) and supporting practice (P) factors to the equation, and Musgrave (1947) considered climatic factor (i.e., rainfall) to create the Musgrave equation. However, these equations were usually state-specific or soils-specific, thus were local or regional in their applicability and not readily adaptable to other areas. At the time, the concept of a soil loss tolerance was also introduced (Foster 1991).

By contrast, the real modeling of soil erosion began with the Universal Soil Loss Equation (USLE) concept of a generally applicable equation in the 1950s, at the same time as rising public awareness in soil erosion (including on-site and off-site impacts) and planning needs for nature conservation (Wischmeier 1976; Meyer 1984). A similar function for wind erosion prediction, the wind erosion equation (WEQ), based on Chepil's major works on erosion of agricultural soils by wind (Chepil and Woodruff 1963), was released in 1965 (Woodruff and Sidoway 1965). So far, many soil erosion models have been established, varying substantially in their aims, space and time scales involved, and in their conceptual foundation. In particular, three groups of erosion models, namely physics-based models, conceptual models, and empirical or regression models, have been thoroughly described in many recent review archives (De Vente and Poesen 2005).

There is no doubt that empirical/regression erosion models, characterized by the popular USLE (plus the subsequent Revised USLE [RUSLE] [Renard et al. 1991]), were the first generation of real soil erosion models. These often were of a selected factorial form, supported by field (plot) data and use of required statistics. However, considerable constraints exist in such models (Wischmeier 1976):

- Although the USLE was named "universal" by presenting key factors affecting water erosion, it cannot be directly used in areas that were not considered in the model development. Therefore, model adaptation is needed when applied to nonfarmlands or outside the United States.
- The models are often lumped ones assuming in principle a spatially homogenous uniform hillslope, with difficulty for use for more complex field conditions, particularly when applied over larger areas (Jetten et al. 2003). In addition, slope gradients exceeding 20% were a void in the research for the USLE (Meyer 1984).
- The models often account for long-term average erosion, but are incapable of dealing with the erosion of daily, weekly, monthly, yearly, or event-based situations.
- Although empirical/statistical models can be used as powerful tools for soil conservation, they play few roles in helping understand the underlying physics responsible for the actual erosion processes occurring.

To overcome these deficiencies and limits, conceptual models, such as Soil and Water Assessment Tool (SWAT; Arnold 1998), Agricultural Non-Point Source pollution model (AGNPS; Young et al. 1989), and Morgan–Morgan–Finney model (MMF; Morgan 2001), and process-based physical models, such as Water Erosion Prediction Project (WEPP; Nearing 1989), Groundwater Loading Effects of Agricultural Management Systems (GLEAMS), Chemicals, Runoff, and Erosion from Agricultural Management Systems (CREAMS; Knisel 1980), European Soil Erosion Model (EUROSEM; Morgan et al. 1998), Wind Erosion Prediction System (WEPS; Hagen 1991), and many others (see review by Webb and McGowan 2009), have been created. With the rise in computing and geographic information system (GIS) abilities, spatially distributed models have been emerging to simulate the runoff and erosion dynamics of larger and more complex catchments (Jetten et al. 2003), e.g., the Limberg Soil Erosion Model (LISEM; De Roo et al. 1996), Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS; Beasley et al. 1980), and Griffith University Erosion System Template (GUEST; Yu 2003). All these point to characterizing the second generation of erosion models. In terms of process descriptions, these models can be found to evolve from rainfall- or wind-based erosion prediction, via conceptual estimations (e.g., Soil Conservation Service Curve-Number–based runoff estimations), to more physically based approaches (Jetten et al. 2003). However, to date, some results indicate that more complex physically based erosion models do not generally perform better than lumped regression-based models (Jetten et al. 2003). The cause has been attributed to increased input errors following the increasing model complexities. This raises the question if we still should develop more detailed physical process-based erosion models (which usually mean greater complexities in model structure and input parameter descriptions).

WHAT EROSION MODEL DO WE REALLY EXPECT?

The above discussion has been raising a question for us to further consider—What erosion model do we really need to build? Despite many achievements and major disputes or puzzles that still exist in erosion modeling, here, we raise several concerns, probably complementary to commonly thought ones, with regard to envisioning a future unifying soil erosion model (probably ideal). Through properly addressing these concerns and incorporating them into the design, we may be able to precisely formulate the basic framework of the anticipated model.

An Omnivorous Model Capable of Coping with Simultaneous Inputs of Multiple Erosive Forces. The search for omnivorous abilities of erosion models is the first concern towards the unification. As mentioned earlier, albeit many erosion models have been established either in success or with limitations to some degree, they are focused on erosion driven by separate single erosive agents with no exceptions (Williams et al. 1996). By contrast, an omnivorous model that is able to handle simulating or predicting the hybrid soil erosion processes driven by multiple erosion forces is still absent. Here, a true omnivorous erosion model does not mean that the model is merely a direct integration of several existing erosion models combined together; instead, it should be constructed completely based upon new understandings of hybrid erosion processes, emphasizing the interactions between the various erosive agents (Hu 2012), and the single-agent-dominated erosion processes. Therefore, such a model may actually be omnipotent, being capable of dealing with not only the major hybrid erosion situations, but also the major single-agent-induced erosion processes such as wind erosion and water erosion. Some work towards a portion of simulating combined wind and water detachment processes has very recently been published by Erpul et al. (2013). Much additional work is needed, though, to comprehensively understand

and model other interacting wind and water erosion processes.

Because all simulation models operate in response to their variables' inputs, we may be able to fulfill such an omnivorous erosion model via recognizing the inputs' features. A combining mechanism integrating all considered erosion processes could be included in a single model to enable the omnivorous ability. Under this new framework, the logic flow of the model (i.e., which model component, either single-force–driven, such as rainfall, runoff, or wind, or hybrid-force–driven, will be triggered) may simply depend on recognition by the model of the daily climatic input data. In other words, if wind speed exceeds the kick-off value leading to erosion but there is no erosive rainfall, then it is only a wind simulation; if rainfall is erosive but there is no substantial wind speed, then it is only a water simulation; or if there is rainfall as well as appreciable wind speed, then these are combined hybrid erosion processes. Moreover, because a large part of effort goes into the construction of the input data set in soil erosion modeling (Jetten et al. 1999), the use of easily-obtained daily climate data may be able to alleviate the often heavy data requirements while in applications of the new model.

A Model with Readily Spatially Scaling-Up and Scaling-Down Ability. Spatial scales are a long-standing and critical issue affecting how to correctly understand many scale-dependent processes in geoscience and ecology research (Boix-Fayos et al. 2006). For instance, research results have shown that soil erosion rates measured at one scale are not representative for sediment yield measured at another scale level (De Vente and Poesen 2005). This is especially true in that splash, sheet, interrill, and rill erosion processes are dominant at field (plot) and small catchment scales, while other geomorphic processes (e.g., channel degradation, sediment storage, and classical gully development) are dominant at landscape, basin, or broader scales (Kirkby et al. 1996; De Vente and Poesen 2005; Boardman 2006). Therefore, due to insufficient systems knowledge, lack of all erosion processes descriptions, and unfeasible data requirements, erosion models designed at a specific scale usually cannot be successfully applied for describing the erosion processes at another scale. As a result, although many erosion models adapted for use at diversely specific scales can be found in the literature, their cross-scale use particularly for nonselective erosion conditions simulation is troublesome (De Vente and Poesen 2005).

Scaling-up and scaling-down methods thus have been suggested to deal with such a dilemma (Kirkby et al. 1996; Kim and Barros 2002). However, both methods, particularly the downscaling technique which aims at transferring broader-scale coarse information into finer-scale detail, are a challenge. This precludes widespread use of these methods in erosion modeling. The answer therefore may lie in the rich sources of remotely sensed data at multiple resolutions, with the aid of rapid data acquisition and required image processing techniques (Kim and Barros 2002).

A Model Based on Erosion Events. Temporal scales are another crucial issue affecting erosion modeling. For example, it has been recognized that erosion models often do better at estimating long-term, i.e., multiyear, averages, due to temporal error propagation (Jetten et al. 1999). Many early models, e.g., the USLE, were built to estimate long-term erosion of a particular area (Meyer 1984). In contrast, findings are less clear when a particular time period is considered for estimating soil loss (Jetten et al. 1999): in some cases, daily results are best, while in others, annual results are best. Jetten et al. (1999) found that there were overall more overestimates than underestimates of soil loss from large erosion events. In addition, the GCTE results have also shown that many models have problems with the prediction of extreme events (Jetten et al. 2003). This may be partly due to the extreme sensitivity that event-based models have to initial conditions, which are usually difficult to specify (Boardman 2006). However, not all storm events will result in soil losses due to the spatial variability of rainfall, infiltration, runoff, or wind events, and the total discharge often consists of only a few percent of the total rainfall (Jetten et al. 1999). On the Loess Plateau of China, the criteria for discerning erosive storm events have been defined (Wang 1984). In this regard, therefore, a sounder, new-generation erosion model should be built based on the perspective of continuous event simulation, similar to the WEPP and WEPS models. However, event-filtering technology must be developed and built into the modeling system so that erosive events, particularly the extreme events, can be properly parameterized and included in generated climate and receive proper weighting during erosion model simulations.

A Model Adaptive to New Technology and Multiple Operating Platforms. Users play vital roles in influencing erosion prediction technology, which often determines if the purpose of the modeling is to build applied tools for use by field conservationists or build research tools for sole use by scientists (Foster 1991). Some research models are not appropriate for development into applied ones, and many research models are developed but never applied by users.

The technical abilities of users, their personal preferences, and other application needs directly affect the user interfaces required for an erosion model. A user's personal and/or agency computing equipment and operating system(s) also can impact the type of model and interface system required. The new erosion model should take advantage of rapid developments in computer science, information technology, remote sensing, GIS, web technology, cloud data storage, and use of portable handheld devices.

CONCLUSION

Almost every technological development that reached application is based on science that is at least two decades old (Foster 1991). This is also the case with soil erosion modeling. The major erosion models that are being used worldwide today were mostly developed more than ten years ago (Hu 2012); although, in some cases they are continuously being improved and updated.

The question remains, though, is current soil erosion mechanics process research sufficient, creative, and innovative? Based on the analyses and discussions above, we have many reasons to believe that the expected new-generation soil erosion models will come to fruition in the near future.

ACKNOWLEDGEMENTS

This research is supported by the National Natural Science Foundation of China program (41071189), the Jilin Provincial Sci-Tech Services International Joint Research program (20090713), and the Jilin Provincial Personnel Services program for Selected

Innovative Sci-Tech Activities by Returnees with Study Record Overseas.

REFERENCES

Arnold, J.G., R. Srinivasan, R.S. Muttiah, and J.R. Williams. 1998. Large area hydrologic modeling and assessment: Part I. Model development. Journal of the American Water Resources Association 34 (1):73-89.

Baver, L.D. 1938. Ewald Wollny—a pioneer in soil and water conservation research. Soil Science Society of America Proceedings 3:330-333.

Beasley, D.B., L.F. Huggins, and E.J. Monke. 1980. ANSWERS: a model for watershed planning. Transactions of the ASAE 23(4):938-944.

Boardman, J. 2006. Soil erosion science: reflections on the limitations of current approaches. Catena 68:73-86.

Boix-Fayos, C., M. Martinez-Mena, E. Arnau-Rosalen, A. Calvo-Cases, V. Castillo, and J. Albaladejo. 2006. Measuring soil erosion by field plots: understanding the sources of variation. Earth-Science Reviews 78:267-285.

Chepil, W.S., and N.P. Woodruff. 1963. The physics of wind erosion and its control. Advances in Agronomy 15:211-302.

Cook, H.L. 1936. The nature and controlling variables of the water erosion process. Soil Science Society of America Proceeding 1:60-64.

De Roo, A.P.J., C.G. Wesseling, and C.J. Ritsema. 1996. LISEM: a single event physically-based hydrologic and soil erosion model for drainage basins. I: theory, input and output. Hydrological Processes 15:1107-1117.

De Roo, A.P., and V. Jetten. 1999. Calibrating and validating the LISEM model for two data sets from the Netherlands and South Africa. Catena 37:477-493.

De Vente, J., and J. Poesen. 2005. Predicting soil erosion and sediment yield at the basin scale: Scale issues and semi-quantitative models. Earth-Science Reviews 71:95-125.

Erpul, G., D. Gabriels, L.D. Norton, D.C. Flanagan, C. Huang, and S. Visser. 2013. Mechanics of interrill erosion mechanics with wind-driven rain (WDR). Earth Surface Processes and Landforms 38:160-168.

Flanagan, D.C., and S.M. Visser. 2004. Chapter 2. Commonalities in WEPP and WEPS and efforts towards a single erosion process model. *In* Wind and Rain Interaction in Erosion. Tropical Resources Management Papers 50, eds. S.M. Visser and W. Cornelis, 15-30. Wageningen, The Netherlands: Wageningen University and Research Center.

Flanagan, D.C., J.E. Gilley, and T.G. Franti. 2007. Water Erosion Prediction Project (WEPP): development history, model capabilities, and future enhancements. Transactions of the ASABE 50:1603-1612.

Foster, G.R. 1991. Advances in wind and water erosion prediction. Journal of Soil and Water Conservation 46(1):27-29.

Hagen, L.J. 1991. A wind erosion prediction system to meet user needs. Journal of Soil and Water Conservation 46(2):106-111.

Hu, L.J., H.J. Yang, Z.M. Wang, and D.L. Wang. 2009. Alternate actions of freeze-thaw, wind and water generate a unique hybrid soil erosion phenomenon. Journal of Soil and Water Conservation 64(2):59A-60A. doi:10.2489.jswc.64.2.59A.

Hu, L.J. 2012. Towards exploring the hybrid soil erosion processes: Theoretical considerations. Journal of Soil and Water Conservation 67(6):155A-157A. doi:10.2489/jswc.67.6.155A.

Imeson, A.C., and H. Lavee. 1998. Soil erosion and climate change: The transect approach and the influence of scale. Geomorphology 23:219-227.

Ingram, J., J. Lee, and C. Valentin. 1996. The GCTE Soil Erosion Network: A multi-participatory research program. Journal of Soil and Water Conservation 51(5):377-380.

Jetten, V., A. de Roo, and D. Favis-Mortlock. 1999. Evaluation of field-scale and catchment-scale soil erosion models. Catena 37:521-541.

Jetten, V., G. Govers, and R. Hessel. 2003. Erosion models: quality of spatial predictions. Hydrological Processes 17:887-900.

Kim, G., and A.P. Barros. 2002. Downscaling of remotely sensed soil moisture with a modified fractal interpolation method using contraction mapping and ancillary data. Remote Sensing of Environment 83:400-413.

Kirkby, M.J., A.C. Imeson, G. Bergkamp, and L.H. Cammeraat. 1996. Scaling up processes and models from the field plot to the watershed and regional areas. Journal of Soil and Water Conservation 51(5):391-396.

Knisel, W.G., 1980. CREAMS: A Field Scale Model for Chemicals, Runoff, and Erosion from Agricultural Management Systems. Conservation Report No. 26. Washington, DC: USDA Science and Education Administration.

Laflen, J.M., L.J. Lane, and G.R. Foster. 1991. WEPP: A new generation of erosion prediction technology. Journal of Soil and Water Conservation 46(1):34-38.

Lee, J.J., D.L. Phillips, and V.W. Benson. 1999. Soil erosion and climate change: Assessing potential impacts and adaptation practices. Journal of Soil and Water Conservation 54(3):529-536.

Meyer, L.D. 1984. Evolution of the universal soil loss equation. Journal of Soil and Water Conservation 39(2):99-104.

Miller, M.F. 1926. Waste through soil erosion. Journal of American Society of Agronomy 18:153-160.

Morgan, R.P.C. 2001. A simple approach to soil loss prediction: A revised Morgan–Morgan–Finney model. Catena 44:305-322.

Morgan, R.P.C., J.N. Quinton, R.E. Smith, G. Govers, J. Poesen, K. Auerswald, G. Chisci, D. Torri, and M.E. Styczen. 1998. The European Soil Erosion Model (EUROSEM): A dynamic approach for predicting sediment transport from fields and small catchments. Earth Surface Processes and Landforms 23:527-544.

Musgrave, G.W. 1947. The quantitative evaluation of factors in water erosion, a first approximation. Journal of Soil and Water Conservation 2:133-138.

Nearing, M.A., G.R. Foster, L.J. Lane, and S.C. Finkner. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. Transactions of the ASAE 32(5):1587-1593.

Pimentel, D., C. Harvey, P. Resosudarmo, and K. Sinclair. 1995. Environmental and economic costs of soil erosion and conservation benefits. Science 267:1117-1123.

Renard, K.G., G.R. Foster, G.A. Weesies, and J.P. Porter. 1991. RUSLE: Revised universal soil loss equation. Journal of Soil and Water Conservation 46(1):30-33.

Renschler, C.S., and J. Harbor. 2002. Soil erosion assessment tools from point to regional scales—the role of geomorphologists in land management research and implementation. Geomorphology 47:189-209.

Smith, D.D. 1941. Interpretation of soil conservation data for field use. Agricultural Engineering 22:173-175.

Webb, N.P., and H.A. McGowan. 2009. Approaches to modelling land erodibility by wind. Progress in Physical Geography 33(5):587-613.

Williams, J., M. Nearing, A. Nicks, E. Skidmore, E. Valentin, K. King, and R. Savabi. 1996. Using soil erosion models for global change studies. Journal of Soil and Water Conservation 51(5):381-385.

Wang, W.Z. 1984. The relationships between rainfall characteristics and the soil losses on the Loess Plateau. III. About the criteria of erosive storms. Chinese Bulletin of Soil and Water Conservation 2:58-63.

Wischmeier, W.H. 1976. Use and misuse of the universal soil loss equation. Journal of Soil and Water Conservation 31:5-9.

Woodruff, N.P., and F.H. Sidoway. 1965. A wind erosion equation. Soil Science Society of America Proceedings 29:602-608.

Young, R.A., C.A. Onstad, D.D. Bosch, and W.P. Anderson. 1989. AGNPS: a nonpoint-source pollution model for evaluating agricultural watersheds. Journal of Soil and Water Conservation 44 (2):168-173.

Yu, B. 2003. A unified framework for water erosion and deposition equations. Soil Science Society of America Journal 67:251-257.

Zingg, A.W. 1940. Degree and length of slope as it affects soil loss in runoff. Agricultural Engineering 21:59-64.