Analysis of Some Existing Erosion and Deposition Models

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ABSTRACT

This paper analyzed the following models: The Universal Soil Loss Equation (USLE), the Griffith University Erosion System Template (GUEST), the Water Erosion Prediction Project (WEPP), the Unified WEPP and GUEST Model (UWGM), and the Wind Erosion Equation (WEQ). Some of the models predict simultaneous erosion and deposition were represented mathematically. The main parameters were identified as rainfall detachment, sediment deposition, and soil entrainment like in GUEST. Others looked at the transport capacity alone.

A total of 13 models identified from literature and desk review was done. Finally a sample of 5 was analyzed. The models analyzed do not specifically look at the features formed on erosion paths, and the unsteady state terms are ignored when it comes to numerical examples. So the models were compared on how well they predict erosion and deposition and possible improvements were suggested. They included the use of the boundary element method (BEM). This is in addition to other robust techniques like the finite element method, and finite difference methods. Similarly, a new approach of looking at the features formed after a series of erosion processes was suggested. It was also noted that the simplification of some models and their analysis by numerical examples should consider the unsteady state in addition to the steady state as well, for better results.

Keywords: BEM, Deposition, Erosion, Models, Soil.

1.0 INTRODUCTION

Soil erosion prediction models play an important role both in meeting practical needs of soil conservation and in advancing the scientific understanding of soil erosion processes. Several approaches to water erosion and deposition modeling have been developed in the recent decades to predict the rates of soil erosion and sediment deposition over the landscape (Yu, 2003). This has been brought about by the efforts aiming at striking a balance between economic developments with environmental protection. Thus there are several kinds of complex erosion processes that exist today. The complexity has depended on a number of factors. Theoretical developments of sediment transport functions for different flow and sediment conditions were based on assumptions of different degrees of complexity. The major categories are material and mathematical models. Whereas material models represent the physics of the system being modeled, mathematical models on the other hand, are normally empirical or process-based (Misra and Rose, 1996). Both the iconic and analog models are physical in nature. It should be noted that the first models on erosion were empirical and developed primarily from statistical analysis of erosion data. However, recent models have been based on equations that describe the physical, biological, and chemical processes that affect soil erosion (Knisel, 1980). The dimensional classification was outlined basing mainly on erosion by river flows. They included: three-dimensional, two-dimensional and one-dimensional. Other types of erosion modeling were similarly classified in the same way but with different approaches (Yang, 1971). Sediment models are also classified as steady-state or unsteady-state, coupled or uncoupled, equilibrium or un-equilibrium, and uniform or non-uniform models. The focus of this paper is on steady and the unsteady states. A model is steady if the flow and sediment conditions in a model are constant; otherwise it is unsteady (Yang, 1971). The problem that was addressed was pointing out that existing models do not specifically look at the features formed on erosion paths, and the unsteady state terms are ignored when it comes to numerical examples. Thus the main objective of this paper was to analyze some existing models, outline their loopholes and suggest possible improvements.

2.0 METHODOLOGY

The models were identified from literature and desk review was done. The study was basically qualitative, although relatively quantitative as well. A total of 13 models were identified plus some other related literature on erosion and deposition was considered.

A non random sample of only 5 models was identified for analysis. This sampling frame was specific on models that deal with erosion, transportation and deposition or sedimentation. Models to do with computer simulations, cellular automata, and other specifications were left out for this frame. Data was analyzed by the comparative study approach. A comparison between erosion and deposition models selected was done and conclusions reached.

3.0 FINDINGS

This paper based on findings around the original equations of the models and how they work by way of analysis of the numerical examples given. The following are some of the models that were considered.

3.1 Universal Soil Loss Equation (USLE)

This equation (Wischemeier and Smith, 1960, 1965, 1978) is one of the first empirical models that was developed in the United States of America (U.S.A) during the 1950's. It was based on erosion plots of 9% slope with length 22.13m, width 1.83m, and considered for a period of 1 year. It has the form:

[illegible] (1)

Where A = average annual soil loss over the area of a hill slope that experience net loss, R = rainfall erosivity (driving forces of rain), K = soil erodibility (soil resistance term), L = slope length factor, S = slope steepness factor, C = cropping factor, P = conservation practices factor.

3.2 The Griffith University Erosion System Template (GUEST)

It is one of the process-based models developed in Australia (Misra and Rose, 1996). It basically has its foundation on the simultaneous erosion
and deposition. The governing equation in GUEST takes the form:

$$\frac{\partial(c_i D)}{\partial t} + \frac{\partial(c_i Q)}{\partial x} = \text{[illegible]}$$

(2)

Where D = water depth (m), C_i = sediment concentration for particle-size class i (kg m^{-3}), [illegible] and [illegible] are rates of rainfall detachment and re-detachment (kg $m^{-2}s^{-1}$), [illegible] and [illegible] are rates of flow entrainment and re-entrainment(kg $m^{-2}s^{-1}$), [illegible] = rate of deposition(kg $m^{-2}s^{-1}$).

The terms on the RHS of equation (2) are further defined as:

$$e_{ri} = (1 - H)\frac{aP^{p}}{I}$$

$$[illegible]$$

$$d_i = \alpha_i v_i c_i \quad (3)$$

For equations (3), we define H = fraction of the original soil covered with deposited sediment, [illegible] = detachability parameter, [illegible] = detachability parameter for the deposited layer, P = rainfall intensity (ms^{-1}), I = arbitrary number of size classes, S_i = amount of sediment in size class I in the deposited layer, S_t = total amount of deposited sediment, F = fraction of stream power effective in entrainment and re-entrainment, J = specific energy of entrainment (J kg^{-1}), γ and γ_o are stream power and threshold stream power per unit area (W m^{-2}), respectively, [illegible] = wet density of sediment (kg m^{-3}), ρ = water density (kg m^{-3}), g = gravitational acceleration (m s^{-2}), α_i = ratio of sediment concentration across the entire depth (Corley, 1982), and v_i = fall velocity for size class i (m s^{-1}).

Several modifications were made by various researchers, for example the exponent p and the ratio α_i have been set to unity (Misra and Rose, 1996; Hairsine *et al*., 2002). Similarly, equations (3) were modified and substituted in equation (2). Finally, the GUEST equation was simplified (Yu, 2003) to:

$$[illegible] \quad (4)$$

3.3 Water Erosion Prediction Project (WEPP)

This model was developed in the U.S.A (Flanagan and Nearing, 2000; Nearing et al, 1989). It mostly represents the transport capacity (Foster *el al*, 1995), and based on mass balance in rills. Its governing equation for sediment movement in a rill is given by

$$\frac{dG}{dx} = D_f + D_i \quad (5)$$

Where G = sediment discharge per unit flow width (kg m^{-1} s^{-1}), D_f = rill erosion or deposition rate (kg $m^{-1}s^{-1}$), D_i = Interill sediment delivery rate ($kgm^{-2}s^{-1}$), and x = distance in the down slope direction (m).
This model has net erosion in rills modeled by:

$$[illegible] \text{ for } [illegible]$$

$$\text{Or } [illegible] \text{ for } [illegible] \quad (6)$$

Where [illegible] = is a rill erodibility parameter (ms^{-1}), [illegible] and [illegible] are the flow and critical shear stress (Pa) respectively, [illegible] = sediment transport capacity (kg m^{-1} s^{-1}), [illegible] = raindrop induced turbulence coefficient, V_f = effective fall velocity of sediment (m s^{-1}). This velocity is calculated from an effective particle diameter and it's specific gravity (Foster et al., 1995). Q = unit discharge or the flow rate per unit flow width (m^2 s^{-1}). On the other hand, the interill sediment delivery in WEPP is modeled by:

$$D_i = K_{iadj} I_e \sigma_{ir} SDR_{RR} F_{nozzle} \left(\frac{R_s}{w}\right) \quad (7)$$

Where K_{iadj} = the adjusted interill erodibility (kg m^{-4} s), I_e = effective rainfall intensity (m s^{-1}), SDR_{RR} = sediment delivery ratio, F_{nozzle} = adjustment factor to account for sprinkler irrigation energy variation, σ_{ir} = interill runoff rate (m s^{-1}), R_s = spacing of rills (m), w = rill width (m).

3.4 Unified WEPP and GUEST equations

Both WEPP and GUEST equations were unified by making some rearrangements in the original equations Yu (2003). It was only showed that the two models are structurally identical under the steady state conditions. The unifying equations were given as:

[illegible]

[illegible] (8)

Net erosion occurs when [illegible], in the first equation and net deposition occurs when [illegible]. The term [illegible] = upward movement of sediment from the original soil matrix, [illegible] = downward movement of suspended sediment because of gravity, and [illegible] = source term representing the lateral sediment input.

3.5 Wind Erosion Equation (WEQ)

Wind erosion is initiated when wind speed exceeds the saltation threshold velocity for a given field condition. The idea of modeling wind erosion goes back to 1930's, though publication work begun in 1940's by Ralph Bagnold. At first the concern was on desert sand dunes, but later shifted to agricultural fields. Noted however, is that on these fields modeling processes became more complicated. This is because of some properties that change over time such as soil aggregate size, stability, crusts, random and oriented roughness, field size, and vegetative cover. The WEQ equation has the form of a function

$$E = f(I, K, C, L, V) \quad (9)$$

Where E = potential average annual soil loss, I = soil erodibility index, K = soil ridge roughness factor,
C = climate factor, L = unsheltered distance across a field, V = equivalent vegetative cover.

4.0 DISCUSSION

In a bid to come up with the best approaches to handling erosion effects, this paper had specific observations for the various models revised as seen in table 4.1. For the USLE, it was noted that it predicts soil loss, and not sediment yield. In other words, the model was not intended to predict soil loss for storms or for individual years, but rather to predict average annual soil loss. However, it was revised and renamed the Revised USLE 1 (RUSLE1) in the 1990's (Renard *et al* , 1997). Later on RUSLE2 was also released in 2003 to highlight about more queries on USLE and RUSLE1. Both RUSLE 1 and RUSLE2 are land-use independent and simple combination of existing index process-based equations. However, RUSLE2 expands on the hybrid model structure and uses a different mathematical integration than does USLE and RUSLE 1.

The GUEST equations on the other hand were simplified for the steady-state condition only, i.e when neither c_i nor D changes in time. This paper suggested about the elimination of the term [illegible] being crucial for proper results analysis.

The WEPP was also identified with its interill erodibility adjusted to account for the effects of the canopy cover, ground cover, roots, sealing and crusting (Alberts et al., 1995). This was a tremendous discovery by Albert and others. More so the effective rainfall intensity was defined in this model as the average intensity evaluated for a period when rain rate exceeds infiltration rate (Foster *et al*., 1995). Noted also is that in WEPP, the interill sediment delivery ratio in this model is calculated as a function of the random roughness of the soil surface, the fall velocity of individual particle-size classes of sediment, and the size distribution of the sediment (Foster *et al*., 1995); Flanagan and Nearing, 1995). The time factor in this model was ignored to be modeled as a different term but mixed with other terms. The unified WEPP and GUEST equations or rather the comparative analysis of these governing equations was based on steady-state conditions. Cancellation of some terms would be impossible for the unsteady-state.
The inter relatedness of the factors is not clear in the WEQ. It was later modified by some other models which also did not consider the effects of wind say dusting of structures, but only the sand dunes in deserts and the agricultural plots. Also noted is that today the satellite images can be used to develop an index which maps the severity of wind erosion.

Basing on the models reviewed above, most of them end up with numerical examples regarding the steady-state situations. Yet flow and sediment conditions in most erosion flows are unsteady due to the changing hydrologic conditions over a time.

The process-based models explain erosion on a relatively fundamental level using mass balance differential equations to describe sediment continuity on a land surface. With this, the modeling of various features like sand dunes, gorges, are ignored. These features formed along the erosion path, affect erosion from both perspectives and therefore need not be ignored. All models can predict erosion and therefore they are better than none at all. Erosion being a serious economic development problem, there is a surety of handling it to a particular level.

Table 4.1: Analysis of erosion models

Model	Erosion prediction	Deposition prediction	Modeling Parameters modeled	Use of [illegible] in numerical examples	Modeled features on erosion bed/path	Gaps/More to be done
USLE	Yes	Yes	No	No	No	▪ Modeling Features on erosion paths ▪ Consideration of [illegible] term ▪ Use of BEM instead of FEM, FDM. ▪ Modeling effects like dust on engineering structures.
RUSLE	Yes	Yes	Yes	No	No	
GUEST	Yes	Yes	Yes	No	No	
WEPP	Yes	Yes	Yes	No	No	
UWGM	Yes	Yes	yes	No	No	
WEQ	Yes	No	No	No	No	

The general effects of erosion on engineering structures still desire some special consideration. For instance the dust effect from wind erosion on structures, need special attention.
Most sediment transport models assume that channel width is a constant and cannot be adjusted. This is an unrealistic assumption can lead to wrong results when applied to an alluvial flow.

5.0 CONCLUTIONS /SUGGESTIONS

The study reached the following conclusions and suggestions:

Flow and sediment conditions in most erosion flows are unsteady due to changing hydrologic conditions over a time or a particular flow. Yet most numerical examples are focused on steady-state conditions. Most empirical solutions (based on site-specific observations and data) may be useful for particular sites where data was collected. So the application of the same results to other sites should be treated with caution. This paper suggested new possible improvements which will involve both the empirical and process-based modeling techniques. The consideration of the features formed is one key issue regarding time. The eliminated term should be taken seriously for numerical examples given.

The selection of a modeler is more important than the selection of a computer model. This is because he/she should have the ability to make necessary modification to an existing general model for solving site-specific problems. The paper suggested further improvements in the models for better results.

There are many well-established schemes for solving sediment transport equations. The finite difference method (FEM) being the most quoted. The use of the boundary element method (BEM) may be a better robust solver for better results. The BEM has an advantage of discretizing the boundary unlike the FEM. Therefore the re-formulation of the erosion equations towards the boundary and its exterior focus will be a good venture.

Engineers can analyze or simulate fluvial processes of different degrees of complexity. This is because of the advancement of computer technology. So the neglected terms for the unsteady-state can as well be handled in the same line.

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