REGEM: THE REVISED EPHEMERAL GULLY EROSION MODEL

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Abstract: Ephemeral gullies serve as effective links transferring sediment and associated agrichemicals from upland areas to stream channels. Current erosion prediction technologies often require the exact topographic position (the length) of an ephemeral gully *a priori*, which greatly limits the utility of such models. The Revised Ephemeral Gully Erosion Model has been developed as a rational approach to predict ephemeral gully erosion and development. REGEM incorporates analytic formulations for plunge pool erosion and headcut retreat within single or multiple storm events in unsteady, spatially-varied flow at the sub-cell scale. The model employs sediment continuity equations for five soil particle-size classes to predict gully evolution and transport capacity. Event-based simulations demonstrate the model's utility for predicting the initial development of an ephemeral gully channel, while continuous simulations allow the channel to evolve over multiple runoff events accounting for seasonal variations in management operations and soil conditions.

REGEM currently functions as a stand alone tool, but it has now been integrated as an additional module within the Annualized Agricultural Non-Point Source (AnnAGNPS) suite of watershed modeling tools developed by the USDA. REGEM allows a more accurate and physically based examination of sediment sources in agricultural catchments, providing practitioners the tools necessary to effectively manage the Nation's water and soil resources.

INTRODUCTION

Over the past several decades the USDA-NRCS has focused its efforts on enhancing and extending the utility of the Universal Soil Loss Equation (USLE) (*Wischmeier and Smith*, 1978) through the development of the revised USLE (RUSLE) (*Renard et al,* 1997). RUSLE technology has been developed using standard runoff plots on which rill and interrill erosion were intensively studied on planar surfaces of uniform slope. When opposing slopes converge, however, overland and subsurface flow is concentrated, resulting in a different hydrologic regime. The channels formed by this concentration of runoff on agricultural lands are known as ephemeral gullies, recognized as a distinct erosion phenomena (*Foster*, 1986) that have been shown to account for more than two-thirds of the total erosion occurring on farmland in a range of environments (*USDA-NRCS*, 1996; *Bennett et al.*, 2000).

The recognized importance of ephemeral gully erosion has prompted the USDA-NRCS to stress its inclusion in future assessment studies because RUSLE-based technologies do not account for such erosion phenomena (*USDA-NRCS*, 1996). The few erosion models that incorporate routines to account for ephemeral gully erosion (EGEM, CREAMS, WEPP) use the same theoretical framework of changing channel dimensions developed by *Foster and Lane*, 1983. While this theory was considered a significant step with respect to the physically-based modeling of ephemeral gully erosion, its applicability is substantially limited by the extensive data requirements, namely the concentrated flow length. That is, the length of an ephemeral gully must be known before the model can be applied. Moreover, these models are limited to the processes of incision and widening only, neglecting the lengthwise growth of an ephemeral gully system within single or over multiple runoff events.

Additional limitations of ephemeral gully erosion routines in EGEM, CREAMS, and WEPP involve the use of the diameter and specific gravity of a representative particle to calculate sediment transport capacity. There are two significant limitations to this approach: (1) for any material to be detached, the amount of sediment carried by the water must be below transport capacity, thus deposition cannot be simulated; and (2) because soil particle diameter and specific gravity are simplified to some representative or dominant value, the soil material delivered to the mouth of the ephemeral gully contains the same ratios of clay, silt, sand and aggregates as the soil *in situ.*

The Revised Ephemeral Gully Erosion Model (REGEM) has been developed with two basic objectives: (1) to overcome some of the limitations of current technology with regard to ephemeral gully erosion; and (2) while functioning as a stand-alone tool, to be incorporated as an individual module within the Annualized Agricultural Non-Point Source Model (*Bingner* and *Theurer*, 2001), giving it the ability to explicitly account for ephemeral gullies in its erosion routines at the sub-cell scale (i.e. field-scale).

MODEL DEVELOPMENT

Four fundamental improvements have been integrated within REGEM to overcome major limitations of current technology. They include: (1) runoff or storm events as unsteady, spatially-varied flows; (2) addressing the upstream migration of a headcut, thereby removing the ephemeral gully length as an input parameter; (3) determining channel width from discharge, allowing channel dimensions to be explicitly predicted at any point in time and space; and (4) routing five distinct particle-class sized (clay, silt, sand, and small and large aggregates) through the gully and the downstream sorting of these sediments.

REGEM has been designed specifically to comply with the computational framework of the Annualized Agricultural Non-Point Source (AnnAGNPS) suite of watershed modeling tools. An AnnAGNPS cell is considered homogeneous in terms of topography, and soil and management conditions. REGEM operates at the sub-cell scale. That is, parameters dealing with topography, soil, and management are singular and static for an modeled ephemeral gully.

Input Requirements: Table 1 lists the input requirements to REGEM, and many of these are available within AnnAGNPS and not unique to the ephemeral gully module. Procedures using Geographic Information Systems to extract data specific to REGEM (drainage area, thalweg slope) are currently being developed to extend the utility of ephemeral gully modeling within AnnAGNPS.

Table 1 Input requirements to REGEM

Notation	Description	Units
Q_p	event peak discharge	$m^3\ sec^{-1}$
V_r	event runoff volume	m^3
S	average thalweg slope	$m\ m^{-1}$
n	Manning's roughness	---
D_t	tillage depth	m
A_d	drainage area to gully mouth	ha
R_{clay}	clay ratio in surface soil	---
R_{silt}	silt ratio in surface soil	---
R_{sand}	sand ratio in surface soil	---
R_{sagg}	small aggregate ratio in surface soil	---
R_{lagg}	large aggregate ratio in surface soil	---
B_d	soil bulk density	$Mg\ m^{-3}$
τ_c	critical shear stress of surface soil*	$N\ m^{-2}$
k_d	headcut erodibility coefficient*	$cm^3\ N^{-1}\ sec^{-1}$
C_{soil}	integer value classifying current soil condition	1 = no-till, 2 = freshly cultivated 3 = established crop

*calculated internally if not user-defined

Hydrology: The drainage area to the mouth of the ephemeral gully, the event peak discharge, and the runoff volume are required as input parameters used to calculate the time to base of the event hydrograph. A triangular hydrograph is constructed an even number of user-defined timesteps. A specific discharge then can be assigned to represent hydraulic conditions during each of the timesteps. Model hydrology will eventually be passed to REGEM by AnnAGNPS, however for the sensitivity analyses presented below, procedures outlined in the standard TR-55 approach, (*USDA-NRCS*, 1986) have been used.

Erodibility: Defining the erodibility or critical shear stress for a particular soil at a discrete point in time and space is not a simple assessment. If the user cannot specify these erodibility parameters, REGEM calculates them internally. As in the original EGEM, (*Woodward,* 1999) the critical shear stress of a freshly cultivated soil is a function of the soil's clay content. This value is then adjusted for changes in tillage condition or crop growth using one of the three tillage conditions (C_{soil}) in Table 1. Once the critical shear stress has been determined, an erodibility coefficient is calculated based on the relationship developed by *Hanson* and *Simon* [2001]. Procedures are currently being developed to more accurately vary soil erodibility over time and space using certain RUSLE subfactors within AnnAGNPS and will be reported at a later date.

Erosion Components: Ephemeral gully erosion is modeled as a combination of three distinct processes: scour to tillage depth, headcut migration, and sediment transport. Bank processes associated with channel widening are not explicitly addressed. Instead, an empirical relationship between dominant discharge and ephemeral gully width developed by *Nachtergaele et al.* [2002] is used to predict channel width at any point in time and space.

Scour to Tillage Depth: A portion of the ephemeral gully channel at the most downstream location (scour hole) with an undetermined length, but with a defined width and depth is evacuated until the tillage depth (a markedly less-erodible layer) is reached. This portion of the model contains algorithms developed for the original EGEM. Excess stress relationships are used to calculate a detachment capacity, which when multiplied by the timestep duration gives a depth of scour for each timestep. All soil material detached in the scour hole is assumed to be evacuated. That is, transport capacity is not addressed during downward scour. If the depth of the scour hole does not reach the tillage depth during a runoff event, erosion is assumed to be zero.

Headcut Migration: The main process resulting in the development and evolution of ephemeral gullies simulated by REGEM is that of headcut migration. Headcuts are step changes in bed surface elevation where intense, localized erosion takes place (*Bennett et al.* 2000a). While other models of ephemeral gully erosion (e.g., EGEM) require the length of an ephemeral gully as an input parameter, REGEM seeks to more accurately describe the lengthwise growth of an ephemeral gully channel over time. *Foster* [1986] describes the detachment and transport of soil material within an ephemeral gully, that is, the incision of the channel. Recently, *Bennett et al.* [2000] and *Casali et al.* [2003] have identified the formation and migration of headcuts as one of the main processes involved in the formation of an ephemeral gully.

Once the scour hole (modeled as a short section of the gully at its downstream end) is evacuated, a headcut is assumed to have formed at the step between the original soil level and the tillage depth. An overfall now exists at a brinkpoint located where the change in elevation occurs. The algorithms based on realistic, physical approximations governing mass, momentum, and energy transfer developed by *Alonso et al*. [2002] are employed during each timestep to determine a rate of headcut migration, and thus a certain length to which the ephemeral gully has grown. As the gully grows longer, the drainage area contributing runoff to the headcut is reduced. A relationship between channel length and drainage area presented by *Leopold et al.* [1964] is used to define the maximum potential ephemeral gully length for a given drainage area and to partition the spatially varied discharge, which, when used to predict channel width causes the ephemeral gully to be widest at its mouth and most narrow at the location of the headcut. As discharge and headcut migration rate are constant within a given timestep, a single three-dimensional rectangular section of ephemeral gully channel is formed during each timestep having a width proportional to the discharge at the time the section is formed, a length equal to the distance of headcut migration, and a depth equal to the tillage depth.

Sediment Transport: The adjustments in flow discharge over time (the runoff event) and space (the length of the ephemeral gully) are held in a two dimensional array built with each successive runoff event. Water associated with a specific event must be routed through the entire length of the ephemeral gully. An examination of sediment transport capacity along the entire gully is necessary for two reasons: (1) often there will be deposition in downstream gully sections that were formed during a previous event (e.g., *Bennett et al.*, 2000); and (2) previously formed gully sections are allowed to adjust laterally in case a larger channel-forming discharge occurs and widens the downstream sections of the gully (e.g., *Nachtergaele et al*., 2002). The algorithms used by REGEM to calculate sediment transport capacity for each of the five particle-class sizes have been adapted from those used in other modules of the AnnAGNPS model and detailed in *Bingner et al.* [2002].

There are three possible sources of sediment available for transport within a gully section during a timestep: (1) incoming sediment from upstream sections; (2) internal sediment due to headcut migration and/or channel widening within the gully section; and (3) previously deposited sediment that resides on the bed within the gully section. These three possible sources are combined to determine the amount of each particle-class size available for transport in each gully section during a timestep. If this amount is less than the sediment transport capacity for that timestep, all available sediment will be moved to the next downstream section, where it is again compared to that section's transport capacity and so on until the gully mouth is reached. Should transport capacity be exceeded for a particular particle-class size, the excess amount is deposited in a layer on the channel bed, possibly re-entrained during subsequent timesteps. If in a given timestep, the available sediment is less than transport capacity, previously deposited sediment will be entrained and eroded until transport capacity is reached.

Sensitivity Analyses: Simulations using REGEM were conducted to examine the performance of the program as well as its stability, and may be classified into three basic categories: (1) total event simulations designed to represent overall output at the end of a single runoff event; (2) within-event simulations designed to demonstrate variations in model output in time (over the event hydrograph) within a single runoff event; and (3) continuous simulations designed to examine how gullies develop and evolve over several runoff events.

Default Input Parameters: Tables 2, 3, and 4 summarize default values used during the sensitivity analyses. Here we examine a 5.0 ha field, tilled to 0.2 m, with a Manning's roughness of 0.03, at a 1% slope, subjected to rainfalls varying from 1.0 to 5.0 inches, with a default soil containing equal parts clay, silt, and sand, and smaller but equal parts as aggregates.

Table 2 Default hydrologic values calculated by TR-55 for five event rainfall amounts on a 5.0 ha drainage area.

Rainfall mm	**Runoff volume** m^3	**Peak Discharge** m^3/s
25.4 (1.0 in)	5.9	0.00025
38.1 (1.5 in)	106.5	0.01092
50.8 (2.0 in)	305.5	0.06888
76.2 (3.0 in)	907.0	0.27410
101.6 (4.0 in)	1688.5	0.54870
127.0 (5.0 in)	2586.0	0.86330

Table 3 A summary of the default values for field-scale input and the range of values tested.

Input Parameter	**Default Value**	**Range Tested**
slope	0.010 m/m	0.005 to 0.100 m/m
Manning's 'n'	0.030	0.030 to 0.060
tillage depth	0.2 m	0.1 to 0.3 m
drainage area	5.0 ha	0.5 to 20.0 ha

Table 4 A summary of the default values for input soil properties.

Soil Type	R_{clay}	R_{silt}	R_{sand}	R_{sagg}	R_{lagg}	B_d	τ_c	k_d
default	30	30	30	5	5	1.5 g/cm^3	1.09 N/m^2	.096 cm^3/N-s
clay loam	55	28	17	0	0	1.8 g/cm^3	3.12 N/m^2	.057 cm^3/N-s
silt loam	13	73	14	0	0	1.6 g/cm^3	0.54 N/m^2	.137 cm^3/N-s
loam	22	38	40	0	0	1.5 g/cm^3	0.72 N/m^2	.113 cm^3/N-s

RESULTS / DISCUSSION

Figures 1, 2, and 3 present basic results from sensitivity analyses performed on the REGEM model. Overall results from a single simulation, within event variation, and continuous simulation results are given.

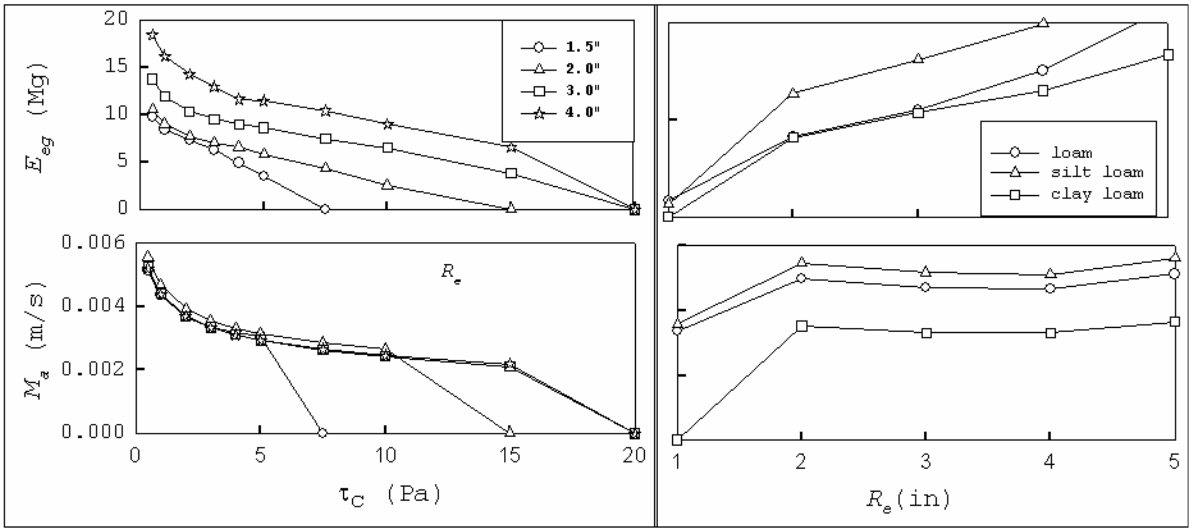

Figure 1 Single event results for different critical shear stresses (τ_c) and rainfall events (R_e) using default storms and soil types, where E_{eg} is total ephemeral gully erosion and M_a is average event headcut migration rate.

For all event rainfalls, slopes, drainage areas, and tillage depths examined, an increase in the critical shear stress reduces the amount of simulated ephemeral gully erosion (Figure 1). A higher critical shear stress not only limits the time for soil detachment, it reduces the rate of headcut migration by decreasing the erodibility coefficient. In fact, the average headcut migration rate appears more dependent on the erodibility of the soil than the magnitude of the runoff. While headcut migration rate remains relatively constant regardless of increased rainfall, ephemeral gully erosion is markedly increased because of the larger channel widths associated with higher discharges.

At the sub-event scale (Figure 2) no erosion occurs until critical shear stress is exceeded and tillage depth is reached, and this occurs more quickly when critical shear stress is low (30 v.70 min, e.g., Figure 2). Headcut migration rate is shown to be relatively constant over the event hydrograph, varying more with differences in erodibility than discharge. Higher critical shear stresses cause headcut migration to begin later during a given event because time devoted to scour is greater.

During continuous simulation (Figure 3), erosion amounts decline after several storm events. This is due to the reduction in drainage area and the corresponding reduction in storm discharge in the upper reaches of an ephemeral gully. Several small events result in a longer and narrower gully than several large events beacuse these smaller events have much longer base times and therefore a longer duration of active headcut migration. This may be due to the nature of the TR-55 calculations and will be investigated further. Smaller magnitude events result in more deposition while larger events are more capable of transporting detached sediment.

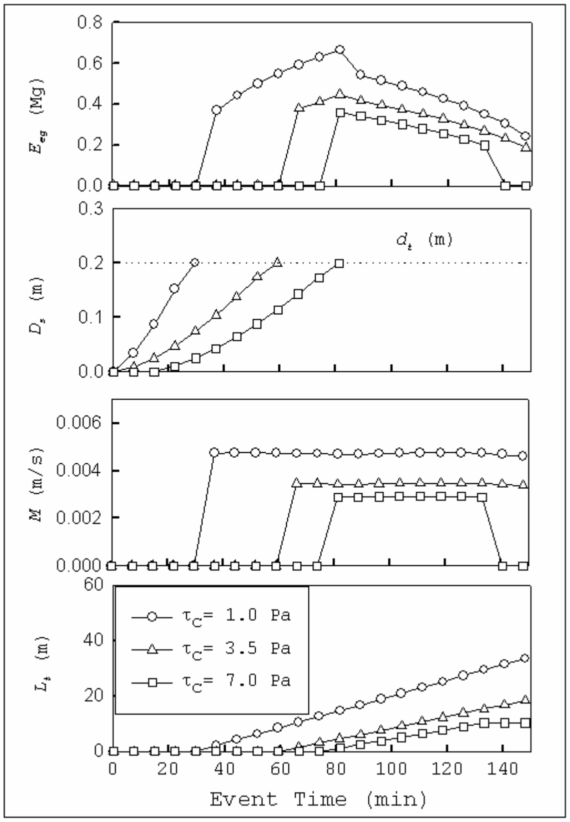

Figure 2 Within event variations in erosion (E_{eg}), scour depth (D_s), where d_t is tillage depth, headcut migration rate (M), and ephemeral gully length (L_t) over a 2.0 inch (50.8mm) rainfall event hydrograph for different critical shear stresses (τ_c).

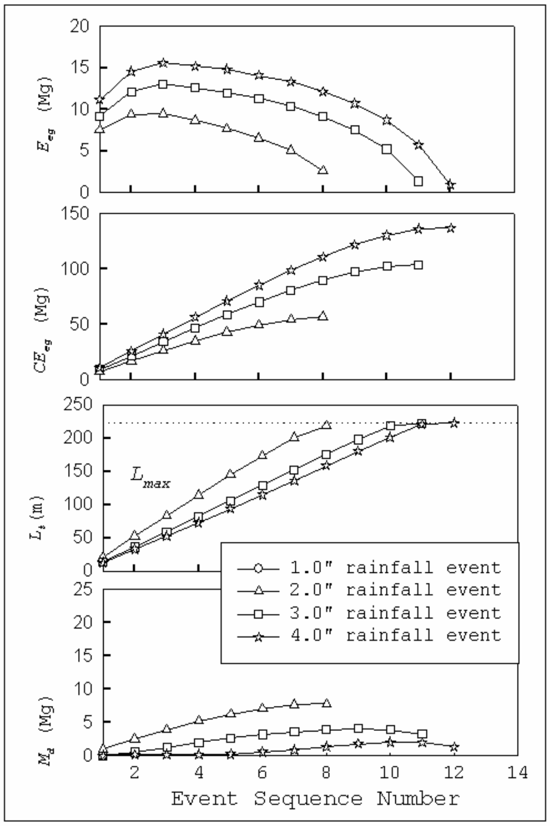

Figure 3 Continuous simulations for different rainfall events showing variations in event erosion (E_{eg}), cumulative erosion (CE_{eg}), total ephemeral gully length (L_t) where L_{max} is maximum possible ephemeral gully length for a 5.0ha drainage area and deposition mass within the ephemeral gully channel (M_d).

CONCLUSION

REGEM effectively overcomes several limitations of previous technology. The ephemeral gully length has been removed as an input parameter as gullies now develop along a given length through headcut migration and plunge-pool erosion processes. Unsteady, spatially-varied flows allow sediment transport and deposition to be examined explicitly. Sediment routing calculations address five particle-size classes accounting for differences between the ephemeral gully sediment flux and the *in situ* soil material. REGEM has been integrated with the AnnAGNPS model, giving AnnAGNPS the ability to explicitly account for ephemeral gully erosion with a minimum of additional input data. Future improvements to REGEM will follow its verification and validation.

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