SCALING A REPRESENTATIVE STORM SEQUENCE TO ESTIMATE EPHEMERAL GULLY EROSION WITH RUSLE2

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Abstract Recent enhancements to RUSLE2 allow determination of a representative runoff event sequence that is intended for calculating concentrated flow erosion. The approach relies on creating estimates of monthly runoff, the number of runoff events per year, and the scale parameter of a gamma distribution describing runoff events for any RUSLE2 climate, soil, and management combination. A sequence of runoff events that totals expected average annual runoff is calculated based on the return period of the largest storm in the sequence, which is assumed to occur on the day of the year with the maximum runoff as determined by disaggregating monthly runoff estimates to daily values. The period between runoff events in the sequence is calculated from the ratio of the maximum event to the maximum daily disaggregated value. A sensitivity analysis was conducted to determine the effect of variation in the return period of the maximum annual runoff event on erosion computed when the resulting storm sequence was coupled with the channel erosion equations of the CREAMS model. We hypothesized that for management systems with more than one tillage operation, there would be at least one maximum in predicted average annual channel erosion as the return period of the maximum storm was increased and the total number of events per year decreased. The channel erosion resulting from the proposed RUSLE2 representative runoff event sequence was then compared with that resulting when 30-year stochastic runoff event populations predicted by AnnAGNPS for the same combination of climate, soil, and management descriptions were coupled with (1) the channel erosion component within CREAMS or (2) the tillage-induced ephemeral gully erosion model (TIEGEM) implemented within AnnAGNPS. The responses of these two channel erosion models to variations in soil erodibility, critical shear stress, and depth of a non-erodible layer were explored.

INTRODUCTION

RUSLE2 (Revised Universal Soil Loss Equation, version2) is the most recent in the family of USLE/RUSLE/RUSLE2 models proven to provide robust estimates of average annual sheet and rill erosion from a wide range of land use, soil, and climatic conditions. However, RUSLE2 currently cannot estimate concentrated flow erosion, which may be of a similar magnitude as sheet and rill erosion in fields experiencing ephemeral gully erosion.

Two alternative process-based formulations are currently used to estimate ephemeral gully erosion in the WEPP (Water Erosion Prediction Project) and AnnAGNPS (the Annualized version of the AGricultural Non-Point Source Pollution Model) (Bingner and Theurer, 2001). WEPP (Ascough et al., 1997) and GeoWEPP (Renschler, 2003) use the channel erosion equations developed by Foster et al. (1980b) for CREAMS (Chemicals, Runoff and Erosion from

Agricultural Management Systems). In CREAMS, ephemeral gully erosion is calculated through a procedure that assumes soil detachment occurs from the shear force and unsatisfied transport capacity of flowing water in a flat-bottomed but enlarging channel. The equations that describe change in channel dimensions were developed by Foster and Lane (1983). Haan et al. (1994) provide a clear conceptual derivation of the channel erosion theory represented by the process-based equations used in CREAMS to describe ephemeral gully erosion. The theory is based on several assumptions: (1) that Manning's equation applies, (2) that the shear stress distribution around the cross section of a channel can be represented by a hard-coded dimensionless distribution, (3) that the soil consists of a uniform erodibile layer with characteristic erodibility and critical shear stress values overlying a non-erodible layer at a specified depth, (4) that potential detachment rate is proportional to excess shear stress, (5) that actual detachment is proportional to the unsatisfied transport capacity of a steady-state runoff rate, (6) that transport capacity can be determined by the set of equations proposed by Yalin (1963), and (7) that deposition occurs if sediment load exceeds transport capacity.

In contrast to the steadily varying channel bottom assumed in CREAMS, ephemeral-gully in AnnAGNPS is conceptualized as due to the advancement of a single headcut. The formulation is termed TIEGEM (Tillage-Induced Ephemeral Gully Erosion Model) and is based on a modification of REGEM (Revised Ephemeral Gully Erosion Model) (Gordon et al., 2007 and 2008), which incorporates plunge pool formation and headcut retreat (Alonso et al., 2002) but with plunge pool depth restricted by a non-erodible layer. TIEGEM operates within single or multiple storm events in unsteady, spatially varied flow with watershed contributing area determined as described by Theurer et al. (1996). TIEGEM has five optional ephemeral gully width algorithms, and determines sediment delivery to the mouth of the channel, and therefore the flow transport capacity, using HUSLE (Hydro-geomorphic Universal Soil Loss Equation) procedures (Theurer and Clarke, 1991).

Both CREAMS and TIEGEM descretize sediment into five particle-size classes, assume a permanently non-erodible layer exists at some depth that is commonly taken as either the deepest or last tillage depth, and allow for gully repair and reset when fields are tilled.

Dabney et al. (2010) described a method for developing a series of representative runoff events whose sizes, durations, and timing are estimated from information already available in RUSLE2 databases. This method has been incorporated into RUSLE2 and is available on the USDA-ARS RUSLE2 web site (http://www.ars.usda.gov/Research/docs.htm?docid=6038). The purpose of this report is (1) to explore the utility of this representative series of runoff events for predicting ephemeral gully erosion and (2) to compare the predictions of two alternative physically-based concentrated flow erosion prediction models. This is done by linking the RUSLE2 representative runoff event series and RUSLE2 hillslope sediment yield estimates to the channel erosion component of CREAMS and comparing the average annual results obtained with averages derived from using a 30-year stochastic weather series as inputs to AnnAGNPS driving the CREAMS channel erosion component and TIEGEM within AnnAGNPS with the resulting 30-year stochastic runoff event and hillslope sediment delivery populations.

METHODS

Thirty-year synthetic GEM (Harmel et al. 2002) weather simulations were developed for six locations and were used as inputs for AnnAGNPS to estimate runoff, hillslope erosion, and ephemeral gully erosion for factorial combinations of four soils (soil hydrologic classes A, B, C, and D) and four managements (tilled fallow, F; tilled maize [*Zea mays*, L.], CT; no-till maize, NT; and pasture, P) for a hypothetical 5 ha rectangular field. Soil disturbing events associated with each management are reported in Table 1. The pasture management was modeled as having no soil disturbing operations that would reset an ephemeral gully. Because the no-till planting operation disturbed only 20% of the soil, it was not considered to reset the ephemeral gully in TIEGEM but did reset the gully in CREAMS.

The hypothetical field was assumed bisected with a potential ephemeral gully flanked on each side by 22.1 m hillslopes, so the maximum length of the channel was about 1130 m. A non-erodible layer was assumed at either 0.05 m or 0.2 m depth, representing the shallowest and deepest depths of soil disturbing operations listed in Table 1. Computations were done at four ephemeral gully thalweg slopes (0.5, 1, 2, and 5%).

Table 1 Soil disturbances associated with simulated managements; pasture management was simulated with no soil disturbing operations.

Tilled Fallow		Tilled Maize		No-till Maize	
Date	Soil Disturbance	Date	Soil Disturbance	Date	Soil Disturbance
4/15	moldboard plow	4/15	moldboard plow	5/10	planter, double disk opnr
4/15	disk, tandem	5/1	disk, tandem		
4/15	harrow, spike tooth	5/5	cultivator, field		
5/15	disk, tandem	5/10	planter, double disk opnr		
5/15	harrow, spike tooth	6/10	cultivator, row		
6/15	disk, tandem				
6/15	harrow, spike tooth				
7/15	disk, tandem				
7/15	harrow, spike tooth				
8/15	disk, tandem				
8/15	harrow, spike tooth				
9/15	disk, tandem				
9/15	harrow, spike tooth				

AnnAGNPS and RUSLE2 use compatible management descriptions. The same managements and soil hydrologic groups were also used to generate RUSLE2 hillslope sheet and rill erosion estimates. A representative "channel forming" runoff event sequence was determined within RUSLE2 using methods described in detail by Dabney et al. (2010). This runoff event sequence and associated sediment loads were linked with the CREAMS channel erosion module for the factorial combination of the same six locations, four soils, and four managements. In most of the RUSLE2 event sequences the maximum event in the sequence was set to be the 24-hour runoff depth with a 0.5 y return period ($Q_{0.5y,24h}$). At all six locations, the effect of selecting an maximum event alternative return period of 10, 5, 2, 1, 0.5, 0.2, 0.1, or 0.05 y was investigated for the combination of CT management and hydraulic class C soil.

To provide a comparison of the TIEGEM output and the results from CREAMS when linked to the RUSLE2 representative event sequence, the AnnAGNPS 30-year event runoff and hillslope erosion estimates were also used as input to the CREAMS channel erosion module. In the CREAMS simulations, soil erodibility was assumed to be equal to 13.8 g N^{-1} s^{-1} in all situations, but critical shear stress was assumed to be higher in NT and P managements (30 Pa) than in F and CT (4.5 Pa), which was the value suggested for seedbed conditions in the CREAMS documentation (Foster et al, 1980a). In the TIEGEM simulations the erodibility and critical shear stress parameters were calculated internally.

RESULTS

Climatic and selected runoff event characteristics of AnnAGNPS and RUSLE2 are summarized in Table 2. It may be noted that the RUSLE2 predictions of runoff event population statistics,

Table 2 Thirty-year average AnnAGNPS results and RUSLE2 regression predictions of curve number (CN), annual runoff, the gamma distribution scale factor, and the number of runoff events per year for tilled maize yielding 7 Mg ha^{-1} on a hydraulic class C soil at six locations.

County State	Jefferson AL	Panola MS	Dare NC	Tulsa OK	Ingham MI	Spokane[1] WA
			AnnAGNPS 30-yr averages			
annual rainfall (mm)	1422	1332	1284	1078	739	433
average CN	85	84	86	80	82	79
annual runoff (mm)	369	346	292	180	68	28
gamma distribution σ (mm)	13.5	14.5	11.5	12.2	5.1	4.5
events per year (y^{-1})	54.7	47.7	50.7	29.7	26.0	12.5
			RUSLE2 predictions			
annual rainfall (mm)	1446	1402	1316	989	786	435
average CN	86	86	87	85	83	77
annual runoff (mm)	381	363	288	158	57	31
gamma distribution σ (mm)	13.9	14.6	11.7	9.9	3.5	3.6
events per year (y^{-1})	57.8	49.7	56.6	31.4	24.7	9.8
			RUSLE2 representative sequence properties			
gully events per year (y^{-1})	30	20	20	21	27	35
day of max runoff event	Mar 21	Dec 10	Jan 8	Sept 14	Mar 6	Feb 16
$Q_{0.5y,24h}$ runoff event (mm)	33.1	32.9	26.4	17.5	5.5	3.0
$Q_{0.5y,24h}$ runoff rate (mm h^{-1})	27	22	14	23	2.1	1.3

[1] for elevation giving RUSLE2 annual R = “16-18”.

such as the gamma distribution scale factor and the number of runoff events per year are similar to those of the population predicted by AnnAGNPS. However, it should be noted that although the AL, MS, and NC locations have similar rainfall amounts, the number of events in the representative gully forming event sequence and the magnitude and intensity of the maximum event vary among these locations. For example, the AL location has 30 events, with the maximum event, which occurs on March 21, being 33 mm. This represents the 0.5 y event for the location, soil, and management. In contrast, in Mississippi, although the size of the peak event and the total annual runoff amounts are of similar magnitude, there are only 20 events per year, indicating somewhat smaller within-year variation of event size in MS than in AL.

The impacts of selecting alternative return periods for the maximum event of the RUSLE2 event sequence are illustrated in Fig. 1 and Fig. 2. Selecting a larger maximum event return period results in fewer but larger events in the event sequence. Fig. 1 indicates that, averaged over six locations, average annual ephemeral gully erosion predicted by the channel erosion component of CREAMS was insensitive to the selection of return period as long as the return period was at least 0.5 to 1y.

However, results in Fig. 2, which represents only the 2% channel steepness, demonstrate that there can be significant location by return period interactions. The behavior observed in Fig. 2 reflects the complex impacts of having fewer but larger events in the representative event sequence predicted by RUSLE2. Assuming an initially uneroded channel, event erosion increases with event size. However, since the gully is reset by tillage events that are spaced 5, 15, or 30 days apart (Table 1), if no runoff event falls between gully resets, a considerable amount of potential event erosion may be missed by having few events. Thus, channel erosion increases

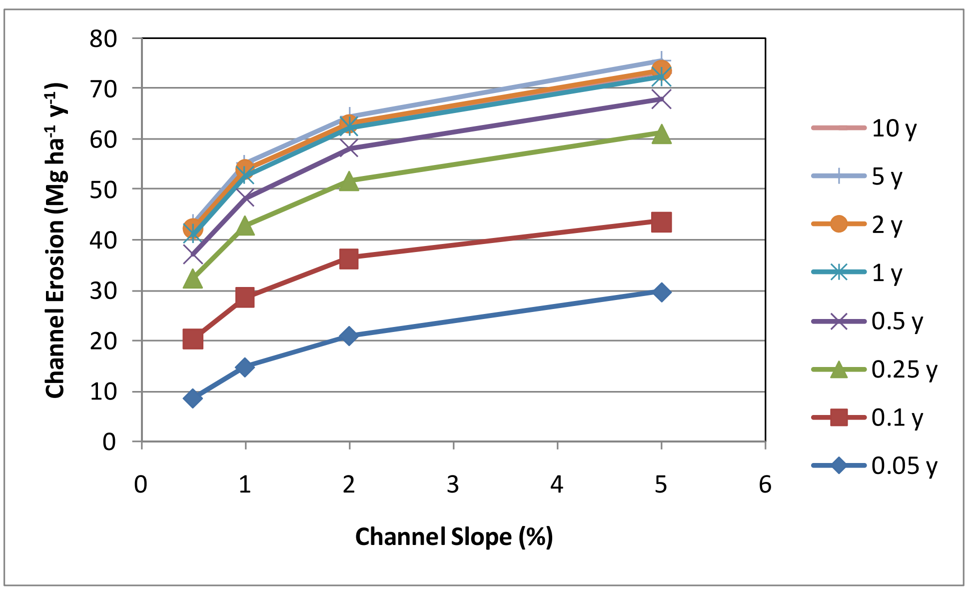

Figure 1 CREAMS channel erosion predicted from RUSLE2 runoff event sequence with varying return period of maximum event and channel slope steepness, a non-erodible layer at 5 cm, and tilled maize grown on hydraulic class C soil, averaged over six locations.

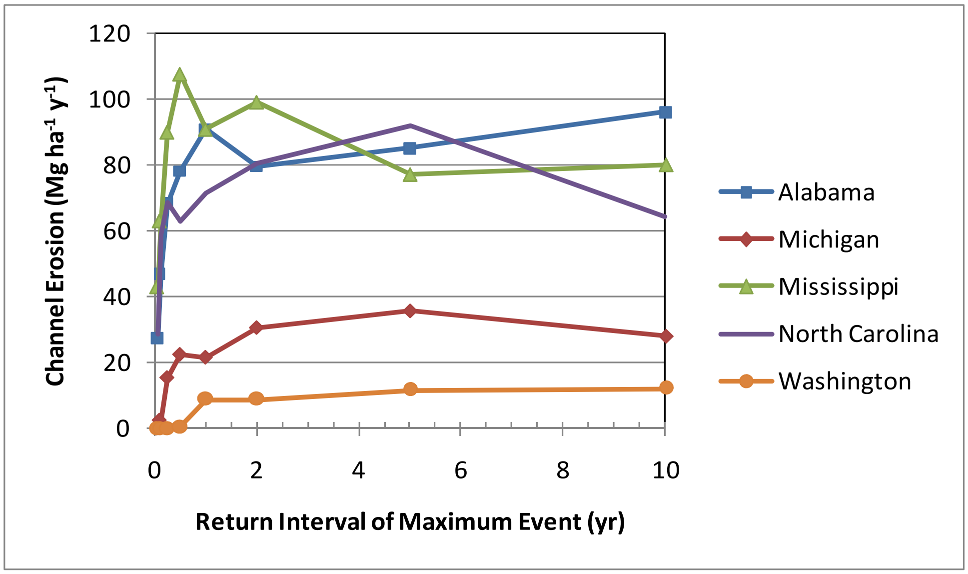

Figure 2 CREAMS channel erosion predicted from RUSLE2 runoff event sequence for varying return period for maximum event for tilled maize on hydraulic class C soil at six locations, for a 2% channel slope steepness and 5 cm depth to a non-erodible layer.

with event size, but then drops before increasing again. The exact point of the drop depends on the timing of events at a particular location relative to the soil disturbing events in Table 1.

The pattern of erosion predicted by CREAMS when linked to the 30-year stochastic series of runoff and hillslope erosion events predicted by AnnAGNPS is illustrated in Fig. 3.

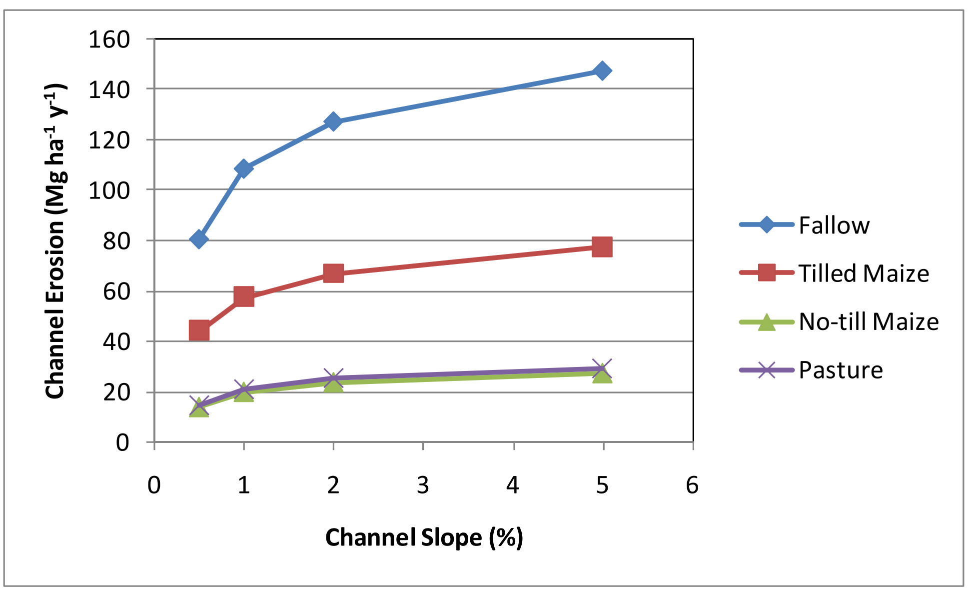

Figure 3 CREAMS channel erosion predicted from 30-year stochastic runoff event sequences predicted by AnnAGNPS for four managements and four channel slope steepness, a 5 cm depth to a non-erodible layer, and hydraulic class C soil averaged over six locations.

Comparison of the tilled maize results in Fig. 3 with the results in Fig. 1 suggests that the results obtained with a 1-y or larger return period may be similar to those obtained by running a much more complex 30-year stochastic simulation for managements receiving several soil disturbing tillage events each year. In fact, using the 0.5-y return period produces comparable results, particularly when the rainfall intensity adjustment to the runoff curve number proposed by Dabney et al. (2010) is employed (Table 3). This adjustment increases runoff amounts when rainfall intensity or erosivity density exceeds a threshold.

Table 3 Average annual ephemeral gully erosion from a hypothetical 5 ha rectangular field with a central channel bordered on each side with 22.1 m hillslopes with four managements and two depths to a non-erodible layer, averaged over six locations, four soils, and four channel slopes.

	30-y AnnAGNPS Stochastic Series			RUSLE2 Event Sequence†	
	AnnAGNPS		CREAMS	CREAMS 5 cm‡	
	5 cm‡	20 cm‡	5 cm‡	no EI adjust	EI adjust§
	Channel Erosion (Mg ha^{-1} y^{-1})				
Tilled Fallow	18	99	110	79	110
Tilled Maize	11	62	58	45	57
No-till Maize	0	0	20	3	3
Pasture	0	0	19	2	3

† Based on a maximum event size based on a 0.5 y return period.
‡ Depth to a non-erodible layer
§Runoff amounts adjusted for rainfall intensity as proposed by Dabney et al. (2010).

For a 20-cm depth to the non-erodibile layer depth, CREAMS channel erosion estimates would equal approximately four times the values reported for a 5 cm depth. However, a note of caution is warranted regarding the magnitude of the CREAMS channel erosion estimates. The results reported were calculated from the voided channel volume and the soil bulk density. These results were found to be approximately double those obtained directly from CREAMS channel erosion output reports and the source of this discrepancy remains under investigation by the authors. Therefore, while the trends reported for CREAMS are correct, the absolute magnitude of the channel erosion estimate may be high by a factor of two. For comparison with the ephemeral gully erosion predictions in Table 3, averaged over locations, AnnAGNPS estimated sheet and rill erosion from tilled fallow ranged from 22 to 56 Mg ha^{-1} y^{-1}, depending on soil texture; from 0.5 to 4 Mg ha^{-1} y^{-1} for tilled maize; and less than 2 Mg ha^{-1} y^{-1} for no-till maize and pasture.

The TIEGM predicted ephemeral gully erosion was considerably lower than that predicted by CREAMS for the same stochastic series of runoff events (Table 3). For a 5 cm depth to a non-erodible layer, CREAMS predicted more than five times more ephemeral gully erosion than did AnnAGNPS using TIEGEM. The lack of any channel erosion prediction for No-till and Pasture by AnnAGNPS resulted because without a tillage operation that disturbs more than 50% of the soil surface, the channel computation routines are not turned on in AnnAGNPS.

Increasing the depth to the non-erodible layer by a factor of four increases TIEGEM predicted ephemeral gully erosion by more than a factor of four. This results from the increase jet angle, which is a critical parameter driving headcut advancement rates (Alonso et al., 2002). In contrast, increasing the depth to the non-erodible layer in CREAMS would increase predicted channel erosion by slightly less than the relative increase in depth.

TIEGEM predicted ephemeral gully erosion responses to channel slope (Fig. 4) with a 20 cm depth to a non-erodible layer were similar to those of CREAMS, but for a 5-cm non-erodibile layer, TIEGEM was insensitive to channel slope within the range investigated.

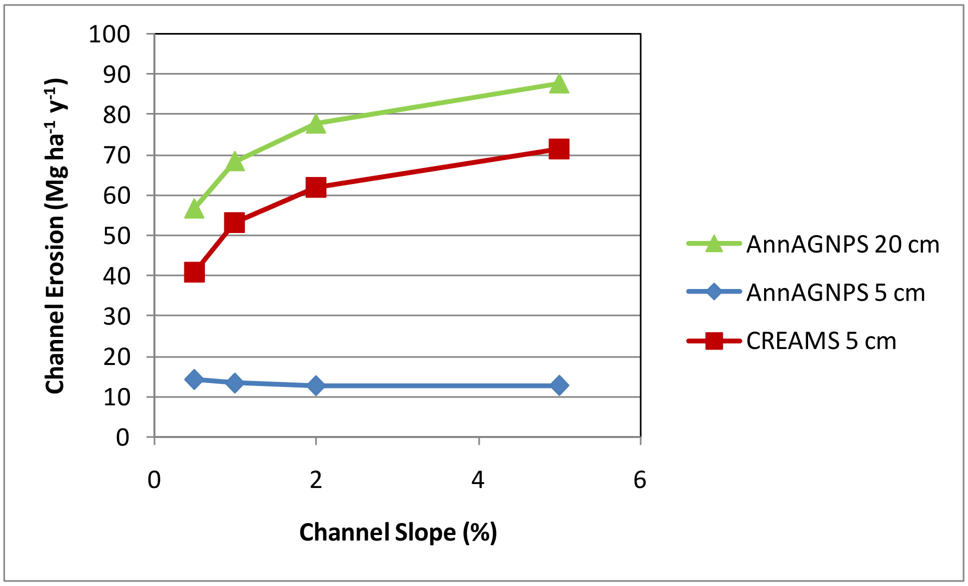

Figure 4 30-year average annual ephemeral gully erosion predicted by AnnAGNPS for 5 and 20 cm depth to a non-erodible layer and for CREAMS with a 5 cm depth to a non-erodible layer for tilled maize on hydraulic class C (clay loam) soil for four channel slope steepness values, averaged over six locations.

DISCUSSION AND CONCLUSIONS

For the field configuration considered, the magnitude of the predicted ephemeral gully erosion exceeded estimated sheet and rill erosion except for the fallow condition and the TIEGEM estimate for a 5 cm non-erodible layer depth. However, the ratio of potential ephemeral channel length to field area (220 m per ha) is probably not realistic. Nevertheless, the magnitude of estimated ephemeral gully erosion and the variability in predicted magnitudes between two process-based models and the trends predicted by these models with changing channel slope and non-erodible layer depth indicates: (1) that this process may be of major importance but (2) our confidence in the available state-of-the art tools is low.

Both models rely on estimates of soil erodibility and critical shear stress, but the magnitudes and impacts of these parameters differ considerably between the two models. Both models assume a non-erodible layer and neither currently handles multiple soil layers with varying erodibility. There is a pressing need for more quantitative measurements of ephemeral gully erosion so that the available models can be validated and improved.

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