SPATIAL VARIABILITY AND MODEL COMPLEXITY IN EROSION PREDICTION ON A SEMIARID RANGELAND WATERSHED

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Abstract

Process-based hydrologic models have the capability to describe where and when erosion is occurring on a watershed. Unfortunately, there have been few successful applications at the watershed scale. One of the problems has been determining which erosion processes are acting where, and accounting for the spatial complexity of the erosion processes in the hydrologic model. Furthermore, since runoff drives the erosion process, is it really necessary to describe the spatial complexity of the erosion process, if the runoff is modeled adequately? In this study, the results of a model complexity that preserved the complexity of the drainage network observed in the field were compared with results from a simplified model representation of the watershed. Runoff and erosion were modeled for a 4.4 ha watershed near Tombstone, Arizona. The more complex representation of the watershed had 312 upland and channel elements, which included all identifiable rills on the watershed. The simplified representation had 18 elements. The results showed that both representations produced good simulated hydrographs. However, the simulated sedigraphs from the more complex representation of the watershed were better than those from the simplified representation of the watershed. In general, the more complex the hydrograph, the poorer the simplified representation simulated the sedigraph. The results indicate that preserving the drainage network complexity observed in the field is more important for modeling erosion than for modeling runoff.

Introduction

Significant progress has been made in describing and predicting the movement of water using hydrodynamics, but describing the movement of sediment on small watersheds is a task that continues to be most accurately described using empirical methods. Reliance on empirical methods indicates that the processes themselves are not well understood. This study is an attempt to further the understanding of the erosion process through better characterization of the scale at which various erosion mechanisms occur.

In recent years, physically based models using hydrodynamic principals have been used successfully to model rainfall and runoff (e.g. Goodrich 1990). Among the most successful physically based rainfall-runoff models are those relying on the kinematic wave approximation to the full dynamic wave equation. The hydrodynamic approach to modeling erosion offers a number of benefits over more empirical methods. One of the major benefits is that these expressions can be used to describe response to a single event, because they describe the physics of water movement. Among the potential benefits of physically based distributed sediment models (i.e. erosion models based on hydrodynamic principals) is the potential to describe where and when erosion and deposition are occurring (Nearing et al. 1994). In contrast, the most widely used empirical method for estimating soil loss (the Universal Soil Loss Equation, USLE) is not intended to be used on an event basis (Wischmeier and Smith 1978). The USLE can be used to estimate annual soil loss, but not to describe erosion on an event basis. It neither describes detachment by flowing water, nor considers the subtractive effect of infiltration on overland flow. In practical terms, physically based distributed water and sediment models have the potential to describe the movement of sediment-borne contaminants and the effect of changes in watershed management practices (Jensen and Mantoglou 1992), as well as model the impact of environmental change on erosion and sediment yield (Hawkins et al. 1991; Tucker and Slingerland 1997).

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Theoretically, a physically based distributed rainfall-runoff model linked to a model describing the entrainment of soil ought to describe where and when erosion occurs on a watershed during a rainfall event. Because the hydrodynamic approach has worked successfully to model erosion on small plots (e.g. Lopes and Lane 1990; Laguna and Girardez 1993; Wicks et al. 1992), it may be possible to scale-up to small watersheds. Unfortunately, successful application of sediment yield models at the watershed scale are few (e.g. Wicks and Bathurst 1996). Furthermore, even results from these isolated cases are inconclusive. The hydrodynamic approach has worked well for modeling rainfall-runoff on the Lucky Hills watershed where this research will take place (Goodrich 1990), so a good description of the hydraulics that drives erosion may greatly improve the likelihood of successfully modeling erosion on the small watershed scale.

Typically, the hydrodynamic approach to modeling erosion and sediment yield in desert environments recognizes two distinct erosion processes: entrainment by raindrop impact and entrainment by flowing water. Although the processes are widely recognized, the understanding of where they begin to dominate on a rangeland watershed is not clear. Channels form as the result of entrainment of soil by flowing water. However, determining where a channel begins, and therefore where entrainment by flowing water dominates, is less clear. Such a determination is typically made with topographic maps (e.g. Lopes 1987; Goodrich 1990). Therefore, recognizing the scale at which different processes dominate, and partitioning a watershed into channel and hillslope elements, becomes somewhat a consequence of the available map scale, and the subjectiveness of the person partitioning a particular watershed.

In this study, the watershed was partitioned so that the model effectively preserved the spatial relationship of entrainment by raindrop to entrainment by flowing water observed in the field. The primary source of additional information about the scale of the erosion processes is the landscape itself. The geomorphology (landscape form) of a natural drainage basin should reflect the interaction between runoff and erosion. Landforms shape the hydrologic response of a watershed, and the hydrologic response, in turn, shapes the form of a watershed through the erosion process. Points of rill initiation represent a threshold to dominance of entrainment by flowing water. Therefore, for this study, points of rill initiation were identified in the field.

The KINEROS2 model (Smith et al. 1995) was used here to simulate erosion on the 4.4 ha Lucky Hills 104 watershed near Tombstone, Arizona. This watershed is well suited for study because the hydrology parameter values for the KINEROS2 model are available. Rainfall and sediment-yield data are available as well. Since the hydrologic component of the model drives the erosion component, and the hydrology is well understood, this research can focus on the erosion modeling. A previous study found that a representation of the watershed that divided the watershed into 232 upland and channel elements modeled runoff no better than one that represented the watershed as a series of 18 upland and channel elements (Goodrich 1990). The question then is this: Since runoff drives erosion, is an adequate model of runoff all that is necessary to model erosion? Or, is it necessary to have a model complexity that preserves the degree of channel and upland complexity observed in the field?

Objective

The objective of this research was to compare the results of a sediment yield model that properly preserved the spatial representation of channel to hillslope, with a simplified representation that is adequate for modeling runoff.

The Lucky Hills and Walnut Gulch

The study area is located on the Walnut Gulch Experimental Watershed near Tombstone, Arizona, and operated by the USDA-ARS in Tucson. The study used data from the Lucky Hills 104 watershed (LH104, 4.4 ha). Lucky Hills 104 contains two nested watersheds, LH102 (1.46 ha) and LH106 (0.36 ha). Vegetation on the watershed is creosote bush and acacia, which are typical invasive species for degraded rangeland in the southwestern United States.

Soils on the watershed are mapped as Luckyhills-McNeal (Ustochreptic Calciorthid; Breckenfield et al. 1995). Hydrology and scale issues related to runoff from this watershed have been studied extensively (Goodrich et al. 1995; Faures et al. 1995; Goodrich 1990; Woolhiser and Goodrich 1988).

Methods

The general approach for this research was to gather data on form and materials and relate these to the erosion process. Specifically, landscape form was characterized using topographic surveys, and the materials on the landscape were characterized using soil particle size analysis. For this research, 2993 survey points were collected on the Lucky Hills 104 watershed. In addition, 132 soil samples were collected and analyzed for 13 particle size classes up through 64 mm. A geographic information system (GIS) was used to calculate landscape variables such as slope steepness and upland drainage area. Statistics and geostatistics were used to relate landscape variables to soil particle size data, so that the spatial variability of soil erodibility and soil hydraulic conductivity could be estimated (Canfield 1998; Canfield and Lopes 1998; Canfield et al. 1998a, b; Canfield et al. 1999).

The locations where rills began were identified in the field, so that the point of spatial dominance of concentrated flow and entrainment by flowing water could be determined. The observed landscape relationships were used as a basis to partition the watershed to preserve the relationship between areas dominated by entrainment by flow and those dominated by entrainment by raindrop impact. Figure 1 shows the partitioning of the Lucky Hills 104 Watershed into 312 upland (hillslope) or channel (rill, gully, or ephemeral channel) elements. Figure 2 shows the partitioning of the watershed into 18 elements. This partitioning into 18 different elements was selected because, as mentioned previously, an 18-element partitioning of the watershed has been found to be adequate for modeling hydrographs. Simulated results from the KINEROS2 (Smith et al. 1995) rainfall-runoff and sediment yield model were compared with observed values.

Hydrologic Modeling

KINEROS2 is a distributed rainfall-runoff and soil erosion model that describes Hortonian overland flow, and is therefore well suited to describing the hydrodynamics of soil erosion on semiarid watersheds. KINEROS2 describes a watershed as a series of cascading plane and channel elements. Each element is characterized with infiltration, hydrologic, and soil erosion parameters, which thus allows the user to input the spatial variability of parameters on the watershed.

Rainfall, runoff, and sediment yield data were available for eight summer monsoon events between 1982 and 1988 from the USDA-ARS Southwest Watershed Research Center in Tucson. The hydrologic parameters were optimized using the approach of Goodrich (1990), who found optimal parameter fits for the Smith and Parlange (1978) infiltration equation. Parameter identification was done using the shuffled complex evolution UA (SCEUA) search algorithm (Duan et al. 1992) and the total sum of squares objective function (TSSR). Goodrich (1990) maintained the distributed nature of the model parameters throughout optimization using multipliers. Initial estimates of the distribution of parameters are based on the distributed soil sampling, subsequent Ks (saturated hydraulic conductivity) estimates based on the particle size distribution, and field description to estimate Manning's roughness coefficient (n). The relative spatial distribution of parameters is preserved by multiplying all distributed parameters by a multiplying factor (multiplier). This multiplier is increased or decreased to improve model simulations. The multiplier was then optimized, thus maintaining the spatially distributed nature of the model parameters. The technique of optimizing multipliers was also used to estimate erosion parameters for this study.

Goodrich (1990), among others (e.g. Binley et al. 1989), has pointed out that a single value of hydraulic conductivity cannot accurately represent the infiltration process on a model element because of the great spatial variability in infiltration rates. For this reason, Goodrich optimized for variability by optimizing the CV_{Ks}, where CV_{Ks} is the coefficient of variation of the hydraulic conductivity. However, he found that this spatial variability effect was more pronounced for smaller events. The distribution of saturated hydraulic conductivity, Ks, and net capillary drive, G, for LH 104 has been determined by Goodrich (1990).

To compare the effect of a complex distributed partitioning with a more simple approach, parameter values were selected for both the 312-element and the 18-element partitioning of the watershed. Optimal parameter multiplier values for K_s, n, and CV_{Ks} were selected for each event individually using the SCEUA and the TSSR.

Modeling Sediment Yield

After optimal values were selected for hydrology parameters, optimal values were selected for sediment yield parameters using the SCEUA with the TSSR objective function. One of the benefits of using KINEROS2 is that it employs an expression that describes movement of multiple particle size classes based on the work of Engelund and Hansen (1967) of the form

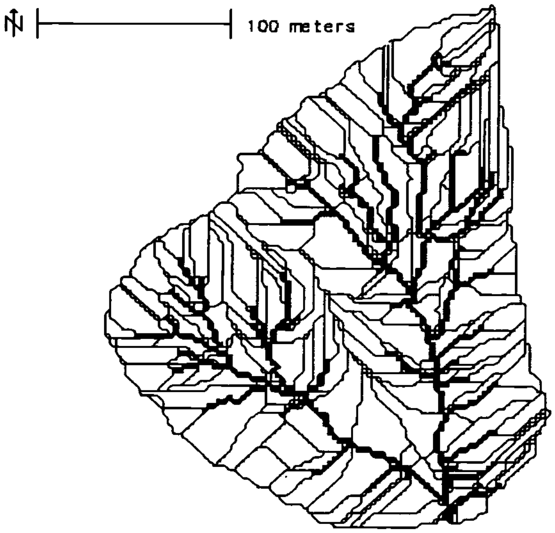

Figure 1. The Lucky Hills 104 watershed partitioned into 312 upland and channel elements. The black areas are channels, and the outlined areas are hillslope elements. The partitioning was done based on field identification of channel heads.

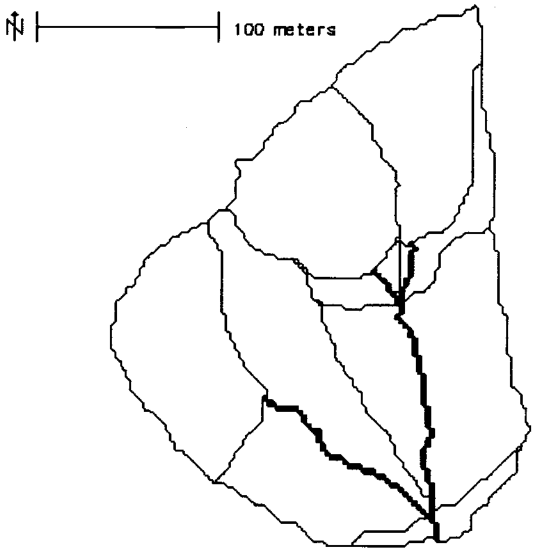

Figure 2. The Lucky Hills 104 watershed partitioned into 18 elements, based on a critical source area of 0.53 ha, which was proposed by Goodrich (1990) as the coarsest simplification at which the hydrology could be accurately modeled.

$$e_{f(n)} = \beta_{l(n)} w\left(Mtc * c_{mx(n)} - c_{s(n)}\right) \qquad [1]$$

where

$e_{f(n)}$ = entrainment by flow for particle size class (n)

Mtc = multiplier for transport capacity

β_l = erosion rate coefficient for particle size class (n)

w = width of flow

$c_{mx(n)}$ = transport capacity of particle size class (n).

In this expression,

$$\beta_{l(n)} = COH * Pct(n) * vsl_{(n)}(1 - PAV) \qquad [2]$$

where

COH = cohesion of soil

Pct(n) = percentage of particle class size n

vsl(n) = settling velocity of particle size n (L/T)

PAV = erosion pavement fraction (i.e. full coarse particle cover = 1).

For non-cohesive soils with no pavement, β_l reduces to the settling velocity [vsl(n)]. Because most of the surface of the Lucky Hills is covered with non-cohesive sediment, this characterization greatly simplifies parameterization. Therefore, for noncohesive soil, the only external input to the expression is soil particle size, which is used in estimating the soil erodibility term, β_l, and in the transport capacity term, $c_{mx(n)}$. Therefore, parameterizing the spatial distribution of flow-induced soil erodibility becomes a task of estimating the spatial distribution of soil particle size class.

Entrainment by raindrop impact (e_i) is described by the following relationship:

$$e_i = Msp * K_i i^2 e^{-ch} \qquad [3]$$

where

Msp = multiplier on the splash parameter

K_i = parameter describing the susceptibility of the soil particles to be detached and entrained by raindrop impact

i = rainfall rate

c = parameter describing the attenuation effect of flow depth.

Success in modeling was determined using the Nash-Sutcliffe (1970) statistic, which is calculated as follows:

$$E = 1 - \left[\frac{\sum_{i=1}^{n}\left(\theta i - \hat{\theta} i\right)^2}{\sum_{i=1}^{n}\left(\theta i - \bar{\theta}\right)^2}\right] \qquad [4]$$

where

θi = observation at time i

$\hat{\theta} i$ = simulated value at time i

$\bar{\theta}$ = mean of all observed values.

This is also referred to as the model efficiency (ME).

Results and Discussion

For six of the eight events, the KINEROS2 model simulated runoff well for both the 18-element and 312-element representations. Neither representation performed adequately on the remaining two events. Since hydrology has been shown to have a pronounced effect on sediment yield with the KINEROS2 model (Smith et al. 1998), use of simulations with minimal hydrologic error provides an opportunity to minimize the compounding effects of hydrology on modeling sediment yield. There was virtually no difference between the goodness of fit for the 18 element or 312 element. The hydrologic simulation for all events for both of the watershed configurations can be considered to be very good because the Nash-Sutcliffe (1970) statistics were between 0.85 and 1 (Table 1).

For example, Figure 3a shows the simulated and observed hydrograph of the 312-element partitioning for the July 30, 1985 event, whereas Figure 3b shows the simulated and observed hydrographs for 18-element partitioning. Figure 4 shows the same for the September 20, 1983 event. Note that for both these events, the hydrologic simulations are good, so that there appears to be no benefit to using a more complex watershed complexity to model runoff.

In contrast, there is a marked difference in some of the sedigraphs. The simulation from the more complex watershed was as good or better than the simulation using the 18-element watershed. Furthermore, the results from the 312-element simulations were better for the largest and smallest of the events. Results are summarized in Table 1. Figures 5 and 6 show the sedigraphs for the 312- and 18-

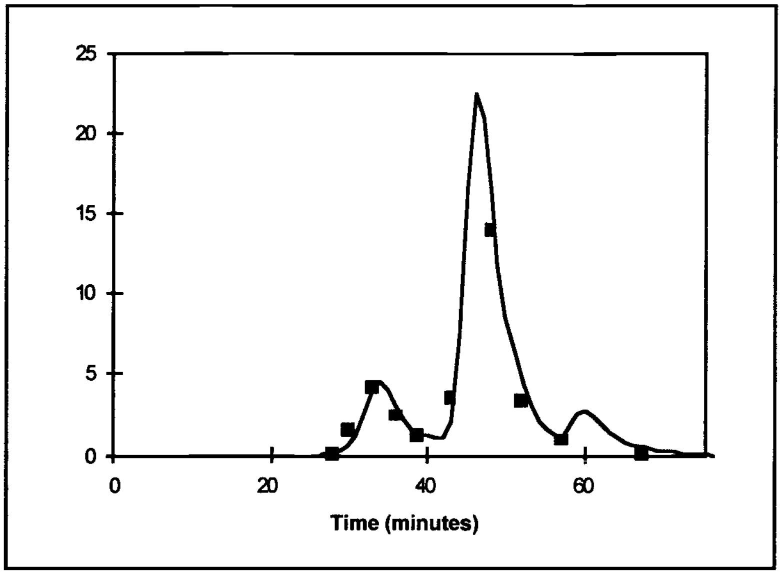

Figure 3a. September 20, 1983 fitted hydrograph for the 312-element watershed configuration.

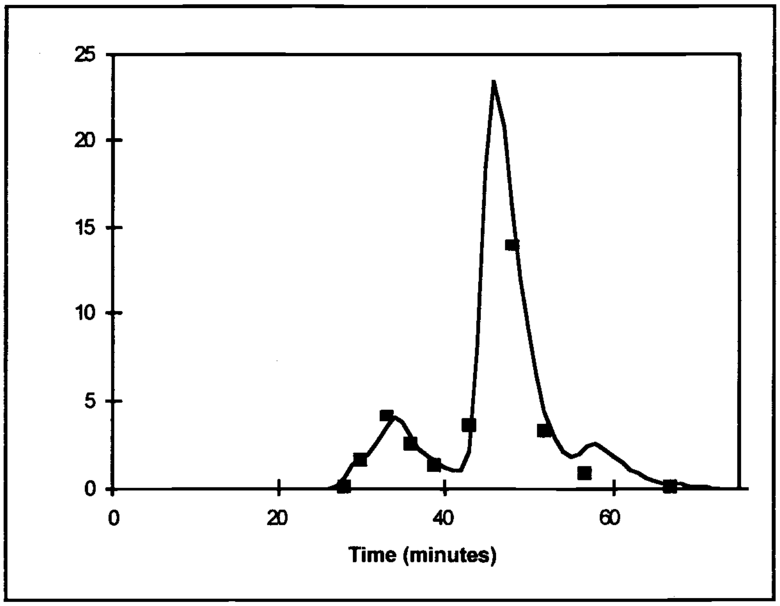

Figure 3b. September 20, 1983 fitted hydrograph for the 18-element watershed configuration.

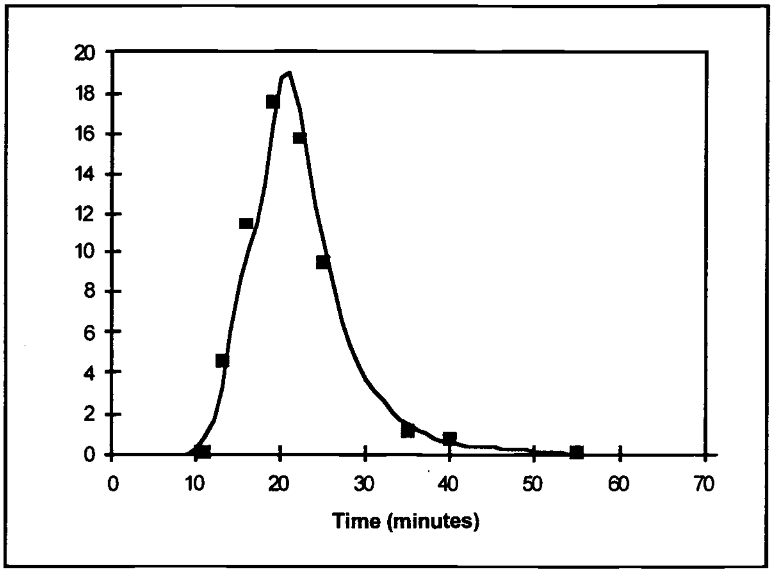

Figure 4a. July 30, 1985 fitted hydrograph for the 312-element watershed configuration.

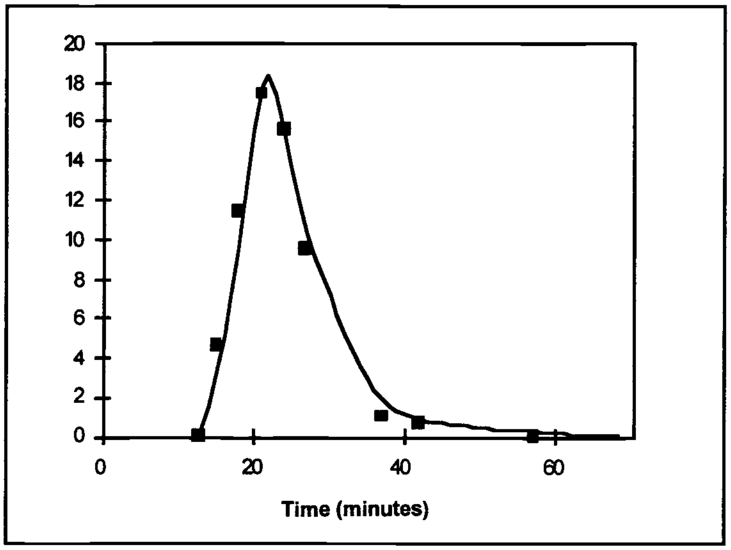

Figure 4b. July 30, 1985 fitted hydrograph for the 18-element watershed configuration.

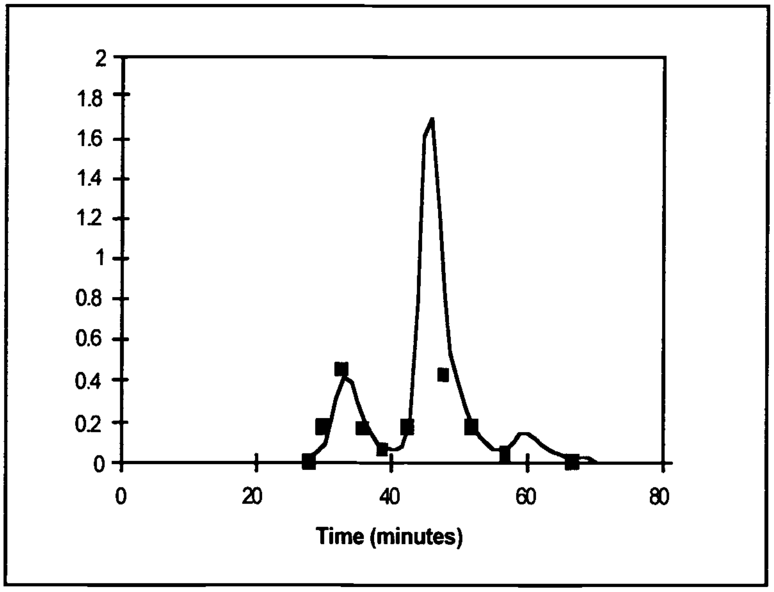

Figure 5a. Fitted sedigraph for the September 20, 1983 event 312-element configuration.

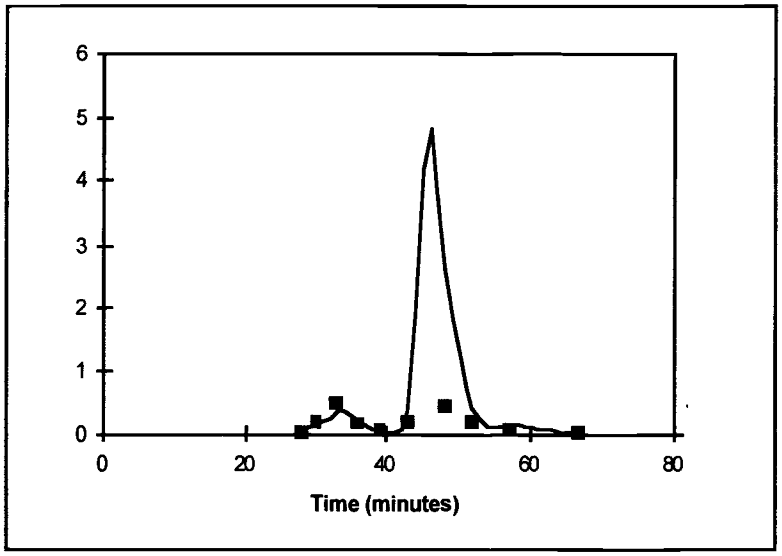

Figure 5b. Fitted sedigraph for the September 20, 1983 event 18-element configuration.

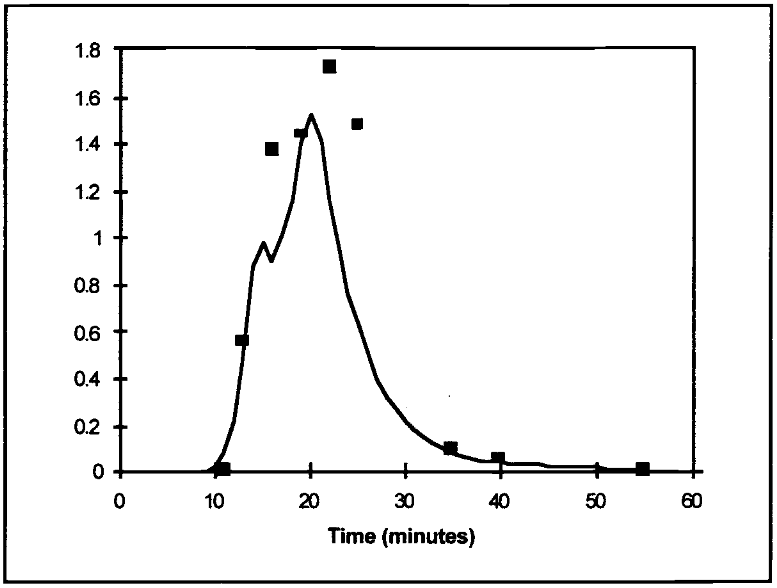

Figure 6a. Fitted sedigraph for the July 30, 1985 event 312-element configuration.

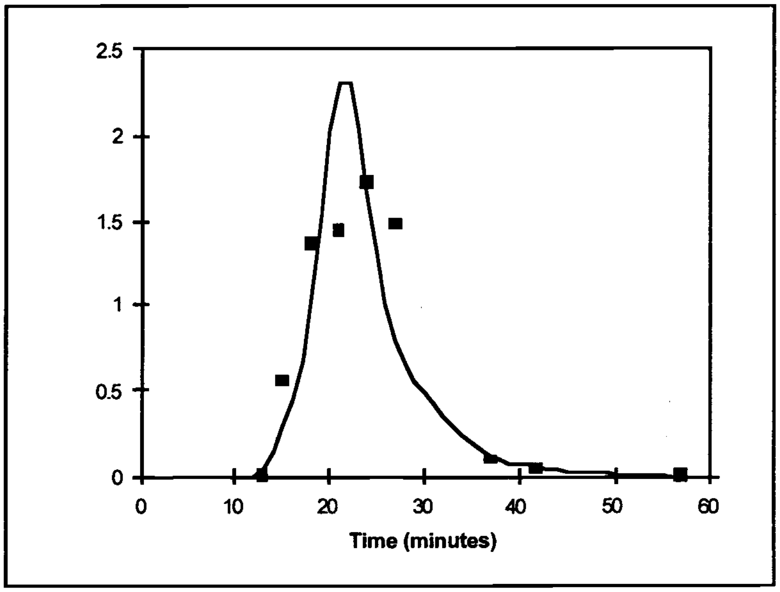

Figure 6b. Fitted sedigraph for the July 30, 1985 event 18-element configuration.

Table 1. Summary of model efficiencies for modeled events.

	Hydrograph		Sedigraph	
Event	312 Element	18 Element	312 Element	18 Element
11 Sep 82	0.99	0.97	0.68	0.50
20 Sep 83	0.99	0.99	0.85	–48.8
30 Jul 85	0.99	0.99	0.61	0.63
10 Sep 83	0.97	0.92	0.97	0.52
24 Aug 84	0.90	0.91	–0.62	–0.45
5 Aug 88	0.98	0.85	0.51	0.09

Note: Model efficiencies are calculated using equation 4.

element partitioning for the September 20, 1983 and July 30, 1985 events respectively. These figures illustrate some of the general trends noted. The simpler complexity had greater errors estimating sediment yield for multi-peaked events. Therefore, the hydrographs might be adequate for multi-peaked events, but resulted in great errors in sediment yield (e.g. Figure 5b). In contrast, the more complex representation resulted in reasonable simulations for virtually all events.

In addition to the problems in modeling sediment yield were problems associated with the magnitude of the physical processes. Multipliers for the two watershed configurations are as follows:

	M Transport Capacity	M Splash
312 Element	1.70	5.04
18 Element	1.24	12.51

Ideally, if the model had been perfectly parameterized, and if the model described the processes well, all multipliers should be 1.0. Therefore, these multipliers suggest that the parameterization was not ideal. In this case, the multiplier on transport capacity has values in line with the expected value of 1.0. Although the apparent parameter interaction suggests that these values may not be representative, values of 1.70 or 1.24 on transport capacity seem reasonable considering the potential sources of error. These sources of error include using current field survey data and soils data to estimate conditions for events that occurred 10 to 16 years ago, and describing channels as having uniform cross-sections when, in fact, the cross-section changes through different reaches. Multipliers on splash on the order of 5 to 12 clearly suggest a problem. However, Smith et al. (1998) multiplied splash by 10 to 20,000 to get reasonable estimates of sediment yield using the KINEROS2 model. Although there is clearly a problem, it is not clear whether it is merely a computational problem, or if it points to a lack of understanding of the rain splash process.

Conclusions

Clearly there is some benefit to using a more complex geometric representation of the watershed. The two very best sedigraph simulations (ME = 0.85 for the September 20, 1983 event and ME = 0.97 for the September 10, 1983 event) were simulated using the more complex representation. In addition, the very worst simulation (ME = –48.8 for the September 20, 1983 event) was produced using the 18-element configuration. However, the simulation from the 312 element for that same event was very good (ME = 0.85). In addition to the goodness of fit statistics, it was apparent that in some cases, the shape of the sedigraph from the 18-element configuration was not as reasonable as the one for the 312-element configuration (e.g. the September 11, 1982 event). The better fits and more reasonable sedigraph shapes suggest that there is a benefit to using a more complex representation of the watershed, and distributed erodibility values estimated from sediment samples. Furthermore, the magnitude of the estimated fluxes from entrainment by raindrop impact and entrainment by flowing water was more reasonable for the more complex representation, suggesting that the more complex representation is a more realistic description of where and when erosion is occurring on a watershed during an event.

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