JOURNAL OF THE AMERICAN WATER RESOURCES ASSOCIATION
APRIL AMERICAN WATER RESOURCES ASSOCIATION 2004

PARAMETER IDENTIFICATION IN A TWO-MULTIPLIER SEDIMENT YIELD MODEL[1]

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ABSTRACT: A process based, distributed runoff erosion model (KINEROS2) was used to examine problems of parameter identification of sediment entrainment equations for small watersheds. Two multipliers were used to reflect the distributed nature of the sediment entrainment parameters: one multiplier for a raindrop induced entrainment parameter, and one multiplier for a flow induced entrainment parameter. The study was conducted in three parts. First, parameter identification was studied for simulated error free data sets where the parameter values were known. Second, the number of data points in the simulated sedigraphs was reduced to reflect the effect of temporal sampling frequency on parameter identification. Finally, event data from a small rangeland watershed were used to examine parameter identifiability when the parameter values are unknown. Results demonstrated that whereas unique multiplier values can be obtained for simulated error free data, unique parameter values could not be obtained for some event data. Unique multiplier values for raindrop induced entrainment and flow induced entrainment were found for events with greater than a two-year return period (~25 mm) that also had at least 10 mm of rain in ten minutes. It was also found that the three-minute sampling frequency used for the sediment sampler might be inadequate to identify parameters in some cases.
(KEY TERMS: erosion; sedimentation; surface water hydrology; watershed modeling; parameter identification; rangeland watersheds.)

Canfield, H. Evan and Vicente L. Lopes, 2004. Parameter Identification in a Two-Multiplier Sediment Yield Model. Journal of the American Water Resources Association (JAWRA) 40(2):321-332.

INTRODUCTION

In recent years, process based models using hydrodynamic principles have successfully been used to model runoff and sediment yield on small plots (Nearing *et al.,* 1989; Lopes and Lane,1990; Wicks *et al.,* 1992; Laguna and Girardez 1993), and runoff on small watersheds (Goodrich, 1990; Lopes and Lane 1990). However, there have been few successful applications of sediment yield models on small watersheds (Wicks and Bathurst, 1996; Jetten *et al.,* 1999; Smith *et al.,* 1999). The hydrodynamic approach to runoff erosion modeling offers a number of benefits over more empirical methods. One of the major benefits is that these models can be used to describe response to a single event, because they describe the physics of water movement on a watershed. Another benefit is the potential to describe where and when erosion and deposition occur (Nearing *et al.,* 1994). In addition, process based distributed runoff erosion models have the potential to describe the movement of sediment borne contaminants, and the effect of management practices (Jensen and Mantoglou, 1992) and climate change (Hawkins *et al.,* 1991) on erosion and sediment yield.

Typically, the hydrodynamic approach to runoff and erosion modeling recognizes two distinct sediment entrainment processes on a hillslope: sediment entrainment by raindrop impact (sometimes called rainsplash), and entrainment by flowing water. Entrainment by flowing water also occurs in rills and channels. One problem that arises is that it may be impossible to identify the relative contributions of these two processes to sediment yield from a small watershed. This has been a serious problem in determining optimum parameter values in these types of models (Blau *et al.,* 1988; Freedman *et al.,* 1998).

[1]Paper No. 02023 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2004). **Discussions are open until October 1, 2004.**
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Parameter identification is an automated process by which model parameters are identified (or calibrated). It comprises the following three major components: (1) an objective function that determines how well model estimates fit the observed data, (2) a search algorithm that selects possible parameter values to compare, and (3) a means to determine if the selected parameter values are physically realistic. Researchers have found that for sediment entrainment some search algorithms and objective functions work better than others (Freedman *et al.,* 1998), and that some types of sediment entrainment equations have more identifiable parameters than others (Freedman *et al.,* 2001). Often, researchers have to make assumptions about the system's behavior to find optimum parameter values successfully. For example, Nearing *et al.* (1989) set the ratio of rill to interill entrainment constant, and found good parameter identifiability for the predecessor of the WEPP model (Lane *et al.,* 1987).

Contrary to previous studies, this study uses observed data from an experimental watershed rather than from rainfall simulators on small plots. This study further differs from previous studies in that it begins with a spatial representation of the watershed that includes the channel network complexity as observed in the field. This representation was chosen in an attempt to minimize the potential effect of process scale interaction by using a field identifiable measure of process scale (i.e., the location on the watershed where flow entrainment processes are dominant enough to produce an incision onto the hillslope).

Because entrainment by flowing water and raindrop impact are scale dependent processes, it was assumed that identifying parameters might not be possible unless a watershed representation that included all the recognizable indicators of scale processes observed in the field was used. In addition, because these two processes have a nonlinear response to sediment entrainment, it was assumed that parameter identifiability might be impacted by the intensity of the runoff event. Furthermore, synthetic data were used to test the effectiveness of the parameter identification methods for different types of events. The study also attempted to determine if the sampling frequency at the study site (every three minutes once the sampler is triggered) is adequate to distinguish the relative contributions of sediment entrainment by raindrop impact and flowing water. Finally, the technique was shown to result in reasonable estimates of sediment yield parameters when used to calibrate event data.

The objective of this study was to determine whether it is possible to identify the relative contributions of sediment entrainment by raindrop impact and by flowing water. In particular, the following questions were addressed. (1) What kinds of rainfall/runoff events have the best potential for determining the relative contributions of sediment entrainment from raindrop impact and flowing water? (2) Is the observed frequency of sampling every three minutes adequate for identifying parameter values? (3) Based on what is learned about the types of events that produce identifiable parameters and the necessary sampling frequency, is it possible to estimate entrainment from raindrop impact and flowing water that are physically realistic and produce a good fit between observed and simulated sediment yields?

STUDY AREA

The study was conducted on a 4.4 ha experimental watershed (Lucky Hills) of the Walnut Gulch Experimental Watershed in southeastern Arizona, which is operated by the U.S Department of Agriculture-Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center in Tucson, Arizona.

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) (Breckenfeld *et al.,* 1995, unpublished soil survey). The distribution of soils and surface armoring has since been studied in greater detail (Canfield *et al.,* 2001), as has soil erodibility (Canfield, 1998).

METHODS

The KINEROS2 Model

In recent years, distributed watershed models based on hydrodynamic principles have successfully been used to model runoff and sediment yield on small plots (e.g., Lopes and Lane, 1990), and small watersheds (Goodrich, 1990; Lopes and Lane, 1990). Some of the more widely used process based models of watershed hydrology are those relying on the kinematic wave approximation to the full dynamic equations (e.g., Woolhiser *et al.,* 1990; Lopes and Lane, 1990; Lopes, 1995). KINEROS2 (Smith *et al.,* 1995; Smith and Quinton, 2000) is an update of the model used by Blau *et al.* (1988) for their parameter identifiability study. KINEROS2 simulates Hortonian overland flow, which occurs in semiarid rangeland watersheds in the southwest, where rainfall is infrequent but intense, and exceeds the infiltration rates. KINEROS2 describes variable rainfall input, channel transmission losses, and spatial variability of watershed characteristics (soils, slopes, vegetation, etc.). Runoff is treated in KINEROS2 with a one-dimensional continuity equation in both overland flow and channel flow: KINEROS2 has performed well in estimating sediment yield in comparison with other models (Smith *et al.,* 1999).

Sediment entrainment and transport on hillslopes and in channels is treated in KINEROS2 as an unsteady, convective transport phenomenon, using a one-dimensional continuity equation,

$$\phi_s(x, t) = \delta(cA)/\delta t + \delta(cQ)/\delta x \qquad (1)$$

where $\phi_s = \sum\phi_s$ = sediment flux (M/L/T), and c = sediment concentration (M/L^3). A flow reach is conceptualized as a string of computational elements of length Δx, linked sequentially to one another via the mechanism of flow and sediment transport. Sediment flux on a hillslope has two independent sources, raindrop-induced entrainment q_r [M/L/T], and flow induced entrainment q_f (M/L/T). Sediment entrainment by raindrop impact is described as

$$q_r = Kq_i i^2 e^{-mh} \qquad (2)$$

where, K_i is a parameter describing the susceptibility of soil particles to be detached and entrained by raindrop impact, i is the rainfall rate (L/T), and m is a parameter describing the attenuation effect of flow depth, h(L), on raindrop impact.

Flow induced entrainment rate, qf (M/L/T), represents the rate of exchange between flowing water and the underlying soil. It can be either positive or negative. The relationship is given for particle size class (i) as follows

$$qf_i = Cg_i(c_{mx(i)} - c_{s(i)})w \qquad (3)$$

where Cg_i is the erosion rate coefficient for particle size class (i) (L/T), w is the width of flow (L), $c_{mx(i)}$ is the sediment concentration at transport capacity for particle size class (i) (M/L^2), and $c_{s(i)}$ is the sediment concentration for particle size class (i) entering the node (M/L^2). For noncohesive soils, such those occurring on the Lucky Hills watershed, the erosion rate coefficient for flowing water (Cg_i) is given as the settling velocity of particle size (i) divided by the hydraulic depth (h). For cohesive soils this erosion rate would need to be reduced.

Watershed geometry is represented in KINEROS2 as a combination of overland flow plane and channel elements, with plane elements contributing lateral flow to the channels or to the head of first order channels (Figure 1). Each plane may be described by its unique parameters, initial conditions, and precipitation inputs. Each channel element may be described by its unique parameters as well. Channel segments may receive uniformly distributed but time varying lateral inflow from adjacent contributing planes on either or both sides of the channel, or from one or two channels at the upstream boundary, or from a plane at the upstream boundary. Infiltration is calculated interactively with runoff calculations to simulate infiltration losses during recession flow, after rainfall has ceased, or to simulate runoff advancing down an ephemeral stream channel.

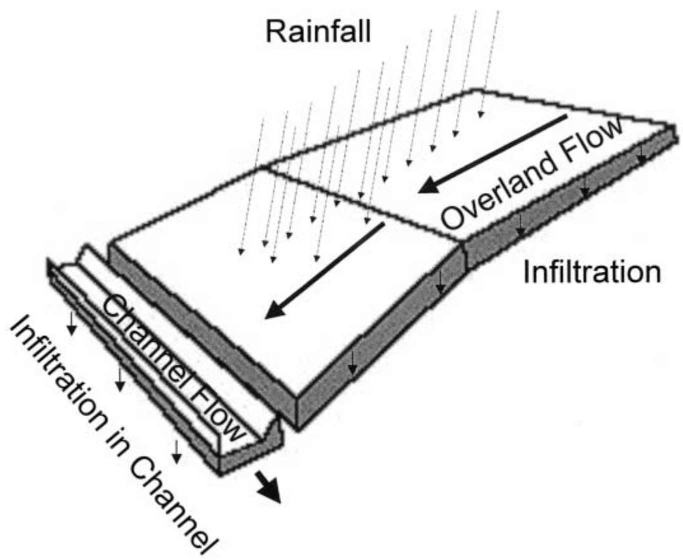


Figure 1. Plane and Channel Representation. Hillslopes in KINEROS2 are represented as a series of cascading planes.

Initial Parameter Estimates

The methods used to estimate initial parameter values are described in Lopes and Canfield (2004). Statistical relationships between landscape form and soil particle size were used as a basis for initial spatial estimates of parameter values. The most complex parameter file reflected the watershed complexity as observed in the field, which comprised 312 hillslope and channel elements (Figure 2). Antecedent soil moisture for observed events was estimated using the BROOK90 hydrologic model (Federer, 1995) with parameter values selected using soil moisture data from time domain reflectometer (TDR) moisture measurements collected on the Lucky Hills watershed in 1990 and 1991. BROOK90 uses the Shuttleworth and Wallace (1985) model for evapotranspiration and the

Clapp and Hornberger (1978) equations for describing soil moisture movement. The model performed well in estimating the antecedent soil moisture in the upper 15 cm (Canfield and Lopes, 2000), which was found to be the only part of the soil horizon in which soil moisture varied on a daily basis.

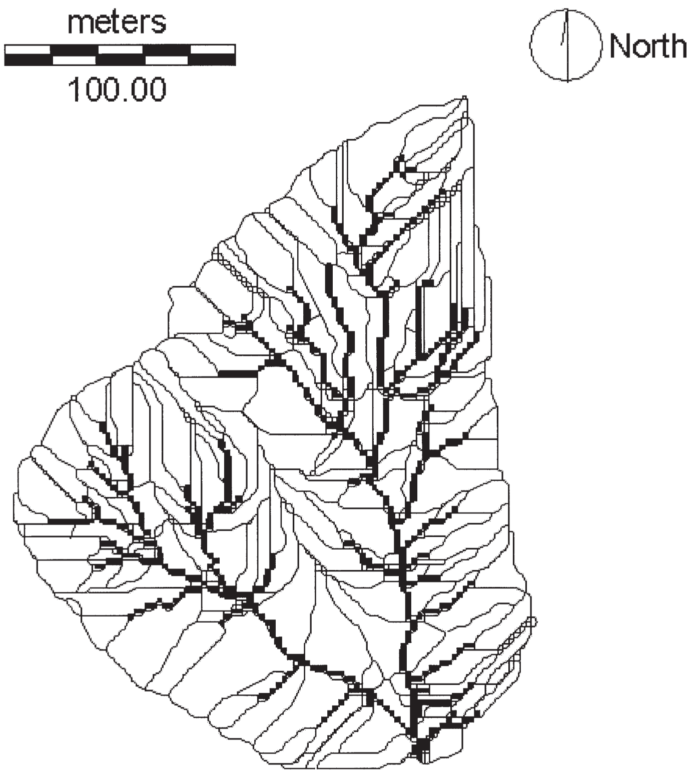


Figure 2. Partitioning of the Lucky Hills Watershed Into 312 Different Plane and Channel Elements for Use in the KINEROS2 Hydrologic Model. The partitioning was done using the TOPAZ DEM Processing Program (Garbrecht and Campbell, 1997), and reflects the channel complexity identified in the field.

The Parameter Identification Process

The parameter values were identified in a two-step process. First, parameter values for hydrology were identified. Second, once the hydrologic parameters were selected, the parameters for sediment were identified. Parameters were calibrated by multiplying all elements by a single multiplier, therefore maintaining the spatial complexity observed in the field while constraining the free parameter dimensional space (Figure 3). This approach requires that the initial spatial estimates are reasonable, and that the true distributed parameter values do not display significant nonlinear behavior that would be distorted by multiplying all initial estimates by the same multiplier value.

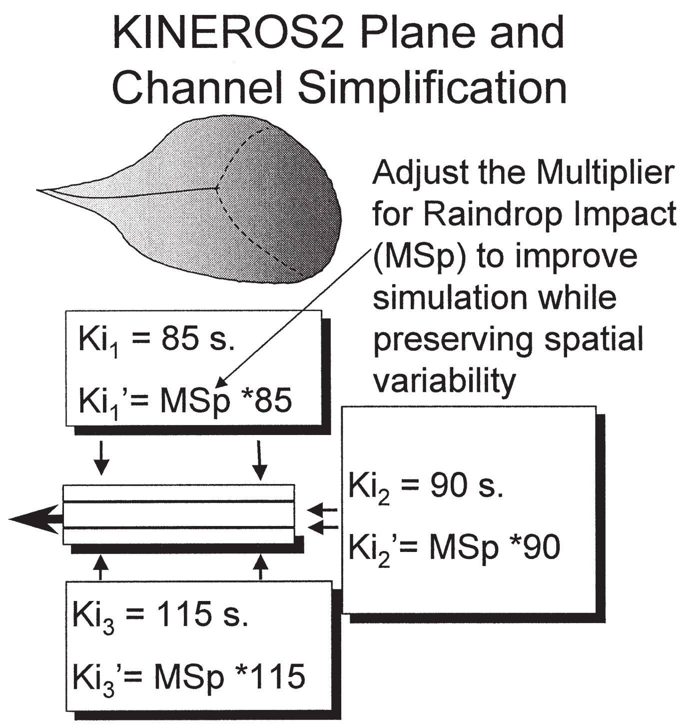


Figure 3. Example of the Use of Multipliers for Parameter Estimation.

Information on selecting multipliers for hydrographs is available from Goodrich (1990) and Canfield (1998). Figure 4 illustrates the general process used for parameter identification. The total sum of squared residuals (TSSR) is the objective function criteria. The Shuffled Complex Evolution UA (SCEUA) (Duan *et al.,* 1992) is the search algorithm used. For hydrology, multipliers for Manning's n, saturated hydrologic conductivity K_s, and the coefficient of variability of K_s (CV_{ks}) were used as fitting parameters. For sediment, two multipliers were used to estimate the relative contributions of sediment entrainment by raindrop impact and sediment entrainment by flowing water. The multiplier for raindrop induced sediment entrainment is

$$q_r = MSp^{*} K_i i^2 e^{-mh} \tag{4}$$

where MSp is the multiplier for raindrop induced sediment entrainment, and all remaining symbols are as described in Equation (2). This description implies that a new value of Ki (e.g., Ki') is simply a linear multiple of the original Ki. The multiplier for sediment entrainment by flowing water is

$$qf_i = Cg_i\,(MTC{*}c_{mx(i)} - c_{s(i)})w \qquad (5)$$

where *MTC* is a multiplier on sediment concentration determined by transport capacity, and the remaining symbols are as described in Equation (3).

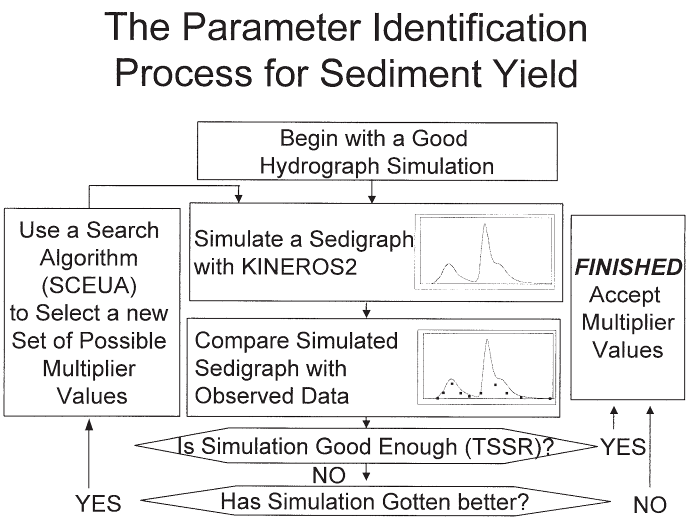


Figure 4. The Method for Parameter Identification Used in This Study. TSSR refers to the total sum of squared residuals. SCEUA refers to the Shuffled Complex Evolution UA (Duan *et al.,* 1992).

Parameter Identification

Automatic parameter identification used the Shuffled Complex Evolution UA (SCEUA) search algorithm (Duan *et al.,* 1992). Essentially, this is a search algorithm that is an extension of the simplex method (Nelder and Mead, 1965). In the simplex method, error between predicted and observed values is calculated at n +1 different parameter combinations, where n is the number of parameters. For example, for the two multipliers used here, error would be calculated at three points in the two-dimensional space defined by the range of possible multiplier values. Three points in a two-dimensional space provides the search algorithm with enough information to determine which direction to move to reduce the error between observed and predicted response. The simplex can expand or contract in an effort to find the minimal error between observed and predicted model response. The SCEUA uses multiple simplexes, and after several search steps, the points in the simplex are shuffled with points from other simplexes. New simplexes are formed using points from the previous simplexes. The primary benefit to the SCEUA over the standard simplex method is that it is better able to find a global minimum, when there are multiple minima in the sample space. The SCEUA has been found to be a useful technique for complex parameter identification problems in hydrology (Eckhardt and Arnold, 2001).

For both runoff and sediment, the observed value for each measured time was compared with the simulated value for that time. In this way, the full hydrograph or sedigraph was fit, rather than by simply optimizing, for peak or volume. The sum of squared residuals and the Nash and Suttcliffe (1970) model efficiency were used as objective functions. The TSSR objective function required fewer shuffling loops to find the optimum parameter set than did the Nash and Suttcliffe (1970) objective function, and was, therefore, selected for this study.

Generation of Synthetic Data

To determine whether model parameters are identifiable in the presence of error free data, it is helpful to assess the identification process with computer generated data. This process was conducted in two steps. In the first step, a series of synthetic sedigraphs was produced using the model and a set of preselected initial parameter values. In the second step, the optimization process was implemented with the model to find the original parameter set for the sediment concentration data. In this experiment, if the optimization procedure is unable to identify the original parameter set, the parameter identifiability problem is linked to model error, not to data errors. The rainfall characteristics of the events used to produce synthetic sedigraphs are summarized in Table 1.

All events were simulated using a one-minute time step. For generating synthetic sedigraphs, the value for each minute of the simulation was used. When simulated data were used to determine the effect of sampling frequency on parameter identification, only every third minute of the simulated sedigraph was used, because the observed sedigraphs from the Lucky Hills watershed were sampled only every third minute.

Parameter Identification and Observed Data Sets

Six events with sediment, rainfall, and hydrograph observations were available from the 1980s on the

TABLE 1. Summary of Rainfall Events Used to Generate Synthetic Sedigraphs for Testing Parameter Identifiability.

Date	Depth (mm)	Maximum 10-Minute (mm)	Maximum 60-Minute (mm)	Return Period (yr)	Identifiable Error Response	Event Data Available
July, 17, 1975	72.7	21.6	56.4	17.5	X	
August 12, 1990	52.9	21.3	38.2	11.7	X	
August 10, 1986	39.4	16.8	35.7	8.8	X	
August 18, 1996	40.9	14.2	33.9	7.0		
August 2, 1991	38.6	22.4	33.3	5.8	X	
July 27, 1973	39.9	16.3	32.3	5.0	X	
September 8, 1970	36.6	14.2	31.8	4.4	X	
September 1, 1984	32.8	16.0	30.9	3.9	X	
August 13, 1965	39.4	17.9	29.6	3.5		
July 29, 1992	30.2	17.8	28.7	3.2		
August 10, 1971	27.4	16.6	26.6	2.9		
August 6, 1988	26.9	17.4	26.4	2.7	X	X
August 25, 1994	28.7	18.0	25.2	2.5		
June 6, 1972	29.0	11.6	24.3	2.3	X	
July 25, 1978	27.7	14.2	23.9	2.2		
September 10, 1983	26.7	13.7	23.4	2.1		X
July 30, 1985	25.7	13.1	22.1	1.9		X
July 19, 1974	26.4	9.3	19.3	1.7		
September 26, 1877	53.9	8.4	17.5	1.5		
July 29, 1987	32.5	8.2	14.8	1.1		
September 11, 1982	23.4	8.9	18.7	~1.6		X
September 20, 1983	18.5	8.0	18.3	~1.6		X
August 25, 1984	12.5	8.4	12.5	<1		X
WEPP Wet	30.0	10.0	30.0	~3.8		

Note: The return period is based on ranking the annual series 60-minute, rainfall depth. In general, the events with identifiable error response surfaces have greater than two-year, 60-minute, return period, and greater than 10 mm falling in 10 minutes.

Lucky Hills watershed. The hydrograph and sedigraph data came from a total load automatic traversing slot sediment sampler in a supercritical flume (Renard *et al.,* 1986). Events are available prior to this time, but a total load sampler had not been installed. Other sediment data were available from the 1990s, but they have not been subject to sufficient quality control and therefore were not used for this study.

Because the clocks on the rain gauges and flumes were analog and not highly precise, the starting times of the rainfall and runoff might not be known precisely. For this reason, the objective function was calculated by shifting the hydrograph forward and backward in time from three to seven minutes from the estimated time to peak. Therefore, if Manning's n changed, for example, and the peak shifted in time slightly, the optimization function would still find the best fit.

RESULTS AND DISCUSSION

Findings From Synthetic Data Studies

We found that for the majority of smaller events, the relative contributions of sediment entrainment by raindrop impact and flowing water cannot be determined. Figure 5 shows the error response surface for a typical event. Contour values are TSSR, which have been normalized to the mean for the error response. The multiplier values used to produce the sedigraph are MSp = 1 and MTC = 1, which is the true minimum.

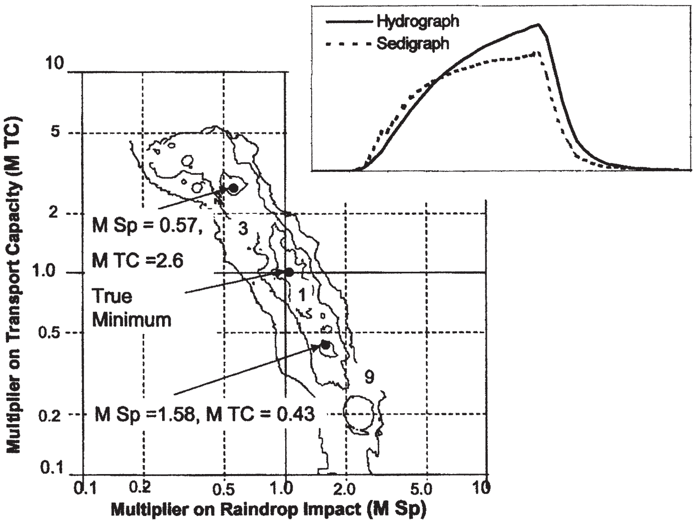
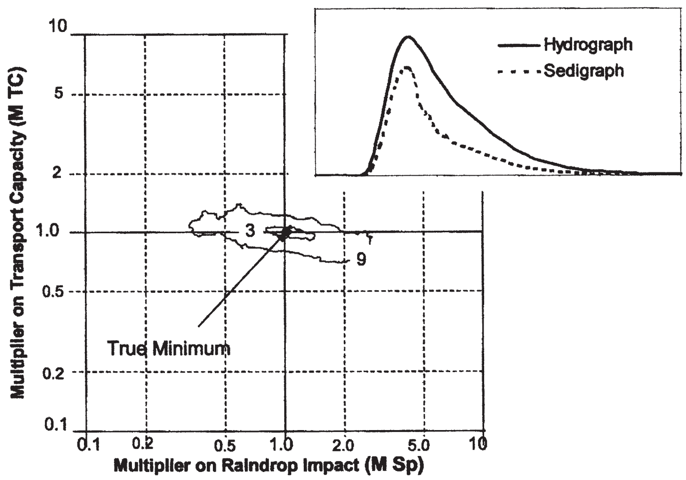


Figure 5. An Error Response Surface for a Poorly Identifiable Parameter Case. Contour values are Total Sum of Squared Residuals (TSSR), which have been normalized to the mean for the error response.

Note that in this event, there is an elongated minimum. This indicates that the relative contributions of sediment entrainment by raindrop impact and flowing water will be difficult to determine, because very little difference exists between observed and simulated sediment yield for a simulation that increases raindrop induced entrainment by a factor of 1.58 and entrainment by transport capacity by 0.43, and one that increases raindrop induced entrainment by a factor of 0.57 and entrainment by transport capacity by 2.6. This response reinforces the findings of many previous studies of parameter identifiability of sediment yield modeling (Lopes, 1987; Blau *et al.,* 1988; Freedman, 1998; Rojas and Woolhiser, 2000), which concluded that it was impossible to obtain unique values of sediment entrainment parameters for raindrop impact and flowing water. The fact that the response surface tends to be elongated more parallel to the vertical (concentration determined by transport capacity) axis indicates that these events are more sensitive to raindrop induced entrainment (i.e., a small difference in sediment entrainment by raindrop impact contributes more to sediment yield than a small difference in sediment entrained by transport capacity).

In contrast, for larger events, such as the August 6, 1988, rainfall event, a unique minimum can be observed, indicating that the relative contributions of sediment entrainment by raindrop impact and flowing water can be identified (Figure 6). The multiplier values used to produce the sedigraph are MSp = 1 and MTC = 1, and the only minimum on this surface occurs at this point on the error response surface. This indicates that this event has identifiable parameter characteristics. In general, identifiable rainfall events had a 60-minute duration with a return period greater than two years, and an intense rainfall period within the event that produced at least 10 mm of rain in 10 minutes. It is worth noting that a typical rainfall simulator event, WEPP (Elliot *et al.,* 1990) wet run, for instance, does not produce an identifiable error response surface when used to produce a synthetic sedigraph on this watershed. Though a WEPP wet run event would be greater than a two-year return period and does have 10 mm of rainfall in 10 minutes (Table 1), it does not contain an intense portion in that rainfall. This results in hydrographs and sedigraphs without the intense peak needed to limit the range of possible multiplier values. This finding is consistent with a previous study using synthetic data that also concluded that only larger events have identifiable characteristics (Rojas and Woolhiser, 2000).



igure 6. An Error Response Surface for an Identifiable Parameter Case. Contour values are Total Sum of Squared Residuals (TSSR), which have been normalized to the mean of the error response surface.

The Effect of Sampling Frequency on Parameter Identifiability

While all parameter identification studies with synthetic data had a sampling frequency of one observation per minute, sediment data from actual samplers may not be collected on this frequency. On the Lucky Hills watershed, for example, samples are collected every three minutes once the sampler has been activated at a specified flow depth. It was found, however, that parameter values for raindrop induced and flow induced entrainment continued to be unique with the three-minute sampling frequency for most of the events. However, for the largest event used (July 17, 1975), a second minima occurred in the region of higher entrainment by flowing water. Figure 7a shows the response surface generated from synthetic data with values taken each minute. Figure 7b shows the error response surface when synthetic data are available only once every three minutes. The true minimum still exists, but there is a region of alternative minima with the multiplier on concentration determined by transport capacity (MTC) of about 3, and the multiplier on raindrop impact (MSp) anywhere from 0.1 to 1. Because this region is essentially parallel to the raindrop impact entrainment multiplier (MSp), it indicates that the sediment yield response of this event is relatively insensitive to sediment entrainment by raindrop impact. The interpretation is that for some larger events, the effect of entrainment by flowing water dominates sediment contribution from entrainment by raindrop impact, so that the contribution from raindrop impact is insignificant relative to the contribution from flowing water.

Examination of the error response surface for different events shows that larger events with approximately two-year, 60-minute return periods, for which both sediment contributions from raindrop impact and flowing water are sufficiently important, produce an identifiable response surface. These events do not display the sensitivity to raindrop impact entrainment that smaller events exhibit, nor do they display the insensitivity of larger events to sediment contributions from raindrop impact.

Findings From Actual Event Data Studies

There was very little error between observed and simulated hydrographs for the six events studied. All simulations had model efficiencies (Nash and Sutcliffe, 1970) in excess of 0.93 (Table 2). Figure 8 shows

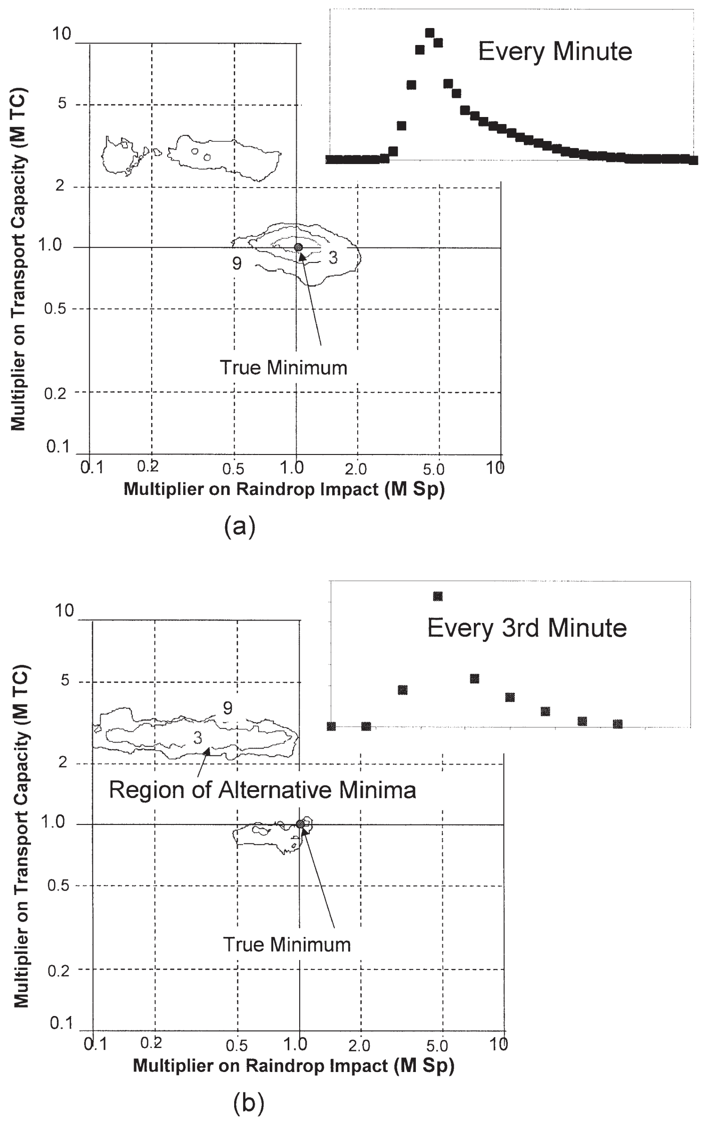


Figure 7. Error Response Surface for a Large Event Comparing the Effect of Sampling Frequency on Parameter Identification. (a) Sedigraph data at one-minute intervals. (b) Sedigraph data at three-minute intervals. Contour values are in TSSR.

TABLE 2. Summary of Rainfall and Runoff Characteristics of Observed Events Used for Parameter Identification.

Date	Rainfall (mm)	Volume (mm)	Peak Discharge (mm/hr)	Model Efficiency Nash-Suttcliffe
July 30, 1985	24.4	3.5	18.7	0.98
August 6, 1988	25.3	5.5	29.4	0.99
August 25, 1984	12.4	1.8	12.0	0.95
September 10, 1983	26.9	3.9	19.7	0.97
September 11, 1982	24.0	7.9	35.9	0.98
September 20, 1983	18.1	2.2	16.3	0.93

the simulation for the lowest model efficiency. Note that since the fit is still 0.93, all the hydrograph simulations with better model efficiencies fit the data better than this and there is little difference between observed and simulated hydrographs for these six events.

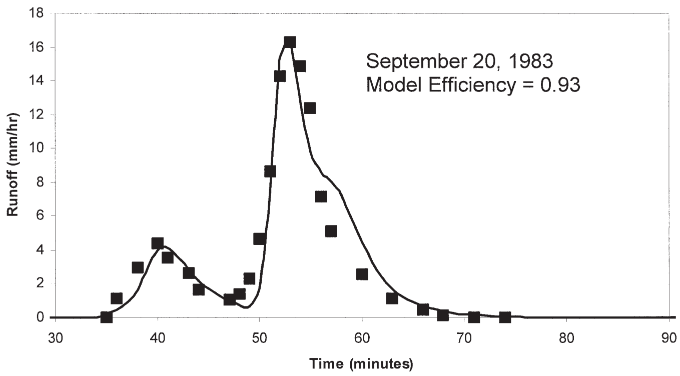


Figure 8. The Worst Hydrograph Used in Simulation. This shows the result of parameter identification for hydrologic variables (Ks, CVKs, and Manning's n).

For the sedigraphs, one event displayed identifiable characteristics (August 6, 1988), which was the event that produced the most sediment of the events used in this study. With the sum of squared residuals, the larger events tend to dominate the determination of error more than do the smaller events. The error response surface for the six events is dominated by that of August 6, 1988 (Figure 9). The multiplier for raindrop impact (MSp) is 2.1 and the multiplier for concentration determined by transport capacity (MTC) is 2.75. A factor of two increase in raindrop impact is reasonable considering that raindrop impact entrainment coefficients can vary by an order of magnitude using the infiltration based estimates used to parameterize the raindrop impact component of the model (Ben-Hur and Agassi, 1997). Likewise, sediment concentrations from different total load relationships with the same data sets can vary by more than an order of magnitude (Julien, 1998, p. 220). Therefore, increasing sediment concentration by nearly three to fit the data set is reasonable.

While the August 6, 1988, event dominated the search process, the parameter values also produced good simulations for the other events. Figure 10a shows the simulation for the August 6, 1988, event, which had the best simulated sedigraph. Figure 10b shows the worst simulation for the observed events (September 11, 1982). However, a Nash and Suttcliffe coefficient of 0.51 still indicates little error between simulated and observed sedigraph values (Figure 10b). Table 3 summarizes the findings of the sedigraph fits.

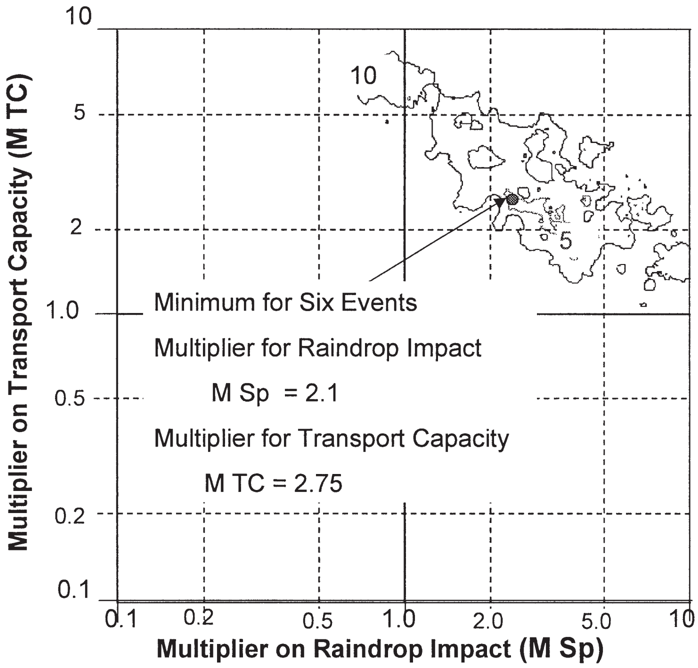
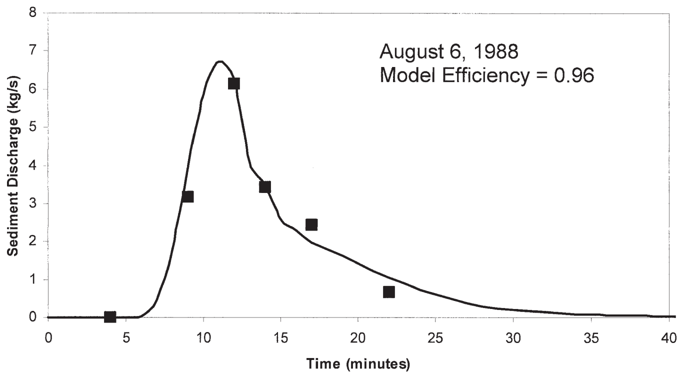
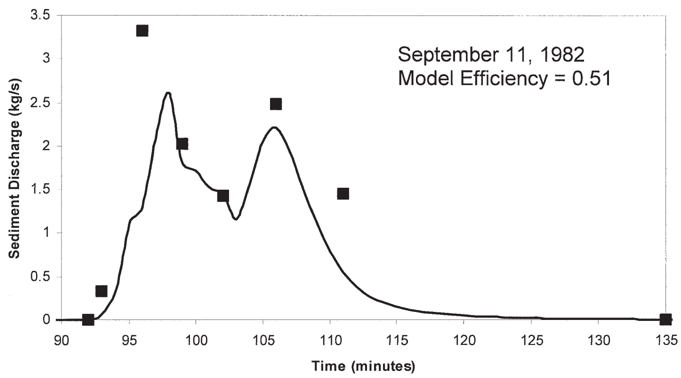


Figure 9. The Error Response Surface for Sedigraphs Generated From Six Observed Events. Contour values are Total Sum of Squared Residuals (TSSR in kg^2/s^2).

These results represent an advance in the understanding of parameter identification problems in process based runoff and erosion modeling by indicating the possible conditions in which differentiation between sediment entrainment by raindrop impact and flowing water might be possible. Because for most events it is impossible to find unique values for raindrop induced and flow induced entrainment parameters, without a simulation such as the August 6, 1988, event, it would be impossible to determine the relative sediment contributions from raindrop impact and flowing water for these events. The fact that the observed and simulated sediment yield values are satisfactory for all events suggests that these are reasonable multiplier values, even for events for which unique multipliers cannot be found. While these parameters are effective, they should not be considered optimal. Because of the variability of hydrologic response, the limitations in our knowledge of the inputs and outputs, and the limitations of the model, the concept of “optimal” does not adequately describe the range of possible responses of the system being modeled (Beven and Binley, 1992).



(a)



(b)

Figure 10. The Best and Worst Simulated Sedigraph. (a) The best simulated sedigraph produced by the August 6, 1988, event. (b) The worst simulated sedigraph produced by the September 11, 1982, event.

CONCLUSIONS

This study shows that for a few large events it may be possible to determine the relative fluxes of sediment entrained by raindrop impact and flowing water. Unique multipliers for raindrop impact (MSp) and sediment concentration by transport capacity (MTC) can be obtained using the KINEROS2 model and the Shuffled Complex Evolution UA (SCEUA) optimization algorithm with the total sum of squared residuals (TSSR) as the objective function. However, since these larger events have a return period of at least two years, for most events it may be impossible to distinguish the relative sediment contributions from these processes. We attribute the ability to identify parameter values for these events to the capability of these large events to entrain sediment from rills and channels (Lopes and Canfield, 2004).

Even for large events, however, we found that multiple good fits (minima) are possible if the sedigraphs do not have a sufficiently high sampling frequency. We noted, for instance, that the sampling frequency of every three minutes used on the Lucky Hills watershed might be inadequate for identifying parameter values. This results in a window of events that are sufficiently intense to entrain sediment stored in channels and rills, but not so intense that entrainment from the rills and channels overwhelms the contributions from hillslopes as occurred for the July 17, 1975, event (Figure 7b).

For six observed events, a reasonable set of multipliers for raindrop impact (MSp) and sediment concentration determined by transport capacity (MTC) produced good simulations of sediment yield for the observed data. The multipliers obtained from the parameter identification process for these events were dominated by the behavior of the single large identifiable event (August 6, 1988). However, the set of multiplier values also produced little error between the observed and simulated sedigraphs for the remaining

TABLE 3. Characteristics of Sedigraphs Used for Parameter Identification and KINEROS2 Model Efficiencies.

Date	Rainfall (mm)	Peak Discharge (mm/hr)	Peak Sediment Discharge (Kg/s)	Model Efficiency Nash-Suttcliffe
July 30, 1985	24.4	18.7	1.72	0.71
August 6, 1988	25.3	29.4	6.14	0.96
August 25, 1984	12.4	12.0	2.13	0.56
September 10, 1983	26.9	19.7	1.55	0.86
September 11, 1982	24.0	35.9	3.32	0.51
September 20, 1983	18.1	16.3	0.45	0.81

five events, which suggests that they are both reasonable and physically realistic.

For researchers attempting to model sediment entrainment on small watersheds, it is recommended that they consider the intensity of the events to be modeled, for it appears that sediment entrainment in smaller events tends to be dominated by raindrop impact. Furthermore, for very large events, the capability of the flow to entrain sediment from rills and channels may cause the parameter identification method to underestimate sediment entrainment by raindrop impact on hillslopes. Therefore, only larger events that have significant contributions from both raindrop impact and flowing water have the potential to have their parameters properly identified.

Finally, despite the fact that unique parameters could be identified, and simulations were satisfactory when compared with observed hydrographs and sedigraphs, this study suffers the shortcomings of a single calibration point (i.e., flume). Additional spatial sampling points (flumes) would improve the capability of the model to describe what actually occurs in the field, as would more frequent sampling of the sediment during an event.

ACKNOWLEDGMENTS

The authors would like to thank the USDA-ARS for the Lucky Hills data. David Goodrich and Carl Unkrich provided advice on the use and parameterization of the KINEROS2 model, and Hoshin Gupta provided the SCEUA computer program and advised on its use. The authors also would like to acknowledge Leonard Lane for many helpful discussions on parameter identifiability in sediment yield modeling. Furthermore, Dale Fox and David Grow provided critical review of the manuscript prior to submission.

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