#1419

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

EFFECTS OF WATERSHED REPRESENTATION ON RUNOFF AND SEDIMENT YIELD MODELING[1]

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ABSTRACT: This paper evaluates the effects of watershed geometric representation (i.e., plane and channel representation) on runoff and sediment yield simulations in a semiarid rangeland watershed. A process based, spatially distributed runoff erosion model (KINEROS2) was used to explore four spatial representations of a 4.4 ha experimental watershed. The most complex representation included all 96 channel elements identifiable in the field. The least complex representation contained only five channel elements. It was concluded that oversimplified watershed representations greatly influence runoff and sediment yield simulations by inducing excessive infiltration on hillslopes and distorting runoff patterns and sediment fluxes. Runoff and sediment yield decrease systematically with decreasing complexity in watershed representation. However, less complex representations had less impact on runoff and sediment-yield simulations for small rainfall events. This study concludes that the selection of the appropriate level of watershed representation can have important theoretical and practical implications on runoff and sediment yield modeling in semiarid environments.

(KEY TERMS: erosion, sediment transport; watershed modeling; storm runoff; semiarid watersheds; scale effects; watershed representation.)

Lopes, Vicente L. and H. Evan Canfield, 2004. Effects of Watershed Representation on Runoff and Sediment Yield Modeling. Journal of the American Water Resources Association (JAWRA) 40(2):311-319.

INTRODUCTION

Modeling hydrologic response to climate and land use change is a fundamental issue in both theoretical and applied hydrology. Over the past decades, an improved understanding of process scale interaction has indicated that the space time variability of hydrologic phenomena plays a significant role in determining the hydrologic impacts of human activities and climate variability on watersheds.

Recent research on process based, spatially distributed modeling of watershed hydrology has focused on the effects of grid scale on parameter values (Beven, 1989, 1995, 1996; Grayson *et al.*, 1992a,b; Bloschl and Sivapalan, 1995) and the role of parameter uncertainty on model output (Binley *et al.*, 1991; Beven and Binley, 1992; Ewen and Parkin, 1996; Lopes, 1996; Parkin *et al.*, 1996; Quinton, 1997).

Because hydrologic processes are known to be spatially variable, researchers have studied the effect of model input scale on process representation (Klemes, 1983; Beven, 1991; Lane *et al.*, 1998) and the transfer of parameter values across scales and between geographic regions (Pilgrim, 1983). The most effective model scale in terms of how well the model performs in comparison with observed data may be a function of what model output is being examined (Gove *et al.*, 2001; Kalin *et al.*, 2003). Furthermore, greater spatial complexity in watershed representation may not improve model performance (Hernandez *et al.*, 1997; Gove *et al.*, 2001).

Monitoring of runoff and erosion on southwestern rangelands has long shown that runoff and erosion are scale dependent processes (Kincaid *et al.*, 1966). Both watershed state and rainfall inputs are spatially varied resulting in hydrologic response that is spatially varied. Furthermore, rainfall input from convective rainfall is so highly spatially variable that a single recording rain gauge cannot adequately measure

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[1] Paper No. 02025 of the *Journal of the American Water Resources Association* (JAWRA) (Copyright © 2004). **Discussions are open until October 1, 2004.**

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rainfall input on watersheds less than 5 ha (Goodrich *et al.,* 1995), which can result in significant errors in model predicted runoff volume and peak (Faures *et al.,* 1995; Lopes, 1996).

The objective of this paper is to demonstrate the effect of watershed representation (i.e., overland flow plane and channel representation) on runoff and sediment yield simulations. In particular, the effect of different levels of watershed representation on simulations of storm runoff volume, peak runoff, and sediment yield was examined. This was achieved by applying a process based, spatially distributed model to four representations of a 4.4 ha experimental watershed. Watershed representation methods were developed to allow a watershed to be subdivided into multiple hillslope and channel elements using a digital elevation model (DEM). One way of describing the level of complexity of watershed representation is to use the concept of contributing source area (CSA). The CSA is defined as the hillslope area required to initiate a channel in a given watershed representation. In this study, the most complex representation included all channels identifiable in the field and had an average contributing source area of 200 m^2. The least complex representation had a CSA of 5000 m^2. This representation was selected because it was shown previously that this representation had little effect on simulation of runoff volume (Goodrich, 1990). Moreover, two additional representations were used with CSAs of 500 m^2 and 1200 m^2, respectively.

STUDY AREA

The study was conducted on a 4.4 ha experimental rangeland watershed (Lucky Hills 104) of the Walnut Gulch Experimental Watershed in southeastern Arizona, operated by the USDA-ARS Southwest Watershed Research Center in Tucson. The vegetation in Lucky Hill watersheds is shrub dominated with a stone pavement. Average annual rainfall is about 350 mm, and the watershed is located at an elevation of about 1,350 m.

Hydrology and scale issues related to runoff were previously studied in this watershed (Woolhiser and Goodrich, 1988; Goodrich, 1990; Goodrich *et al.,* 1995; Faures *et al.,* 1995; Canfield and Goodrich, 2003). Lopes and Lane (1988) and Canfield *et al.* (2001) presented results of sediment yield modeling studies on the Lucky Hills.

METHODS

Description of Watershed Model

Models based on kinematic wave equations are among the most successful models of watershed hydrology (Lopes and Lane, 1988; Woolhiser *et al.,* 1990; Lopes, 1995). KINEROS2 (Smith *et al.,* 1995; Smith and Quinton, 2000), a kinematic runoff erosion model based on Hortonian overland flow theory, was used in this study. KINEROS2 simulates runoff and erosion processes as conceptualized in semiarid watersheds, where infiltration rates are low and rainfall is infrequent but intense. Runoff is simulated using a one-dimensional continuity equation applicable to both overland and channel flow. Sediment entrainment and transport on hillslopes and channels is simulated using a one-dimensional convective transport equation. Sediment flux on a hillslope has two independent sources: raindrop induced entrainment and flow induced entrainment. Flow induced sediment entrainment for a particle size class is treated as the net difference between entrainment and deposition. Sediment discharge is computed for up to five particle size classes. Sediment contributions to a channel element from surrounding hillslopes are treated as either an upper boundary condition or distributed lateral inflow.

Watershed geometry is represented in KINEROS2 as a network of overland flow plane and channel elements, with plane elements contributing lateral flow to the channels or to the upper end of first order channels. Each plane may be described by its unique parameter values, initial conditions, and precipitation inputs. Each channel element may be described by its unique parameter values as well. Channel elements may receive uniformly distributed but time varying lateral inflow from adjacent contributing planes on either or both sides of the channel (Figure 1), 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.

Watershed Representation and Initial Parameter Estimates

In this study, the general approach used to obtain initial estimates of parameter values for KINEROS2 was to gather data on the landscape form and materials and to relate them to hydrologic and erosional processes. Landscape form was characterized using topographic surveys to produce a 2.5 m by 2.5 m DEM. The materials on the landscape were characterized using soil particle size analysis. A total of 132 soil samples were collected and analyzed for 13 particle size classes 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 soils particle size data. Saturated hydraulic conductivity (K_s) was estimated using empirical relationships between particle size and saturated hydraulic conductivity (Goodrich, 1990). Cokriging was used to produce spatial estimates of saturated hydraulic conductivity and conditional simulation was used to estimate the spatial variability of the coefficient of variation of hydraulic conductivity (CVK_s) as described by Canfield and Goodrich (2000).

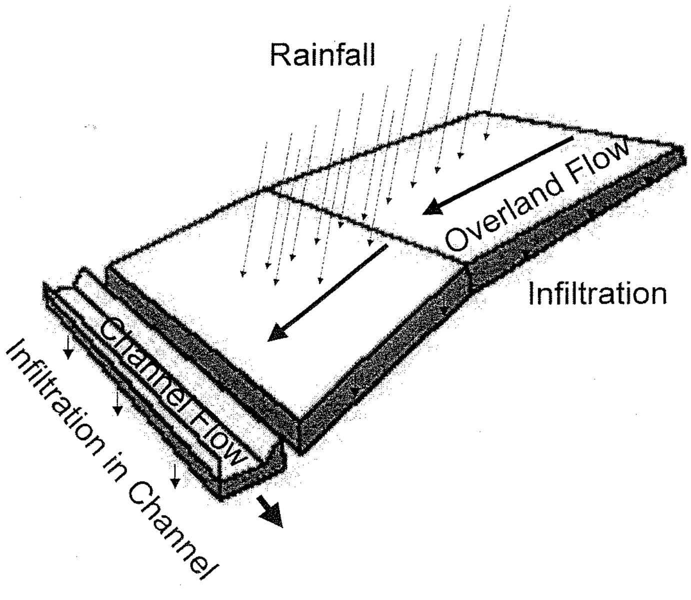

Figure 1. Representation of Plane and Channel Elements in KINEROS2.

It was observed that K_s is correlated with landscape position variables derived from the DEM, including percent slope and drainage accumulation area. This is not surprising because soils on the study area tend to be coarser with increasing slope and drainage area. Therefore, this secondary relationship of the correlation of landscape position to K_s was used to improve the spatial estimates of K_s through the use of cokriging techniques. Drainage accumulation area was used with location of K_s estimates to develop spatial estimates of K_s by developing variograms and cross variograms that related the spatial variability of K_s to both location and accumulated drainage area. Gaussian simulation was used to determine the range of possible values that might be represented on the study area. The variogram for K_s was used to characterize the spatial distribution of K_s. In this case, 30 different simulations were performed to develop a distribution of K_s values. The mean and standard deviation from these values were used to estimate the coefficient of variation of K_s (CV K_s) for input into the KINEROS2 model.

Estimates of Manning's n were based on field assessment (Goodrich, 1990). Estimation procedures of other hydrologic parameters are described in Goodrich (1990) and Canfield (1998). Initial estimates of sediment entrainment parameters, as described in the accompanying paper (Canfield and Lopes, 2004), were based on the spatial variability of particle size data. The raindrop impact entrainment parameter was estimated from K_s values using the methods described by Ben-Hur and Agassi (1997) who provided several different equations based on the kinetic energy of raindrops for the original WEPP model (Lane *et al.*, 1987).

Since sediment is relatively cohesionless on both hillslopes and channels in the study area, it was assumed that the raindrop impact entrainment parameter is largely a function of particle size class. Initial estimates of the flow-induced entrainment parameter were determined using regression relations developed by Canfield *et al.* (2001) to estimate the spatial variability of particle sizes on hillslopes. Regression relationships relating particle size to slope and drainage area were used to estimate particle size in channel elements.

These techniques generated initial parameter values on the 2.5 m by 2.5 m grid cell scale. These grid cell estimates were then averaged for determining parameter estimates for hillslope and channel elements represented in KINEROS2. The TOPAZ DEM processing tool (Garbrecht and Campbell, 1997) was used to produce four spatial representations of the study watershed. The most complex representation included 96 channel elements, was based on field identified channel heads, and included all channels identifiable in the field. Upslope contributing source areas (CSA) for this representation varied from 90 m^2 to 350 m^2 and averaged 200 m^2 (Figure 2a). The least complex spatial representation had an average contributing source area of approximately 5,000 m^2 (Figure 2d). Two intermediate levels of complexity with average contributing source areas of 500 m^2 (Figure 2b) and 1,200 m^2 (Figure 2c) also were used. These scales were selected because KINEROS2 has been shown to be able to estimate runoff volumes effectively across a range of watershed complexity with CSAs from 200 m^2 to 5,000 m^2 (Goodrich, 1990; Canfield, 1998). In this study, the "true" parameter values were assumed to be those identified for the most complex representation (200 m^2 CSA). For this representation, hydrologic and sediment yield parameters yielded good agreement between observed and simulated hydrographs and sedigraphs, as indicated in the accompanying paper (Canfield and Lopes, 2004). In simplifying from this most complex representation to less complex representations, area weighted averaging was used to estimate input parameter values. Therefore, each watershed representation included distributed input parameter values that were based on the same spatial estimates of parameter values.

The effect of rainfall size on model response was also examined in conjunction with watershed representation using simulation results from six large rainfall events (Table 1a) and six small rainfall events (Table 1b). The return period for the small events was about one year based on the 60-minute rainfall depth. The large events had a return period greater than three years.

TABLE 1. Summary of Event Characteristics (total storm depth, maximum 60-minute depth, and maximum 10-minute depth) for (a) Six Large and (b) Six Small Rainfall Events.

Date	Duration (min)	10-Minute Depth (mm)	60-Minute Depth (mm)
	(a)		
September 8, 1970	87	14.2	36.0
September 1, 1984	89	16.0	32.5
August 10, 1971	64	16.6	27.3
August 6, 1988	58	17.4	26.9
July 17, 1975	125	21.6	72.2
July 27, 1973	68	16.3	39.1
	(b)		
September 20, 1983	66	8.0	18.3
August 12, 1984	109	7.9	13.6
July 19, 1974	110	9.3	23.9
July 12, 1996	149	7.6	18.6
July 24, 1983	78	7.5	20.0
August 14, 1986	115	8.4	20.1

RESULTS

Effect of Watershed Representation on Runoff for Large and Small Rainfall Events

Figure 3 shows the effect of decreasing complexity in watershed representation on runoff volume and peak runoff for small and large rainfall events. For both large and small rainfall events, runoff volume and peak runoff decreased systematically. However, the decrease was greater for small rainfall events, indicating the effect of increased infiltration on hillslopes with increasing CSA values. For the small rainfall events, the mean runoff volume and peak runoff simulated with the less complex watershed representation were about 75 percent of the values simulated using the most complex representation. However, for the large rainfall events, the effect of simplification on watershed representation was to reduce runoff volume and peak runoff by about 45 percent of the values for the most complex representation.

These trends seem to be reasonable considering that channel elements have been lumped into overland flow elements in the less complex watershed representation. More overland flow planes result in more infiltration because overland flow elements have a greater wetted perimeter than channel elements and an increased time of opportunity for infiltration to occur. Furthermore, the fraction of storm rainfall that infiltrates is greater for small rainfall events.

Effect of Watershed Representation on Sediment Yield for Large and Small Rainfall Events

Figure 4 shows the effect of decreasing complexity in watershed representation on sediment yield for small and large rainfall events. Again, the trends observed for large rainfall events contrast with those for small rainfall events. For small rainfall events, the least complex watershed representation produced nearly the same sediment yield as the most complex representation (88 percent). For the large rainfall events, however, the least complex watershed representation produced substantially less sediment (58 percent). Therefore, the relative effect of decreasing complexity in watershed representation on sediment yield was greater for large rainfall events than for small rainfall events.

It is interesting to note that simplification in watershed representation reduces the area of channel represented in the watershed configuration, which then has an impact on runoff and sediment yield

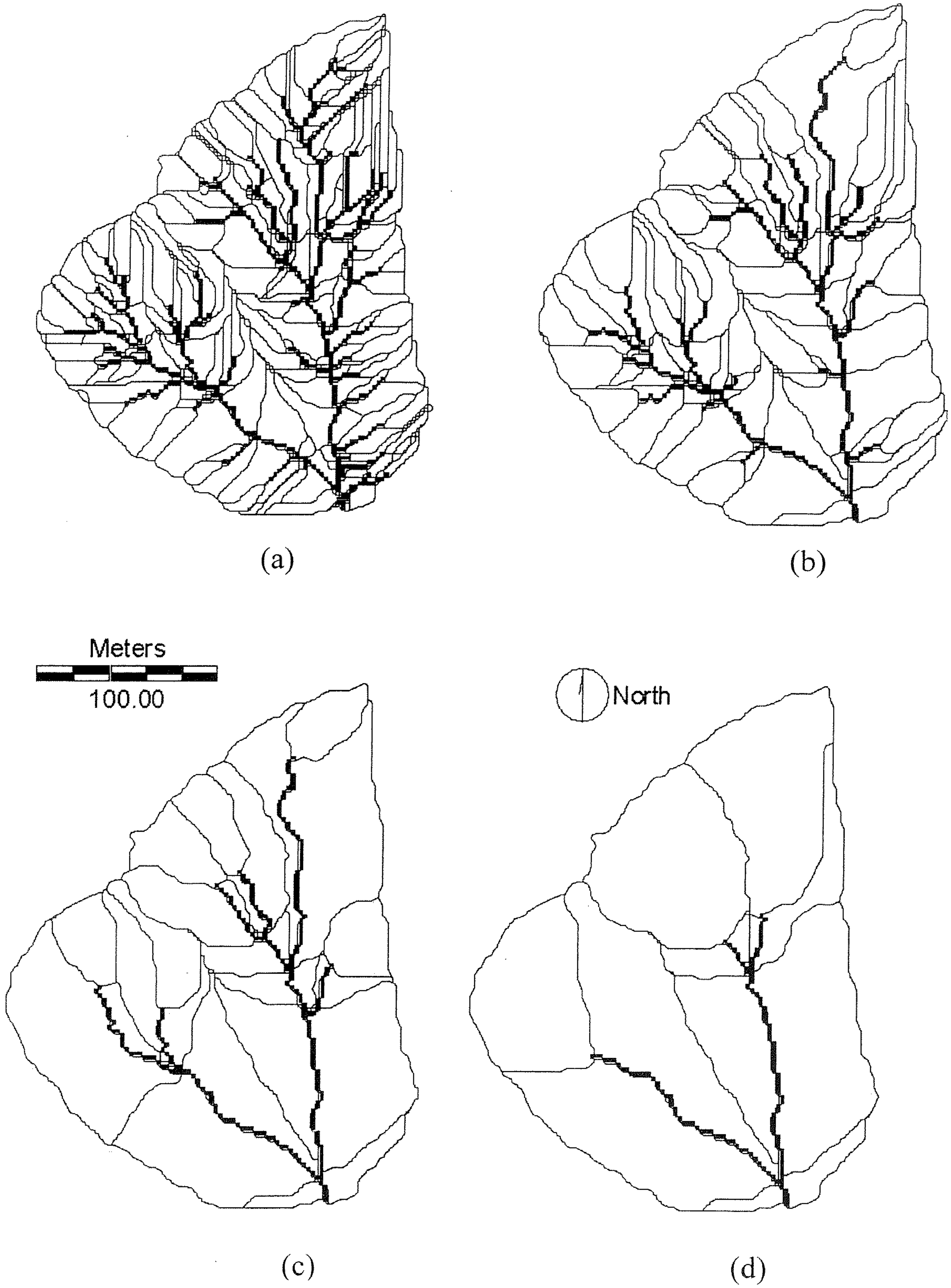

Figure 2. Watershed Representations With Respective Average Contributing Source Areas (CSAs): (a) 200 m^2, (b) 500 m^2, (c) 1,200 m^2, and (d) 5,000 m^2.

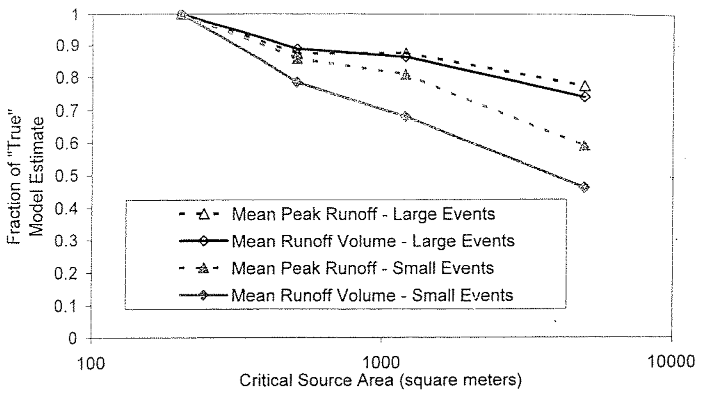

Figure 3. Effect of Watershed Representation on Runoff Volume and Peak Runoff Simulations.

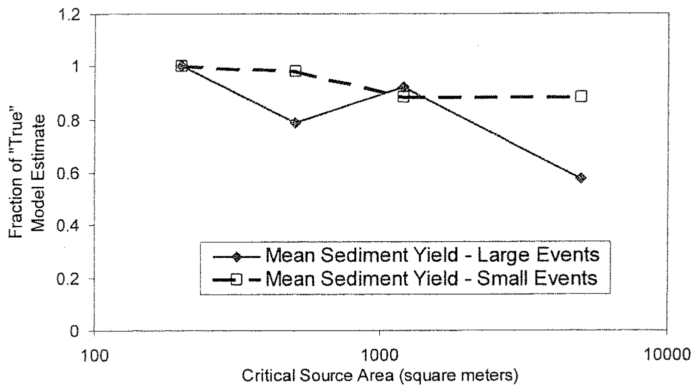

Figure 4. Effect of Watershed Representation on Sediment Yield Simulations.

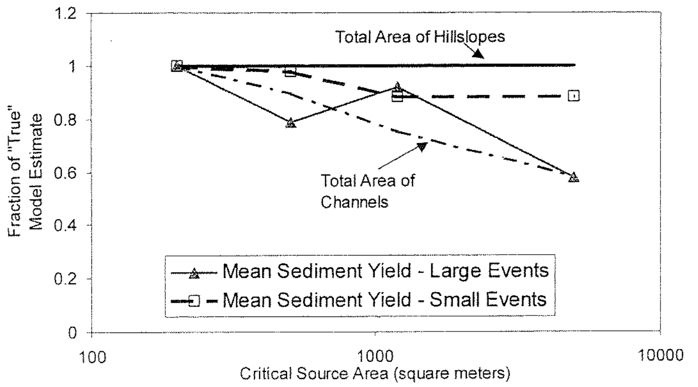

Figure 5. Effects of Hillslope and Channel Area on Sediment Yield Simulations.

simulations. The area of the channels in the most complex representation is about 780 m^2, while in the least complex representation it is about 450 m^2. In contrast, the change in the area of hillslopes is relatively unaffected by simplification. In Figure 5 both the fraction of the initial channel area and the sediment yield for the large rainfall events followed a similar trend and decreased to about 58 percent of the original value. This relation indicates that decreasing complexity in watershed representation reduces both the channel area and sediment yield for large rainfall events.

The fact that sediment yield simulations are only minimally affected for small rainfall events, even though runoff is substantially affected, suggests that the controlling mechanism for sediment simulations for small rainfall events is raindrop impact. If flowing water were the predominant mechanism for sediment simulation, one would expect sediment yield to be affected strongly by changes in runoff (and runoff from small rainfall events was even more affected by simplification in watershed representation than it was from large rainfall events, as indicated in Figure 3). Furthermore, the fact that for small rainfall events, sediment yield simulation is relatively unaffected by watershed representation suggests that raindrop impact, which in the model is assumed to occur only on hillslopes, seems to be the controlling mechanism for simulating sediment yield for small rainfall events.

Effect of Watershed Representation on Particle Size Distribution for Large and Small Rainfall Events

The effect of simplifications of watershed representation on particle size distribution further supported the notion that more sediment was derived from hillslope elements in less complex watershed representations. Figure 6 shows the effect of decreasing complexity in watershed representation on simulated particle size distribution. For the small rainfall events, watershed representation had little effect on particle size distribution, with about 43 percent of the sediment simulated falling within the smallest particle size (0.03 mm). In contrast, for the large rainfall events, the effect of simplification in watershed representation was to increase the smallest particle size component at the expense of the coarsest particle sizes (> 4 mm).

Since there are more fine particles on hillslopes than in channels, this indicates that less complex watershed representations must derive more sediment from hillslopes. Figures 7a and 7b shows histograms of particle size distribution for hillslopes and

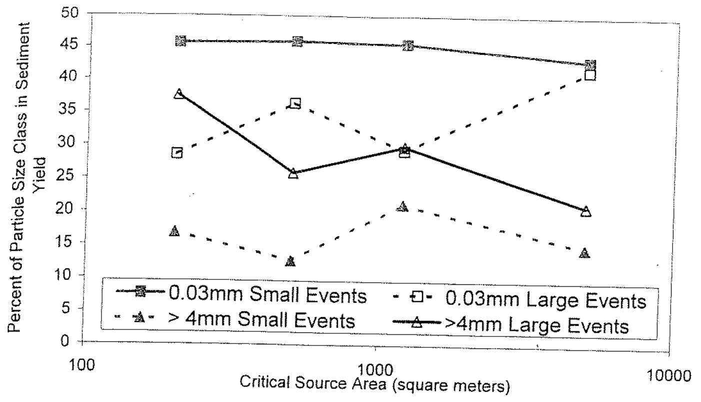

Figure 6. Effect of Watershed Representation on Simulations of Particle Size Distribution for Large and Small Rainfall Events.

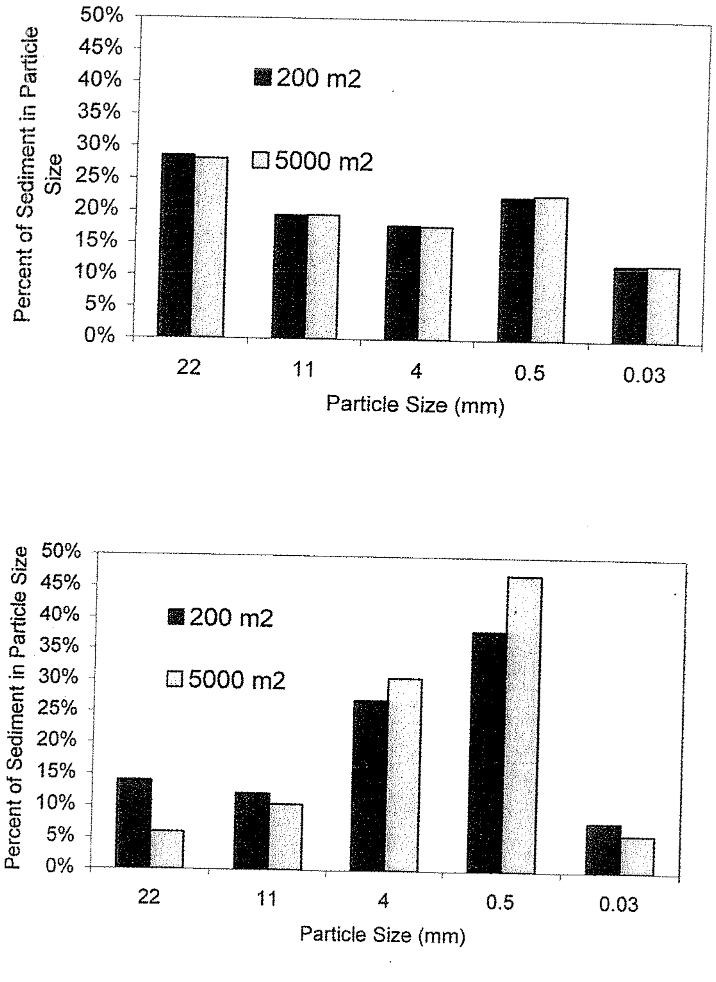

Figure 7. Histogram of Particle Size Distribution for (a) Hillslopes (top) and (b) Channels (bottom).

channels for the most complex and least complex watershed representation, respectively. Note that particle size distribution on hillslopes was virtually identical for both the least complex and most complex watershed representations (Figure 7a). However, there was a marked difference in particle size distribution in the channels for the two types of representations (Figure 7b). While there is general downstream fining in the channels at the study watershed (Canfield, 1998), there is also downstream sorting. As the simulated histograms show, more fine sediment was available from hillslopes than from channels, and the primary source of fine sediment was the hillslopes, especially for the less complex watershed representations.

DISCUSSION

Results of this study indicate that watershed representation has an important effect on runoff and sediment yield simulations in semiarid environments. These effects are also related to rainfall event size. While the effect of decreasing complexity in watershed representation for small rainfall events is to reduce runoff volume and peak runoff through increased infiltration on hillslopes and transmission losses in the channels, sediment yield is not greatly affected. In contrast, for large rainfall events, decreasing complexity in watershed representation has a relatively small effect on runoff volume and peak runoff, but a substantial effect on sediment yield simulations.

The reduced effect of watershed representation on sediment yield simulations for small rainfall events indicates that sediment yield simulation is controlled primarily by raindrop impact. This conclusion is supported by the observation that simulations of particle size distribution for small rainfall events are dominated by fine particles, which are more abundant on hillslopes than in the channels.

For large rainfall events, runoff volume and peak runoff are less affected by decreasing complexity in watershed representation, while sediment yield and particle size distribution are strongly influenced. As indicated in Figure 5, sediment yield simulations from large rainfall events decrease as the area of channels decreases, which indicates that sediment entrainment simulation in channels is an important process for large rainfall events. Decreased complexity in watershed representation may result in a decrease in the simulation of coarse particles and an increase in fines in the sedigraph (Figure 6). This indicates that with large rainfall events there is a contribution of coarse particles from concentrated flow (channels and rills) in addition to the fine sediment entrained on hillslopes. For the large rainfall storms, replacing channels with hillslope elements on the simplified watershed representation has the effect of removing the contribution of coarser particles from channels, while maintaining the contribution of fines from hillslopes. The net result is a decrease in sediment yield, and an increase in fine particle sizes.

As storm runoff volume and peak runoff are reduced by increased infiltration, sediment concentration increases, and ultimately sediment deposition takes place. The more frequent small flows trend to deposit sediment, some of which is later reentrained and moved downstream by the more infrequent large stormflows. This stepwise movement of sediment in ephemeral streams causes problems in relating sediment concentration to streamflow discharge and sediment yield to watershed area in semiarid environments as reported by Renard *et al.* (1993).

Since the model was parameterized with instream sediment under average conditions, readers should understand that the sediment in the channel reflects the composition stored after the more frequent small rainfall events and that this will have an impact on sediment availability. The small rainfall events are unable to mobilize this relatively coarse sediment stored in the channels, and there is little net change in stored channel sediment. Therefore, simplification in watershed representation matters little for small rainfall events.

However, large rainfall events have the transport capacity to entrain the coarse sediment stored in the channels. Therefore, the most complex watershed representation also has the most stored coarse sediment available for entrainment by large flows. The net effect of decreased complexity in watershed representation is, therefore, to replace channel sources of coarse sediment with finer grained hillslope sources. Thus, the composition of the sedigraph is significantly affected by watershed representation.

Since simulations from different representations have been shown to respond differently to the same rainfall input, predictions of the movement of sediment are representation dependent. This is particularly important for simulating sediment related contaminants in water quality models.

CONCLUSIONS

This paper examined the effect of watershed representation on runoff and sediment yield simulations. This objective was achieved by applying a process-based, spatially distributed watershed model to four levels of representation of a 4.4 ha watershed in a semiarid environment. Results indicated that oversimplified representations greatly influence runoff (peak and volume) and sediment yield simulations by inducing excessive infiltration of hillslopes and distorting runoff patterns and sediment fluxes. It was observed that runoff simulations decrease systematically with decreasing complexity in watershed representation, while sediment yield varies significantly depending on the magnitude of the rainfall event. In addition, decreased complexity in watershed representation may cause the model to underestimate coarse grained particle size distribution available from channel sources and overestimate finer-grained particle size distribution available from hillslope sources.

Therefore, for applications that require estimates of sediment yield by particle size, like contaminant transport modeling, it may be necessary to use more complex watershed representations to capture the dynamics of the events that move most of the sediments and sediment related contaminants.

ACKNOWLEDGMENTS

The authors would like to thank the U.S. Department of Agriculture-Agricultural Research Service (ARS) for providing data on Lucky Hills 104. They also would like to thank Carl Unkrich and David Goodrich of the ARS for their assistance with KINEROS2. Finally, they would like to thank Leonard Lane for calling the attention of the authors to the the importance of process intensity on watershed response. Susan Schwinning and anonymous reviewers selected by the *Journal of the American Water Resources Association* provided comments that improved both the substance and presentation of this paper.

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