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The impact of parameter lumping and geometric simplification in modelling runoff and erosion in the shrublands of southeast Arizona

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Abstract:

There have been many studies of hydrologic processes and scale. However, some researchers have found that predictions from hydrologic models may not be improved by attempting to incorporate the understanding of these processes into hydrologic models. This paper quantifies the effect of simplifying watershed geometry and averaging the parameter values on simulations generated using the KINEROS2 model. Furthermore, it examines how these changes in model input effect model output. The model was applied on a small semiarid rangeland watershed in which runoff is generated by the infiltration excess mechanism. The study concludes that averaging input parameter values has little effect on runoff volume and peak in simulating runoff. However, geometric simplification does have an effect on runoff peak and volume, but it is not statistically significant. In contrast, both averaging input parameter values and geometric simplification have an effect on model-predicted sediment yield. Copyright © 2005 John Wiley & Sons, Ltd.

KEY WORDS hydrologic modelling; erosion; scale; geographic information systems; semiarid

INTRODUCTION

Scale issues are a source of continued research and discussion in hydrology. Monitoring of runoff and erosion on southwestern rangelands has long shown that runoff and soil loss are scale-dependent processes (e.g. Kincaid *et al*., 1966; Wilcox *et al*., 2003). Distributed hydrologic models have the ability to include spatially varied descriptions of hydrologic input parameters and rainfall to account for this spatial heterogeneity. Studies have shown that there are diminishing returns to modelling runoff by subdividing a watershed into increasingly small subwatersheds in an effort to account for field-observed variability (Goodrich, 1990; Miller, 2002). Furthermore, 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). Therefore, there are no clear guidelines on how to implement these distributed models for simulating either runoff or erosion. Canfield (1998) concluded that the best simulations of sedigraphs are produced based on a geometry complexity that is consistent with channel watershed representation observed in the field. The study described herein further examines the effect that model representations have on model-predicted output.

Scale and process representation

Process-based models describe the physical processes themselves and, therefore, can be used to understand the interaction between each of the processes better. In semiarid watersheds, such as in the one used in this

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study, such processes include infiltration, runoff generation, flow routing, sediment detachment and sediment transport.

Research on process-based, distributed modelling of watershed hydrology has focused on the effects of grid scale on model 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). Moreover, concern has been expressed with regard to the effect of 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).

Studies have shown that estimates of model parameter values at the point scale do not scale up to the plot scale (e.g. Paige and Stone, 2003), and that parameter values that work at one watershed representation may not work effectively at other watershed scales (e.g. Canfield *et al*., 2002). Partial area response is known to be the primary mechanism producing runoff in semiarid rangeland watersheds (Smith and Goodrich, 2000). Rainfall simulation experiments show that only a portion of the plot contributes runoff at any given rainfall intensity, and increasingly more of the plot contributes runoff as rainfall intensity increases (e.g. Stone and Paige, 2003). Furthermore, replicate plots themselves can produce different quantities of sediment (Nearing *et al*., 2000). Therefore, more spatially explicit descriptions of infiltration patterns and erosion may improve a model's capability to predict runoff and erosion, assuming that data are available to parameterize these spatially explicit descriptions. However, widely available spatial data sets (such as soil survey maps and vegetation maps) do not describe this degree of spatial heterogeneity. It is already known that the inability to describe the spatial pattern of rainfall on southwestern rangelands can result in significant errors in model-predicted runoff volume and peak, even on watersheds as small as 5 ha (Faures *et al*., 1995).

Scale and watershed representations in hydrologic models

Watershed discretization methods have been developed to subdivide a watershed into multiple hillslope and channel elements using a digital elevation model (DEM) processing program. Parameters that describe the hydrologic characteristics of each of these discretized hillslope or channel elements allow the spatial heterogeneity observed in the field to be included in the hydrologic parameters in the model.

Most discretization methods rely on defining where channels are, and then defining the remainder of the watershed as hillslopes. One of the most common methods used in a geographic information system (GIS) is to define an upslope contributing source area (CSA; sometimes called critical source area or channel source area) to initiate a channel, such as is used in the Automated Geospatial Watershed Assessment tool (Miller *et al*., 2002; http://www.tucson.ars.ag.gov/AGWA/). Once the location where channels begin is identified, all downstream grid cells will be channels and upstream grid cells (i.e. grid cells draining areas lower than the CSA threshold) are defined as hillslope elements. Hillslope elements are differentiated based on what channel they flow into, and these criteria are used to subdivide a watershed.

Scale Studies with KINEROS2

KINEROS2 (Woolhiser *et al*., 1990; Smith *et al*., 1995; Smith and Quinton, 2000; http://www.tucson.ars.ag.gov/Kineros/), a spatially distributed hydrologic model, has previously been used to assess the necessary spatial complexity to model runoff and erosion. In KINEROS2, a watershed is described as a series of cascading hillslope planes and channels. Each of these hillslope planes and channels has its own set of input parameters describing infiltration, runoff and erosion parameters, as well as the spatial location of these hillslope planes and channels in relation to measured rainfall at rain gauges.

Goodrich (1990) concluded that an average first-order CSA of about 14% of the watershed is typically adequate for modelling runoff volume, whereas Miller (2002) concluded that diminishing returns occur if the CSA is smaller than 2·5% of the watershed. Thieken *et al*. (1999) studied the effect of coarsening the DEM input on model output using KINEROS2, and concluded that the grid cell size itself makes a large difference in the simulation. That study showed that shorter flow paths and less complex networks result from coarser DEMs. Therefore, time to runoff peak tends to be shorter, and significantly different than the peak simulated using a channel network derived from a higher resolution DEM. Kalin *et al.* (2003) used KINEROS2 to model runoff and erosion using rainfall excess as the model input and assuming no infiltration. Using this method, they developed a means to estimate the appropriate model complexity (in terms of drainage density) to model hydrographs and sedigraphs given a criterion for the expected quality of the response.

None of these studies with KINEROS began with estimates of the spatial parameter inputs at the grid level used in this study (2·5 m × 2·5 m). As such, they were unable to isolate differences in model performance that could be attributed to the process of lumping parameter values from the effects of geometric simplification.

Scope of this study

In this study we assess whether a lack of spatial heterogeneity reduces model efficiency in modelling runoff and erosion. Two types of spatial heterogeneity are evaluated: the heterogeneity related to spatial variability of soil texture and infiltration characteristics and the spatial heterogeneity related to the complexity of the drainage network. It begins with heterogeneous spatial data on sediment and soil characteristics, and then attempts to determine whether there is significant change of the hydrologic response in using averaging to estimate model inputs in less-complex watershed representations. Finally, it examines the hydrologic response when input is limited to a single value for each input parameter, which reflects the typical case when using widely available spatial data sets.

Less-complex watershed representations can be prepared by increasingly representing a ‘subwatershed’ comprised of a rill with lateral and upstream hillslope elements as a single hillslope. For the purposes of this paper, this process of replacement of a more spatially complex watershed representation with a less complex representation will be called ‘geometric simplification’. Also, for the purposes of this paper, the replacement of spatially varied input parameter values with averaged representative values for hillslopes and channels will be called ‘lumping’. A more complex watershed can include a greater range of parameter values, because each watershed element (i.e. hillslope plane or channel) has its own parameter values, and more elements can describe a greater range of model input parameters. The process of geometric simplification must result in lumping, because less-complex watershed representations will have fewer watershed elements and, as such, a smaller number of input values.

The objective of this paper is to examine the effect of lumping and geometric simplification on model input parameters, model simulated runoff volume and peak, and sediment yield from hillslopes and channels on a 4·4 ha experimental watershed in a semiarid rangeland environment.

METHODS AND MATERIALS

Study location

The study was conducted on a 4·4 ha experimental rangeland watershed (Lucky Hills 104) of the Walnut Gulch Experimental Watershed in southeastern Arizona, which is operated by the United States Department of Agriculture–Agricultural Research Service (USDA-ARS) Southwest Watershed Research Center in Tucson (Renard *et al.*, 1993). The vegetation is shrub-dominated with a desert (i.e. stone) pavement (Canfield *et al.*, 2001). Average annual rainfall is about 350 mm, and the watershed is located at an elevation of about 1350 m. The groundwater table is approximately 50 m below the surface of the watershed.

Runoff and erosion at the site occur almost exclusively during high-intensity summer ‘monsoon’ rainfall, where intensities can exceed 200 mm h^{-1} for short durations. Runoff during these storms tends to be infiltration excess Hortonian overland flow. Hydrology and scale issues related to runoff on the watershed have been previously studied (Goodrich, 1990; Faures *et al.*, 1995; Goodrich *et al.*, 1995; Canfield and Goodrich, 2003). More recent studies on sediment-yield modelling were reported by Canfield *et al.* (2002) and Lopes and Canfield (2004).

Description of the watershed model

KINEROS2 is a distributed runoff-erosion model based on Hortonian overland flow theory. Therefore, it is well suited to describing the hydrodynamics of runoff and erosion processes on semiarid watersheds, where infiltration rates are low and rainfall is infrequent, but intense. Likewise, infiltration patterns on rangeland hillslopes show partial area runoff generation, so that a distribution of runoff values describes infiltration better than a single value (e.g. Woolhiser and Goodrich, 1988; Paige *et al*., 2002). KINEROS2 can be parameterized to describe the variability of infiltration on rangeland hillslopes, using the mean and coefficient of variation of hydraulic conductivity (CVKs; Smith and Goodrich, 2000) to describe the partial area response seen on semiarid rangeland watersheds (such as Lucky Hills) more realistically. Conceptually, a hillslope is divided into a series of strips with different hydraulic conductivities K_s, which represent the range of K_s values described by the CVKs.

Runoff is treated in KINEROS2 with a one-dimensional continuity equation applicable to both overland and channel flow: sediment entrainment and transport on hillslopes and channels is treated as an unsteady, one-dimensional convective transport phenomenon, using a continuity equation similar to that for runoff. 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 using the Engelund and Hansen transport capacity relationship (Engelund and Hansen, 1967). Sediment discharge is computed for 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 combination 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 parameters, initial conditions, and precipitation inputs. Each channel element may also be described by its unique parameters.

Spatial resolution and initial parameter estimates

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 erosion processes. Specifically, landscape form was characterized using topographic surveys to produce a 2·5 m × 2·5 m DEM, and the materials on the landscape were characterized using soil particle size analysis. A total of 132 soil samples were collected and analysed for 13 particle size classes through to 64mm. A 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 (Canfield and Goodrich, 2000; Canfield *et al*., 2001). Therefore, estimates of both topographic parameters (such as slope steepness) and soils data (such as armoured fraction—PAV in the KINEROS2 model—or saturated hydraulic conductivity K_s) were estimated on a grid cell basis.

In channels, systematic downstream fining was noted. However, particle size variation of lower order channels tended to be greater than higher order channels. If a sediment sample was available for a given channel segment, its characteristics were used to characterize the parameter values of the channel segment. If no samples were available for a first-order channel, samples from nearby first order channels were used to characterize that segment. Soil-saturated hydraulic conductivity K_s was estimated using empirical relationships between particle size and saturated hydraulic conductivity (Goodrich, 1990), which proved to be within 25% of the optimal value selected using parameter estimation. For hillslopes, cokriging was used to produce spatial estimates of saturated hydraulic conductivity and conditional simulation was used to estimate the spatial variability of the CVKs (Canfield and Goodrich, 2000). 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 were also 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).

Since sediment is relatively cohesionless on both hillslopes and channels on the Lucky Hills watershed, it was assumed that erodibility is largely a function of particle size class. Initial estimates of the erodibility coefficient of entrainment by flowing water used inverse distance weighting in concert with regression relations (Canfield *et al*., 2001) to estimate the spatial variability of particle sizes on hillslopes (Canfield, 1998). These initial techniques to estimate parameter values resulted in parameter estimates on a 2·5 m × 2·5 m grid cell scale.

Watershed representation

The TOPAZ DEM processing program (Garbrecht and Campbell, 1997) was used to produce four spatial resolutions of the Lucky Hills watershed. For the most complex case, the position of channel initiation was identified in the field as the first occurrence of incision into the landscape caused by concentrated flow. The location of channels identified in the field is consistent with the slope–area transition criteria for channel initiation (Willgoose *et al*., 1991) and, therefore, has a physical basis. The upslope CSAs varied from about 90 to 350 m^2 and averaged about 200 m^2. This results in discretizing Lucky Hills 104 into 312 different channel and hillslope elements.

The least complex spatial resolution had an average CSA of approximately 5000 m^2, which was identified as the least complex representation that could be used to model runoff volume on this watershed (Goodrich, 1990). Two intermediate levels of complexity with average CSAs of 1200 and 500 m^2 were also used to provide information on model response at intermediate scales. Hillslope and channel characteristics for each of the representations are summarized in Table I.

A system of lumping

During lumping, grid cell parameter estimates are averaged over the area of the hillslope or channel element. Log–normally distributed parameters, such as K_s, were transformed to log scale prior to averaging. Figure 1a shows the watershed representation identified in the field. Figures 1b, c and d show the representation of watersheds with CSAs of 500 m^2, 1200 m^2 and 5000 m^2 respectively. For each of these watershed representations, distributed parameter values were estimated by averaging grid-based parameter estimates over the hillslope or channel element. A lumped version of these four representations was also prepared in which all hillslopes in the watershed representation have the same hydrologic parameter values, and all channels have the same hydrologic parameter values. In this way, it is possible to test whether spatially distributed parameter values or geometric representation is more important to the simulation for shrub-dominated watersheds.

Table I. Summary of hillslope and channel characteristics for the four watershed representations

CSA (m^2)	Hillslope characteristics		Channel characteristics					
	Number of hillslope elements	Mean hillslope length (m)	Number of channel elements	Channel area (m^2)	Total channel length (m)	Mean channel length (m)	Channel slope (m m^{-1})	Drainage Density ($\text{m}^2\ \text{m}^{-1}$)
200	215	9·0	96	778	1555	16·2	0·087	0·035
500	91	11·6	37	702	1097	29·6	0·080	0·024
1200	28	18·7	11	584	682	62·0	0·077	0·015
5000	13	26·8	5	454	337	67·4	0·076	0·007

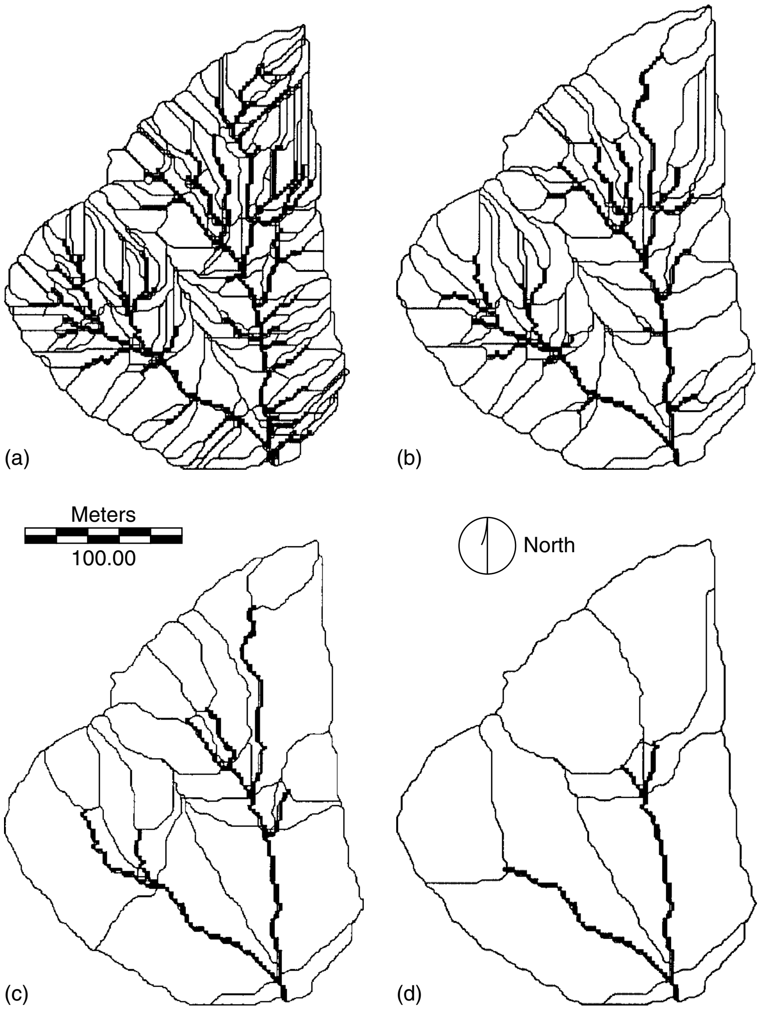

Figure 1. Four watershed representations. The most complex case (a) has an average CSA of 200 m^2, reflecting the channel network complexity observed in the field. The least complex spatial resolution (d) is the least complex representation at which simulated hydrographs fit observed hydrographs well, and has an average CSA of 5000 m^2. (b, c) Intermediate levels of complexity with average CSAs of 500 m^2 and 1200 m^2 respectively

Methods for determining the effect of model input on model output

Parameter estimation. An automatic parameter estimation procedure was applied to the distributed and lumped versions of the most complex watershed representation. Five large rainfall, runoff and sediment yield events from the 1980s were used to estimate parameter values for runoff and sediment yield simulation. The SCEUA automatic parameter identification technique (Duan *et al.*, 1992) was used. The SCEUA has been found to be a useful technique for complex parameter identification problems in distributed hydrologic modelling (Eckhardt and Arnold, 2001; Canfield *et al.*, 2002; Canfield and Lopes, 2004).

Rather than using SCEUA to estimate parameter values for each individual hillslope or channel, the parameters were adjusted up or down by multiplying the spatially distributed initial parameter values by a multiplier (Canfield and Lopes, 2004). In this case, a two-step process was used. Parameters for runoff modelling were identified first by minimizing the error between simulated and measured discharges at multiple points along the hydrograph. Multipliers that can be calibrated in KINEROS2 include Manning's n (Mn), K_s

(MK$_s$) and the coefficient of variability of K$_s$ (MCVK$_s$). These three multipliers were calibrated using SCEUA; a fourth multiplier for net capillary drive (MG) was modified as a function of MK$_s$, because a strong regression relationship between K_s and G can be established (Goodrich, 1990). Once these multipliers for hydrology were selected, multipliers for sediment were calibrated. For sediment, two multipliers are available to estimate the relative contributions of sediment entrainment by raindrop impact (MSp) and sediment entrainment by flowing water (MTC).

For both runoff and sediment, the observed values for each measured time were compared with the simulated values for that time. In this way, the full hydrograph or sedigraph was fit, rather than simply optimized for peak or runoff volume. Both the total sum of squared residuals (TSSR) and the Nash and Sutcliffe (1970) statistic (N–S) were used as objective functions.

Selection of rainfall events. To activate both the rainsplash and sediment transport components of KINEROS2 on this watershed fully, larger events must be studied (Canfield and Lopes, 2004). Furthermore, observations indicate that larger events carry a disproportionately large amount of sediment. In this case, two types of event were selected, to reflect the impact of 2-year and extreme events. Based on analysis of the 37 years of rainfall data from rain gauge 83 at Lucky Hills 104, the 2-year return period event has a 60 min depth of 18 to 22 mm. A 5-year (or greater) return period event exceeds a 60 min depth of 32 mm. In order to develop a statistical basis for understanding the range of possible response, 30 events were chosen for both 2-year and >5-year return period events, because the *t*-statistic for 30 samples approaches the *t*-statistic for an infinite number of samples.

Because there are only 37 years of rainfall data from the Lucky Hills watersheds, it is not possible to assemble 30 events from the data set that meet the 2-year and >5-year return periods from the three rainfall gauges at Lucky Hills (rain gauges 83, 384 and 386). Event data were supplemented with rain gauge data from stations that are within 2 miles of the Lucky Hills watersheds (rain gauges 21, 22, 23 and 27). The events selected to represent 2-year events are summarized in Table II, and the events selected to reflect the extreme events are summarized in Table III.

Criteria for assessing differences between model simulations. Simulations were run with both lumped and distributed parameter values for each of the four watershed complexities to assess whether errors in modelling runoff and erosion are more attributable to lumping or geometric simplification. The mean and standard deviation were calculated for runoff volume, runoff peak, watershed sediment yield, sediment yield from hillslopes and sediment yield from channel sources. The most complex representation with distributed parameter values was expected to yield the best results, because it most accurately represented field conditions.

As a basis of comparison, mean values from each of the geometric simplified representations were compared with the baseline simulation (i.e. 200 m^2 CSA, distributed parameter values). Paired *t*-tests were used to determine whether the model output of runoff or sediment from the lumped or geometrically simplified cases was significantly different from the baseline scenario.

RESULTS AND DISCUSSION

Results of simplification on input parameter estimates

Effect of simplification and lumping on hillslope element parameters. We have recognized two kinds of distortion that can occur during geometric simplification. The first demonstrates the effect of lumping. Watershed attributes such as K_s, particle size distribution, and slope are estimated on a grid cell by grid cell basis. The effect of lumping these values is to simplify to a mean value. Figure 2 shows the fraction of the watershed represented by a given K_s. Based on cokriging of 132 soil samples, grid K_s estimates are were made on the 2·5 m × 2·5 m scale (Canfield and Goodrich, 2000). These estimates do not follow a normal distribution, but are instead skewed slightly to the lower values. As watershed representation is simplified to

Table II. List of 2-year events (rain gauge is provided to distinguish events from the same date at different rain gauges). Events with total 60 min depths between 18 and 22 mm were selected to be indicative of ~2 year return period events at the Lucky Hills. Break point data from rain gauges on the Lucky Hills or within 2 miles of the Lucky Hills were used

Date	Gauge	Depth (mm) total	Depth (mm) 10 min	Depth (mm) 60 min
25 Jul 1955	21	20·6	9·1	19·5
3 Aug 1955	21	22·4	14·4	22·2
18 Jul 1961	21	20·6	10·5	20·3
29 Aug 1961	27	21·3	18·8	21·2
29 Jul 1962	27	21·6	7·8	20·2
4 Sep 1962	21	19·8	11·5	19·5
10 Sep 1967	27	19·1	10·3	19·0
25 Aug 1968	386	22·1	7·9	21·9
31 Aug 1968	384	21·8	7·6	21·7
18 Aug 1971	83	23·9	9·5	19·8
6 Sep 1972	386	20·6	12·2	20·4
14 Jul 1973	21	20·1	6·4	19·7
15 Aug 1977	83	21·6	9·4	21·2
24 Aug 1980	384	22·6	4·8	19·3
8 Jul 1981	83	20·1	7·0	19·1
6 Jul 1982	384	20·6	10·7	20·5
10 Sep 1982	384	20·8	6·9	19·4
24 Jul 1983	83	21·6	7·5	20·0
16 Aug 1984	384	23·1	13·1	19·0
18 Aug 1984	21	19·8	9·1	19·8
17 Jul 1985	21	21·6	5·3	19·1
30 Jul 1985	21	19·8	9·5	19·7
10 Aug 1986	27	20·3	8·2	18·9
14 Aug 1986	83	21·1	8·4	20·1
29 Aug 1986	27	19·6	11·4	18·8
6 Aug 1988	22	20·6	18·2	20·4
4 Jul 1990	83	21·6	11·9	21·2
13 Sep 1992	83	20·3	5·7	18·8
10 Sep 1994	22	20·6	13·2	20·6
7 Sep 1995	21	22·4	8·4	21·7

a representation that includes hillslopes with an average CSA of 200 m^2 (the representation in Figure 1a), the effect of averaging K_s is to reduce the range of K_s values while not greatly changing the mean (or median) K_s value. Further simplification to a CSA of 5000 m^2 (representation in Figure 1d) results in further narrowing of the range of K_s values that will be used in the model. Simplification of topographic inputs also results in a narrowing of the range of input values with simplification, but with little divergence from the mean value input to the model, as indicated for slope (Figure 3). As Figures 2 and 3 demonstrate, if values are estimated on a grid basis, then geometric simplification results in lumping of both topographic and parameter values and increasingly narrowing the range of input values, but not greatly changing the mean or median value input to the model.

A second kind of distortion that may occur in simplification is a shifting of representative values during geometric simplification. Geometrically derived inputs, such as hillslope length, are changed during geometric simplification. Figure 4 shows the effect of simplification on hillslope length. Unlike the distortions introduced by averaging grid data, geometrical distortions brought about by simplifying network complexity result in a mean increase in hillslope length and a corresponding decrease in the mean flow length from the base of the hillslope to the watershed outlet.

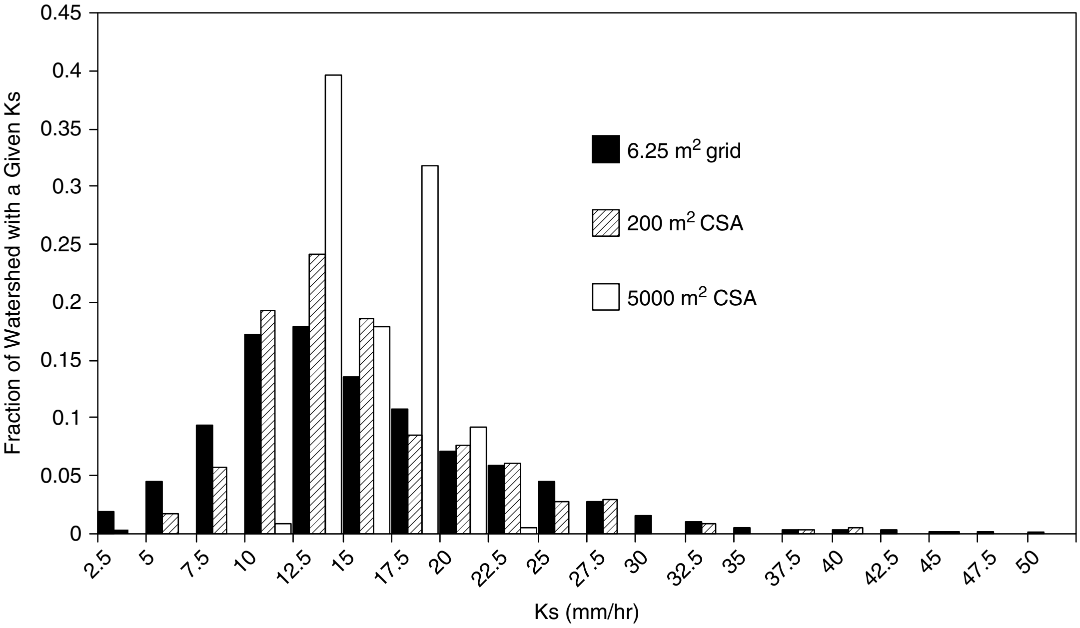

Figure 2. The range of the fraction of the watershed represented by a given K_s decreases as the watershed is represented as increasingly less complex as indicated by the grid estimate (6.25 m^2), most complex (200 m^2 CSA) and least complex (5000 m^2 CSA) watershed representation

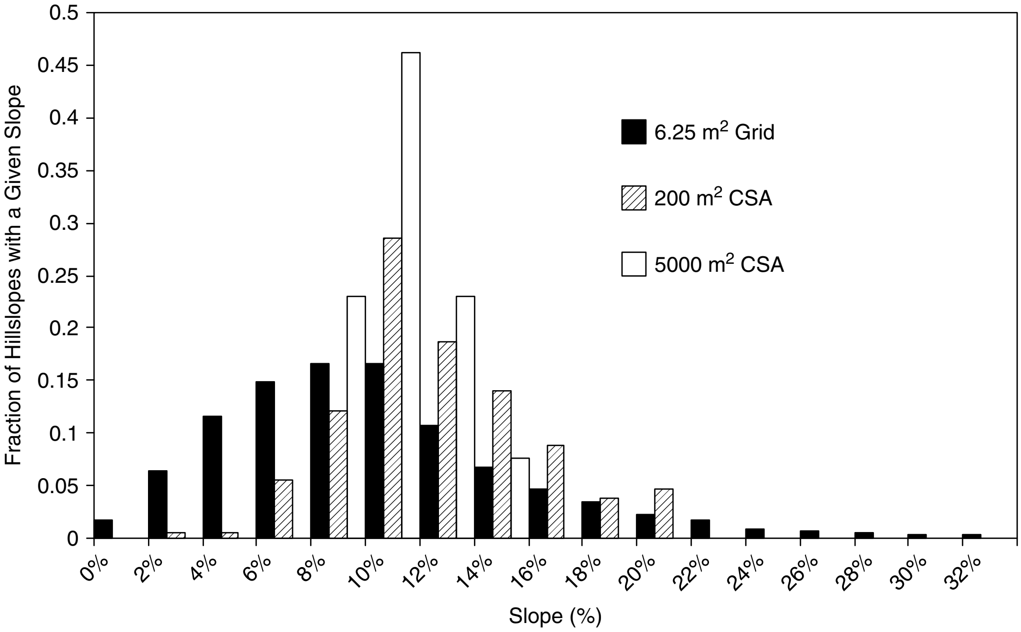

Figure 3. The effect of simplification on estimates of slope steepness. The range of the fraction of the watershed represented by a given slope decreases as the watershed is represented as increasingly less complex as indicated by the grid estimate (6.25 m^2), most complex (200 m^2 CSA) and least complex (5000 m^2 CSA) watershed representation

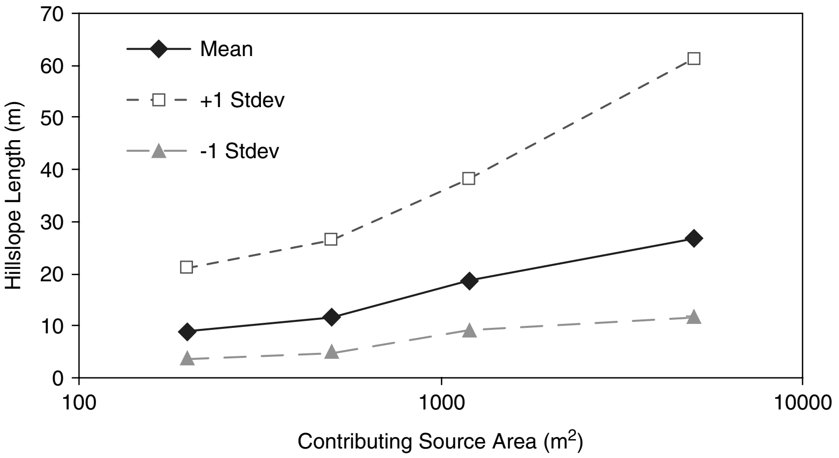

Figure 4. The effect of simplification on hillslope length. This figure shows increasing mean hillslope length as the watershed representation becomes less complex

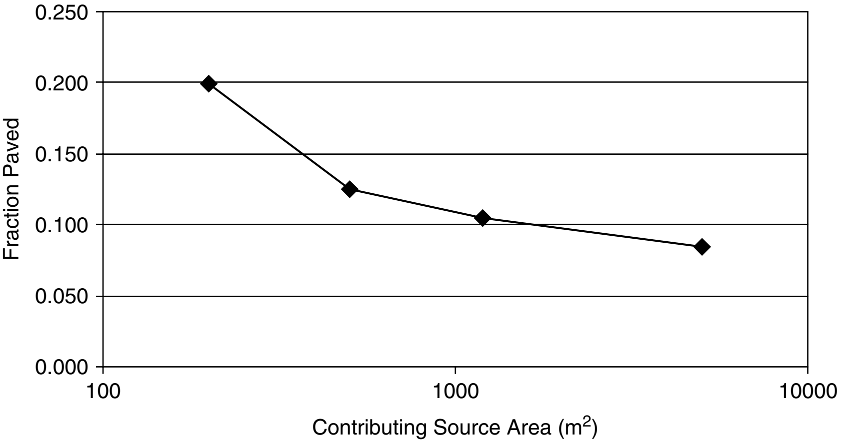

Figure 5. Effect of simplification on estimate of armoured fraction portion (PAV) in channels. Because of downstream fining, simple averaging reduces the faction of coarse material too coarse to move

Effect of simplification and lumping on channel element parameters. Likewise, lumping of parameter values in channels may result in a shifting of the mean value, because the characteristics of smaller channels are removed from averaging in the estimate of channel parameter values. An example is the effect of simplification on the armoured fraction (PAV) of the channel (Figure 5). PAV was estimated as the $>$20 mm fraction on hillslopes, based on studies that have indicated that the $>$20 mm fraction is essentially immobile on hillslopes (Kirkby and Kirkby, 1974). This $>$20 mm fraction was used to estimate PAV in channels, though this fraction would be more able to migrate in channels than hillslopes.

The lumped parameter values illustrate the overall effect of simplification. The overall effect of simplification on model inputs is illustrated in Table IV. As can be seen, grid-based values, such as K_s and PAV, are little changed by simplification on hillslopes. However, those same grid-based parameters are affected by simplification in channels, because downstream fining results in averaging increasingly fine-grained grid values in channel elements. Furthermore, inputs derived from geometry, such as hillslope length, are affected by simplification on both hillslopes and channels.

Table III. List of >5year return period events (rain gauge is provided to distinguish events from the same date at different rain gauges). Events with total depths >32 mm 60 min depths were selected to be indicative of >5year return period events at the Lucky Hills. Break point data from rain gauges on the Lucky Hills or within 2 miles of the Lucky Hills were used

Date	Gauge	Depth (mm) total	Depth (mm) 10 min	Depth (mm) 60 min
19 Jul 1955	27	66·5	16·0	59·4
17 Jul 1956	23	46·5	18·5	44·5
2 Aug 1957	22	43·9	15·7	42·0
14 Aug 1958	27	42·4	24·1	41·7
16 Aug 1958	23	44·7	25·9	42·2
15 Aug 1960	21	58·4	13·5	41·4
18 Jul 1962	27	35·3	14·5	32·6
4 Sep 1962	22	33·8	12·5	33·6
13 Aug 1965	386	38·9	18·3	34·0
11 Sep 1966	27	33·8	14·9	32·8
25 Aug 1968	27	36·3	15·2	36·1
8 Sep 1970	384	36·6	13·7	36·5
10 Aug 1971	27	40·1	23·1	38·9
12 Aug 1971	22	36·1	14·2	34·4
16 Jul 1973	386	41·9	20·2	40·6
24 Jul 1973	21	39·6	10·2	36·8
27 Jul 1973	384	43·4	19·8	42·6
24 Sep 1974	21	34·8	14·0	33·5
17 Jul 1975	83	72·6	21·6	72·2
6 Sep 1976	21	47·8	20·7	45·7
27 Sep 1983	27	32·0	15·8	31·8
30 Aug 1984	21	32·3	9·9	31·8
1 Sep 1984	386	34·0	21·6	33·9
17 Jul 1985	22	37·3	20·6	34·4
30 Jul 1985	27	35·8	20·6	35·4
10 Aug 1986	83	39·4	16·8	37·6
5 Jul 1990	22	36·1	11·4	35·9
12 Aug 1990	83	52·8	21·3	38·9
2 Aug 1991	83	38·6	22·4	38·3
25 Aug 1994	21	34·8	16·8	32·0
18 Aug 1996	83	40·9	14·2	40·2

Results of parameter estimation

The effect of lumping on parameter estimation was determined by evaluating the selected multiplier values, and the relative goodness of fit between the observed and simulated runoff and sediment discharge for the lumped and distributed cases. The multiplier values and goodness of fit criteria for the distributed and lumped model representations are summarized in Table V. Figure 6 shows an optimal fit hydrograph and sedigraph for the largest event used to estimate parameters and demonstrates that the model behaves reasonably with these parameter values. The values of multipliers are approximately the same for the hydrologic parameters n, K_s and CVKs (Mn, MKs and MCVKs respectively) in both the distributed and lumped representations. However, the multiplier on the rainsplash parameter (MSp) is much higher for the lumped case (~10) than it is for the distributed case (~2), and the multiplier for transport capacity (MTC) is about a third lower for the distributed case (0·23 versus 0·33 for the lumped case). The higher multiplier for rainsplash and lower multiplier for transport capacity suggest that the lumped case increases sediment entrained by raindrop at the expense of sediment entrained by flowing water, such as described by Canfield *et al.* (2002).

Table IV. Lumped parameter values for different watershed representations. Grid-based parameters such as armoured fraction (PAV) are little effected by lumping on hillslopes, whereas they are affected by averaging in channels

CSA (m^2)	% >4 mm	% ≤4 mm	PAV (%)	K_s(mm h^{-1})	CVKs
Channel elements					
200	26·8	73·2	20·0	10·9	0·70
500	18·5	81·5	12·5	10·8	0·72
1200	17·3	82·7	10·5	10·4	0·88
5000	16·3	83·7	8·4	9·1	0·83
Plane elements					
200	65·7	34·3	0·4	12·6	0·60
500	65·2	34·8	0·4	12·8	0·60
1200	65·3	34·7	0·4	13·1	0·60
5000	65·3	34·7	0·4	13·4	0·59

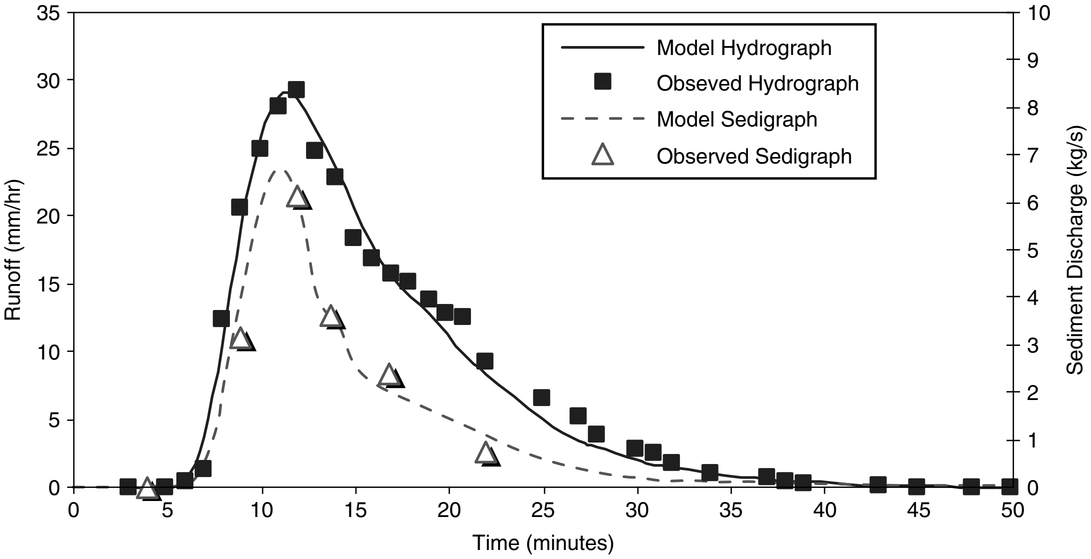

Figure 6. Comparison of observed and simulated runoff and sediment discharge for 6 August 1988 event (which was used in calibration)

The goodness of fit criteria summarized in Table V show that the distributed parameters provide a better fit between observed and simulated hydrograph and sedigraph simulations, but that this benefit is relatively small, as indicated by only a 0·05 increase in N–S statistic (Nash and Sutcliffe, 1970). However, it indicates that there is a benefit to using distributed data if those data are available. This is consistent with rainfall simulator studies of runoff volume, which show that simulations can be improved by accounting for heterogeneity (Paige *et al.*, 2002). In evaluating the goodness of fit, it is important to recognize that observed hydrographs and sedigraphs reflect discharges at the watershed outlet, and cannot be used as a basis for evaluating model performance at interior watershed points.

Effect of lumping and simplification on model output

Effect of lumping and simplification on runoff. The first step used to evaluate the effect of simplification and lumping was to plot the mean runoff volume and peak against CSA. Mean runoff volume (Figure 7) and mean peak runoff (Figure 8) are nearly identical for the lumped and discretized cases for both the 2-year and

Table V. Multiplier values and goodness of fit criteria for lumped and distributed parameter values multiplier values from parameter estimation goodness of fit statistics for hydrographs and sedigraphs for five runoff and sediment yield events. The total sum of squared residuals (TSSR) between the observed and simulated runoff and sediment yield discharge and the Nash–Suttcliffe goodness of fit criteria are used

	Distributed	Lumped
Runoff multipliers		
MK$_s$	1·22	1·25
Mn	1·81	1·80
MCVKs	3·99	4·00
Hydrograph goodness of fit		
TSSR	4294	4890
Mean N–S	0·78	0·73
Sediment yield multipliers		
MTC	0·34	0·23
MSp	1·99	10·35
Sedigraph goodness of fit		
TSSR	6·75	9·23
Mean N–S	0·80	0·75

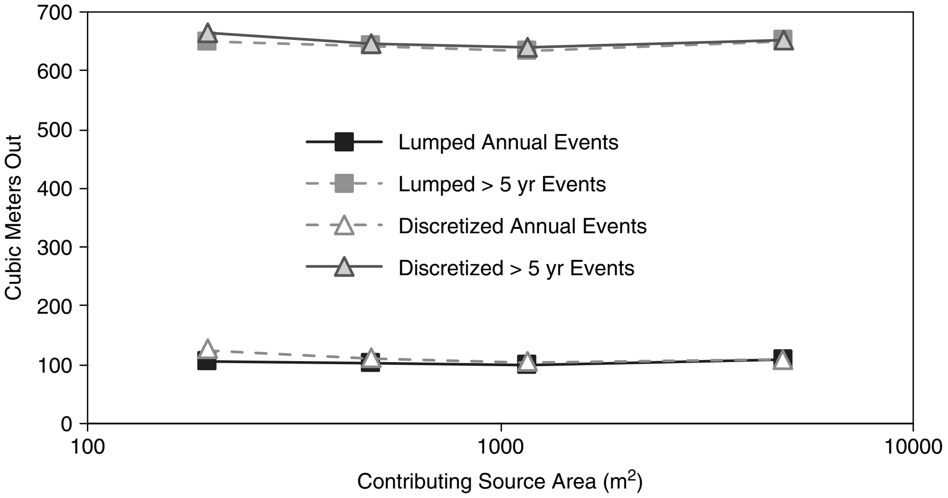

Figure 7. Effect of simplification on mean runoff volume estimate for 2-year and >5-year return period events. Little difference in mean runoff is noted in either the lumped or distributed representation, indicating that runoff volume is not significantly affected by either lumping or simplification

>5 year return period events at each level of geometric simplification. The fact that these values are nearly identical indicates that lumping has very limited effect on the simulation of runoff peak and volume.

Figures 7 and 8 do, however, show that geometric simplification has an effect on the simulation of runoff peak and volume. In all three cases, runoff peak and volume initially decline as the complexity is decreased from a CSA of 200 m^2 to CSAs of 500 and 1200 m^2. However, runoff volume and peak increase with the least complex representation (CSA = 5000 m^2). This finding is consistent with the observations of Thieken

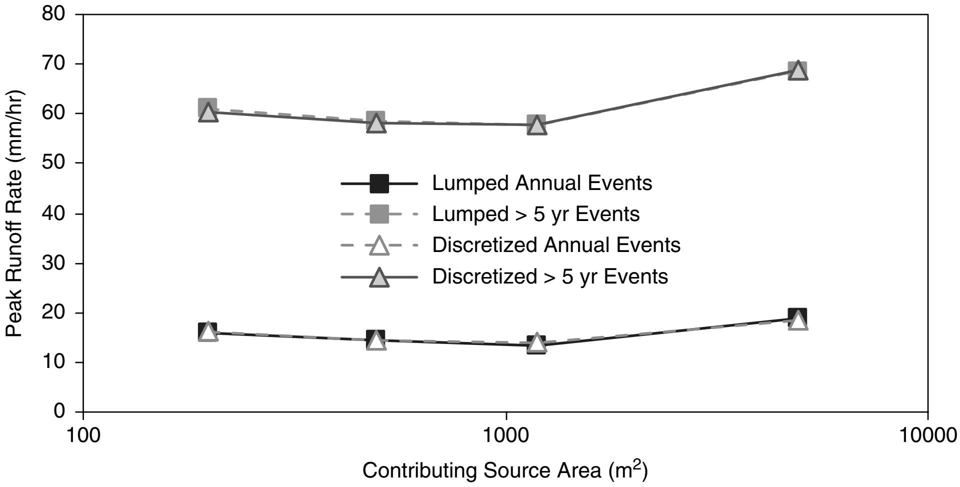

Figure 8. Effect of simplification on mean peak runoff estimate for 2-year and >5-year return period events. Whereas peak runoff appears to be affected by simplification (as indicated by a decrease and increase in peak runoff), lumping seems to have little effect, as values are nearly identical for both lumped and distributed watershed representations for both the 2-year and >5-year events

et al. (1999), who showed that using a coarser grid cell decreased the flow length from the model element to the outlet, thus increasing peak runoff rate.

Although the trends illustrated in Figures 7 and 8 are interesting, there was no statistically significant difference in the mean runoff peak and volume values between the least complex watershed representation with lumped parameter values and the most complex representation with distributed parameter values, according to paired *t*-tests with a 0·05 level of significance. This conclusion is consistent with previous studies that have concluded that more-complex watershed representations may not improve simulations of runoff at a watershed outlet (Goodrich, 1990; Hernandez *et al.*, 1997; Miller, 2002).

Effect of lumping and simplification on sediment yield simulations. In contrast, there are some statistically significant differences in evaluating the effect of geometric simplification and lumping on sediment yield. Mean sediment yield out of the watershed is little affected by simplification for the 2-year events; however, sediment yield from the watershed is greater for the lumped representations for the >5 year return period events (Figure 9).

For these larger events, statistically more sediment is derived from hillslopes for the lumped representation (Table VI), whereas approximately equal amounts of sediment are derived from the hillslope and the channel for the discretized representation (Figure 10). Total sediment yield depends both on the sediment from the channel and from the hillslope. Therefore, although there is not a statistically significant difference in total sediment between the discretized and lumped cases, there is a significant difference in the predicted source of the sediment. The increased sediment derived from hillslopes is consistent with the higher multiplier for rainsplash in the lumped case, since rainsplash is a process that occurs only on hillslopes, whereas entrainment of sediment by flowing water occurs in both hillslopes and channels.

It should be noted that both sediment and runoff are being measured at the outlet of the watershed, and that the calibration process will increase or decrease both hillslope and channel sources so that simulated and observed values are as close as possible at the outlet. Both runoff and sediment are generated on hillslopes. The area of channels is relatively small in all of the geometric representations used in this study (<800 m^2 in 44 000 m^2, Table I), and channels are not a source of runoff (though they may be a sink). However, the highest discharges and, therefore, the highest transport capacities for sediment on a watershed occur in channels, so they must be more important for modelling sediment transport than for modelling runoff. Likewise, if sediment

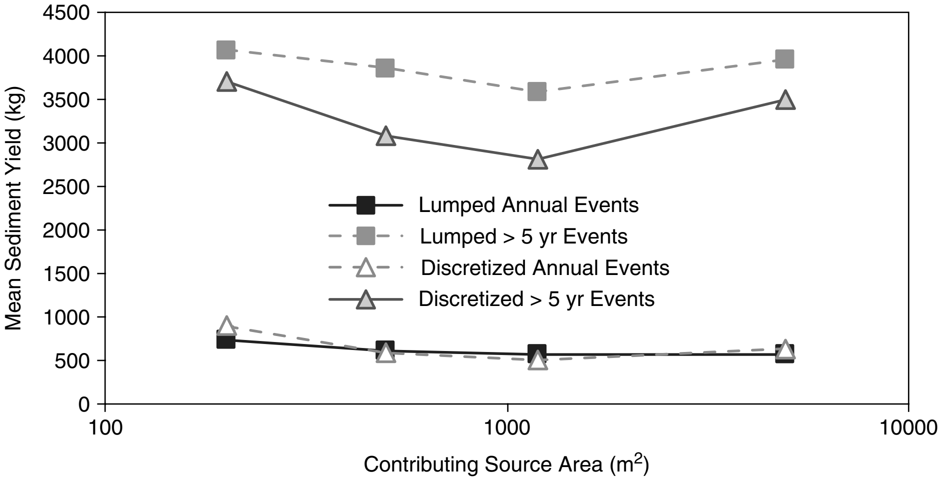

Figure 9. Effect of simplification on mean sediment yield estimates for 2-year and >5-year return period events. Sediment yield for the 2-year event is little affected by either simplification or lumping. However, for the > 5year event, lumping simulations show different estimates of sediment yield for lumped and distributed cases for all watershed representations

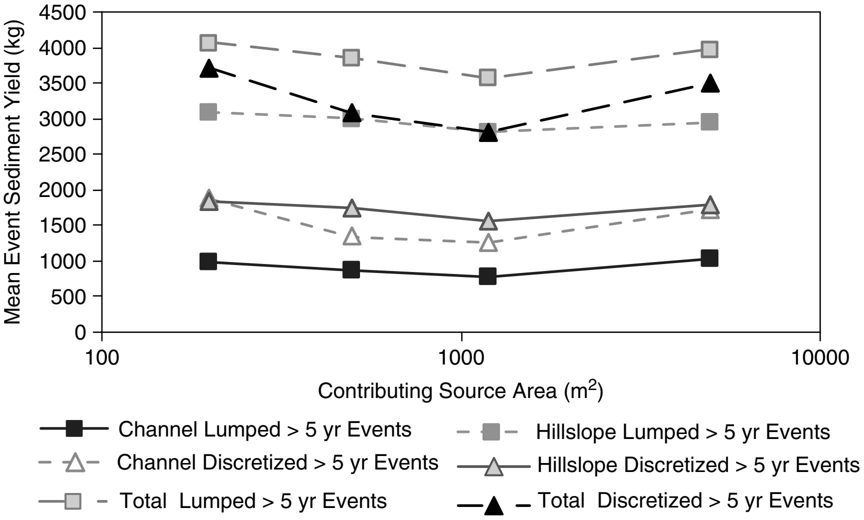

Figure 10. Effect of simplification on mean sediment yield and sediment yield from hillslopes and channels for >5-year return period for lumped and distributed simulations. Hillslope sediment yield and channel sediment yield are approximately the same magnitude for the distributed case, but much more sediment is derived from sediment in the lumped case. Whereas the total sediment yield is approximately the same for both the lumped and distributed representations, the source is different

generated on a hillslope arrives at the channel with a relatively low sediment concentration, then scour will occur in the channel so that the sediment concentration approaches transport capacity. Therefore, differences in scour that may appear to be related to channel scour may in fact be more related to hillslope sediment production. Furthermore, the calibration process is highly dependent on the transport capacity of the flow at the point of measurement.

The finding that geometric simplification and lumping have no statistically significant impact for runoff from 2-year and extreme events (Table VII), while having a statistically significant impact on hillslope and channel sediment yield, indicates that accounting for watershed representation is more important in modelling erosion

Table VI. Paired *t*-test values for sediment yield with decreasing complexity (statistically significant *t* values at 0·05 level in bold). The purpose of this comparison was to determine the effect of watershed complexity, so the paired *t*-tests compare the results from a given watershed complexity are compared with the results from the results with the least complex watershed representation (CSA = 200)

CSA (m^2)	Lumped		Discretized	
	annual	>5 years	annual	>5 years
Total sediment (kg)				
200				
500	0·45	0·60	1·10	1·38
1200	0·59	1·59	1·42	**2·05**
5000	0·59	0·23	0·85	0·41
Channel-derived sediment (kg)				
200				
500	0·97	0·80	1·40	**1·99**
1200	1·33	1·41	1·44	**−2.6**
5000	0·78	−0·21	0·65	**−3.6**
Hillslope-derived sediment (kg)				
200				
500	0·10	0·30	0·67	0·43
1200	0·10	1·18	1·03	1·32
5000	0·44	0·45	1·07	0·17

Table VII. Paired *t*-test values for difference from the most-complex distributed case, i.e. CSA ~200 m^2, spatially distributed rather than lumped parameter values (statistically significant *t* values at 0·05 level in bold, positive values indicate that the compared value is greater than the most complex, discrete case)

CSA (m^2)	Lumped		Lumped	
	2 years	>5 years	2 years	>5 years
	Runoff volume (m^3)		**Total sediment (kg)**	
200	−0·83	−0·19	−0·48	0·64
500	−0·98	−0·27	−0·95	0·28
1200	−1·17	−0·39	−1·07	−0·28
5000	−0·65	−0·14	−1·07	0·48
	Peak runoff (mm h^{-1})		**Channel-derived sediment (kg)**	
200	−0·13	0·13	−0·89	**−3.45**
500	−0·45	−0·29	−1.70	**−4.19**
1200	−0·64	−0·45	−1.95	**−4.63**
5000	0·40	1·24	−1.56	**−3.42**
	Hillslope runoff volume (m^3)		**Hillslope-derived sediment (kg)**	
200	−1·04	−0·36	−0·01	**4.06**
500	−1.37	−0·75	−0·11	**3.99**
1200	−1.69	−0·96	−0·11	**3.62**
5000	−1.48	−0·85	−0·47	**3.57**

than in modelling runoff. The KINEROS2 model accounts for variability in runoff response by describing partial area response in runoff by describing infiltration excess by both a mean K_s and a CVKs, with the underlying assumption that K_s in log–normally distributed. In contrast, there is no means to describe variability in sediment production outside of describing some hillslopes as having different sediment parameters than other hillslopes. Therefore, little flexibility exists within the sediment-yield component of the model to address variability in sediment yield sources. As such, these problems are exacerbated by simplification.

Recent studies have recognized that sediment entrainment increases substantially when sediment can be entrained from the least runoff- and sediment-producing portions of plots (Paige and Stone, 2003). Although sediment production by rainsplash may be a process similar to partial area runoff generation, there is currently no way in the KINEROS2 model to describe this variability other than having some hillslopes with different sediment entrainment parameters than other hillslopes. Therefore, describing entrainment by rainsplash as a range (much like partial area response for runoff) may have the potential to improve the predictive capabilities of a lumped erosion model, so that there is little need to account for spatial variability of parameter values.

These results show that watershed representation affects the model response of shrub-dominated watersheds in the southwest that are subjected to convective rainstorms. In contrast, runoff peak and volume are not significantly affected by watershed representation across the scales of watersheds considered in this study. It must be recognized that this study applies to a relatively homogeneous watershed dominated by Hortonian overland flow. In more heterogeneous watersheds it may be necessary to account for this heterogeneity in order to simulate hydrologic response accurately. Furthermore, in hydrologic environments where soil moisture conditions dominate hydrologic response (such as saturation excess overland flow and subsurface return flow) the findings about both runoff and erosion may be different.

CONCLUSIONS

Although this research applied the KINEROS2 model on a specific small watershed, the results are representative for process-based distributed rainfall-runoff sediment yield applied to shrublands in the southwest USA dominated by infiltration excess runoff generation. The results of this study show that, given parameters are available on a grid basis, the process of lumping produces effective parameter values that contain less variability than the distributed parameter values, but which capture the average response for peak runoff and volume at the watershed outlet for 2-year and extreme events. This is indicated by the fact that there is no statistically significant difference in the response of any model output for runoff for either the 2-year or large events at the most distributed case. Furthermore, the optimal parameter set for runoff for both the lumped and distributed parameter sets is nearly identical, indicating that for the 4·4 ha Lucky Hills 104 watershed there is little benefit to using distributed parameter values to predict runoff at the watershed outlet.

In contrast, both lumping and geometric simplification affect sediment yield predictions, particularly for the >5-year events, which move the most sediment. Although lumping results in very different estimates of the source of sediment than the distributed case, the estimates of sediment yield at the outlet in the distributed case are not significantly different than the lumped case. The process of geometric simplification and resulting lumping results in statistically significant different estimates of hillslope and channel erosion for these extreme events.

These simulations support previous research in the area of runoff modelling, which indicate that there is little gained from increasing watershed representation to predict runoff at the outlet. It further shows that there may not be a statistically significant benefit to developing spatially explicit estimates of runoff parameter values, though there may be a benefit to describing a range of runoff response.

However, these simulations indicate that geometric simplification affects erosion prediction for the largest, most sediment-producing events. This indicates that erosion prediction is a more scale-dependent process than runoff production. As such, these simulations indicate that parameter estimates developed at one scale cannot be applied across other scales without producing statistically significant differences in the predicted source of the sediment yield.

Therefore, one area of future research is to find a way to transfer sediment entrainment parameters across scales. A second area of future research is to determine whether simulations can be improved by accounting for variability in the sediment entrainment component in sediment entrainment in a way similar to the partial area response of runoff. In addition, comparable work should be performed in more complicated catchments whose runoff response results in saturation excess runoff generation or a combination of infiltration or saturation excess runoff generation. One should not expect the conclusions presented herein to apply to these types of catchment without further research.

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