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Abstract

Rainfall and wind data obtained from a dense raingage network on a 4.4 ha semiarid catchment were used as input to a distributed rainfall–runoff model. It was shown that the wind direction and velocity have a relatively small impact on peak rate and runoff volume for this low relief watershed. However, even at this small scale, spatial variability of precipitation can translate into large variations in modeled runoff. When five model runs were conducted using input from one of five recording raingages, one at a time, the coefficient of variation for peak rate and runoff volume ranged from 9 to 76%, and from 2 to 65%, respectively, over eight observed storm events. By using four well distributed gages the variations in modeled runoff volume approach the sampling resolution of the raingages as well as the estimated accuracy of runoff volume and peak rate observations. The results of this study indicate that if distributed catchment modeling is to be conducted at the 5 ha scale in an environment dominated by convective air-mass thunderstorm rainfall, knowledge of the spatial rainfall variability on the same scale is required. A single raingage with the standard uniform rainfall assumption can lead to large uncertainties in runoff estimation.

1. Introduction

Accurate representation of rainfall in time and space is essential for rainfall–runoff modeling, as it is typically one of the primary model inputs. Schilling and Fuchs (1986), Krejci and Schilling (1989), and Bonacci (1989) all note the dominant impact

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of spatial rainfall variability on runoff modeling. The need to accurately describe temporal rainfall variability for modeling small catchment response is relatively well known (e.g. Osborn and Lane, 1969; Woolhiser, 1986; Van der Zweep, 1992). At larger scales, the crucial importance of spatial rainfall pattern estimates for runoff modeling has been demonstrated (Dawdy and Bergman, 1969; Jacobi and Dawdy, 1973; Osborn and Laursen, 1973; Osborn et al., 1979; Beven and Hornberger, 1982; Troutman, 1983; Hromadka, 1987a,b; Berndtsson and Niemczynowicz, 1988; Michaud and Sorooshian, 1992). For urban drainage design the impact of spatial rainfall variability on runoff modeling has been shown to be important on basins of decreasing size with increasing raingage density (Schilling, 1984, 100 km^2; Wilson et al., 1979, 70 km^2; Niemczynowicz, 1984, 25 km^2; Schilling and Fuchs, 1986, 7.3 km^2). At yet a smaller scale of eight raingages in a 0.4 km^2 Swiss catchment, Mutzner (1991) found only one event from a set of 177 in which spatial rainfall variability of large enough to impact runoff modeling.

With data from the USDA-ARS Walnut Gulch Experimental Watershed in southeastern Arizona, Osborn et al. (1972) noted the necessity of a greater density of raingages for correlating rainfall to runoff than for strictly defining rainfall spatial variability. Based on the data available at the time, they recommended that one centrally located raingage would be sufficient for watersheds up to about 50 ha. Osborn (1984) simulated different rainfall patterns as input for a distributed runoff model in a subcatchment (225 ha) of the Walnut Gulch watershed. He concluded that for small watersheds (< 1.6 km^2), spatial and temporal distributions of precipitation exert a significant influence on peak discharge and total runoff. Obviously, the impact of spatial rainfall variability on runoff prediction is related to the scale of the watershed and the physical properties of the storm. However, in most cases, the assumption of uniform rainfall is still applied for small areas (5–10 ha), whether they are studied as individual catchments or as elementary areas in a distributed model.

Early evidence of spatial rainfall variability over scales of hundreds of meters or less in the convective storm environment of Walnut Gulch was presented by Osborn and Keppel (1966). For an extreme case where the 'sharp edge' of a thunderstorm fell between two gages approximately 300 m apart, the total storm depth for a 1963 event was 10 mm at one gage and 20 mm at the other. Working with more recent data from same two Walnut Gulch gages, Goodrich (1990) noted significantly different recorded rainfall depths and intensities over a range of event sizes. When rainfall data from these two gages were used independently as input for a runoff model in three small catchments (0.4–4.4 ha), the model produced relative variations in modeled runoff volume of up to 43% of observed runoff and 37% for peak rate. The question then arises: At what catchment scale is it valid to assume that rainfall is spatially uniform for runoff modeling? This question is of prime importance in assessing the reliability of small watershed runoff and natural resource models which utilize rainfall data as a primary model input.

2. Objectives and overview

The overall objective of this study is to better understand how spatial rainfall variability impacts the performance of runoff models for small catchments (< 5 ha). Four objectives must be addressed to provide this understanding:

(1) assess precipitation measurement uncertainty owing to gage type, calibration, data reduction and placement;

(2) assess the impacts of wind on precipitation observations;

(3) evaluate, at a very small catchment (< 5 ha) and temporal (< 5 min) scale, if sufficient spatial and temporal rainfall variability exists to have a significant effect on the estimate of areal precipitation over the catchment;

(4) assess the impacts of the above three factors on runoff prediction accuracy?

The first three objectives were addressed in the companion paper by Goodrich et al. (this issue) via an experimental investigation on the 4.4 ha Lucky Hills watershed (LH-104) in the USDA-ARS Walnut Gulch Experimental Watershed near Tombstone, Arizona, USA using a detailed measurement network (Goodrich et al., 1995, this issue, fig. 1 and table 1). This study will focus on objective four by using the data obtained in the companion study and additional historical data to better understand how rainfall uncertainty and variability influence the performance of a rainfall–runoff model at this small spatial scale.

The description of the study is organized as follows. First, an overview of the rainfall–runoff model employed in the study is presented. This is followed by a description of adaptations made to the model to accommodate non-recording raingage data and inclined rainfall as estimated from wind and vectopluviometer measurements. The 'Analysis and discussion' section follows with subsections devoted to the impacts of data reduction, rainfall inclination, number of recording raingages, and number of non-recording gages, respectively, on runoff model results. Finally, conclusions are presented.

3. The rainfall–runoff model

The KINEROSR rainfall–runoff model (Goodrich, 1990) which is a research version of KINEROS (Woolhiser et al., 1990) was used to assess the impact of wind and spatial rainfall variability on modeled runoff. It is a distributed, event-based model employing the kinematic wave approximation to overland and channel flow. The watershed of interest is discretized into overland flow, channel or pond elements to treat topographic, soils and vegetation variation. A finite difference approximation is used to solve the one-dimensional kinematic routing equations over a set of computational nodes on each overland flow or channel model element. The model assumes that surface runoff production results from infiltration excess (Hortonian mechanism). Therefore, it is well adapted to regions such as Walnut Gulch with a deep water table, where subsurface flow does not play an important role in runoff generation. The model accounts for infiltration at each computational node of overland or channel model elements using the method of Smith and Parlange (1978). For parametrization and computational simplicity a uniform soil depth profile with a uniform initial soil water content is assumed in this method. The surface routing and infiltration components are interactive so that when rainfall ceases, infiltration continues, provided water remains on the surface or is supplied by upslope runoff. The model also accounts for spatial and temporal variability of rainfall. For each overland flow element, a space–time interpolation scheme computes rainfall intensities at the element centroid as a linear combination of intensities at the three nearest gages forming a piece-wise planar approximation of the rainfall field over the catchment (Goodrich, 1990). The interpolated centroid intensity is applied uniformly over that individual model element. Model rainfall input is in the form of breakpoint rainfall data from multiple raingages. The minimum time between rainfall breakpoints from the recording raingages used in this study was 1 min. Each time a new rainfall breakpoint is encountered during the course of the model run the space–time interpolation scheme recomputes the rainfall field approximation.

The KINEROSR modeled watershed geometry for LH-104 divided the catchment into 54 elements (38 overland flow elements with a mean area of 0.11 ha, 15 channels and 1 pond). The model was calibrated by adjusting soil saturated hydraulic conductivity (Ks) and the Manning's roughness coefficient (n_m) and verified using an independent sample of 20 events as described in Goodrich (1990). Model performance was judged using the Nash–Sutcliffe (1970) forecast coefficient of efficiency for peak runoff rate (E_Q) and runoff volume (E_V). The coefficient of efficiency was selected because it is dimensionless and is easily interpreted. If the model predicts observed runoff volume or peak runoff rate with perfection, E_Q and E_V equal one (1), respectively. If $E < 0$, the model's predictive power is worse than simply using the average of observed values. For the independent verification event set, E_Q was 0.92 and E_V was 0.99. The calibrated parameter estimates from Goodrich (1990; Ks ranged from 3.3 to 19.8 mm h^{-1} and n_m ranged from 0.044 to 0.066) were used in this study as an insufficient number of events was observed with the detailed raingage network to perform split-sample calibration and verification. Model performance using the calibrated parameter estimated from Goodrich (1990) with the detailed raingage network data employed in this study is discussed later.

3.1. Model adaptations

Two modifications were performed to allow the model to account for spatial and temporal rainfall variability and rainfall inclination owing to wind on model results. The first adaptation enables the model to account for information provided by non-recording raingages. In the modified version, the temporal rainfall intensity distribution on an overland flow model element can be computed by scaling a nearby recording gage hyetograph with the value obtained by averaging measurements from nearby non-recording gages. This results in rainfall element input having timing errors associated with the recording gages and errors in total depth associated with the non-recording gages (see Goodrich et al., 1995, this issue).

The second modification of the model was made to compute hydrologic rainfall (the amount of water that actually reaches the ground, Peck, 1973) from inputs of vertical (meteorological) rainfall observations, its inclination and direction, as well as overland flow element geometry by using the equation from Sharon (1980) which was based on the ideas presented by Fourcade (1942)

$$P = P_0[1 + (\tan a)(\tan b)\cos(z_a - z_b)] \quad (1)$$

where P is the hydrologic rainfall per unit projected area, P_0 is rainfall measured by a conventional vertical raingage, a is the slope of the overland flow model element (planar model surface), b is the inclination of rain from the vertical, z_a is the aspect of the overland flow model element, and z_b the direction from which rain is falling.

Eq. (1) shows that the catch of a slope oriented at right angles to the direction of the rain is independent of the inclination of the rain. The correcting factor is negative when the slope is on the leeward side and positive when it is on windward side. The model requires the individual azimuth of each overland flow element (estimated from a 1:480 scale, 0.3 m contour interval map of LH-104) and the characteristics of the rain as estimated from wind and vectopluviometer measurements. Also note that for the correction in Eq. (1), the variation in total precipitation $\Delta P_T(P/P_0 \times 100)$ is a function of the catchment geometric characteristics and the rainfall inclination and aspect. It does not vary with the total rainfall amount or its distribution in time.

Because rainfall inclination and azimuth were computed using total storm observations from vectopluviometers a series of assumptions must be made when applying the correction factor. First, that although wind speed and direction vary during a storm for any given time period, that values obtained from using total storm observations represent the resultant vectorial average of wind speed and direction over the entire event. In addition, the rainfall inclination is considered uniform over the drop size spectrum (Sharon, 1980). No topographic influence on rainfall inclination is considered. This assumption becomes less realistic with increasing relief and is a function of the catchment scale. It implies that inertia plays a dominant role in the trajectory of raindrops reaching the ground. Studies of rainfall by Tracy et al. (1984) suggest this assumption is realistic for the relatively low-relief Lucky Hills-104 watershed. In addition, the effect of wind on the overland flow friction factor was not considered in this study. Interception by vegetation cover could also vary with rainfall inclination but was not taken into account here.

4. Analysis and discussion

The relative importance of rainfall temporal and total depth variation resulting from data reduction at a single raingage on modeled runoff was examined first. Wind impacts on computed runoff were studied next using model results for various combinations of rainfall inclination on simple catchment configurations. Recorded data were then used to assess the impact of wind on modeled runoff in the LH-104 catchment. The impact of the number of gages was then analyzed using data collected from eight events in 1990 covering a range of rainfall depths and initial soil moisture conditions. Five recording raingages and the long-term 24 h rotation reference gage (no. 83, see fig. 1 of Goodrich et al., 1995, this issue) were used in the analysis, as well as the non-recording gages (see table 1 and table 2 of Goodrich et al., 1995, this issue).

4.1. Impact of data reduction on modeled runoff

The recording raingages trace accumulated rainfall depth as a function of time. The recorded trace is digitized at breaks in slope and rainfall intensities are obtained by differencing the accumulated depth between breakpoints and dividing by the intervening time increment. This differencing and subjective operator selection of breakpoints tends to increase the temporal variability of the rainfall hyetograph (intensities). Because rainfall intensity controls runoff generation in the dry, deep aquifer environment of Walnut Gulch, it was necessary to study how variations in digitized rainfall reading would affect runoff prediction.

For the 5 July and 3 August event, five readings of the same chart were performed for gages 83 (24 h rotation) and 602 (6 h rotation). For the four sets of five readings the standard deviation of total rainfall was around 0.07 mm (coefficient of variation (CV) less than 1% in all cases) which approximates the error in positioning the cursor on the chart. This is roughly one tenth of the average standard deviation in total observed depth for the five recording raingages for the study storm set (average of column 12, in table 2 of Goodrich et al., 1995, this issue). However, the coefficient of variation in maximum intensity of rainfall was much greater, ranging from 9 and 26%. KINEROSR was then run five times for each raingage (using one at a time) with rainfall input from the five digitized readings to model the hydrograph for each of the two storms to assess the impacts of variation owing to data reduction on modeled runoff.

As expected, the hyetograph variation from digitizing was attenuated when routed through the model as measured by the variation in modeled runoff volume and peak rate. The resulting coefficient of variation ranged from 1.5 to 2.5% for runoff volume and 3.2–5.5% for peak rate with larger percentage variation in the modeled hydrographs for the smaller event (3 August) and for the 24 h chart. Spatial scale is also an important factor in the assessment of the error introduced by the digitizing process. As an extreme case, the raingage itself can be considered as an impervious watershed, in which case the error is considerable. Yet, the results described here show that, at the scale of this experiment, the catchment is large enough to attenuate the digitizing variations by roughly a factor of three and reduce the resulting variation in modeled runoff to the 3 to 5% range.

4.2. Impact of rainfall inclination on modeled runoff

The amount of rain falling on a hillslope can be quantified by two methods: (1) measurements from a gage tilted with its rim parallel to the mean slope of the hill; (2) measurements from a conventional gage, with application of a correction factor involving rainfall inclination and aspect. The second method was applied here because it clearly shows the influence of wind on model input.

The impact on modeled peak runoff rate and runoff volume of rainfall inclination and aspect was initially studied on a single north facing overland flow plane and an 'open book' configuration with two identical, opposing, north–south facing overland flow planes linked by a channel. Various model runs were performed over a range of

Table 1
Correction for wind influence on runoff model results

Event date dd-mm-yy	b Deg.	z_b Deg.	Obs. runoff		Not wind corrected				Wind corrected				Analysis[e]		
			Q_P (mm h^{-1})	VOL (mm)	P_{Tv}[a] (mm)	TTP[b] (min)	Q_{Pv}[c] (mm h^{-1})	VOL_v[d] (mm)	P_{Ti}[a] (mm)	TTP (min)	Q_{Pi}[c] (mm h^{-1})	VOL_v[d] (mm)	ΔP_T (%)	ΔQ_P (%)	ΔVOL (%)
27-07-73	39	47	76.0	17.3	41.3	20	72.3	19.1	40.8	20	71.0	18.6	−1.2	−1.7	2.9
19-07-74	18	202	32.1	6.6	25.6	26	25.5	5.7	25.9	26	26.2	5.9	1.5	2.2	3.0
28-07-74	27	131	33.0	4.5	16.5	12	28.6	4.8	16.9	12	31.0	5.1	2.4	7.3	−6.7
30-07-74	22	180	9.7	1.6	10.3	37	5.8	1.6	10.5	37	6.4	1.8	1.9	6.2	−12.5
12-10-74	0	–	15.2	1.3	7.6	19	2.7	0.5	7.6	19	2.7	0.5	0.0	0.0	0.0
12-07-75	23	240	86.4	10.4	26.3	14	77.9	10.7	26.4	14	78.4	10.7	0.0	0.6	0.0
17-07-75	45	159	134.9	47.8	70.9	15	118.5	49.3	74.8	15	128.5	53.1	5.2	7.4	−7.9
07-09-75	18	96	16.7	1.7	11.0	15	9.4	1.4	11.2	15	9.9	1.5	1.8	3.0	5.9
13-09-75	34	142	20.5	4.9	17.5	26	15.7	3.3	18.2	26	17.4	3.7	3.8	8.3	8.2
												Mean	1.7	3.7	−1.4
Ave. of b = 25°, SD of b = 13°															

[a] P_{Tv} is vertical rainfall as observed at raingage no. 83; P_{Ti} is total inclinced rainfall (see Eq. 1).
[b] TTP is time to peak runoff.
[c] Q_{Pv} is peak runoff from vertical rainfall; Q_{Pi} is peak runoff from inclined rainfall.
[d] VOL_v is runoff volume from vertical rainfall; VOL_i is runoff volume from inclined rainfall.
[e] $\Delta P_T = (P_{Ti} - P_{Tv})/P_{Ti} \times 100$; $\Delta Q_P = A[|(|Q_{Pi} - Q_P| - |Q_{Pv} - Q_P|)|]/Q_P \times 100$; $\Delta VOL = A\{|[|VOL_i - VOL| - |VOL_v - VOL|]|\}/VOL \times 100$.
$A = 1$: if |inclined − obs| $\leqslant$ |vertical − obs| (i.e. improvement using wind corrected).
$A = -1$: if |inclinced − obs| $>$ |vertical − obs| (i.e. degradation using wind corrected).

rainfall inclinations for different values of plane slope, permeability and initial soil moisture. Runoff model runs for a single impervious plane confirmed the expected result of an increasing impact on modeled runoff with increasing plane slope and rainfall inclination. Over the same range of slope and rainfall inclination there was no deviation in modeled runoff from the vertical rainfall case for the impervious open book configuration as the losses on one plane were exactly compensated by the gains on the other plane. With infiltrating open book planes, exact compensation was no longer observed. In this case the modeled runoff response to rainfall inclination was non-linear, particularly when rainfall intensities were small owing to thresholds associated with infiltration excess runoff generation.

A series of tests was then performed with the previously described LH-104 modeled watershed geometry using measured rainfall events with an assumed spatially homogeneous rainfall inclination field. The general orientation of the watershed is approximately on the northwest–southeast axis, as measured by the average orientation of the two primary watershed channels. For LH-104 the mean overland plane slope is about 7° which results in relatively low correction factor values (Eq. 1).

A prior experimental study of wind-driven rainfall, conducted from 1971 to 1975, employed vectopluviometer measurements in Lucky Hills at raingage 83 (see fig. 1 of Goodrich, et al., 1995, this issue). These measurements provided a good estimate of rainfall inclination for several storm events, among them, nine that were used for runoff model calibration and verification (Table 1). These events represent a broad range of storm volumes, wind directions and wind intensities (rainfall inclination ranges from 0° to 45°), as well as initial, prestorm soil moisture conditions. In this study, the correction factor owing to wind (Eq. 1), computed from the vectopluviometer measurements was applied to rainfall inputs from gage 83 and the resulting hydrograph was compared with the observed data and with a 'no wind' (vertical rainfall) model runs.

Initially, a high inclination of 45° was assigned to the storm event of 30 July 1974 to assess extreme impacts on modeled runoff over the eight major cardinal wind directions. For this event, the total rainfall measured with the conventional gage was 12.4 mm corresponding to a medium sized event. The results are illustrated in Fig. 1 as departures from the results obtained with 'no wind', vertical rain case, for total rainfall, peak runoff rate and total runoff. As expected from the general orientation of the watershed, the highest increase in peak and volume occurred with wind coming from the southeast and the lowest when it comes from the northwest. A more pronounced effect on peak rate than on total runoff was also observed. The results using a 45° inclination suggest that even in a watershed with moderate relief, wind could play an important role in the distribution of rainfall and the shape of the computed hydrograph.

However, the distribution of observed rainfall inclinations and aspects among the nine events in Table 1 is considered more representative of the regional situation. 'Wind' and 'no wind' runs were carried for these events and the results are summarized in Table 1. The mean value of the error on precipitation is only 1.7%, with individual values ranging between −1.2 and 5.2%. A measure was developed (Table 1, footnote e) to indicate the relative improvement or degradation in modeled

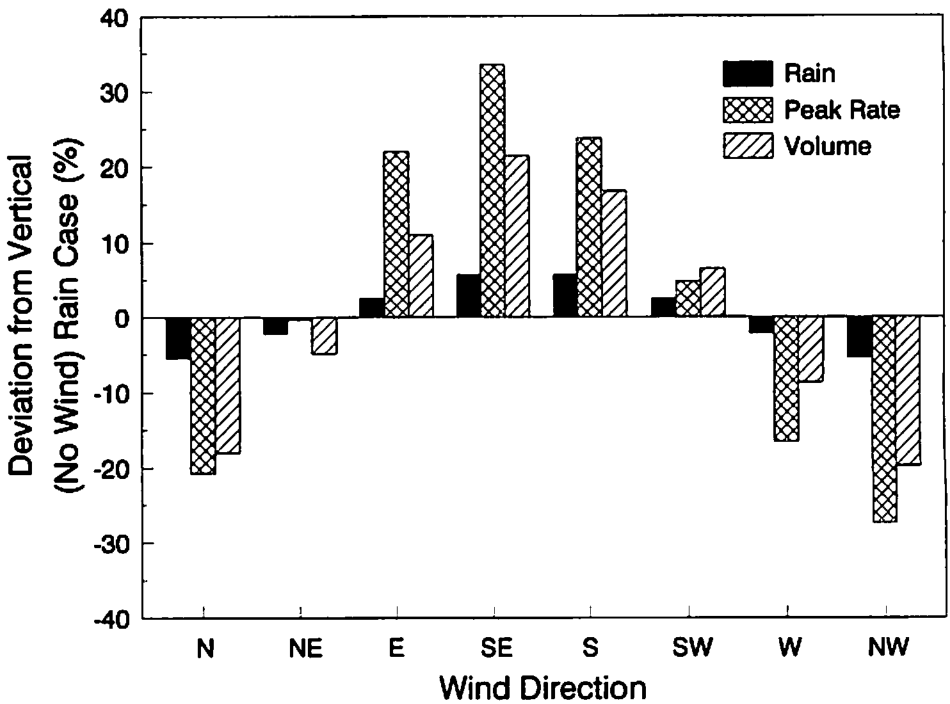

Fig. 1. Lucky Hills 104. Variations in total precipitation, peak rate and runoff volume for different aspects of rainfall inclination (angle from vertical: 45°; storm event 53).

runoff in terms of the percentage of observed runoff by using the wind corrected rainfall inputs over the 'no wind' cases. The resulting mean of this measure for modeled peak rate and total runoff from the 'wind' to 'no wind' cases were 3.7% and −1.4%, respectively, and no substantial influence on time to peak was observed. The wind-corrected model output showed an improvement in predicted peak discharge for seven of the nine events and four of the nine events for runoff volume. No notable increase in the influence of rainfall inclination was observed for decreasing rainfall amount. One reason could be that initial soil moisture and spatial rainfall intensity pattern also play an important role as the storms become smaller. The sample size is too small to support a more detailed analysis. Another important point to keep in mind is that the impact of wind on rainfall catch is significant only for certain combinations of wind aspect and intensity.

4.3. *Impact of the number of recording gages on runoff modeling*

Prior analysis of rainfall showed that input from two adjacent gages roughly 300 m apart could produce very different modeled hydrographs (Goodrich, 1990). The assumption that the rain falling over the catchment can be accurately represented by a unique raingage was tested in terms of the predicted hydrograph with the dense raingage network data. It was expected that, by increasing the number of gages used in modeling runoff, one would reduce the runoff model uncertainty at two levels. First, given the rainfall interpolation scheme of the model, a better representation of the spatial variability of the rainfall field would be achieved. Second, by increasing the number of gages, one would expect partial compensation of the random portion of measurement errors. This method contrasts to the geostatistical method of optimal raingage selection for defining a single areal average for runoff model input (Bastin et al., 1984) as addition of each gage alters the time-variant patterns of rainfall through the space–time rainfall interpolation scheme.

To study the validity of these assumptions, runoff computations were performed for each of the eight storms described in Table 2 (observed runoff volume ranged from 0.5 to 15.4 mm; event numbers obtained from table 2, Goodrich et al., 1995, this issue). For combinations of one, two, three and four recording gages, five runoff model runs, and one run with all five gages, were performed (26 total runs for each storm). When two or three gages were used, the combinations of gages were chosen randomly without consideration for their relative location. However, each of the five gages was forced to appear the same number of times in the five runs. It should be noted that because of the limited number of recording raingages these combinations of model results are not truly independent with unique and distinct raingage combinations. This is overcome in the following section by using the larger sample of non-recording raingage data.

The results of the combination of recording raingage analyses are summarized in Table 3 for all eight events and illustrated in Fig. 2 for the 3 August 1990 event. A decrease in the coefficient of variation for peak runoff and volume was observed in all but one case when two gages were used instead of one. It was also found that model output variation as a function of the number of raingages was generally greater for

Table 2
Summary of runoff observations

Event	Date	Pre-storm volumetric water content[a] (% porosity)	Observed runoff[b]	
			Peak rate (mm h^{-1})	Volume (mm)
2	07-05-90	43.2	29.4	11.5
3	07-11-90	30.7	12.8	1.8
5	07-14-90	46.0	3.2	0.6
6	07-15-90	44.7	9.1	2.2
9	07-19-90	33.7	15.2	1.9
12	07-21-90	42.1	3.2	0.5
14	08-03-90	30.9	17.5	3.5
16	08-12-90	22.1	46.5	15.4

[a] Basin average from daily surface (top 15 cm) time domain reflectometry measurements at the nine recording raingage locations adjusted to storm start time via an exponential drying function obtained from dry-down periods during the data collection period.

[b] An average potential error of 10% in runoff quantities was estimated resulting from errors in measurement and data processing as well as errors in the stage–discharge relationship (Freimund, 1992).

small events than for large ones. This reflects the difficulty of modeling small runoff events when runoff to rainfall ratios are low and measurement error may be larger relative percentage of the input rainfall signal (a high noise to signal ratio). Whenever relative infiltration and rainfall rates are close, resulting in small runoff ratios the model becomes very sensitive to both input and parameter changes.

In regards to model performance in comparison with observed data, when all five recording raingages were employed, $E_Q = 0.63$ and $E_V = 0.87$. When using a single raingage, the worst efficiencies were $E_Q = 0.35$ and $E_V = 0.79$, respectively and approached the five raingage case depending on which gage was selected for input. As illustrated in Table 3 the model had a general tendency to overestimate large events and underestimate small events.

The variability in runoff model results presented in Table 3 and Fig. 2 emphasizes the need for more than a single raingage and the importance of the spatial distribution of the gages in the catchment. For the medium-sized 3 August 1990 event, the five model runs using five different gages one at a time (upper left of Fig. 2), produced a range of variation for modeled peak runoff rate and runoff volume of 14.96 mm h^{-1} ($CV = 38.8\%$) and a 2.6 mm ($CV = 40.0\%$), respectively. For the LH-104 runoff measuring flume Freimund (1992) estimates an average potential error of 10% in runoff volume and peak runoff owing to errors in measurement, data processing and in the stage–discharge relationship. The uncertainty in modeled runoff using a single raingage as measured by the coefficient of variation exceeds the measurement uncertainty in all but two of the storms modeled in Table 3. This has important implications for parameter estimation during model calibration if a single raingage is used in an environment with spatial rainfall variability comparable to the data presented in this study. If the uniform, single raingage assumption were used during parameter fitting in the midst of spatial variability, the variation in modeled hydrographs could be mistakenly assigned to variability of other model parameters.

4.4. *Use of non-recording gages*

There are several reasons why use of the data from the non-recording gages could improve the results of the runoff model. First, if several gages are available, their measurements can help reduce the uncertainties resulting from measurement error and spatial variability of the rain. Secondly, the use of non-recording gages makes it possible to overcome a major constraint in the analysis of the impact of the number of recording gages performed above. Owing to the limited number of recording gages, it was impossible to model runoff with independent combinations of recorded data. The same recording gage had to be used in several runs and this situation accounts for a portion of the decrease in runoff variability illustrated in Fig. 2 and Table 3 as the number of raingages was increased.

The non-recording raingages were used to provide various unique combinations of rainfall input data by using five independent combinations of one, two, three, four, six, and eight non-recording gages used in connection with intensity data derived from recording raingage 83 (the reference gage — 24 h chart rotation with a practical postprocessing time resolution of 2.5 ± 5 min; Chery and Kagan, 1975; Freimund,

Table 3
Statistics[a] of runoff model results (peak rate and volume) obtained with different combinations of one to five recording raingages

Number of gages	Date	Observed Q_P (mm h^{-1})	Peak rate Avg (mm h^{-1})	Peak rate Range (mm h^{-1})	Peak rate CV (%)	Observed volume (mm)	Runoff volume[b] Avg (mm)	Runoff volume[b] Range (mm)	Runoff volume[b] CV (%)
1	7/5	29.4	42.35	13.69	11.15	11.5	14.27	1.00	2.49
2	7/5		41.98	8.53	7.33		14.16	0.57	1.70
3	7/5		41.43	6.84	5.92		14.14	0.50	1.37
4	7.5		41.25	3.33	2.90		14.12	0.39	0.96
5	7/5		40.99				14.06		
1	7/11	12.8	17.80	14.85	30.36	1.8	2.59	1.66	23.94
2	7/11		15.30	9.57	21.16		2.39	1.10	17.02
3	7/11		15.34	6.05	12.59		2.40	0.76	10.88
4	7/11		15.64	1.96	4.21		2.49	0.24	3.80
5	7/11		16.00				2.56		
1	7/14	3.2	0.51	1.15	75.94	0.6	0.16	0.32	65.10
2	7/14		0.41	0.59	53.53		0.17	0.15	32.25
3	7/14		0.42	0.21	18.08		0.15	0.05	12.06
4	7/14		0.47	0.11	8.05		0.17	0.03	5.25
5	7/14		0.51				0.18		
1	7/15	9.1	2.25	4.67	73.83	2.2	0.58	1.00	63.78
2	7/15		3.19	1.07	12.04		0.74	0.18	8.67
3	7/15		3.09	0.80	9.46		0.75	0.15	6.81
4	7/15		3.20	0.49	6.10		0.76	0.08	4.07
5	7/15		3.30				0.76		
1	7/19	15.2	4.90	8.89	62.65	1.9	0.85	1.26	50.64
2	7/19		4.69	4.83	36.61		0.90	0.60	26.17
3	7/19		4.67	1.40	13.64		0.88	0.26	12.99
4	7/19		4.83	0.96	7.30		0.93	0.20	7.74
5	7/19		4.93				0.96		
1	7/21	3.2	2.24	1.20	20.65	0.5	0.52	0.20	14.40
2	7/21		1.79	1.18	28.72		0.43	0.17	15.56
3	7.21		1.57	1.19	28.96		0.42	0.16	14.16
4	7/21		1.44	0.71	18.23		0.41	0.08	6.95
5	7/21		1.32				0.40		
1	8/3	17.5	13.17	14.96	38.80	3.5	2.28	2.60	40.01
2	8/3		11.35	6.53	22.35		2.46	1.04	15.56
3	8/3		12.48	4.60	14.04		2.46	0.66	11.98
4	8/3		12.67	3.26	8.45		2.55	0.45	6.15
5	8/3		12.75				2.59		
1	8/12	46.5	65.71	15.85	8.75	15.4	19.67	3.04	5.10
2	8/12		65.66	17.11	8.62		19.46	1.52	2.81
3	8/12		63.15	9.96	5.62		19.55	1.25	2.16
4	8/12		62.43	3.64	2.29		19.49	1.14	1.85
5	8/12		61.92				19.49		

[a] $n = 5$ using model runs with rain input from combinations of one, two, three and four recording raingages.
[b] Using all five gages the Nash–Sutcliffe (1970) forecast coefficient of efficiency equals 0.63 for peak rate and 0.87 for runoff volume.

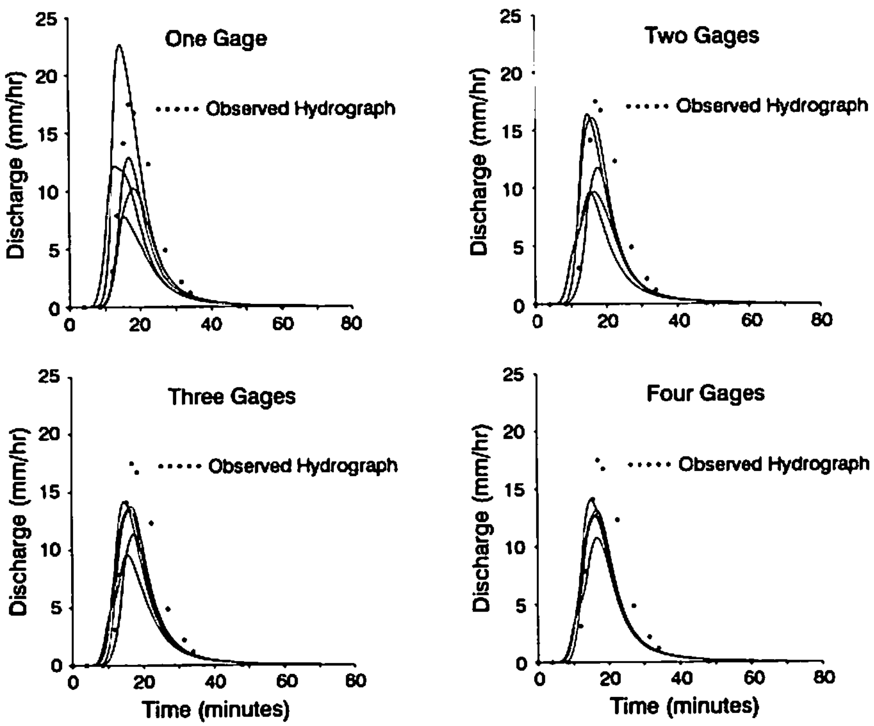

Fig. 2. Modeled hydrographs for five combinations of one, two, three and four recording raingages in Watershed LH-104 (3 August 1990).

1992). Given the temporal resolution of this raingage it was assumed that the time distribution of the rain was spatially invariant (see Goodrich et al., 1995, this issue). Care was taken to select raingage combinations that were spatially well distributed in the watershed (centrally located in the case of one gage). In addition, one further model run was performed with the whole network of 48 gages. Three storms (11 July, 3 August, and 12 August) qualified for these analyses as high-quality non-recording raingage, recording raingage and runoff measurements were available. The results are illustrated in Fig. 3.

In Fig. 3, for the five model runs using unique combinations of one, two, three, four, six, and eight gages, the range and coefficient of variation of the modeled peak runoff rate and runoff volume are plotted as a function of the number of gages used. The relatively large variations in computed peak rate and runoff volume using input from different, single raingages, illustrated in Fig. 2 is also illustrated in Fig. 3. The range of variations appears to stabilize when four gages are used. It is also interesting to compare the range in computed runoff volume (0.3–0.7 mm for four gages, 0.2–0.8 mm for six gages, and 0.4–0.6 mm when eight gages were used) to an estimate of sampling and reading error obtained from the standard deviation of the four non-recording collocated gages placed at site 606. The respective standard deviations are 0.3, 0.7, and 0.3 mm for the events of 11 July, 3 August, and 12 August, respectively

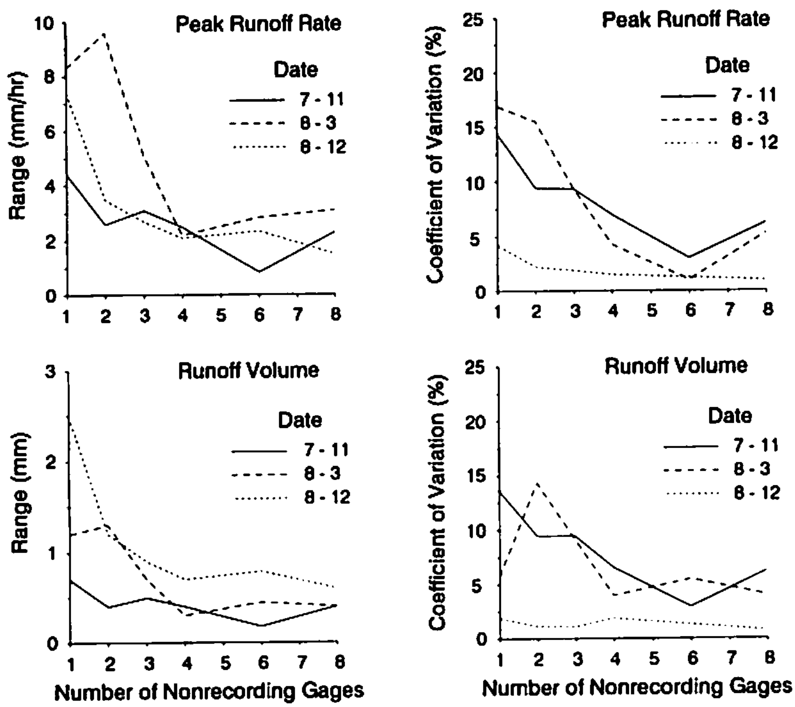

Fig. 3. Range of coefficient of variation over five model runs of peak runoff rate and volume as a function of the number of non-recording input gages (one, two, three, four, six, and eight).

(see table 2 of Goodrich et al., 1995, this issue). Assuming this standard deviation is indicative of the sampling resolution of the raingages one would not expect modeled runoff volume accuracy to exceed the raingage resolution, or expect modeled peak rate accuracy to exceed the variation owing to digitizing (3–5% coefficient of variation as discussed above). Indeed, from Fig. 3 it appears that by using four to six well-distributed gages, the variations in modeled runoff volume approach the sampling resolution of the raingages themselves as well as the estimated 10% accuracy of peak rate and runoff volume observations for the LH-104 supercritical flume (Freimund, 1992).

The decrease in the coefficient of variation in both peak and volume with increasing event size is also apparent from Fig. 3 (observed runoff volume for events of 11 July, 3 August, and 12 August were 1.8 mm, 3.5 mm, and 15.4 mm, respectively). This is a logical trend for the reasons discussed earlier, namely, as the event size increases, the rainfall observational error constitutes a smaller percentage of the overall input signal (decreasing noise to signal ratio).

The model runs using recording raingage 83 alone, the five additional recording gages, and the 48 non-recording gages with gage 83 for temporal reference are summarized in Table 4. Compared with the results from gage 83 alone, the use of the non-recording gages systematically improved the computation of total volume. In one case, it even performed better than the case with the five recording gages. The

Table 4
Comparison between cases with one and five recording input gages and the network of non-recording gages (a) for peak rate, and (b) for runoff volume.

Date	Observed ($mm\ h^{-1}$)	RG-83 ($mm\ h^{-1}$)	Five gages[a] ($mm\ h^{-1}$)	RG-83 + NRG[b] ($mm\ h^{-1}$)
(a) *Peak runoff rate*				
07-11	12.8	17.3	16.0	13.8
08-03	17.5	19.7	12.7	22.8
08-12	46.5	65.4	61.9	65.1
(b) *Runoff volume*				
07-11	1.8	3.9	2.6	2.5
08-03	3.5	3.1	2.6	3.6
08-12	15.4	20.9	19.5	20.7

[a] Recording raingages.
[b] Non-recording raingages.

number of events is too low to draw definitive conclusions, but these results would encourage the use of non-recording gages as a viable alternative to expensive networks of recording gages on small catchments.

5. Conclusions

The objective of this study was to examine how various rainfall measurement uncertainties and spatial rainfall variability affect runoff modeling for a small catchment (4.4 ha). The motivation underlying this research was generated by the necessity to assess the validity of the typical assumption of uniform rainfall in modeling small catchment hydrology. While the results of this experiment provide information for an environment dominated by convective air-mass thunderstorms, extrapolation to other situations or at other scales must be carried out with extreme prudence. The conclusions must also be tempered by noting the dependence of using the KINEROS rainfall–runoff model with it's associated formulation and implementation assumptions.

The impacts on runoff modeling of three principal aspects of rainfall observation were considered; measurement and data processing errors, the influence of rainfall inclination, and spatial rainfall variability. The major conclusions drawn from this study follow.

(1) While multiple digitization realizations of recording raingage charts resulted in coefficients of variation of maximum rainfall intensity ranging from 9 to 26%, these rainfall input variations were attenuated in the rainfall–runoff model resulting in coefficients of variation that ranged from 1.5 to 2.5% for runoff volume and 3.2 to 5.5% for peak runoff rate.

(2) The mild topography of watershed LH-104 restricted the importance of the wind impact and resulting rainfall inclination to very particular combinations of rainfall depth and wind characteristics. For nine historical events with rainfall

inclinations ranging from 0° to 45°, the mean improvement (see Table 1, footnote e) in modeled peak rate was 3.7%, with a mean decrease of −1.4% for runoff volume using rainfall input corrected for wind.

(3) Runoff model runs performed with data from variable numbers of recording gages demonstrated that the uncertainty in runoff estimation is strongly related to the number of input gages. In particular, the use of two gages reduced the variability of computed runoff. Modeling of small events suffered greater relative variations than larger storms due the larger relative percentage of measurement error. In the presence of spatial rainfall gradients observed in five of the eight observed events in this experiment, the location of the gage becomes a crucial parameter in modeling the storm hydrograph (a coefficient of variation greater than 20% for peak rate and runoff volume for five modeling scenarios using a different input raingage). The gradients observed in this experiment are not unusually large (Hershfield, 1969).

(4) Modeling of a small number of events using the network of non-recording gages associated with a unique recording gage showed that by using four well-distributed gages the variations in modeled runoff volume approach the sampling resolution of the raingages themselves as well as the estimated 10% accuracy of runoff volume and peak rate observations (Smith et al., 1981). The use of single recording raingage to define the temporal rainfall distribution and a small set of non-recording gages to define the spatial rainfall distribution appears to be a workable alternative when only one recording gage is available if the assumption of stationarity in the time distribution of the rain is valid. This may be to case for small catchments such as the one employed in this study but this assumption will deteriorate with increasing catchment size (Berndtsson and Niemczynowicz, 1988)

(5) The results of this study indicate that if distributed catchment modeling is to be conducted at the 5 ha scale, knowledge of the spatial rainfall variability on the same or smaller scale is required. A single raingage with the standard uniform rainfall assumption can lead to large uncertainties in runoff estimation.

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