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CHARACTERIZATION OF THUNDERSTORM RAINFALL FOR HYDROLOGIC MODELING

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Abstract

Rainfall and runoff records for 30 events from a 630-hectare subwatershed on the USDA-ARS Walnut Gulch Experimental Watershed in southeastern Arizona were used to estimate the desirable spatial resolution of rainfall data required as input to a hydrologic model (KINEROS, Woolhiser, et al., 1990). Runoff peaks and volumes modeled from data at a centrally-located raingage and from a dense 10-gage network were the basis for judging model performance as a function of rainfall representation. In addition, a 100-yr thunderstorm was modeled on three adjacent subwatersheds of different sizes and shapes to explore the relation between the spatial characteristics of watersheds and thunderstorms. For the watersheds examined it was found that if a spatially uniform thunderstorm rainfall assumption is made, significant overestimation of 100-yr runoff volume and peak rate estimates can occur, leading to overdesign of flood protection.

Introduction

The higher variability of convective air-mass thunderstorm rainfall has always been important to hydrologists and engineers in the Southwestern United

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States. Accurate representation of this variability has become more important than heretofore with the increasing use and complexity of distributed-parameter rainfall-runoff models. There is both a need to be able to accurately represent this variability for model input in order to examine the best uses and needs for such models.

In the Southwest, thunderstorms produce larger flood peaks and discharge volumes in small (certainly less than 100 km^2) watersheds than winter frontal storms. To date, thunderstorm runoff has usually been modeled with data from collected from the few dense networks of recording raingages that exist (including Walnut Gulch). In this study, we first examined the sensitivity of the model to the spatial resolution of the rainfall input by comparing the results generated through the use of 10 recording raingages versus a single gage on the same watershed. We then assessed the relation between rainfall variability and watershed morphology (i.e. size and shape) in order to judge the value of using data-intensive models that are sensitive to the short-duration, high-intensity, areally-limited thunderstorm rainfall that dominates runoff generation in the Southwestern United States.

Data from three rangeland subwatersheds in the upper reaches of the 150 km^2 Walnut Gulch Experimental Watershed subwatersheds were used in this study (Figure 1). The watershed is operated by the Southwest Watershed Research Center of the USDA, Agricultural Research Service. The 630 hectare subwatershed 11 (excluding a small portion contributing to a stock pond) was used to assess the sensitivity of the runoff model to rainfall input. Subwatersheds 11, 9 (2360 hectares) and 10 (1660 hectares) were used to investigate the influence of rainfall spatial characteristics and watershed size and shape on runoff production. Subwatershed 11 is somewhat elliptical, with a length/width ratio of about 2.4; subwatershed 10 is long and very narrow, with a length/width ratio of 8.1; and subwatershed 9 has a length/width ratio of 3.2. All three subwatersheds are characterized by mixed grasses, low shrub cover and ephemeral stream channels with coarse sand beds that typically abstract significant runoff. The primary soils have a sandy loam texture and high surface rock content. Soil infiltration rates range from 10 to 13 mm/hr and channel bed abstraction rates are as high as 225 mm/hr (Renard, 1970).

Description of Runoff Model

Many different mathematical models have been used to estimate runoff peaks and volumes for small watersheds, but few models are sufficiently sophisticated to detect the influences of rainfall variability and watershed characteristics on runoff. A kinematic-cascade model, KINEROS (Osborn, 1983; Woolhiser et al., 1990), was chosen for this study because it is responsive to both rainfall and watershed characteristics. KINEROS is a nonlinear, deterministic, distributed-parameter model which has been well tested (Lane and Woolhiser, 1977; Rovey et al., 1977; Goodrich, 1990). Inputs are the rainfall hyetograph, the watershed surface and channel geometry, hydraulic roughness, and infiltration characteristics.

In the first part of a two-part study, measured rainfall and runoff data for 30 selected events were used to calibrate and verify the KINEROS model for subwatershed 11. Ten calibration events within the 30-event subset were then used to evaluate the relative sensitivity of model output to different rainfall input representations (ten gages versus one). In the second part of the study, the entire historical record of rainfall/runoff is reinterpreted based on synthesizing 100-yr rainfall input and modeling different spatial configurations between the storm cell and the three subwatersheds.

Evaluation of Rainfall Representation

Prior application of KINEROS to subwatershed 11 was conducted by Goodrich (1990) using data from ten raingages located in and around the catchment (see Figure 1) and a space-time rainfall interpolation scheme to represent the spatial distribution of rainfall over the area. In that study split-sample calibration and verification of a research version of KINEROS (Goodrich, 1990) using events from 1966 to 1988 employed using the Nash-Sutcliffe forecast coefficient of efficiency for runoff volume (E_V) evaluation criteria (Nash and Sutcliffe, 1970). The coefficient of efficiency was selected because it is dimensionless and easily interpreted. If the model predicts observed runoff volume with perfection, $E_V = 1$ (1). If $E < 0$, the model's predictive power is worse than by simply using the average of observed values.

For subwatershed 11, 10 calibration events which ranged from small to large with a range of dry to wet antecedent soil moisture conditions were modelled with the forecast coefficient of efficiency for runoff volume of $E_V = 0.86$. For the 20 independent verification events of the 30-event subset, the efficiency dropped to $E_V = 0.49$. Scatter plots of the observed versus simulated runoff volumes for the calibration event set are presented in Figure 2. Possible explanations for the model's poorer performance with the verification set include differing channel losses and antecedent soil conditions and large random rainfall variability that may not have been captured in the small subset of ten calibration events. However, the results cannot be dismissed outright as being unacceptable and are good when compared to other modeling efforts with Walnut Gulch data (Hughes and Beater, 1989).

With the calibrated parameters the model was rerun for the 10 calibration events using data from a single raingage located near the center of subwatershed 11 (see Figure 1), implying a spatially uniform rainfall representation. In Figure 2 the modeled runoff volumes for the single raingage are also plotted. The figure illustrates that for 6 of 10 of the calibration events, and all of the medium to large events, the uniform representation overestimated runoff volume (from 14 to 93%). In addition the forecast coefficient of efficiency for runoff volume dropped to 0.07. Because peak runoff rate is highly correlated with runoff volume in this environment (Goodrich, 1990), similar impacts on peak runoff rate occurred when the single raingage was used instead of the ten-gage network. This suggests that even on the scale of subwatershed 11 the uniform rainfall representation results in poor estimations.

Comparison of Actual Runoff Peaks and Volumes

Runoff peaks and volumes for 28 years of record were compared for subwatersheds 9, 10, and 11 (Table 1). For the years of record, the largest peak discharge occurred on subwatershed 11, whereas the maximum recorded peaks on subwatersheds 9 and 10 were much smaller. The situation for runoff volumes between the three subwatersheds was similar.

The evidence that the largest recorded peak discharge occurred on the smallest of the three watersheds has at least two possible explanations. One is simply that a 30-year record is too short to assume a representative sample of runoff in a region where rainfall is extremely variable in time and space. Another is that the combination of high thunderstorm rainfall variability and watershed characteristics, including channel infiltration and basin shape, is meaningful in determining frequencies for major runoff peaks and volumes. This was investigated using synthesized rainfall input.

Synthesized Rainfall Input an Associated Model Output

The synthesized 100-yr, 30 min rainfall input was based on the entire raingage network on Walnut Gulch (Osborn, 1983). The model storm isohyets form concentric ovals with intensities in 3-min increments (Figure 1, Table 2). In effect, the storm shape is similar to the shape of subwatersheds 9 and 11. Several spatial alignments of subwatershed and storm were studied. In the first case, the storm was centered on the watersheds, with the main axis parallel to the general flow direction. In the second case, the storm was centered with the axis normal to the flow direction. In the third case, the storm was animated to propagate both up and down the watersheds, parallel to the flow direction. In every case, the model indicated runoff from the entire area of subwatershed 11. By contrast, less than 1/2 of subwatershed 10 received runoff-producing rainfall in cases 1 and 2. Only in case 3, when the storm moved parallel to the watershed axis was the watershed covered by runoff producing rainfall. For subwatershed 9, the model storm area was smaller than the watershed area, so there was partial-area response in each case. In case 2, the storm could be placed to be contained entirely within the watershed boundaries.

The simulated peak discharges based on the expected 100-yr point rainfall storm model for subwatersheds 11, 10, and 9 were 138 cms, 142 cms, and 303 cms, respectively (Table 3). Primarily because of watershed shape, but also because of travel time and channel-bed abstractions, the flood peak for subwatershed 10 was smaller than would be expected if the peaks were based on watershed size alone. The maximum expected flood peaks (Table 3) for subwatersheds 11, 10, and 9, based on storms centered on the watershed, parallel to the long axis of the watershed, and moving down the watershed were 162 cms, 259 cms, and 406 cms, respectively. We cannot attach frequencies to the runoff peaks based on the synthesized rainfall input, but flood peaks extrapolated from the 28 years of record for the three subwatersheds suggest that the estimates for the 100-yr event based on the 100-yr rainfall event are reasonable.

Conclusions

Convective air-mass thunderstorm rainfalls typical of the Southwestern United States are limited in areal extent and highly variable in both time and space. For a 630-hectare watershed, modeled runoff peaks and volumes were generally overestimated by using a spatially uniform representation of rainfall. Based on records from the dense raingage network on Walnut Gulch, runoff producing rainfall usually is restricted to only portions of the subwatersheds, and is not evenly distributed within those areas. Adopting rainfall-runoff relations for thunderstorm rainfall in the Southwestern United States for models that assume runoff from 100 percent of the watershed area or spatially uniform rainfall could significantly overpredict the 100-yr runoff peak and volume, thus leading to overdesign of flood protection, especially those for urban drainages. However, the "maximum" which might occur should always be noted, because a flood of greater than 100-yr frequency would cause catastrophic losses.

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Table 1. Ranked flood peaks observed on three selected subwatersheds on Walnut Gulch, 1965-1992.

Ranked Peak Rates	WG 9 (cms)	WG 10 (cms)	WG 11 (cms)
1	69	63	96
2	58	22	48
3	33	20	28
4	25	17	25
5	23	15	25

Table 2. Rainfall intensites for 100-yr, 30-min. simulated Walnut Gulch thunderstorm rainfall (mm).

Time interval (min)							
0-3	3-9	9-15	15-18	18-21	21-24	24-27	27-30
Accumulated Interval Depth (mm)							
152	203	152	127	102	51	30	15

Table 3. Flood peaks and volumes for simulated 100-yr, 30-min. storms on three selected subwatesheds on Walnut Gulch.

Subwatershed	100-yr		Maximum	
	Peak (cms)	Depth (mm)	Peak (cms)	Depths (mm)
WG 9	303	33.9	406	34.0
WG 10	142	33.1	259	33.3
WG 11	138	37.6	162	30.3

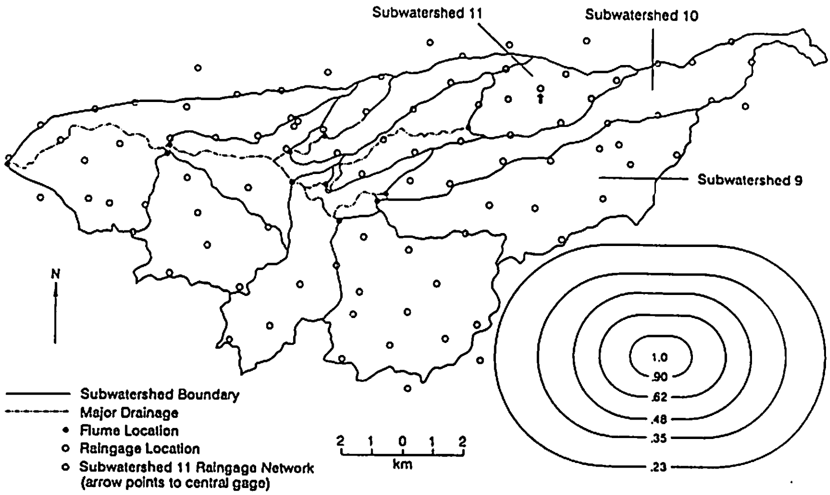

Figure 1. Map of Walnut Gulch Experimental Watershed Showing Raingage Network, Major Drainages, Subwatersheds, and Model Storm Overlay with Point to Area Fractional Reduction.

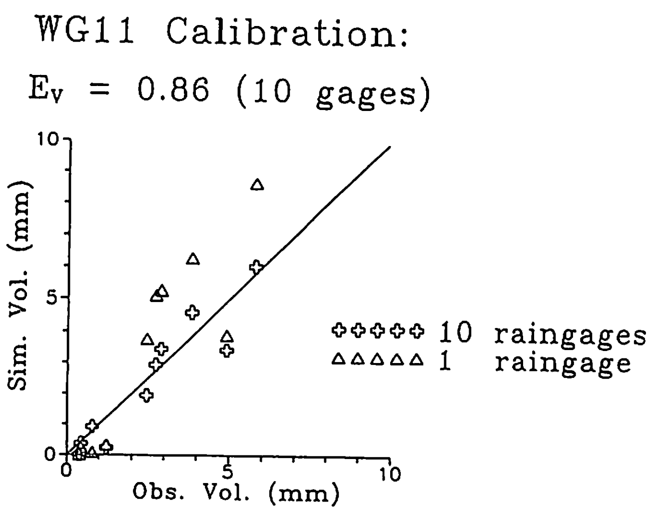

Figure 2: Observed vs. simulated runoff volumes for WG11 calibration event set for 10 and 1 raingages.