IMPORTANCE OF SHORT DURATION RAINFALL INTENSITIES FOR HYDROGRAPH MODELING

Rhey M. Solomon
James R. Maxwell
Larry J. Schmidt
USDA Forest Service
Albuquerque, New Mexico

Abstract

Flood flows and water quality in the Southwest are most dramatically influenced by short, intense rainstorms. Runoff from these storms has been modeled with some success. One key element that has often been overlooked, however, is the importance of intra-storm rainfall distribution on runoff response. Actual storms were modeled for small experimental watersheds in the Southwest using different time increments of intra-storm rainfall. Increments of 5 minutes or less proved satisfactory for accurate hydrograph simulation. As increments became longer than 5 minutes, the ability to simulate actual hydrographs became increasingly difficult. Increments of 30 minutes or longer proved unacceptable for most storms. Hydrologic models must be sensitive to short time increments of intra-storm rainfall to accurately predict peak flows in the Southwest. Watershed treatments will be more cost-effective if their design considers intense bursts of intra-storm rainfall in addition to total storm volume.

Introduction

Over the last decade, tremendous strides have been made in computer hardware and software. These advances have made computer systems accessible to natural resource scientists. Many new rainfall-runoff models have been developed, tested and their results published. Many are process-based models that solve complex or tedious differential equations with numerical approximations or other techniques which would require unreasonable amounts of time if done by hand. These process-based models have promoted a clearer understanding of the hydrologic cycle in general, and the factors controlling the rainfall-runoff process in particular.

Extensive work has been done in the Southwest to quantify rainfall-runoff relationships. Much of this research has studied the depth-area and energy-erosion relationships of thunderstorms (Osborn et al., 1980). Investigators have understood and accepted the importance that time plays in the runoff process. Unfortunately, the importance of time in hydrograph synthesis has not been passed on to field engineers and hydrologists that make planning decisions and design flood control improvements. This paper points out the importance of time in hydrograph synthesis, and illustrates the size of error that can be expected by using hourly or even 30-minute rainfall data to calculate peak runoff in areas dominated by intense rainstorms.

The Problem

Engineers and hydrologists are often given the task of predicting flood peaks for small basins. Since local stream records are usually inadequate or nonexistent, runoff models must often be used to make such predictions. With computer technology now available, the Rational, SCS, and other simplistic models are losing favor in preference for more sophisticated process-based models. However, these new models often produce no more accurate results than the traditional methods (Naef, 1981). They require more sophisticated data, much of which are estimated using professional judgment. These estimated data often produce inaccurate results. The models can correctly depict rainfall-runoff processes, but the required data are often insufficient to predict peak flows that agree with observed values.

Almost all rainfall-runoff models require some input of rainfall, the area of the watershed, and some abstraction of infiltration. Even the simple Rational formula contains these factors:

$$q = CIa$$

where q = peak flow

C = runoff coefficient based upon flood-producing characteristics of the basin (abstraction of infiltration and delivery).

I = rainfall intensity, customarily averaged over the time of concentration.

a = area of the basin.

The relationship between I and a is one aspect of accurate hydrograph synthesis, and has received adequate attention (Osborn et al., 1980). The infiltration-rainfall relationship has also been dealt with in part by numerous investigators. Attention has focused primarily on adjustments to the infiltration index, for example, the C factor in the Rational formula or the curve number in the SCS model (Bondelid et al., 1982). The importance of I as a function of time within storms has not been adequately addressed.

An analysis of model performance reveals the importance of intra-storm rainfall distribution. The performance of the Rational formula and the SCS model was tested for over 50 storms (Hiemstra and Reich, 1967). The SCS model substantially underpredicted, while the Rational formula overpredicted peak flows. Hiemstra and Reich (1967) pointed out that the Rational formula can account for rather small time increments of rainfall while the SCS model is limited to longer increments. The original SCS model was not designed to account for intra-storm rainfall distributions and computes infiltration eratically for 5 minute increments (Kumar and Jain, 1982). When Hiemstra and Reich (1967) accounted for intra-storm rainfall distribution, the SCS model performance improved.

Recent studies have recognized the shortcoming of the SCS model and other simple models to accurately predict runoff from short, intense rainstorms (Kumar and Jain, 1982; Aron et al., 1977). Many computer based models can account for short time increments of rainfall, although the importance of corresponding rainfall data is often understated. This problem results in part from data being published by clock hour, with one hour as the shortest time increment (Frederick et al., 1981).

Importance of Short Time Increments

Surface runoff is the result of rainfall excess. Two factors influence excess water, the soil's infiltration capacity and the rate of rainfall. Given a set of initial conditions, the soil infiltration curve can be defined (i.e., the soil will infiltrate water at predictable rates given initial moisture conditions and soil properties). The rainfall rate determines the amount of excess surface water in two principal ways: (1) it can shift the location of the infiltration decay curve because it affects the time to ponding (Smith and Cherry, 1973); and (2) it affects the separation of rainfall excess from infiltrated water (i.e., the higher the rate of rainfall the larger the excess). Rainfall rates averaged over longer time intervals are lower and produce less excess water.

The integrated effect of these two principles is demonstrated in Figure 1. A short, intense (5.0 in/hr) rainfall is shown for a time increment of five minutes. If this same volume were spread across 10 minutes the rainfall rate would be 2.5 in/hr. The excess water produced from these two rates is shown by blocks A and B, respectively. The 10 minute increment underestimates actual excess and resultant runoff volume. This is precisely the problem encountered when using models that have coarse time-increment requirements or use rainfall data published with one-hour or 30-minute increments.

Study Methods

The importance of short time increments of rainfall has been demonstrated conceputally (Engman and Hershfield, 1981). But this concept has not been displayed for actual watershed cases. To better explore the implications of short rainfall time increments, 14 storms on three experimental watersheds were modeled. The three watersheds are located near Albuquerque, New Mexico and range in area from 40 acres to 246 acres (Hickok et al., 1959). The 14 storms ranged in duration from 19 minutes to over three hours. The rainfall data were collected by recording rain gages, and the streamflow data were collected by recording gages on precalibrated triangular weirs. The period of record was 1948 through 1967.

A simple computer model that simulates infiltration and runoff processes was used to show the effects of varying time increment. The model and its performance have been described by Solomon et al., (1982) and Solomon (1983). Regardless of which process-based model is used, the results should be comparable.

Each of the 14 storms was partitioned into one minute time increments and modeled. Adjustments were made to infiltration coefficients until observed hydrographs matched predicted hydrographs. The time increment was then increased from one to two to five minutes, etc. the longest time increment used was one hour.

Of the 14 storms modeled, only two had one-minute partitioning as part of the original reported data. Six storms were reported with two-minute increments. All storms were reported with at least five-minute increments. The assumption was made that rainfall values in the original data were given for the smallest increment that showed differences in rainfall intensity (i.e., if the rate of rainfall was constant for five minutes, the data were reported for a five-minute increment).

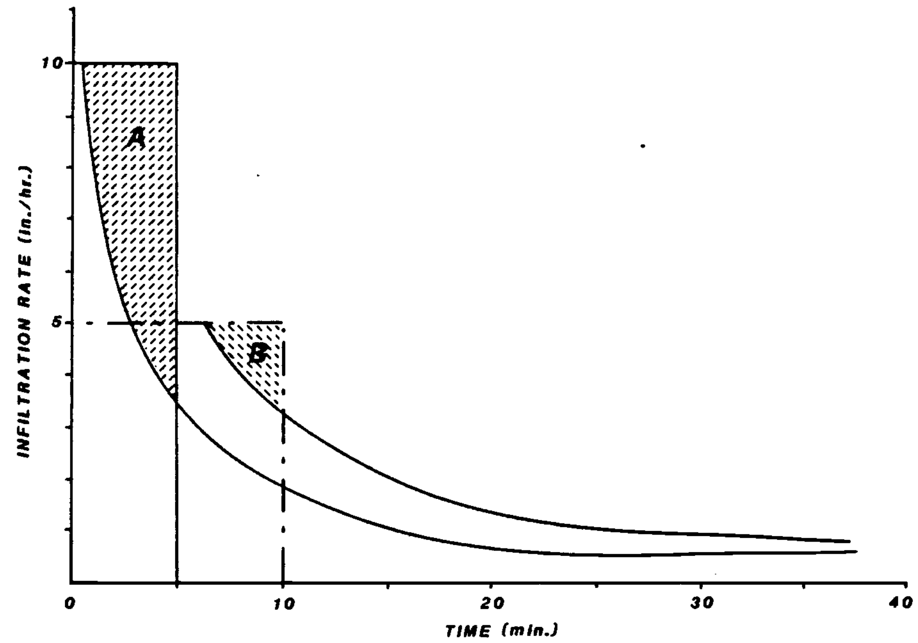

Figure 1. Precipitation Excess for Two Rainfall Intensities and Durations.

Results

These 14 summer storms serve as a base for evaluating the effects of intra-storm rainfall distribution on hydrograph synthesis. Table 1 shows the effect of increasing the length of intra-storm time increments on predicted peak flow. Peak flows using one-minute increments match observed values. As increments are lengthened, predicted peak flows drop dramatically and are substantially underpredicted.

Figure 2 illustrates these effects graphically for intra-storm time increments of one minute to one hour. The use of time increments up to five minutes produces predicted peak flows that average 86% of the observed peaks. As time increments are expanded to 10 and 15 minutes, ability to model peak flows diminishes dramatically. Beyond 30 minutes, differences in peak flow are not as abrupt but errors are substantial. Note in Figure 2 the range in peak flows for any given intra-storm time increment. This range is due to the extremely variable rainfall distributions for the storms evaluated. Some storms were dominated by one short, intense burst of rainfall less than 5 minutes long while other storms were characterized by a 10 to 15 minute dominant period. No storm had a maximum rainfall intensity longer than 15 minutes. Other hydrograph characteristics, such as time to peak and runoff duration, did not change substantially with changes in length of time increments.

Changes in hydrograph characteristics are shown in Figure 3. The storm of August 12, 1967 was modeled for various intra-storm time increments. The 1 minute, 5 minute and 30 minute intra-storm time increments are shown. For this storm, the 30 minute time increment produced a peak less than one-half the actual peak and a total runoff volume at about 60 percent of the actual runoff volume.

Implications

For rainfall-runoff models to accurately predict peak flows in the Southwest, they must be sensitive to short time increments of rainfall. Engineering designs should evaluate short time increments of intra-storm rainfall and not rely on prediction tools that use one hour or longer time periods of precipitation accounting. Rainfall for intra-storm time increments might be estimated by establishing a standard distribution for the one hour rainstorm (Farmer and Fletcher, 1972; Engman and Hershfield, 1981; Frederick et al., 1981) or by using five minute or 10 minute rainfall probabilities (Kangieser, 1969).

Table 1. Peak Flows From Hydrograph Synthesis Using Varying Intra-Storm Time Increments.

Watershed	Event	Total Rainfall (in)	Highest Intensity (in/hr)	1 min [2]	2 min	3 min	4 min	5 min	10 min	15 min	20 min	30 min	60 min
				Peak Flows (cfs)									
47.001	Sept. 5, 1963	.45	1.9	24.2	-	-	-	22.9	19.7	16.4	-	12.4	2.8
47.001	Aug. 3, 1964	.97	2.2	51.2	50.9	-	-	46.7	43.6	42.3	43.5	32.8	27.5
47.001	July 31, 1965	.65	5.9	125.1	-	-	123.4	112.0	77.2	65.0	-	35.1	12.3
47.001	Sept. 12, 1965	.75	2.0	48.5	-	-	98.5	46.8	36.9	30.7	32.6	24.2	20.3
47.001	Jun. 10, 1966	1.0	10.2	223.0	213.9	-	198.0	170.9	158.3	134.5	-	64.0	38.4
47.001	Aug. 11, 1967	1.3	3.4	151.5	151.3	-	143.0	125.3	117.1	90.8	94.6	71.4	64.4
47.002	Aug. 4, 1948 [1]	.49	2.4	26.1	-	24.9	-	22.5	15.1	12.2	-	6.2	0.0
47.002	Aug. 4, 1948 [1]	.41	2.8	40.5	40.0	-	35.3	35.1	21.3	21.0	-	8.9	3.2
47.002	Aug. 3, 1964	.90	3.0	42.1	41.7	-	-	39.2	32.2	25.3	27.3	10.3	8.5
47.002	Aug. 14, 1965	.69	3.5	52.1	51.8	-	37.0	43.5	29.4	28.3	-	16.5	6.5
47.002	Sept. 2, 1965	.62	2.2	41.7	-	40.7	-	35.4	27.6	24.2	24.2	17.3	5.1
47.002	Jun. 10, 1966	1.20	12.0	112.0	107.0	-	-	101.4	74.6	79.7	-	44.4	26.1
47.002	Aug. 13, 1967	1.2	5.7	91.2	-	-	85.4	81.3	66.7	63.2	52.1	43.0	28.0
47.003	Aug. 4, 1948	.52	3.3	27.9	27.3	-	-	26.7	20.2	16.9	11.5	3.2	0.0

1/ There were two storms within the same day.

2/ 1-min predicted peaks approximately match observed peaks.

Peak flows depend more on short, intense bursts of intra-storm rainfall than on total storm volume. Small volumes of rain falling over a short enough time period can produce significant runoff. Time is the lever that land managers can use to control surface runoff. Introducing short delays in the runoff process reduces the effective rainfall intensity. In the short term, the manager can increase surface detention storage through structural treatments such as contour furrowing and ripping. Properly designed contour treatments can usually accommodate the small runoff volumes involved. In the long term, the manager can increase ground cover of plants and litter to increase infiltration as well as detention storage. These implications suggest that land management agencies need to measure rainstorms with greater resolution and design standard rainfall distributions that reflect local intra-storm characteristics.

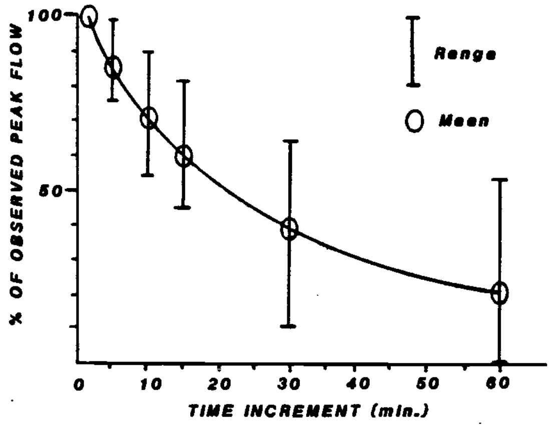

Figure 2. Changes in Predicted Peak Flow Resulting from Changes in Length of Intra-Storm Time Increments.

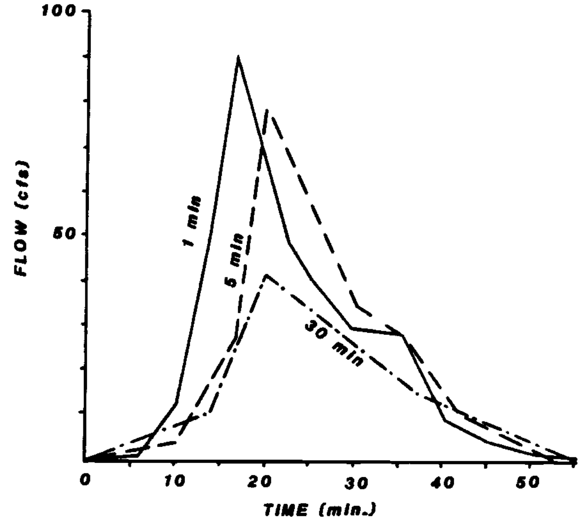

Figure 3. Comparison of Hydrographs Resulting from Changes in Length of Intra-Storm Time Increments.

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