

EFFECT OF RAINGAGE DENSITY ON RUNOFF SIMULATION MODELING

by
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ABSTRACT

Rainfall and runoff data for a 3.08 square mile urban watershed in Denver, Colorado was used to investigate the effects of raingage density and hyetograph compositing on urban stormwater runoff simulation. This watershed has rainfall data from five raingages and flow data from two gages, all in 5-minute time increments. The data were used to calibrate the EPA Storm Water Management Model (EPA SWMM, version 5.0), and the Urban Drainage and Flood Control District's version of an earlier EPA SWM model (UDSWMM). This calibrated model served two purposes; first, to examine the effects on runoff calculations using a single composite hyetograph for each of the recorded storm rainfall and runoff events modeled and second, to determine the effects of raingage density on volume of runoff and peak flow simulations.

The effects of raingage density were investigated by processing rainfall data from each raingage using several different combinations of raingage densities. The data were used to drive the calibrated SWMM model and the results compared against recorded runoff volumes and flow rates for the recorded storms. It was demonstrated that raingage density does affect the accuracy and the scatter of simulated results.

The effects of compositing recorded rainfall data at several raingages into a single rainfall hyetograph were also investigated. Two types of compositing were performed. One method simply used area weighted averaging of rainfall recorded at each time increment. This method was defined as straight across compositing. In the second method, each hyetographs at the five gages was examined and all values were time shifted to line up the most intense five-minute rainfall values of the storms. The simulation results were then compared to the recorded flows.

This paper describes the findings of this study and discusses their implications for urban stormwater runoff modeling. It presents a summary the collaborative work and findings by the authors over the last 17 years.

INTRODUCTION

This report is based on a draft MSCE Thesis prepared by Mike Jansekok in 1990 (an abbreviated summary of which was presented at the International Conference on Computer Applications in Water Resources, Tamsui, Taiwan, July 1991), and on the author's analyses of new rainfall and runoff data collected during the 15 years since.

Two questions arise with hydrologic computer modeling. The first is whether that modeling appropriately accounts for the temporal and spatial variations in rainfall patterns that occur in

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nature. If only one raingage is used to represent the rainfall for an entire watershed, any given storm could easily concentrate its main intensities near the raingage and totally miss most of the watershed altogether. The resulting rainfall/runoff ratio could vary from either very high to very low, and attempting to establish any relationship between the two would be problematic, as much of past attempts have shown, especially for larger catchments. Specifically, this question can be broken down into the following components:

- Does this rainfall/runoff ratio become more constant when raingage density increases?
- How does compositing of several rainfall records affect the calculated surface runoff?
- Is there a compositing technique that yields more realistic results?
- What impact does the rainfall data time increment have on the model results?

The last question regards the impact of a large (e.g. 60-minute) inputted rainfall time step vs. a smaller (e.g. 5-minute) rainfall time step on the rainfall/runoff ratio

Much of what is written about the effects of raingage density and hyetograph compositing methods in runoff modeling revolves around synthetically manufactured design storm hyetographs. The authors were fortunate to have access to 23 years of simultaneous rainfall and runoff records incremented at 5-minute time steps for a relatively small and stable urban watershed with a high raingage density. This paper attempts to show both the variance in runoff calculations which can occur when raingage density is increased or decreased and the effects of hyetograph compositing on stormwater runoff modeling of peak flows and runoff volumes, and to compare the results when using 60-minute, 15-minute, and 5-minute rainfall input data.

RAINFALL AND RUNOFF GAGES USED BY THIS STUDY

Rainfall/runoff data was recorded between 1979 and 2002 for the Harvard Gulch drainage watershed ware obtained from the U.S. Geologic Survey at the Denver Federal Center in Lakewood, CO. The data were collected under a cooperative agreement between the Urban Drainage and Flood Control District and USGS. Data from two stream flow gages and five rain gages were used in the investigations. Detailed records of rainfall were obtained using a recording tipping bucket raingage at each site and a flow-stage data collected at the two stations by digital recorders. The locations of all gages are shown in Figure 1.

SELECTION AND PREPARATION OF DATA FOR ANALYSIS

Minimum Rainfall & Runoff Criteria for this Study

From the rainfall/runoff data set recorded between 1979 and 1987, seventeen storms were selected for further hydrologic analysis based on the following criteria:

1) Five (5) raingages and two (2) flow gages must be reporting during the storm.
2) Minimum recorded rainfall at any gage must equal or exceed 0.08 inches during at least one 5 minute period within a storm.
3) The recorded peak flow at any gage must equal or exceed 50 cubic feet per second (cfs).

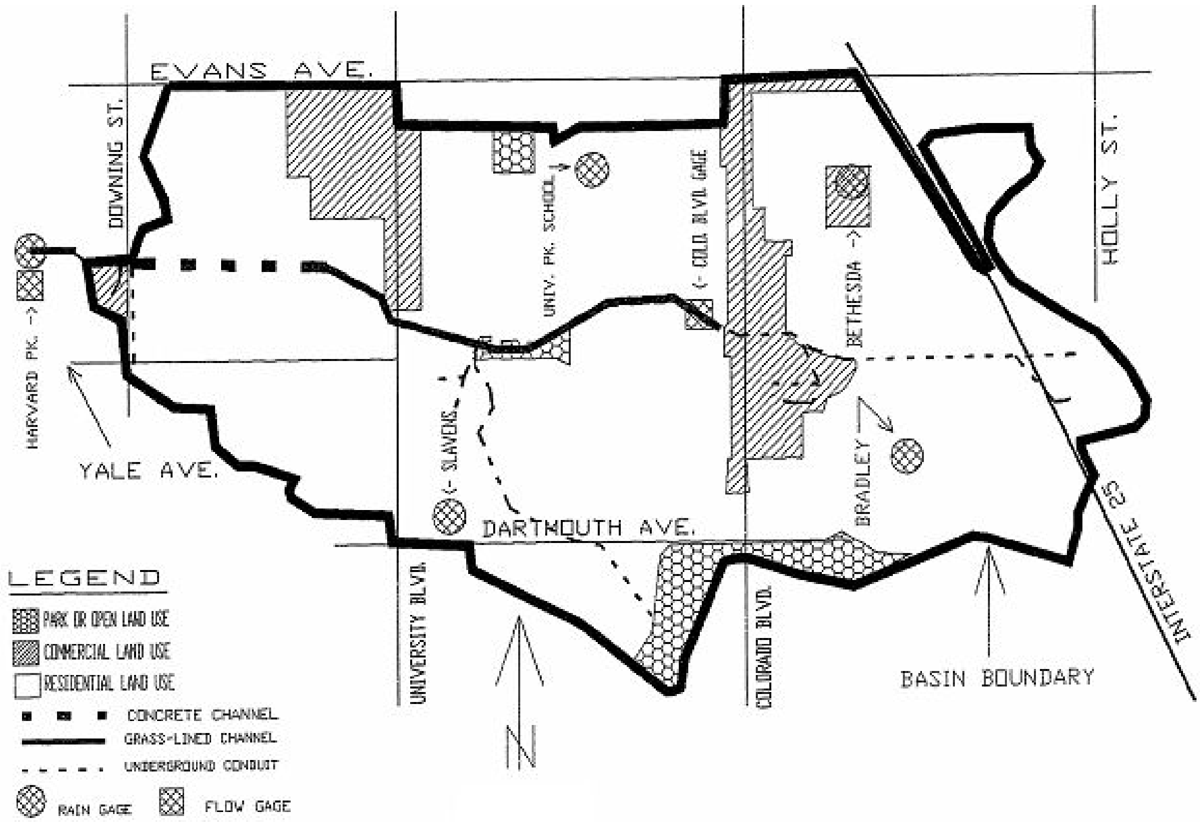

Figure 1. Harvard Gulch Watershed Stream and Rain Gage Location Map.

Preparation of UDSWM Model

The drainage conveyance element layout consisted of 78 conveyance elements, which were divided into five types as either pipe, pipe with overflow, channel, channel with overflow, or non-routing. One detention element was incorporated into the model to reflect a sump area in the upper watershed at Colorado Boulevard.

Calibration of UDSWM Model

Each one of the seventeen selected storms was processed through the UDSWM model. Calculated runoff volumes and peak discharges were plotted against observed values, and data regression was used to draw a best-fit line through plotted points. Adjustments were made to modeling parameters such as imperviousness, roughness, sub-catchment tributary width, etc., and the model was calibrated for each of the seventeen storms, until each best-fit line approximated 45 degrees between modeled results and recorded data for both peak flows and runoff volumes in each watershed.

USE OF CALIBRATED SWMM MODEL

Investigating the Effects of Raingage Density

Five increasing raingage density combinations were used to show the effects of raingage density on peak flows and runoff volumes. Two different scenarios of these five-gage combinations were simulated. All these simulation scenarios are shown Table 1.

Normalized values of deviations from the calibrated 5-raingage UDSWM model output for peak flows and runoff volumes were plotted against number of raingages used in simulations for both upper and total watersheds. Comparisons were made for (1) 5-gage calibrated UDSWM model vs. 1 through 4 gage for both scenarios and (2) actual recorded data vs. 1 through 5 gage calibrated UDSWM model, also for both scenarios. The normalizing method for defining percent variance is described by the following equation:

$$Vi = [(Ri-Rci)/Rci]*100$$

in which, Vi = variance from the calibrated five rain gage peak flow or runoff volume for storm i, Ri - peak flow or runoff volume for the test run for storm i, Rci = peak flow or runoff volume for calibrated model or recorded data for storm i.

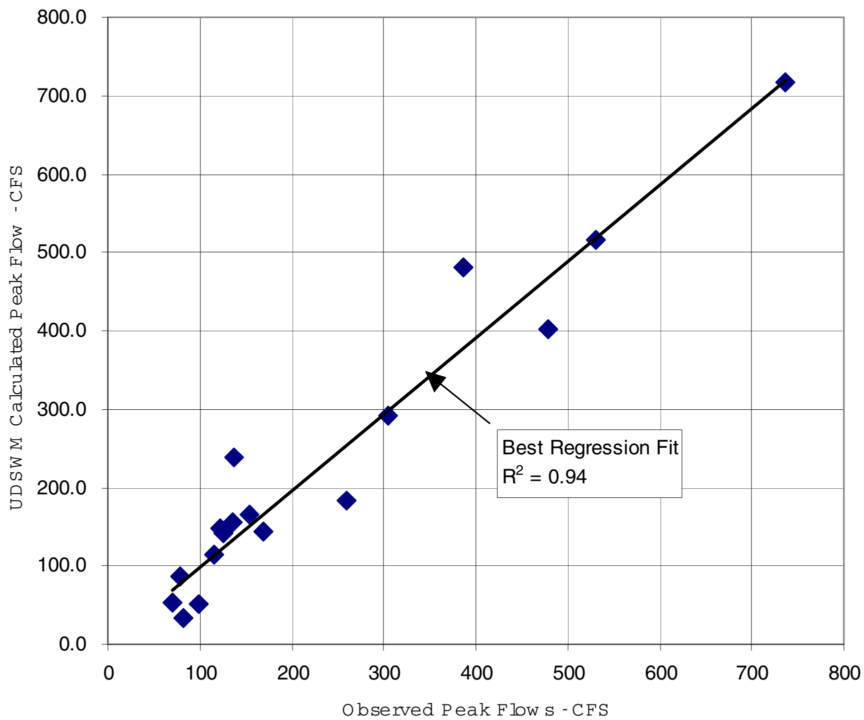

Figure 2: Calibration of UDSWM Peak Flows.

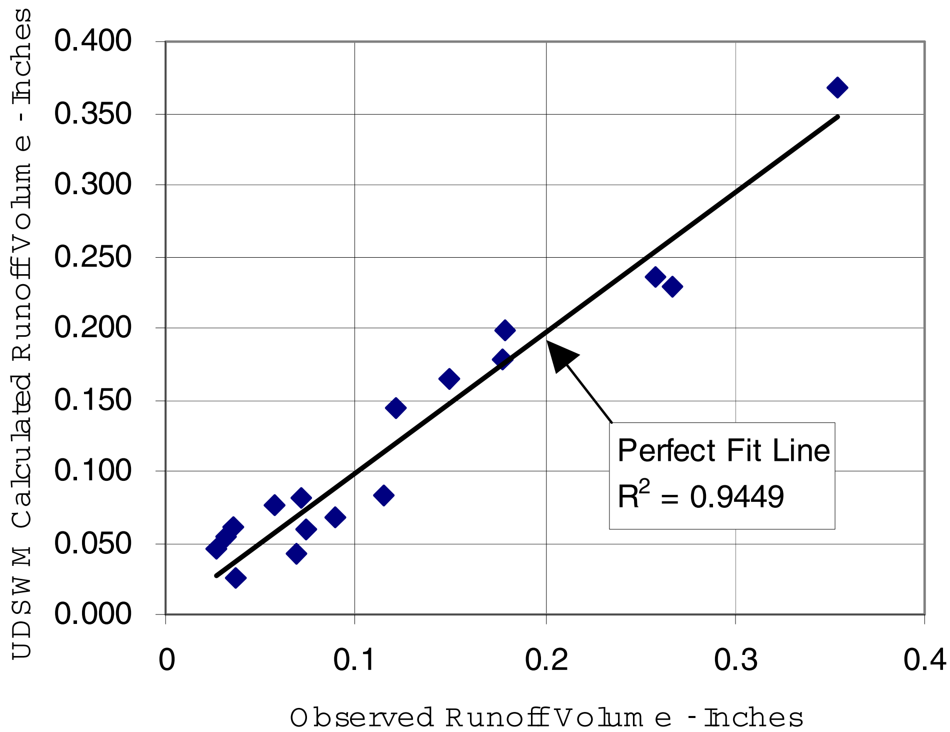

Figure 3: Calibration of UDSWM Runoff Volumes.

TABLE 1. SIMULATING RUNOFF UNDER DIFFERENT GAGE SCENARIOS.

GAGES USED TO MODEL ***SCENARIO #1*** FOR THE TOTAL WATERSHED TRIBUTARY TO HARVARD PARK					
Run Number	Harvard Park	Bradley School	University Park	Slaven School	Bethesda School
1	**X**				
2	**X**	**X**			
3	**X**	**X**	**X**		
4	**X**	**X**	**X**	**X**	
5	**X**	**X**	**X**	**X**	**X**
GAGES USED TO MODEL ***SCENARIO #2*** FOR THE TOTAL WATERSHED TRIBUTARY TO HARVARD PARK					
1				**X**	
2				**X**	**X**
3	**X**			**X**	**X**
4	**X**		**X**	**X**	**X**
5	**X**	**X**	**X**	**X**	**X**

Hydrograph Comparisons

The following two hydrograph comparisons were made using eight selected storms:

1. UDSWM model simulated flows at Harvard Park calibrated using all 5 raingages vs. field observed hydrographs.
2. UDSWM model simulated flows at Harvard Park calibrated using all 5 raingages vs. simulated flows using a single composite rainfall hyetographs for each storm using the following two methods of compositing:
   a. Area weighted composite at each time increment, no consideration for highest peak rainfall
   b. Area weighted composite at each time increment after aligning each hyetograph peak rainfall increments to be at the same time increment (i.e., peak preservation).

PRESENTATION OF DATA AND DISCUSSION OF RESULTS

Effect of Raingage Density and Location

Tables 2 and 3 compare the simulated peak flows and Tables 4 and 5 compare the simulated runoff volume for two scenarios of distributions of one through four raingage combinations used in these simulation against the simulated peak flows for the entire watershed that were obtained using the five raingage calibrated UDSWM model. All these tables show the percent variation in the mean, percent range in the variations and the standard deviation in the variation percentages from the five-gage simulations.

TABLE 2. PEAK FLOW (SCENARIO #1)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-100.0 to 150.0	-24.2	78.5
3	-32.2 to 63.6	15.8	29.4
4	-32.2 to 18.8	-0.9	11.6
5	0.0 to 0.0	0.0	0.0

TABLE 3. PEAK FLOW (SCENARIO #2)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-93.0 to 81.5	-20.7	48.3
2	-76.7 to 75.9	-5.9	38.6
3	-59.2 to 34.3	-4.5	25.2
4	-30.7 to 26.6	-1.3	15.4
5	0.0 to 0.0	0.0	0.0

TABLE 4. RUNOFF VOLUME (SCENARIO #1)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-98.6 to 152.8	-16.5	79.9
2	-66.7 to 85.2	-12.4	38.4
3	-20.3 to 59.4	11.3	22.8
4	-20.8 to 19.1	4.6	10.5
5	0.0 to 0.0	0.0	0.0

TABLE 5. RUNOFF VOLUME (SCENARIO #2)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-78.1 to 61.5	-9.2	46.4
2	-55.6 to 29.7	-8.5	25.3
3	-29.6 to 16.7	-9.8	13.3
4	-41.7 to 22.8	1.0	17.6
5	0.0 to 0.0	0.0	0.0

Similar comparisons were made for the simulated peak flows and runoff volumes results for the two sets of raingage distribution scenarios. For each scenario one through five raingages were used and the simulated results were compared against the observed values at the stream gaging site for the total watershed. Tables 6 through 9 show these comparisons.

TABLE 6. PEAK FLOW (SCENARIO #1)
PERCENT DEVIATION FROM ACTUAL RECORDED PEAKS

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-100.0 to 243.5	-26.8	87.4 Harvard only
2	-79.3 to 189.1	-1.6	66.1 Harvard & Bradley
3	-42.8 to 94.9	11.2	41.1
4	-58.6 to 73.9	-3.4	31.1
5	-59.8 to 73.2	-2.5	29.3

TABLE 7. PEAK FLOW (SCENARIO #2)
PERCENT DEVIATION FROM ACTUAL RECORDED PEAKS

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-92.7 to 77.5	-22.7	50.2 Slaven only
2	-81.7 to 72.5	-8.8	41.6 Slaven & Bethesda
3	-59.2 to 118.8	-8.0	40.2
4	-59.8 to 73.9	-4.7	30.4
5	59.8 to 73.2	-2.5	29.3

TABLE 8. RUNOFF VOLUME (SCENARIO #1)
PERCENT DEVIATION FROM ACTUAL RECORDED VOLUMES

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-98.7 to 234.8	-17.7	86.9
2	-74.0 to 169.6	-1.5	64.5
3	-23.3 to 57.6	12.9	22.3
4	-33.3 to 60.6	9.9	30.6
5	-41.3 to 60.5	5.9	29.6

TABLE 9. RUNOFF VOLUME (SCENARIO #2)
PERCENT DEVIATION FROM ACTUAL RECORDED VOLUMES

NO. OF GAGES REPORTING	RANGE	MEAN	STANDARD DEVIATION
1	-86.8 to 110.7	4.5	67.7
2	-73.9 to 83.7	0.4	43.1
3	-58.7 to 48.8	-4.1	30.4
4	-43.5 to 34.9	3.3	22.3
5	-41.3 to 60.5	5.9	29.6

Effect of Composite Type

One of the notable trends found in this study is the tendency for the composite hyetographs to somewhat underestimate peak flows and runoff volumes. The variation of peak flows from the calibrated five gage model were observed as low as -65 percent and for runoff volumes were observed as low as -20 percent. There no significant difference observed in the results between the two compositing methods investigated. This, however, may be because of the population of rainstorms used in the studies. (For example, peak intensities for most of the 17 selected storm events rarely varied in time by more than 15 minutes from the mean).

Effect of Temporal Density

All of the modeled results tabulated so far in this report was based on 5-minute time step rainfall input data. The question remaining regards how the temporal density of rainfall data will affect the modeled peak flows. For this study, continuous rainfall data collected at the five raingages over the course of 15 years from 1989 to 2004 was used with the EPA Storm Water Management Model (EPA SWMM, version 5.0). The 5-minute time step 15-year rainfall record was used in a continuous simulation, and the resulting peak flows were plotted as a probability distribution.

Next the 15-year continuous rainfall record was converted into a 15-minute time step equivalent rainfall record and a 60-minute time step equivalent rainfall record. These rainfall records were similarly used in a continuous EPA SWMM simulation. The resulting peak flows from these coarser time step rainfall records were also plotted as a probability distribution for comparison with the original 5-minute time step record.

The 5-minute time step record generated 912 peak flows, while the 15-minute record generated 899 peak flows and 60-minute record generated only 834 peaks. This indicated that the lesser temporal density of the data resulted in lesser simulated volumes. More interestingly, the magnitude of the largest peak flow for the 5-minute rainfall simulation was more than 250 percent greater than the magnitude of the largest peak flow for 60-minute simulation and 25 percent greater than the 15-minute rainfall record.

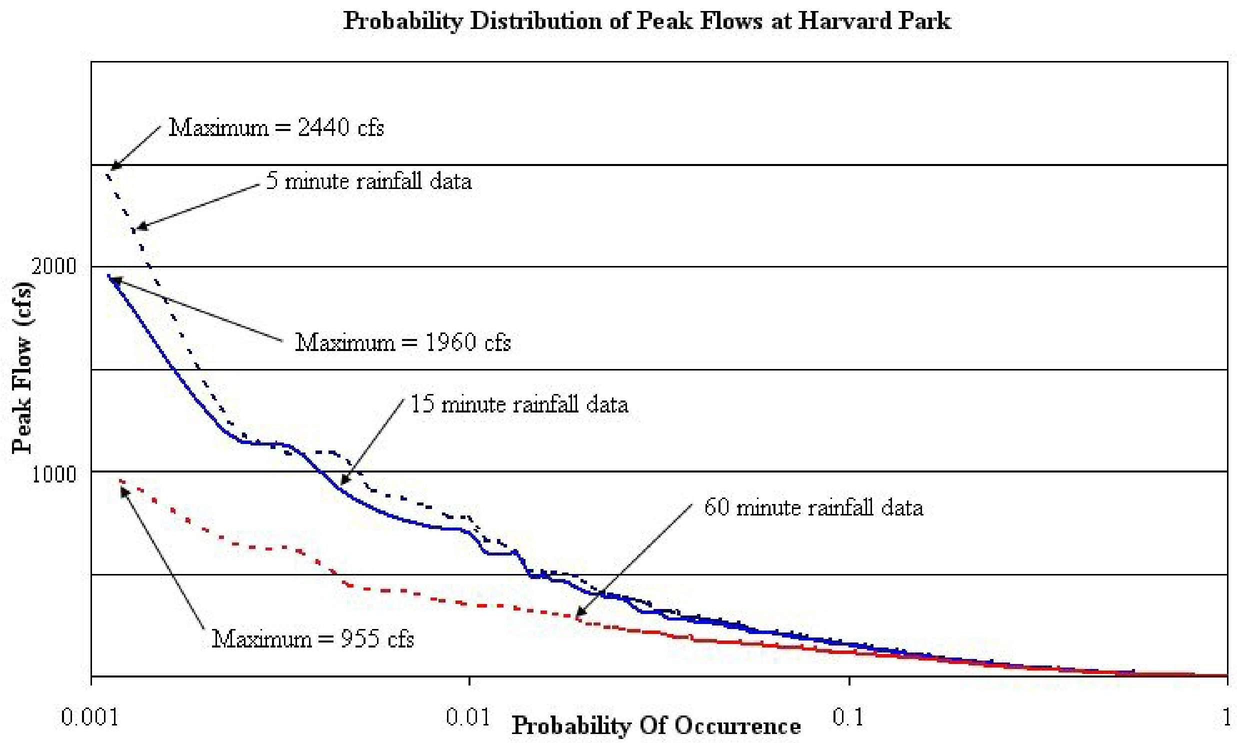

Figure 4: Probability Distribution of Peak Flows for Varying Rainfall Time Step Records

CONCLUSIONS

Regarding Raingage Density and Location

It is clear that variation of the simulated peak flows and volumes increased as the rain gage density decreased. The largest variations occurred when only one rain gage was used to represent the rainfall over the entire watershed.

The location of the raingages had a noticeable impact on how the simulated results varied from the field-observed data. This variation was largest when only one gage was used. The least amount of error occurred when the gage was located closest to the centroid of the watershed and the largest when it was located at the downstream end where the flow gage was located.

When two raingages were used, having the raingages positions near the two ends of the watershed resulted in least variances (Scenario 2). This finding implies that if two gages are used within the watershed of similar size they are best located within the upper and lower 1/3 portions of the watershed.

When comparing the simulated results to the observed data it was observed that when the gage density exceeded approximately one gage per square mile, very little change occurred in the range of variations in the results or in the standard deviation for the five-gage simulated case. Similar results were also seen when simulated results were compared to the observed values, where the variability of the simulated results did not change significantly after a density of one raingage per square mile was reached.

From these observations one can conclude that a raingage density of one raingage per square mile does not have to be exceeded to improve on the simulation results. When lesser raingage densities than one per square mile are used, the placement and distribution of the raingages can have a significant effect on the accuracy of simulated results. The authors postulate that the rainstorm footprints and the direction of the storm track across the watershed (i.e., watershed orientation relative to the track of the storm) affect the accuracy of simulated results for any given rainfall-runoff event.

In conclusion, raingage density plays a very important role in the accuracy of hydrologic modeling. At the same time, it appears that if a sufficient number of rainfall events are used, the averages of peak flows and runoff volumes can be reasonable close to the averages obtained using either multi-gage simulation results or the observed data. Although it appears that one raingage per square mile is sufficient density needed to achieve most representative simulations of rainfall-runoff events, this number will probably vary with climatologic region and the types of storms that dominate it. At the same time, judicious placement of fewer raingages (i.e., 1.5 gages per square mile) can also achieve reasonable simulations of individual events.

Although these findings are appropriate for the Denver, Colorado region, one that is dominated mostly by convective and frontal storms, it is probably not the case for other regions such as Seattle, Washington where rainfall patterns are dominated by lower intensity area-wide upslope storms.

Regarding Hyetograph Compositing Using Several Gages

Very little difference was found in peak flow and runoff volume simulations between the two rainfall compositing techniques tested. Both methods tended to underestimate the simulated peak flows and volumes when compared to field-recorded data.

Some hydrologic models require incremental rainfall depths to be composited into a single input hyetograph when more than one raingage record is available. These numerical models are then calibrated against observed data by modifying runoff coefficients and other parameters in order to increase the calculated peak flows and volumes to bring calculated values in line with observed data.

If this type of model is then used with recorded point rainfall or long-term non-composite rainfall data, the calculated peak flows and volumes are likely to be overestimated by the same percentage by which calibration parameters were adjusted to increase calculated peak flows and volumes. It is this possibility of overestimating during long term simulations that should be considered by modelers when calibrating models using composite hyetographs, particularly when studying larger urban watersheds.

Regarding Temporal Density of Rainfall Record

Raingage data collected on a 60-minute time step, or even a 15-minute time step will not capture the true characteristics of a rainfall event of rapidly varying intensity, and will result in peak flow simulations using long-term continuous simulation procedures that result in considerably lower peak flow and runoff volume populations than those resulting from 5-minute or lesser time step rainfall records. This in turn can result in misleading conclusions on the design of real time control, the design of stormwater control basins and needed volumes, and on the effects on the receiving stream hydrology. When modeling runoff in a region where the majority of storms are of this nature, the modeler should consider this phenomenon, use 5-minute rainfall data when available (and rainfall records with 15-minute time increments when 5-minute data is not available), and calibrate the model accordingly. When modeling in regions where rainfall patterns are dominated by low intensity area-wide upslope storms, coarser rainfall records may provide an adequate basis for long-term continuous simulation.

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