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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 gages, all in 5-minute time increments. This data were used to calibrate Urban Drainage and Flood Control District's version of EPA SWMM (v.2) model, namely, UDSWM. The calibrated model served two purposes; first, to examine the effects on runoff calculations using a single composite hyetograph for each of the 17 storms modeled and second, to determine the effects of raingage density on volume of runoff and peak flow simulations. The effects of raingage density were also investigated by processing several different combinations of raingage densities with the calibrated UDSWM model. This paper describes the findings of this study and discusses their implications for urban stormwater runoff modeling.

INTRODUCTION

The question that keeps arising is whether hydrologic computer modeling appropriately accounts for the temporal and spatial variations in rainfall patterns that occur in nature. If only one raingage record is used to represent the rainfall in a watershed, any given storm could easily concentrate its main intensities near the raingage and totally miss most of the watershed altogether. The resulting runoff-to-rainfall 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.

Some of the questions that arise and need better answers are:

- Does this rainfall/runoff ratio become more constant when raingage density increases?
- And what about those hydrologic models that require compositing of multi-gage rainfall hyetographs into a single rainfall hyetograph input record, such as the CUHP and TR-55 models?
- How does compositing or several rainfall records affect the calculated surface runoff?
- Is there a compositing technique that yields more realistic results?

Much of what is written about the effects of raingage density and hyetograph compositing methods in runoff modeling revolves around synthetically manufactured hyetographs, namely, design storms. The authors were fortunate to have access to eight years of finely incremented (i.e., 5-minute time step) simultaneous rainfall and runoff records for a relatively small and stable urban watershed with a high raingage density. This paper attempts to show both the variance in runoff calculations that 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.

PREVIOUS INVESTIGATIONS

Very little research has been done in compositing simultaneous rainfall records into single model input hyetographs and their effect on calculated stormwater discharges. The same is true for raingage density. An investigation of hyetograph compositions by Avon, Collins and Kibler (1974) was performed for a smaller watershed using two hypothetical, four time increment hyetographs. They recommended

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adopting the hyetograph pattern from one gage and compositing hyetographs using a peak pattern preservation technique. The results from the authors' study reported in this paper using much more detailed simultaneous rainfall-runoff records appear not to support their conclusion.

RAINFALL AND RUNOFF GAGES USED BY THIS STUDY

Rainfall/runoff data recorded between 1979 and 1987 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 2-flow gages and 5-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, which punch the data on 16-channel paper tape at 5-minute intervals. The locations of all gages are shown in Figure 1a, 1b and 1c that also depict the study watershed, its land uses, its major drainageway network, UDSWM catchments and UDSWM conveyance elements used to model this watershed.

Flow Gage

1. HARVARD GULCH AT COLORADO BOULEVARD:

USGS Gage Number 06711570. Location: Latitude 39o40'08", longitude 104o56'32", in SE1/4 SE1/4 section 30, Township 4 S., Range 67 W. Denver City and County, on left bank 100ft (30m) upstream from S. Jackson St. and 400 ft (122m) north of E. Yale Ave. Digital flood-hydrograph recorder. This catchment drains residential area 1.12 mi^2.

2. HARVARD GULCH AT HARVARD PARK:

USGS Gage Number 06711575. Location: Latitude 39o40'21", longitude 104o58'35", in NW1/4 SW1/4 section 26 Township 4 S., Range 68W. Denver City and County, on left bank of Harvard Gulch 200 ft (61m) north of E. Harvard Ave. and 300 ft (91m) west of S. Ogden St., directly north of Porter Hospital. Gage records flood-hydrograph and rainfall records (dual digitals). Tributary watershed is a mix of residential and commercial land uses having an area of 3.08 mi^2.

Rain Gage

1. HARVARD GULCH AT BRADLEY SCHOOL:

USGS Gage Number 393947104555101. Location: Latitude 39o39'48", longitude 104o55'50", in SE1/4 NE1/4 section 31 Township 4 S., Range 67W. Denver City and County, on east side of S. Dahlia St. against the Bradley School ground fence, 2640 ft (804 m) south of E. Yale Ave.

2. HARVARD GULCH AT BETHESDA HOSPITAL:

USGS Gage Number 394028104560201. Location: Latitude 39o40'28", longitude 104o56'02", in SE1/4 NW1/4 section 30 Township 4 S., Range 67W. Denver City and County, on the north edge of a parking lot 300 ft (91 m) east of hospital entrance at East Iliff and Cherry Street.

3. HARVARD GULCH AT UNIVERSITY PARK SCHOOL:

USGS Gage Number 394028104565501. Location: Latitude 37o40'28", longitude 104o56'55", in NW1/4 SE1/4 section 25 Township 4 S., Range 67W. Denver City and County on the school grounds next to the parking lot, 30 ft south of East Iliff and 1 block east of S. St Paul St. Established 1981.

4. HARVARD GULCH AT SLAVEN SCHOOL:

USGS Gage Number 393938104572101. Location: Latitude 39o39'38", longitude 104o57'21", in SW1/4 NW1/4 section 36 Township 4 S., Range 68W. Denver City and County on north side of East Dartmouth, 30 ft. west of S. Clayton St.

5. HARVARD GULCH AT HARVARD PARK:

(See Flow Gage Above - Item #2)

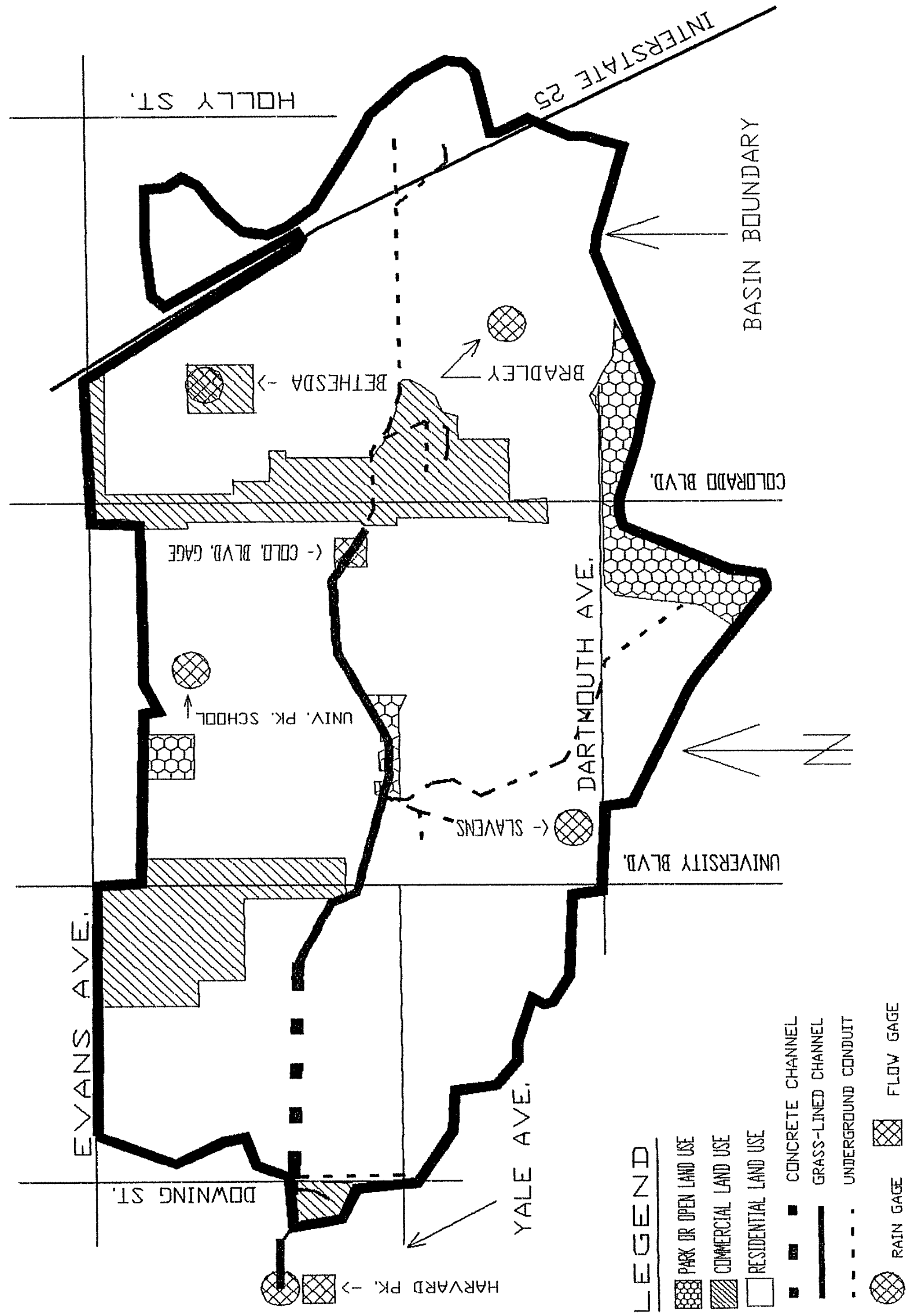

Figure 1a. Harvard Gulch Catchment Land Use and Raingage Location Map.

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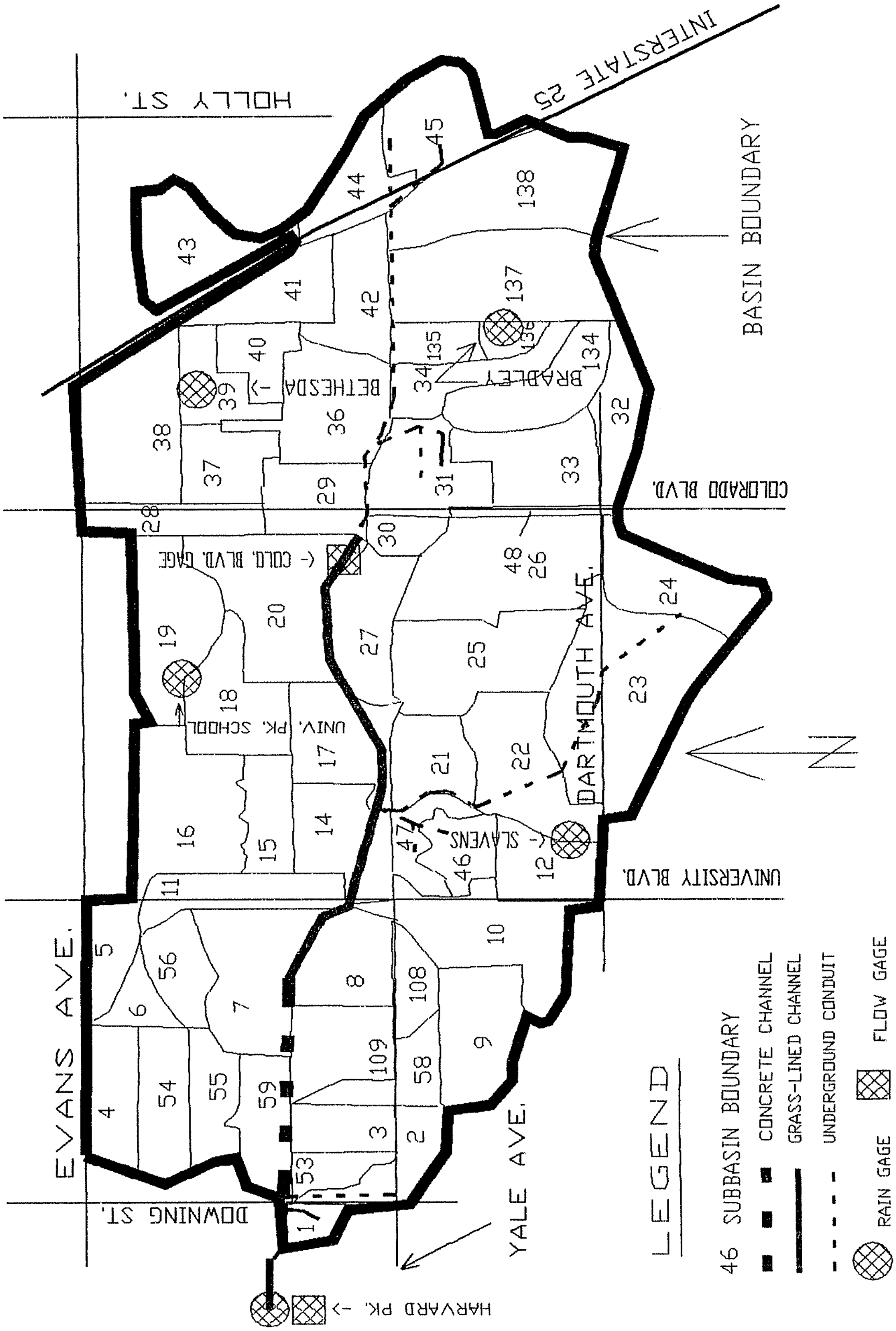

Figure 1b. Harvard Gulch UDSWM Sub-Catchments.

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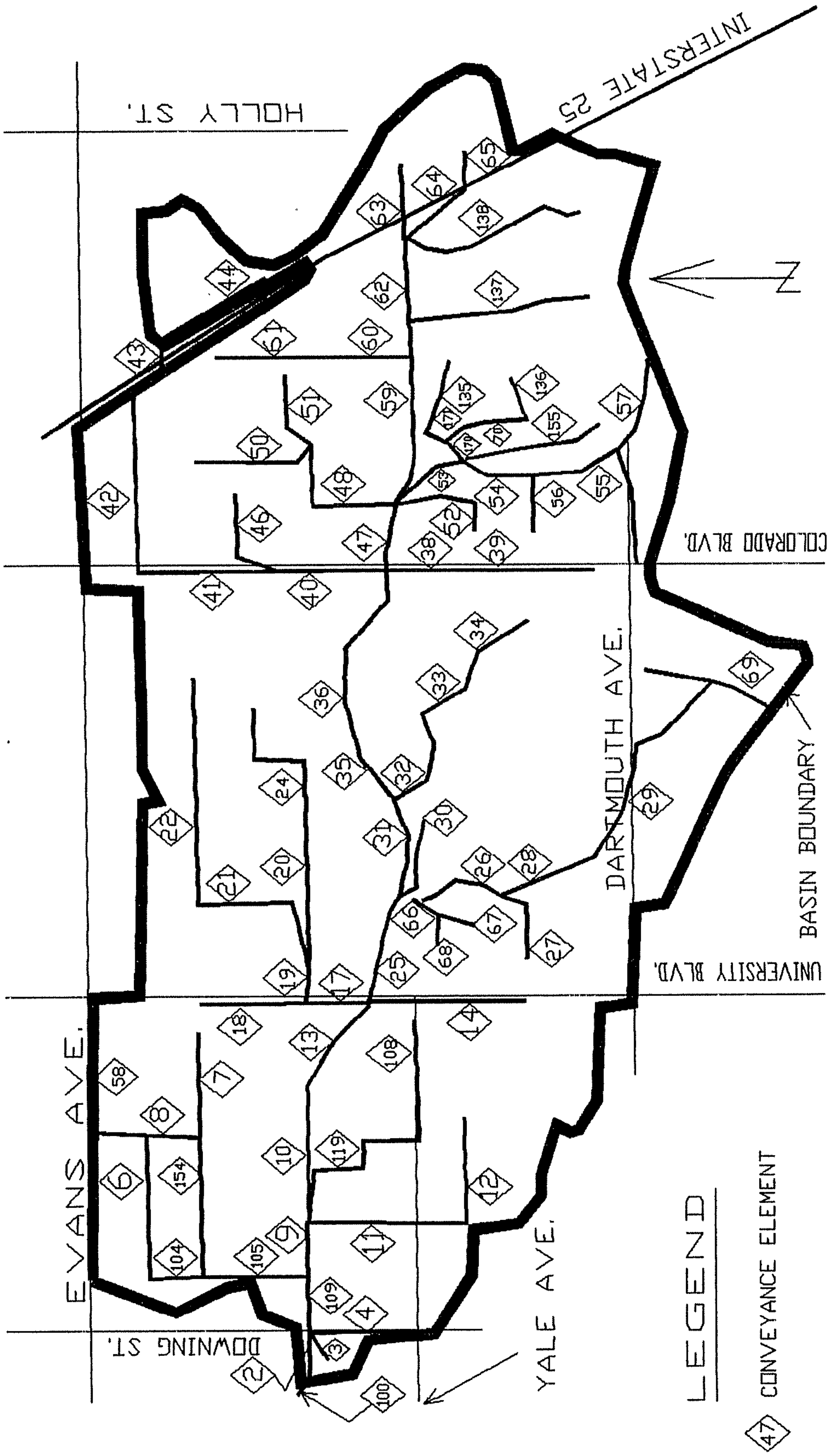

Figure 1c. Harvard Gulch UDSWM Conveyance Elements.

VERIFICATION AND ADJUSTMENT OF USGS RATING CURVES

Initial Runoff Volume Analyses

Initial verification of runoff volumes for lower (at Harvard Park) and upper (at Colorado Blvd) watershed flow gages was performed. All storms within the eight-year record that had a minimum peak flow of 50 CFS and a minimum rainfall depth of 0.08 inches in any 5-minute period at either gage were used in the initial analysis. Forty-eight events between August '79 and September '87 met these criteria. Summaries of the data from these events are listed in Table 1.

The Thiessen Polygon method was used to identify what fraction of the total watershed each raingage was assumed to cover. These resulting weighting factors varied between some of the events, as not all gages were operating during all of the forty-eight events. The total weighted rainfall depth for the entire watershed was calculated for each rainstorm incremental rainfall depths during the event by multiplying the depth at each gage by its appropriate weighting factor and them summing them for that increment it time. Table 2 shows the area weighting factors used for each raingage when different combinations of gages were in operation.

Calculating the volume under each storm runoff hydrograph and dividing it by the tributary area produced the total runoff inches for each of the storm events. Hydrographs for which data points were truncated on the receding limb were extrapolated using semi log - log paper (Time vs. log of Flow). Runoff-volume to Rainfall-volume ratio pairs were plotted against Rainfall inches for both total and upper watersheds. Data regression was performed to arrive at a best-fit line to graphically represent each watershed's runoff coefficient.

Harvard Gulch at Harvard Park and Harvard Gulch at Colorado watersheds were found to have runoff coefficients of 0.15 and 0.34 respectively (see Figures 2 and 3). The upper watershed had a coefficient that appeared to be within a reasonable range for the land uses within it. However, the total watershed tributary to the gage at Harvard Park had a coefficient that was clearly too low for its land uses. Because of this finding it was decided to test the validity of each flow gage-rating curve at this location.

New channel Cross Sections

Fourteen channel cross-sections were surveyed in a 250 foot stretch both upstream and downstream of the Colorado Boulevard flow gage site. Sixteen channel cross-sections were taken in an 850-foot reach at the Harvard Park flow gage site.

Retardance Curve Interpolations for Incremental Stage Values of Manning's n.

Each cross section was divided into 4 or 5 horizontal sections by major changes in topography or grass type. Within each horizontal section 3 vertical divisions (i.e. Left channel, Right channel, and Center channel) were created beginning with the horizontal section directly above the trickle channel. A slope of 1:1 reduced the effects of a vertical boundary of the central channel as water depth increased. Incremental values for Manning's *n* were then developed using the U.S. Soil Conservation Service Vegetal Retardance "*n* vs. *VR*" curve B for high vegetal retardance.

HEC-2 Backwater Curve Calculations

The U.S. Army Corp of Engineers' HEC-2 program was used to calculate backwater curve profiles via the Standard Step Method for both flow gage sites. To verify the elevation datum of the cross-sections relative to the flow gage readings, a bucket of water was placed under each flow gage until a reading was observed on the flow gage stage indicator. This reading was recorded along with the corresponding water surface elevation on the flow gage tube. By processing several different flows ranging from 50 to 1000 CFS with the HEC-2 program and recording the corresponding backwater elevation on the flow gage tube, a set of stage-discharge rating curves were developed and compared with the existing USGS rating curves for both gages.

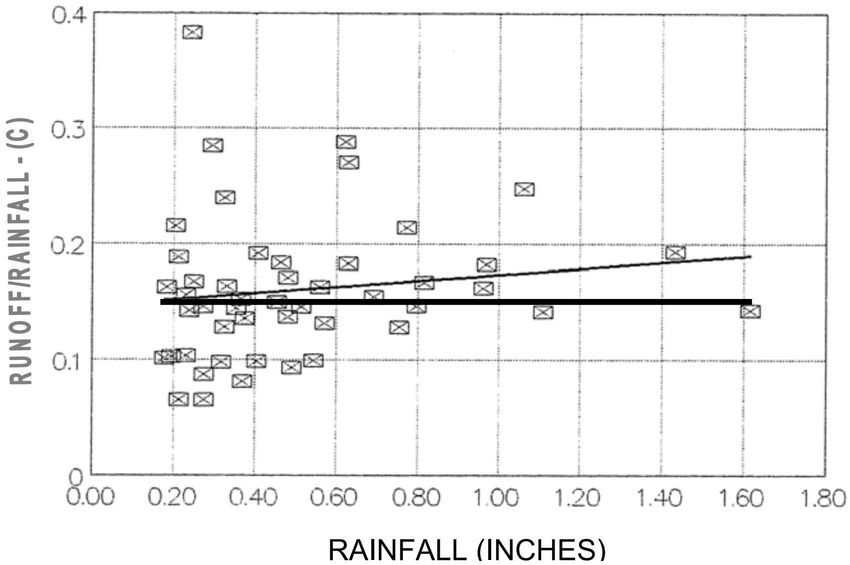

Figure 2. Initial Runoff Coefficient Analysis – Harvard Gulch at Harvard Park

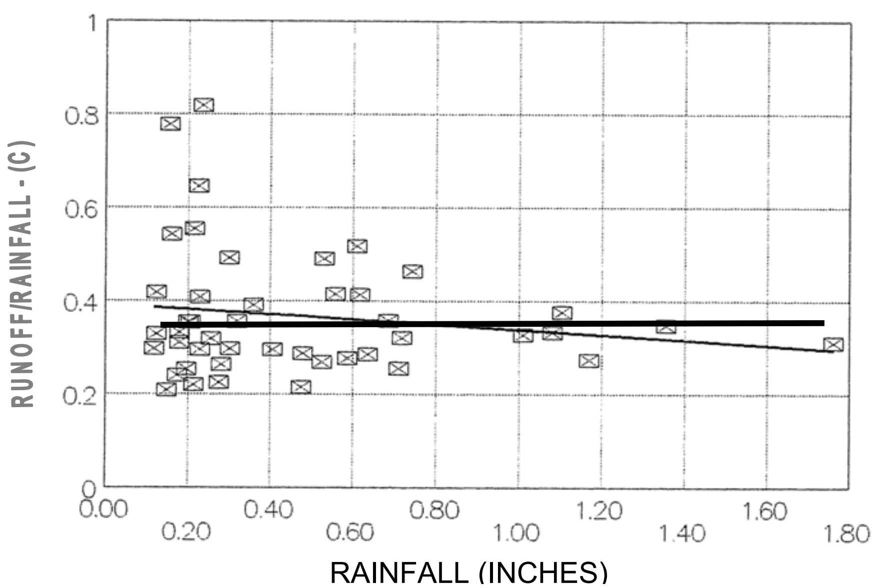

Figure 3. Initial Runoff Coefficient Analysis – Harvard Gulch at Colorado Blvd.

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TABLE 1 INITIAL SUMMARY ANALYSIS OF RAINFALL/RUNOFF AT HARVARD GULCH

	Cumulative Rainfall in Inches					Weighted Rain(in.)	
DATE OF EVENT	H. PARK (1)	SLAVEN (2)	BETHESDA (3)	BRADLEY (4)	U.PK.SCH (5)	@ COLO. (3.4)	@ H.PARK (ALL 5)
16-Aug-79	0.62	0.57	0.11	NO DATA	NO GAGE	0.710	0.628
01-May-80	0.40	0.33	0.25	0.19	NO GAGE	0.216	0.295
10-Jul-80	0.24	NO GAGE	0.31	0.18	NO GAGE	0.236	0.243
14-Aug-80	0.67	NO GAGE	0.53	0.67	NO GAGE	0.610	0.621
25-Aug-80	0.59	NO GAGE	0.22	0.23	NO GAGE	0.226	0.331
03-May-81	0.33	0.54	0.43	0.46	NO DATA	0.447	0.463
28-May-81	0.83	0.96	1.13	0.92	1.35	1.010	1.062
12-Jul-81	0.51	0.65	0.63	0.83	0.51	0.744	0.628
17-Jul-81	0.16	0.32	0.16	0.15	0.21	0.154	0.213
13-May-82	0.09	0.25	NO DATA	0.23	0.20	0.230	0.205
17-Jun-82	0.17	0.16	NO DATA	0.16	0.24	0.160	0.184
24-Jun-82	0.58	0.56	NO DATA	0.36	0.53	0.360	0.481
28-Jul-82	0.36	0.55	0.11	0.49	NO DATA	0.352	0.401
29-Jul-82	0.66	0.95	0.68	0.67	NO DATA	0.674	0.172
04-Jun-83	0.29	0.47	0.27	0.20	0.33	0.230	0.326
05-Jun-83	0.26	0.58	0.81	0.47	1.12	0.616	0.691
12-Jun-83	0.22	0.39	0.18	GAGE	0.26	0.180	0.251
26-Jun-83	0.34	0.14	0.30	0.00	0.57	0.300	0.326
26-Jun-83	0.73	0.00	0.96	0.00	1.08	1.080	0.969
30-Jul-83	0.49	GAGE	0.73	0.38	1.20	0.531	0.755
05-Aug-83	0.66	1.45	1.67	1.83	1.36	1.761	1.433
20-Aug-83	0.81	0.58	0.22	0.95	0.22	0.636	0.544
26-Aug-83	0.20	0.15	0.17	0.09	0.64	0.124	0.275
04-Sep-83	0.16	0.30	0.05	0.18	0.20	0.124	0.194
17-May-85	0.30	0.52	0.25	0.65	0.24	0.478	0.404
02-Jun-85	0.27	0.24	0.22	0.21	0.16	0.214	0.214
03-Jun-85	0.20	0.35	0.27	0.28	0.24	0.276	0.276
18-Jul-85	0.12	0.41	0.44	0.59	0.24	0.526	0.369
19-Jul-85	1.86	0.69	1.47	0.94	3.02	1.168	1.615
19-Jul-85	0.62	1.40	1.08	1.12	1.07	1.103	1.109
23-Ju1-·85	0.32	0.27	0.32	0.11	0.66	0.200	0.353
31-Aug-85	0.28	0.16	0.20	0.21	0.31	0.206	0.231
01-Sep-85	0.32	0.16	0.22	0.04	0.44	0.117	0.239
11-Sep-85	0.10	0.24	0.70	0.50	0.33	0.586	0.366
11-Apr-86	GAGE	0.90	0.28	0.35	0.56	0.320	0.570
08-Jun-86	GAGE	GAGE	0.40	0.19	0.20	0.280	0.231
16-Jun-86	0.64	GAGE	0.36	0.44	0.58	0.406	0.514
19-Jun-86	GAGE	GAGE	0.28	0.24	0.37	0.257	0.317
20-Jul-86	0.60	0.43	0.56	0.41	0.48	0.475	0.481
09-Jun-87	0.47	0.26	0.20	0.11	0.36	0.149	0.274
08-Jun-87	0.61	0.47	1.28	1.41	1.10	1.354	0.962
05-Sep-87	0.95	0.63	0.06	0.27	0.54	0.180	0.491
26-Aug-87	0.37	0.63	0.18	0.21	GAGE	0.197	0.376
25-Aug-87	0.11	0.16	0.26	0.11	GAGE	0.175	0.177
24-Aug-87	0.60	0.61	0.28	0.32	GAGE	0.303	0.453
29-Jun-87	0.31	0.36	0.90	0.58	0.67	0.718	0.559
23-May-87	0.17	1.14	0.66	0.48	1.16	0.557	0.815
14-May-87	0.23	0.75	0.76	0.63	1.28	0.686	0.798

TABLE 1 (continued)

DATE OF EVENT	Runoff Volume (In.)		Revised Runoff Volume(In)/Rain(In)			Rev. r.o. Vol. (In)	Recorded Peak Flow (CFS)		Revised Flow
	COLO.	H PARK	H PARK	COLO.	H PARK	H PARK	COLO.	H PARK	H PARK
16-Aug-79	0.181	0.170	0.259	0.255	0.271	0.413	181	227	313
01-May-80	0.120	0.084	0.135	0.556	0.285	0.458	51	112	155
10-Jul-80	0.193	0.093	0.169	0.818	0.383	0.696	157	65	98
14-Aug-80	0.316	0.179	0.276	0.518	0.288	0.444	240	271	377
25-Aug-80	0.146	0.054	0.101	0.647	0.163	0.305	141	41	69
03-May-81	No Data	0.085	0.132	No Data	0.184	0.285	No Data	153	223
28-May-81	0.332	0.263	0.352	0.329	0.248	0.331	395	672	737
12-Jul-81	0.345	0.115	0.184	0.464	0.183	0.293	225	187	268
17-Jul-81	0.120	0.040	0.079	0.778	0.188	0.372	88	35	61
13-May-82	0.094	0.044	0.080	0.409	0.215	0.391	100	61	93
17-Jun-82	0.087	0.030	0.059	0.544	0.163	0.321	169	28	54
24-Jun-82	0.141	0.082	0.132	0.392	0.171	0.275	177	96	136
28-Jul-82	No Data	0.078	0.121	No Data	0.192	0.297	No Data	103	144
29-Jul-82	No Data	0.165	0.258	No Data	0.214	0.334	No Data	214	302
04-Jun-83	0.068	0.042	0.076	0.296	0.129	0.233	125	52	82
05-Jun-83	0.255	0.101	0.172	0.414	0.155	0.249	268	181	260
12-Jun-83	0.060	0.042	0.076	0.333	0.168	0.303	105	48	77
26-Jun-83	0.148	0.078	0.130	0.493	0.240	0.399	141	115	159
26-Jun-83	0.359	0.177	0.275	0.332	0.183	0.284	179	202	287
30-Jul-83	0.261	0.097	0.145	0.492	0.129	0.192	318	244	339
05-Aug-83	0.547	0.277	0.395	0.311	0.193	0.276	410	519	614
20-Aug-83	0.182	0.054	0.089	0.286	0.099	0.164	208	112	155
26-Aug-83	0.041	0.024	0.046	0.330	0.087	0.167	82	32	58
04-Sep-83	0.052	0.020	0.039	0.419	0.103	0.201	108	27	52
17-May-85	0.137	0.040	0.066	0.287	0.099	0.163	145	79	115
02-Jun-85	0.047	0.014	0.027	0.219	0.065	0.126	96	27	51
03-Jun-85	0.062	0.018	0.034	0.225	0.065	0.123	112	43	11
18-Jul-85	0.141	0.030	0.049	0.268	0.081	0.133	203	88	126
19-Jul-85	0.320	0.231	0.299	0.274	0.143	0.185	350	425	772
19-Jul-85	0.415	0.157	0.220	0.376	0.142	0.198	392	720	530
23-Jul-85	0.071	0.051	0.083	0.354	0.144	0.235	119	85	122
31-Aug-85	0.073	0.036	0.065	0.355	0.156	0.282	141	52	82
01-Sep-85	0.035	0.034	0.066	0.298	0.142	0.277	53	49	78
11-Sep-85	0.163	0.056	0.088	0.278	0.153	0.240	240	124	170
11-Apr-86	0.114	0.075	0.115	0.356	0.132	0.202	91	104	145
08-Jun-86	0.074	0.024	0.043	0.264	0.104	0.186	137	56	87
16-Jun-86	0.120	0.075	0.119	0.296	0.146	0.232	139	127	173
19-Jun-86	0.082	0.031	0.054	0.319	0.098	0.170	139	71	105
20-Jul-86	0.102	0.066	0.115	0.215	0.137	0.239	75	55	86
09-Jun-87	0.031	0.040	0.069	0.208	0.146	0.252	45	66	99
08-Jun-87	0.471	0.156	0.224	0.348	0.162	0.233	335	285	386
05-Sep-87	0.056	0.046	0.074	0.312	0.094	0.151	110	98	138
26-Aug-87	0.050	0.051	0.082	0.254	0.136	0.218	82	80	116
25-Aug-87	0.042	0.018	0.035	0.241	0.102	0.198	58	33	59
24-Aug-87	0.090	0.068	0.104	0.297	0.150	0.230	147	114	157
29-Jun-87	0.231	0.091	0.152	0.322	0.163	0.272	149	58	136
23-May-87	0.232	0.136	0.197	0.416	0.167	0.242	282	372	478
14-May-87	0.246	0.117	0.175	0.359	0.147	0.219	257	215	304

TABLE 2 RAIN GAGE WEIGHTING FACTORS VIA THIESSEN POLYGON METHOD

GAGES REPORTING					WEIGHING FACTOR IN PERCENT				
1	2	3	4	5	1	2	3	4	5
X	X	X	X	X	13.0	26.0	15.0	20.0	26.0
	X	X	X	X		31.0	16.0	24.0	29.0
X		X	X	X	17.0		15.0	31.0	37.0
X	X		X	X	15.0	20.0		37.0	28.0
X	X	X		X	14.0	23.0	42.0		21.0
X	X	X	X		14.0	36.0	27.0	23.0	
X		X		X	19.0		37.0		44.0
X		X	X		29.0		35.0	36.0	
X		X			33.0		67.0		
		X	X	X			17.0	29.0	54.0
		X	X				43.0	57.0	
X	X[2]	X	X		16.0	44.0[2]	16.0	24.0	
X	X[2]	X			17.0	48.0[2]	35.0		

Gage Locations:
1. Harvard Park 2. Slaven 3. Bethesda 4. Bradley 5. University Park

Adjustment of USGS Rating Curves

Based on the results obtained from HEC-2 output and field recorded flow values, adjustments were made to the Harvard Park rating curve. USGS flow values were found to be too low for corresponding gage heights. Three regression equations were developed using the filed data and HEC-2 runs to bring all recorded USGS flow data in line with the revised rating curve. The regression equations were as follows:

When USGS flows X	Adjusted flow Y is given by
<= 20	$Y = 2X$
$20 < X < 150$	$Y = 1.193X + 14.613X^{0.08} + 0.048$
>= 150	$Y = 44.342X - 40.445X^{1.01} - 54.154$

In which, X = USGS flow (cfs) and Y = Adjusted flow (CFS)

The revised runoff/rainfall ratios vs. rainfall results indicate that average runoff coefficient for the Harvard Gulch at Harvard Park watershed is approximately 0.25. This value was judged to be more representative than the 0.15 obtained using uncorrected flow data. No adjustments were made to the Colorado Boulevard flow gage-rating curve.

SELECTION AND PREPARATION OF ANALYSIS DATA

Minimum Rainfall & Runoff Criteria for this Study

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 CFS.

Preparation of UDSWM Model

Stormwater drainage system maps from Denver Wastewater Control Division provided the initial basis for both sub-catchment definitions and the definitions of drainage system networks. Major catchment boundaries and the degree of imperviousness were field verified by UDFCD personnel in 1979 and 1980.

As illustrated in Figures 1b, the Harvard Gulch watershed was sub-divided into 59 sub-catchments. Of this number, 23 were for the upper watershed tributary to the gage at Colorado Boulevard. Average values for imperviousness, slope, tributary width, Manning's *n*, etc. were calculated for each sub-catchment area and were input into the UDSWM model.

The drainage conveyance element layout, which consisted of 78 conveyance elements, 35 providing drainage for the upper watershed is illustrated in Figure 1c. Conveyance elements 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 field verified conditions, namely the sump area at Yale Avenue and Colorado Boulevard.

The Thiessen Polygon Method was used to assign each sub-catchment to a specific raingage. Raingage assignments to sub-catchments for two separate simulation scenarios are listed in the UDSWM model input.

Calibration of UDSWM Model

Two separate models were created for the Harvard Gulch Watershed, namely an upper and a total watershed model. The upper watershed model consisted of the watershed area east of Colorado Blvd. Each one of the 17 selected storms was processed through the UDSWM model for both watersheds. Calculated runoff volumes and peak discharges were plotted against observed values. Data regression was used to draw a best-fit line through plotted points. Adjustments were made to pervious, imperviousness, Manning's n, sub-catchment tributary width, etc. values and the model was rerun for each of the 17 storms, until each best-fit line approximated 45 degrees between modeled results and recoded data for both peak flows and runoff volumes in each watershed. These UDSWM Model calibration results are shown in Figures 4a, 4b, 5a and 5b for the Colorado Boulevard and Harvard Park gaging sites respectively.

USE OF CALIBRATED SWMM MODEL

Investigating the Effects of Raingage Density

For the total watershed, five increasing raingage density combinations were used to show the effects of raingage density on peak flow and runoff volumes. Two different scenarios of these five-gage combinations were simulated. For the upper watershed, three combinations of rain gage conditions were simulated. All these simulation scenarios are shown Tables 3.

Again the Thiessen Polygon Method was applied to assign each sub-catchment to a specific raingage for each of the above-specified conditions. The complete list of rain gage assignments to sub-catchments can be found in the model input file.

Normalized values of deviations from the calibrated 5 rain gage (2 gage at Colorado Blvd) SWMM values for peak flow 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 SWMM Model vs. 1 through 4 gage for both scenarios and (2) actual recorded data vs. 1 through 5 gage calibrated SWMM 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 volume for storm i, Ri - runoff peak or volume for the test run for storm i, Rci = runoff peak or volume for calibrated model or recorded data for storm i.

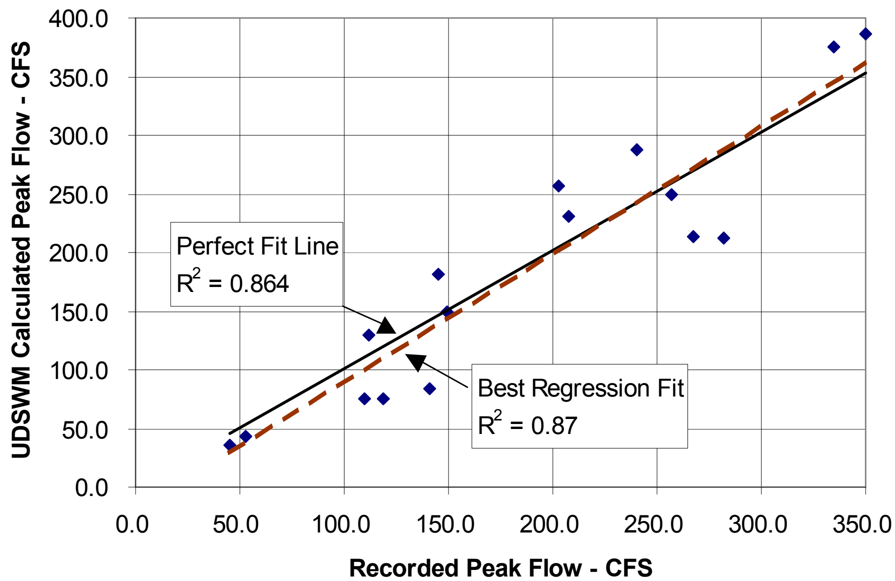

Figure 4a. Calibration of UDSWM to Peak Flows at Colorado Boulevard Gage.

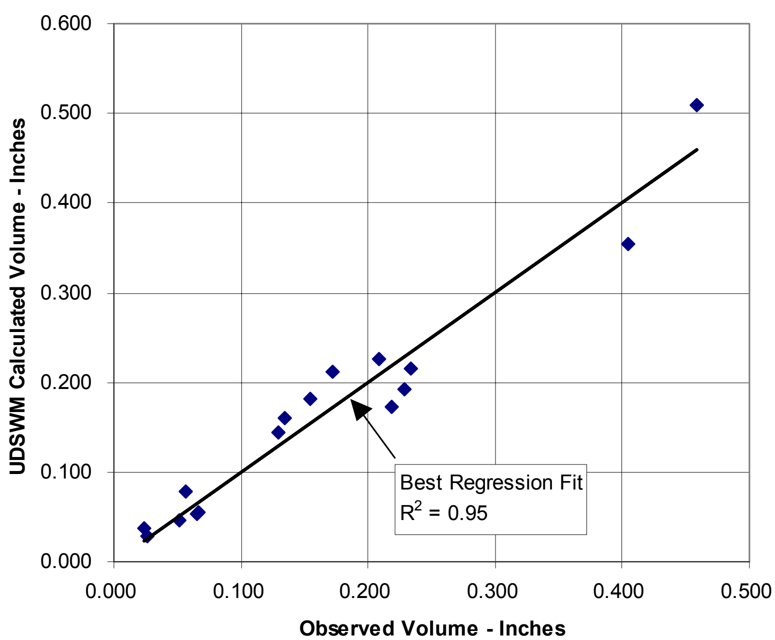

Figure 4b. Calibration of UDSWM to Runoff Volume at Colorado Boulevard Gage.

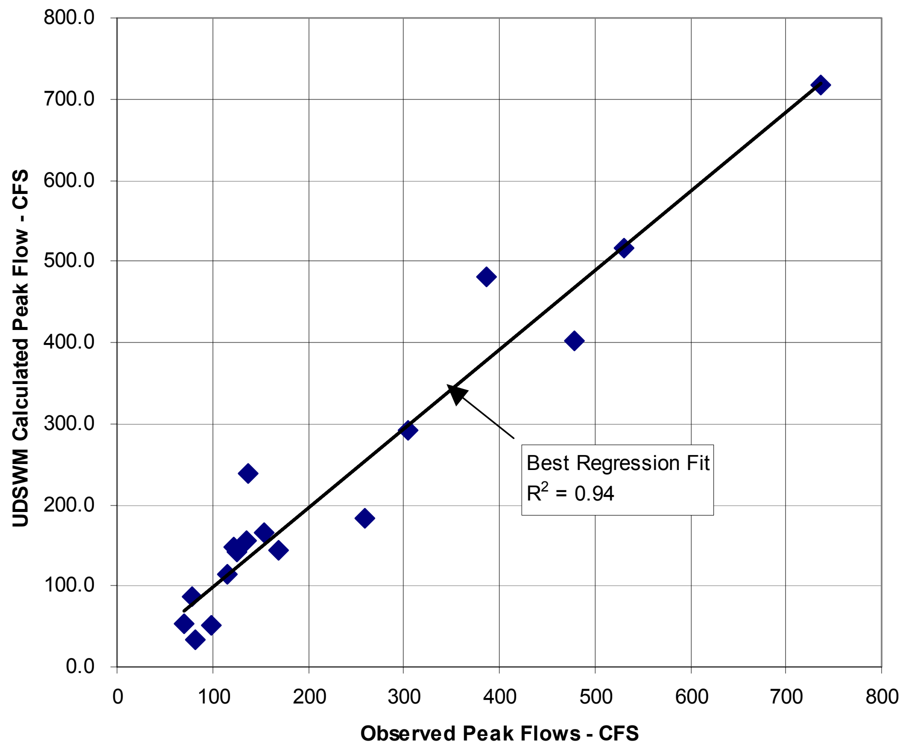

Figure 5a. Calibration of UDSWM to Peak Flows at Harvard Park Gage.

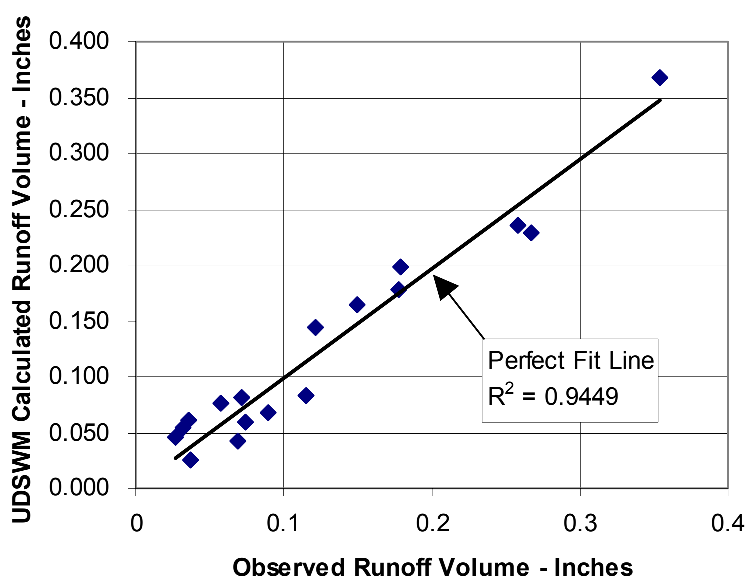

Figure 5b. Calibration of UDSWM to Runoff Volume at Harvard Park Gage.

TABLE 3. GAGES SIMULATING RUNOFF UNDER DIFFERENT GAGE AVAILABILITY SCENARIOS.

GAGES USED TO MODEL ***SCENARIO #1*** FOR THE TOTAL WATERSHED TRIBUTARY TO HARVARD PARK					
Run Number	Harvard Park	Bradley	University Park	Slaven	Bethesda
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**
GAGES USED TO MODEL THE UPPER WATERSHED TRIBUTARY TO COLORADO BLVD.					
1		**X**			
2					**X**
3		**X**			**X**

Composite Type Comparisons

Peak preservation and across composite type comparisons of recorded hyetographs at multiple gages were performed for the upper watershed and for the total watershed. The Thiessen Polygon Method was used to assign a weighting factor to each raingage hyetograph record and transform incremental rainfall from each raingage into one combined composite storm. Each storm was processed through the upper and total watershed calibrated UDSWM Model.

Hydrograph Comparisons

For both upper and lower watersheds the following hydrograph comparisons were made using eight storms:

1. UDSWM simulated flows at Harvard Park calibrated using all 5 raingages (and at Colorado Blvd. Calibrated using 2 raingages) vs. field observed hydrographs.
2. UDSWM simulated flows at Harvard Park calibrated using all 5 raingages (or flow at Colorado Blvd. Calibrated using 2 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 4 and 5 compare the simulated peak flows and Tables 6 and 7 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. Similar comparisons are shown in Tables 8 and 9 for the upper watershed, except here the comparisons are against the two gage 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 4. HARVARD GULCH AT HARVARD PARK - PEAK FLOW (SCENARIO #1)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN PEAK FLOWS

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 5. HARVARD GULCH AT H. PARK - PEAK FLOW (SCENARIO #2)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN PEAK FLOWS

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 6. HARVARD GULCH AT H. PARK - RUNOFF VOLUME (SCENARIO #1)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN VOLUMES

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 7. HARVARD GULCH AT H. PARK - RUNOFF VOLUME (SCENARIO #2)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN VOLUMES

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

TABLE 8. HARVARD GULCH AT COLORADO BLVD. - PEAK FLOW
PERCENT DEVIATION FROM 2 GAGE CALIBRATED RUN PEAK FLOWS

REPORTING GAGE	RANGE	MEAN	STANDARD DEVIATION
Bethesda	-90.7 to 146.5	11.5	58.1
Bradley	-93.0 to 60.0	-6.6	39.3

TABLE 9. HARVARD GULCH AT COLORADO BLVD. - RUNOFF VOLUME
PERCENT DEVIATION FROM 2 GAGE CALIBRATED RUN VOLUMES

REPORTING GAGE	RANGE	MEAN	STANDARD DEVIATION
Bethesda	-84.8 to 106.9	5.7	47.5
Bradley	-82.8 to 67.4	-4.7	37.2

Similar comparisons for the total Harvard Gulch watershed are 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 upper gaging site and the gaging site for the total watershed. Tables 10 and 13 show these comparisons, while Tables 14 and 15 provide similar comparisons for the upper watershed.

TABLE 10. HARVARD GULCH AT H. PARK - 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 Park only
2	-79.3 to 189.1	-1.6	66.1 Harvard Park & 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 11. HARVARD GULCH AT H. PARK - 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 7.12. HARVARD GULCH AT H. PARK - RUNOFF VOLUMES (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 7.13. HARVARD GULCH AT H. PARK - RUNOFF VOLUMES (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

TABLE 7.14. HARVARD GULCH AT COLORADO BLVD. - PEAK FLOW
PERCENT DEVIATION FROM ACTUAL RECORDED PEAKS

REPORTING GAGE	RANGE	MEAN	STANDARD DEVIATION
Bethesda	-93.6 to 100.0	1.1	44.6
Bradley	-94.3 to 84.1	-7.6	48.4
2-Gage	-40.4 to 26.6	-4.6	22.2

TABLE 7.15. HARVARD GULCH AT COLORADO BLVD. - RUNOFF VOLUMES
PERCENT DEVIATION FROM ACTUAL RECORDED VOLUMES

REPORTING GAGE	RANGE	MEAN	STANDARD DEVIATION
Bethesda	-86.3 to 130.8	11.7	56.2
Bradley	-80.8 to 89.0	1.0	44.1
2-Gage	-21.0 to 54.2	5.9	21.3

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. This is shown in Tables 16 and 19. The variation of peak flows from the calibrated five gage model were observed as low as -65 percent (-28 percent for upper watershed model) and for runoff volumes were observed as low as -20 percent (-10 percent for upper watershed model). Standard deviations and the mean for composite type comparisons are also shown in these tables. There was very little 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).

TABLE 16. HARVARD GULCH AT H. PARK - PEAK FLOW (COMPOSITE TYPES)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN

COMPOSITE TYPE	RANGE	MEAN	STANDARD DEVIATION
Peak Preservation	-65.1 to 4.9	-17.4	18.1
Across	-60.5 to 9.7	-16.7	18.0

TABLE 17. HARVARD GULCH AT H. PARK - RUNOFF IN. (COMPOSITE TYPES)
PERCENT DEVIATION FROM 5 GAGE CALIBRATED RUN

COMPOSITE TYPE	RANGE	MEAN	STANDARD DEVIATION
Peak Preservation	-18.8 to 9.0	-3.3	7.7
Across	-20.1 to 9.0	-2.8	7.6

TABLE 18. HARVARD GULCH AT CO. BLVD. - PEAK FLOW (COMPOSITE TYPES)
PERCENT DEVIATION FROM 2 GAGE CALIBRATED RUN

COMPOSITE TYPE	RANGE	MEAN	STANDARD DEVIATION
Peak Preservation	-27.9 to 9.3	-2.7	10.1
Across	-23.3 to 9.1	-1.1	7.4

TABLE 19. HARVARD GULCH AT CO. BLVD. - RUNOFF IN. (COMPOSITE TYPES)
PERCENT DEVIATION FROM 2 GAGE CALIBRATED RUN

COMPOSITE TYPE	RANGE	MEAN	STANDARD DEVIATION
Peak Preservation	-10.3 to 2.2	-2.2	3.8
Across	-10.3 to 2.2	-1.6	3.4

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 calculated peak flow and runoff volumes varied by as much as –91 to +146 percent from the calibrated five gage model runs (over -100 and +100 percent for the calibrated two gage model for the upper watershed). The calculated volumes varied by as much as –99 to + 153 percent from the five gage calibrated model results, depending on the scenario of gages used for simulation.

The calculated peak flows varied by as much as –100 to + 240 percent when compared to the observed peaks (-93 to +100 percent for the upper watershed). The calculated volumes varied by as much as –99 to + 235 percent from the observed values, depending on the scenario of gages used for simulation.

The largest shift in the mean for the simulated peaks flow using the 17 storms was found to be within 25 percent of the average obtained from the 5-gage calibrated model runs. The maximum variation in the simulated mean peak flows was within 27 percent from the field-observed data and within 23 percent when compared to the observed volumes.

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 (1) 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 (1) raingage per square mile does not have to be exceeded to improve on the simulation results. Apparently factors other that raingage densities were in play that affect the accuracy of peak flow or runoff volume simulation for individual storm events.

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. As to the number of rainfall events needed to insure that the averages of simulated results are realistic has yet to be determined, but appear the numbers used in this study, namely 17 selected storm events, were sufficient to achieve this goal. This number is also probably dependent on the types of storms experienced at the study site.

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, namely compositing rainfall straight across or compositing using peak preservation. 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 composite 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 volumes and peaks to bring calculated values in line with observed data.

One possible problem in calibrating a model using composite rainfall data is that if other recorded point rainfall or long-term non-composite rainfall data are used later with the model, the calculated volumes and peak flows are likely to be overestimated. Because the model was calibrated using composite hyetographs which appear to underestimate peak flows and volumes, the percentage by which calibration parameters are adjusted to increase calculated peaks and volumes will be the percentage by which the use of non-composite rainfall data later will overestimate the 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.