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SIMPLIFIED MOUNTAIN CANYON FLASH FLOOD GUIDANCE FOR BOULDER CREEK

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INTRODUCTION

A meteorologic and hydrologic study of the Boulder Creek watershed has been performed. The objectives of the study are to develop simplified guidance for mountain canyon flash flood warning, and to assess the relative magnitude of flood hazard from infrequent, severe storms that may occur in the watershed. The study was performed by developing a rainfall-runoff model of the watershed and then applying both synthetic rainfalls and transposed historic rainfalls to estimate the corresponding flood magnitudes. Synthetic rainfalls are based on the design rainfall criteria from the Urban Drainage and Flood Control District (UDFCD) Urban Storm Drainage Criteria Manual. Historic rainfalls are based on the reconstitution and transposition of three historic storms that have occurred along the front range.

The model development, model verification, and meteorologic analyses are described in this report. The results are presented along with a graph of peak discharge of Boulder Creek at the mouth of the canyon as a function of maximum 1-hour point rainfall in the watershed. The graph can be used to estimate flood discharges that can be expected from a forecast of rainfall.

MODEL DEVELOPMENT

The watershed was modeled using the HEC-1 Flood Hydrology Program (U.S. Army Corps of Engineers, 1988). The model development and selection of model input is described in this section.

The watershed drainage area and subbasin delineation are shown in Figure 1. This map was provided by UDFCD. The subbasin areas and percent of directly connected impervious area (RTIMP) are shown in Table 1. The areas and RTIMP were obtained from file data that was obtained from UDFCD. An RTIMP of 2 percent for all subbasins was also used in one model run.

The 10-year and 100-year rainfalls were developed according to the procedures in the UDFCD Urban Storm Drainage Criteria Manual. Rainfall depths were determined for three elevation bands; the low elevation generally from 5,600 ft to 7,500 ft (subbasins 10, 14 and 15), the middle elevation generally from 7,500 ft tp 8,500 ft (subbasins 2, 4, 6, 7, 8, 9, 12 and 13), and the upper elevation generally above 8,500 ft (subbasins 3, 5 and 11). The rainfall depths were adjusted for area reduction (based on NOAA Atlas 2 depth-area reduction curve), and the 6-hour rainfall distributions were developed and applied to each subbasin. The 6-hour rainfall depths for each subbasin are shown in Table 1.

Three methods were used to estimate rainfall losses; 1) Green and Ampt infiltration equation with a surface retention loss, 2) Initial Loss plus Uniform Loss Rate (IL+ULR), and 3) the CN method. The Green and Ampt infiltration parameters were estimated by procedures contained in the Maricopa County, Arizona, Hydrologic Design Manual. A description of this rainfall loss procedure and methods to estimate the parameters is contained in Appendix A. The Green and Ampt infiltration equation is a three parameter model and is a decay type function that is based on accumulated soil moisture and the antecedent soil moisture condition. The parameters can be estimated according to soil texture classification. Based on field observation and experience, the soil in the watershed was classed as loam.

The IL+ULR parameters were estimated by the methods in the Maricopa County Hydrologic Design Manual. Reports of previous flood hydrology studies in the watershed were researched and it was found that a uniform loss rate of 1.0 inch per hour and an initial loss of 0.05 inch has been used (Muller Engineering Company, Inc., 1983). An uniform loss rate of 1.0 inch per hour is judged to be too high and an initial loss of 0.05 inch is judged to be too low. As a comparison, Mr. Fred Bertle, retired head of the USBR Flood Hydrology Section, recently performed a flood study of Dillon Dam for the Denver Water Department (Bertle, 1982). In that study, Mr. Bertle reconstituted several historic storms in the Blue River basin. Those reconstitutions resulted in uniform loss rates of about 0.25 to 0.40 inch per hour. It is likely that the Blue River watershed would have loss rates comparable to the Boulder watershed.

The SCS Curve Number (CN) method (SCS, 1972) was used for comparison. A CN of 78 was selected as the "best" estimate and a CN of 68 was also used to demonstrate the sensitivity of the CN method.

The values of the loss rate parameters for various model runs are shown in Table 2. The Green and Ampt equation is selected as the best practical method, and the selected parameter values are:

hydraulic conductivity (XKSAT) = 0.25 inch/hr

capillary suction (PSIF) = 4.3 inches

soil moisture deficit (DTHETA) = 0.10 to 0.35.

The surface retention loss is estimated as 0.35 inch.

The Horton method for estimating infiltration losses was not used because data are not available to estimate the Horton equation parameters for this watershed. The Horton equation is not as amenable to adjustments for antecedent soil moisture as the Green and Ampt equation.

A unit hydrograph was used to route the rainfall excess from the watershed. Two types of unit hydrographs were used; S-graphs and the Snyder unit hydrograph. The S-graph that was selected is the one that was developed for Buckhorn Creek near Masonville, Colorado. That S-graph was developed by the USBR in the reconstitution of a severe storm flood. The Buckhorn Creek S-graph is recommended for use for thunderstorms in the Rocky Mountains (Table 3-12, Design of Small Dams, Third Edition, USBR, 1987), and the use of S-graphs is described in that reference and in the USBR Flood Hydrology Manual (1989).

The S-graph is a unit hydrograph with one parameter, lag. The watershed characteristics for each subbasin that were used to calculate lag are shown in Table 3.

HEC-1 does not have an option to use S-graphs directly. However, the Hydrologic Engineering Center has written a HEC-1 preprocessor program that converts S-graph input into a unit hydrograph. That program, LAPRE1, was used with the S-graph runs.

The Snyder unit hydrograph was used with the parameters calculated according to the procedure in the UDFCD Urban Storm Drainage Criteria Manual. The parameters for each subbasin are listed in Table 3.

The flood hydrographs for the subbasins were routed and combined at various flow concentration points. Routing was performed by the Muskingum method. The Muskingum parameters were estimated based on mean flow velocities of 5 to 10 ft/sec. These velocities were estimated using assumed channel sections and the Manning equation. In general, channels in the upper watershed had velocities of about 5 ft/sec, and main channels in the lower end had velocities of about 10 ft/sec. The sensitivity of the Muskingum parameters was evaluated.

MODEL RESULTS

The results of the HEC-1 model for various sets of input are shown in Table 4. The peak discharge, time to peak, and runoff volume for two concentration points are shown; Boulder Creek near the Orodell gaging station and Boulder Creek at the canyon mouth. HEC-1 model number BC2B is judged to be the best model of the watershed based on a comparison of the 100-year flood discharge from the model to other accepted results (discussed below).

FLOOD FREQUENCY ANALYSIS

The results of the model were compared against flood frequency estimates based on stream gage records. Two gaging stations in the watershed are available for flood frequency analysis; Boulder creek near Boulder and Boulder Creek near Orodell. The data are shown in Appendix B. Graphical flood frequency analyses were performed using normal, log-normal, extreme value, and log-extreme value probability papers. The Cunnane plotting position was used for all distributions. The Orodell record is more reliable because of the longer length of record. The data fits the log-normal distribution better than the other distributions, and the graphical analyses are shown in Appendix B.

The flood frequency estimates at Orodell are:

100-year = 1,690 cfs
50-year = 1,490 cfs
10-year = 1,050 cfs

Discharge at that point represents only 56 percent (36.6 sq. miles) of the modeled watershed, and historic records indicate that larger flood magnitudes usually occur from Fourmile Creek. Therefore, these flood estimates should not be used as a representative measure of the flood magnitude at the mouth of the canyon.

Flood frequency analyses have been performed in several other studies. The final hydrology study by the U.S. Army Corps of Engineers that is accepted by both UDFCD and the City of Boulder is referenced in Boulder Creek Flood Hazard Delineation, January 1983, by Muller Engineering Company, Inc. The flood frequency magnitudes that are accepted for Boulder Creek at the canyon mouth are:

500-year = 21,200 cfs
100-year = 11,600 cfs
50-year = 8,000 cfs
10-year = 2,000 cfs

COMPARISON OF MODEL TO FLOOD FREQUENCY RESULTS

The model was run for both the 10-year and the 100-year rainfall and for antecedent soil moisture at field capacity (DTHETA =0.25). That soil moisture would represent the condition to be expected after the watershed had been thoroughly wetted and then allowed to dry somewhat due to gravity drainage and evapotranspiration. This would be representative of the watershed in early summer. The flood peak estimates using the model under those conditions are:

100-year = 9,735 cfs
10-year = 1,570 cfs

These compare favorably with the accepted values that are listed above.

The model was run for the 100-year rainfall under four conditions of antecedent soil moisture. These four conditions and resulting peak discharges are summarized below:

		Peak Discharge
A -	Soil moisture at wilting point Late summer or fall DTHETA = 0.35	8,280 cfs
B -	Soil moisture at field capacity Early summer DTHETA = 0.25	9,735 cfs
C -	Soil moisture at wet condition Spring after snowmelt or after previous storm DTHETA = 0.10	12,690 cfs
D -	Soil moisture at saturation Theoretical limit since saturation is not a practical condition DTHETA = 0.0	17,730 cfs

Comparison of the values listed above with the accepted values indicates that a 100-year flood peak of 11,600 cfs could occur with an antecedent soil moisture that is slightly dryer (more drained) than the soil moisture immediately after snowmelt. That would be a reasonable assumption for conditions that often exist in the watershed. A graph of the accepted flood frequency values and the flood peak discharges from the model under the four assumptions of antecedent soil moisture is shown in Figure 2.

FINAL MODEL CONFIGURATION

The model was run for the condition of 2 percent imperviousness (RTIMP = 2). This increased the peak discharge for the 100-year event from 9,735 cfs to 10,000 cfs, a 3 percent increase. This was not judged to be significant and the imperviousness of each subbasin was left as shown in Table 1.

The 100-year flood hydrographs from the model (both for DTHETA = 0.10 and 0.25) were plotted on a graph of the 100-year hydrograph that was developed by the Corps of Engineers. This is shown in Figure 3. The hydrographs from the HEC-1 model is similar to the Corps' hydrograph. That is, the rising and falling limbs of the hydrographs are parallel and the peaks are comparable.

The Corps hydrograph has a longer tail which is probably attributed to the fact that the Corps included the upper part of the basin in the watershed model. The times to peak do not coincide, but this is probably due to the differences in the rainfall distributions that were used in the two studies.

As a result of these favorable comparisons, the model as presented, is judged to be an acceptable representation of the rainfall-runoff process in the watershed. The model input is summarized below:

Rainfall - as per UDFCD Drainage Manual

Rainfall Losses - Green and Ampt infiltration equation with a surface retention loss

Unit hydrograph - Buckhorn Creek S-graph

Muskingum Routing - mean velocity of 5 to 10 ft/sec.

FLASH FLOOD PREDICTION GRAPH

The final model configuration was used to generate flood peak discharges for various rainfalls. This was performed by running the model with the 100-year rainfall multiplied by ratios from 50 percent to 200 percent. All four assumptions of antecedent soil moisture were used. The results are shown in Table 5. The maximum rainfalls for 6-hours, 1-hour, and 20-minutes are also shown in Table 5.

The results from Table 5 are plotted in Figure 4. Peak discharge at the mouth of the canyon can be predicted as a function of the maximum 1-hour rainfall, averaged over a 10 square mile portion of the watershed, by using Figure 4. An estimate of the antecedent soil moisture is required. Season of the year can be used if an estimate of the antecedent soil moisture is not available.

HISTORICAL STORM RECONSTITUTION AND TRANSPOSITION

The historical rainfall derived for this study is based on the reconstitution and transposition of three significant storm episodes into the Boulder Creek watershed: the Big Thompson flash flood of 31 July 1976; the Cheyenne, Wyoming flash flood of 1 August 1985; and the Masonville, Colorado flash flood of 10 September 1938. Each of these flash floods was produced by intense, short-term thunderstorm rainfalls which occurred within 150 miles of the Boulder Creek watershed. Reasonably accurate historical weather, rainfall and discharge information is available for each of these storms.

The thunderstorm rainfalls produced by each of these storms resulted in significant flash flooding in storm systems that are climatologically germane to the Boulder Creek watershed. These storms are particularly well suited for the development of simplified guidance for mountain flash flood warning within the UDFCD Flash Flood Prediction Program (F2P2) and the assessment of the relative magnitude of flood hazard caused by these infrequent severe storms.

The data used to support the reconstitution were National Weather Service surface observations and upper air observations, upper air radiosonde observations and storm related references and rainfall surveys. In the case of the Masonville storm of 10 September 1938, use was made of aircraft-derived upper air temperature, moisture and wind profiles gathered at Cheyenne, Wyoming. These observations provided a unique opportunity to reconstruct the possible spatial, temporal and quantitative rainfall for a historical storm using today's technology. Mr. Verne Leverson of the Flood Hydrology Branch of the U.S. Bureau of Reclamation kindly provided the Masonville storm data for our analysis.

The methodology of the reconstitution and transposition of each storm required the following steps:

A. Reconstitution of storm rainfall.

1. A complete set of surface, upper air and historical weather records were assembled for each storm case. Surface and upper air features known to influence rainfall production were identified.

2. Next, the vertical temperature and moisture structure of the atmosphere over the basin were prepared and entered into the Convective

Storm Rainfall (CSR) model. CSR model output of peak storm total rainfall, temporal distribution of rainfall in 10 minute steps, storm duration and peak 10-, 30- and 60-minute intensities were calculated.

3. The CSR model output was compared to historical rainfall records of peak point storm total, intensity values and temporal distributions. Comparison of model peak point rainfall for the three storms are shown in Figure 5.

4. The temporal distribution of the CSR model peak point rainfall was then applied in a proportional manner to each 0.5 inch of isopluvial band in the historical rainfall surveys to obtain the temporal rainfall within each of the subbasins. Since each convective storm surveyed covered a relatively large area, more than one CSR model run was needed to cover each storm profile.

B. Transposition of the historic storm events over the Boulder Creek watershed.

1. A prime consideration in the dynamic transposition of a storm event over a watershed is the relationship between the winds in the sub-cloud and cloud layers. The winds in the sub-cloud layer provide the source of moist energy for the storm's growth. These winds establish the location of the updraft within the storm. The cloud layer winds strongly influence the general direction of movement of the storm. The vector difference of the two winds establishes the propogation or general movement pattern of raincells within the storm complex. In essense this vector establishes the axis of ellipticity of the rainfall field.

2. Using the upper air temperature, moisture and wind field observations for the storm event used in the reconstitution, the elevation of the cloud base is obtained and the degree of lift required for its formation. This elevation is compared to the elevation profile of the basin and is used to fix the elevation location of the rainfall field.

Next, the sub-cloud wind field is used in concert with the upper air observations to determine the proper location of the historic rainfall field over the basin. Finally the vector wind difference in the sub-cloud and cloud-layer winds is used to determine the degree of skew in the historic rainfall pattern over the watershed.

3. Next the historical rainfall pattern is placed over the watershed and the isohyetal pattern is planimetered to obtain subbasin average rainfalls. CSR model output is used to establish the temporal distribution of the rainfall in each subbasin.

The transposition of the historic rainfall patterns over the Boulder Creek watershed is shown in Figures 6 to 8 for the Big Thompson flash flood, the Cheyenne flash flood, and the Masonville flash flood, respectively. In each case, the dynamic transposition is different than a direct application of the historic pattern over the watershed.

In the case of the Big Thompson storm, only one of the two heavy rain cells is apparent over the watershed due to the size of the storm. In the case of the Cheyenne storm, the introduction of the topography of the Boulder Creek watershed is considerably different than the rolling plains environment near Cheyenne, Wyoming which results in a more concentrated rainfall pattern. The Masonville storm presented a more difficult problem in that historical rainfall pattern information is severely lacking. Records suggest that the accepted peak point rainfall was 8.1 inches in about 1 hour with about 7 inches occurring in 30 minutes. Output from the CSR model does not support these high rainfall amounts and suggests a peak point total of 5.7 inches in about 90 minutes, 5.4 inches in 60 minutes and 3.5 inches in 30 minutes. Since historic data is missing and the CSR model tends to be within 15 per cent of the historic rainfall in most reconstitutions, the CSR model output was used in this reconstitution.

While historic spatial rainfall patterns were available for the Big Thompson and Cheyenne storms, no pattern was available for the Masonville storm. A subjectively derived spatial pattern was constructed using CSR model output, historic surface maps and observations and experience gained from 11 years of operational storm prediction in the UDFCD F2P2. The resulting pattern should be considered a conservative attempt at the reconstitution and transposition of this storm.

The temporal and spatial distribution of rainfall for each storm over the watershed in presented in Tables 6 to 8. Each table presents the average subbasin rainfall for 10 minute intervals and a storm total rainfall for each subbasin. These values were used as direct input into the basin model to calculate basin discharges. In most cases the basin average rainfalls compare favorably to the historic records. The exception is the Masonville storm for reasons previously indicated.

Since the development of simple guidance for mountain flash flood warning is a goal of this project, Table 9 of meteorologic data is presented which could be of use to operational meteorologists within the UDFCD F2P2. The table presents the observed vertical temperature, dew point and wind field values for surface, 800, 700, 600, 500, 400, 300, 200 and 100 millibar levels. Precipitable water from the surface to 500 millibars, presence of low level convergence features and upper air triggers is also noted. CSR model output of peak point rainfall for each storm is also presented. While this table is not a direct forecast aid, it could be used to "red flag" conditions known to have existed prior to and during several local severe flash floods.

It is beyond the scope of this project to develop forecast aids for the meteorologist to deal with the rare, severe flash flooding threat of intense thunderstorm complexes. However, a partitioning and archieval of upper air observations similar to those in Table 9 and observed or predicted rainfalls associated with severe events would be most useful within the F2P2.

FLOOD DISCHARGES FROM TRANSPOSED STORMS

The average rainfalls for each subbasin for the three transposed storms (Tables 6 through 8) were input to the accepted HEC-1 model of the watershed.

The peak discharges and the times to peak for the flow concentration points that are indicated on Figure 1 are shown in Table 10. A copy of the HEC-1 output files for each of these storms and a diskette with copies of pertinent HEC-1 files has been provided with this report. An index of HEC-1 files on the diskette is shown in Appendix C.

REFERENCES

1. Bertle, Fred A., 1982, Design Flood for Dillon Dam, prepared for Denver Water Department.

2. Flood Control District of Maricopa County, Hydrologic Design Manual (draft), Phoenix, Arizona.

3. Muller Engineering Company, Inc., 1983, Boulder Creek Flood Hazard Delineation.

4. SCS, National Engineering Handbook, Chapter 4-Hydrology.

5. U.S. Army Corps of Engineers, HEC-1 Flood Hydrology Program, June 1988 Version, Davis, California.

6. U.S. Bureau of Reclamation, 1987, Design of Small Dams, Third Edition, Denver, Colorado.

7. U.S. Bureau of Reclamation, 1989, Flood Hydrology Manual, Denver, Colorado.

8. Urban Drainage and Flood Control District, Urban Storm Drainage Criteria Manual, Denver, Colorado.

TABLE 1

Subbasin rainfalls, areas and percent imperviousness (RTIMP)

Subbasin No.	100-yr. Rainfall inches	10-yr. Rainfall inches	Area sq. mi.	RTIMP %
(1)	(2)	(3)	(4)	(5)
2	2.47	2.09	6.00	1
3	2.05	1.92	6.06	0
4	2.47	2.09	3.58	0
5	2.05	1.92	6.31	0
6	2.47	2.09	2.52	1
7	2.47	2.09	4.25	1
8	2.47	2.09	3.72	0
9	2.47	2.09	4.14	0
10	3.04	2.33	2.87	1
11	2.05	1.92	6.50	0
12	2.47	2.09	7.76	0
13	2.47	2.09	3.12	0
14	3.04	2.33	5.30	1
15	3.04	2.33	3.55	1
For Single Basin Model	2.47	--	65.68[a]	1

[a] Drainage area above Barker Reservoir and above watershed area shown in Figure 1 is not included. The total drainage area is about 130 square miles.

TABLE 2

Rainfall Loss Parameters for Various HEC-1 Runs

	Green-Ampt[a]				IL+ULR[b]		CN Method
Run No.	IA	XKSAT	PSIF	DTHETA	STRTL	CNSTL	CN
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
BC1	0.50	0.25	4.3	0.25			
BC2	0.35	0.25	4.3	0.25			
BC3					0.95	0.25	
BC4					0.70	0.25	
BC4A					0.05	1.00	
BC5							68
BC6							78
BC7	0.35	0.25	4.3	0.25			
BC8	0.35	0.25	4.3	0.25			
BC9	0.35	0.25	4.3	0.25			
BC10	0.35	0.25	4.3	0.25			
BC11	0.35	0.25	4.3	0.25			

a
IA = surface retention loss, inches
XKSAT = hydraulic conductivity, in/hr
PSIF = capillary suction, inches
DTHETA = soil moisture deficit, dimensionless

b
STRTL = initial loss, inches
CNSTL = uniform loss rate, in/hr

TABLE 3

Unit Hydrograph Data and Parameter Values for Each Subbasin

Subbasin No.	S-Graph Area sq.mi.	L mi.	LCA mi.	S ft/mi	n	Lag hr.	Snyder Tp hr.	Cp
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
2	6.00	6.8	3.4	264	0.06	1.64	1.56	0.45
3	6.06	3.12	1.59	227	0.06	1.08	0.83	0.44
4	3.58	3.99	2.13	259	0.06	1.30	1.02	0.43
5	6.31	4.84	2.46	269	0.06	1.38	1.18	0.46
6	2.52	2.5	1.5	317	0.06	0.79	0.67	0.39
7	4.25	4.1	2.7	158	0.06	1.54	1.24	0.43
8	3.72	4.1	2.7	306	0.06	1.07	0.96	0.43
9	4.14	5.9	2.7	301	0.06	1.38	1.30	0.44
10	2.87	3.21	1.26	290	0.06	0.83	0.71	0.40
11	6.50	4.7	1.6	290	0.06	1.06	0.95	0.47
12	7.76	6.1	3.6	253	0.06	1.62	1.56	0.48
13	3.12	5.1	1.7	301	0.06	1.11	1.00	0.42
14	5.30	4.2	2.2	232	0.06	1.19	1.06	0.44
15	3.55	3.8	1.4	253	0.06	0.95	0.82	0.41

TABLE 4

Results of HEC-1 Model for Various Input Parameter Combinations

Run No.	Loss Method	U-hg	at Orodell Qp cfs	at Orodell Tp hr	at Orodell Vol ac-ft	at Canyon Mouth Qp cfs	at Canyon Mouth Tp hr	at Canyon Mouth Vol ac-ft
(1)	(2)	(30	(4)	(5)	(6)	(7)	(8)	(9)
BC1B	Grn-Ampt	S-Gr	5031	2.	1209	8395	3.	2452
BC2B	Grn-Ampt	S-Gr	6037	2.	1477	9735	3.	2798
BC3	IL+ULR	S-Gr	7012	2.	1828	11868	3.	3607
BC4	IL+ULR	S-Gr	8690	2.3	2269	14582	3.	4402
BC4A	IL+ULR	S-Gr	6923	2.3	1534	10166	3.	2998
BC5	CN	S-Gr	2280	2.	637	4410	3.7	1556
BC6	CN	S-Gr	4744	3.	1341	8695	3.7	2975
BC7	Grn-Ampt	S-Gr	7979	3.	1477	13305	2.7	2927
BC8	Grn-Ampt	S-Gr	3064	2.3	1477	4530	5.	2924
BC9	Grn-Ampt	CUHP	4184	4.	1471	7664	3.3	2915
BC10	Grn-Ampt	S-Gr	701	3.	146	1566	2.3	398
BC11	Grn-Ampt	S-Gr	---	---	---	10313	3.7	2969

TABLE 5

Peak Discharges at Mouth of Boulder Canyon as a Function of Various Ratios of the 100-year Rainfall and four Antecedent Soil Moisture Conditions

Percent 100-year Rainfall	Rainfall, inches 6-hr	1-hr	20-min	Peak Flows For Various Antecedent Moistures[a] A DTHETA=.35	B DTHETA=.25	C DTHETA=.10	D DTHETA=0.0
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
200	6.08	5.00	2.50	32001	33848	37676	43837
175	5.32	4.38	2.19	25776	27537	31182	37266
150	4.56	3.75	1.88	19745	21378	24866	30715
125	3.80	3.13	1.56	14034	15496	18686	24195
100	3.04	2.50	1.25	8281	9735	12690	17730
90	2.74	2.25	1.13	6094	7428	10350	15174
80	2.43	2.00	1.00	4052	5219	7992	12653
70	2.13	1.75	0.88	2113	3136	5611	10119
60	1.82	1.50	0.75	545	1292	3344	7776
50	1.52	1.25	0.63	56	107	1374	5478

[a]
A - soil moisture at wilting point
B - soil moisture at field capacity
C - wet soil
D - saturated soil

TABLE 6

CONVECTIVE MODEL STORM RAINFALL OUTPUT

Big Thompson, CO Flash Flood (31 July 1976)
Storm 1 Single Cell

Time Step in minutes

Sub-basin	10	20	30	40	50	60	70	80	90	100	10	120	130	140	150	160
1		0		0.1	0.35	0.65	0.3	0.2	0.1	0.1						
2		0.15	0.3	0.55	0.9	1.25	1.25	0.75	0.5	0.4	0.15	0.15				
3				0.1	0.35	0.5	0.2	0.1								
4				0.3	0.45	0.45	1.3	1.05	0.5	0.2	0.2	0.2	0.1	0.1	0.1	
5			0.1	0.55	0.55	0.75	0.75	0.45	0.2	0.1	0.1	0.1				
6	0.1	0.2	0.7	1.25	1.35	1.75	1.5	1.25	0.95	0.75	0.35	0.25	0.25	0.1	0.1	
7	0.3	0.3	0.65	0.9	1.5	0.75	0.75	0.65	0.4	0.25	0.25	0.25	0.25	0.1	0.1	
8		0.25	0.25	0.75	0.25	0.15	0.1									
9		0.25	0.6	0.8	1.05	0.95	0.75	0.7	0.5	0.35	0.15	0.1				
10				0.1	0.55	0.15	0.15	0.1	0.1	0	0	0				
11	0	0	0.15	0.25	0.75	0.45	0.25	0.15	0.15	0.15	0.1	0.1	0.25	0.25	0.1	0.1
12	0.3	0.45	0.75	1	1	1.25	1.25	1.05	0.75	0.45	0.15	0.1	0.1			
13		0.25	0.25	0.85	1.05	1.55	1.05	0.55	0.5	0.45	0.25	0.25	0.15	0.15	0.1	0.1
14				0.1	0.55	1.05	0.25	0.2	0.1							
15					0.15	0.5	0.25	0.15	0.1	0.1						

TABLE 7

CONVECTIVE MODEL STORM RAINFALL OUTPUT

Cheyenne, WY Flash Flood (1 August 1985)

Time step in minutes

Sub-basin	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
1						0.25	0.15	0.1								
2		0.2	0.45	0.7	0.7	0.8	0.7	0.45	0.15							
3		0			0	0.25	0.15	0.1								
4		0	0.25	0.45	0.85	0.65	0.45	0.25	0.25	0.1	0.1					
5			0.25	0.45	0.25	0.25	0.15	0.15	0.15	0.1						
6			0.25	0.65	0.65	0.9	0.95	0.75	0.4	0.15	0.15	0.15				
7		0.2	0.45	0.7	0.85	1.15	1.25	0.85	0.5	0.25	0.15					
8		0.15	0.35	0.55	0.65	0.9	0.75	0.75	0.3	0.15	0.15	0.15				
9		0.25	0.55	0.7	0.85	1.15	0.75	0.75	0.3	0.15	0.15	0.05				
10			0.25	0.45	0.65	0.65	0.3	0.15	0.15	0.15						
11			0.25	0.45	0.25	0.15	0.15	0.15								
12			0.25	0.65	0.65	0.9	0.8	0.65	0.4	0.15	0.15	0.15				
13			0.25	0.65	0.85	0.9	0.95	0.8	0.4	0.15	0.1	0.1				
14			0.15	0.5	0.65	0.1										
15		0.25	0.55	0.45	0.1											

TABLE 8

CONVECTIVE STORM RAINFALL MODEL OUTPUT

Masonville, CO Flash Flood (10 September 1936)

Sub-basin	Time step in minutes															
	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160
1																
2																
3																
4																
5																
6																
7		.25	.5	.15	.25	.1										
8		.5	.15	.75	.5	.45	.15	.15	.1							
9		.25	.5	.15	.25	.1										
10	.25	.75	.15	.75	.75	.5	.15	.1	.1							
11																
12																
13		.1	.5	.15												
14		.25	.5	.15	.25	.5	.25	.25	.25	.25						
15		.25	.5	.15	.25	.5	.25	.25								

TABLE 9

Summary of meteorologic observations associated with the Big Thompson (31 July 1976), Cheyenne (1 August 1985) and Masonville (10 September 1936) Flash Flooding events.

	Big Thompson	Cheyenne	Masonville
Surfc Temp/Dew Pt(F)	72-80/55-62	75-85/60-65	70-80/52-58
Wind speed/direction (Degrees/knots)	120-150/15-35	140-180/25-40	070-130/10-20
800mb Temp/Dew Pt(C)	20-25/12-17 120-140/15-30	20-26/15-18 150-180/25-40	16-18/5-10 090/10-20
700mb " "	13/7 130/15	14/6 150/25	11/3 E180/15
600mb " "	3/0 160/10	3/-1 170/12	-2/-8 E210/15
500mb " "	-4/-19 190/15	-6/-30+ 210/18	E -14/-25 E 230/20
400mb " "	-17/-22 180/18	-20/XX 220/20	E -25/XX E 230/25
300mb " "	-32/XX 180/22	-34/XX 230/35	E -40/XX
200mb " "	-54/XX 130/22	-54/XX 250/50-60	E -62/XX
Low level factors	Frontal sfc Gust front Low level jet	Low level jet Frontal sfc	Frontal sfc Easterly wind
Upper level factors	700mb low Monsoonal flow	Short wave Jet streak	Short wave?
Surface-500mb Precipitable water (inches)	1.15"	0.95-1.00"	0.92"
CSR Model Output			
Peak 10 min rainfall	2.95"	1.65"	1.15"
Peak 30 min rainfall	4.95"	3.75"	3.50"
Peak 60 min rainfall	7.05"	5.75"	5.40"
Peak total rainfall	13.40"	6.35"	5.70"

TABLE 10

Peak discharges and times to peak at selected concentration points from three historic storms transposed to the watershed

	Peak Discharge at Concentration Points[a], in cfs					
Storm (1)	A (2)	B (3)	C (4)	D (5)	E (6)	F (7)
Big Thompson	11,800	23,600	28,900	23,600	47,700	45,500
Cheyenne	4,200	11,600	24,400	12,900	35,500	33,800
Masonville	0	0	10,200	0	15,600	15,800

	Time to Peak at Concentration Points[a], in hours					
Storm (1)	A (2)	B (3)	C (4)	D (5)	E (6)	F (7)
Big Thompson	2.00	2.33	2.67	2.33	3.00	2.67
Cheyenne	2.00	2.33	2.33	2.33	3.00	3.33
Masonville	----	----	1.67	----	1.67	2.00

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[a] Concentration Points as shown in Figure 1:
- A - at confluence of Gordon Creek with Boulder Creek near Switzerland Park
- B - near Sunnyside
- C - near Hydroelectric Plant
- D - at confluence of Gold Run with Fourmile Creek near Salina
- E - near Orodell
- F - at canyon mouth

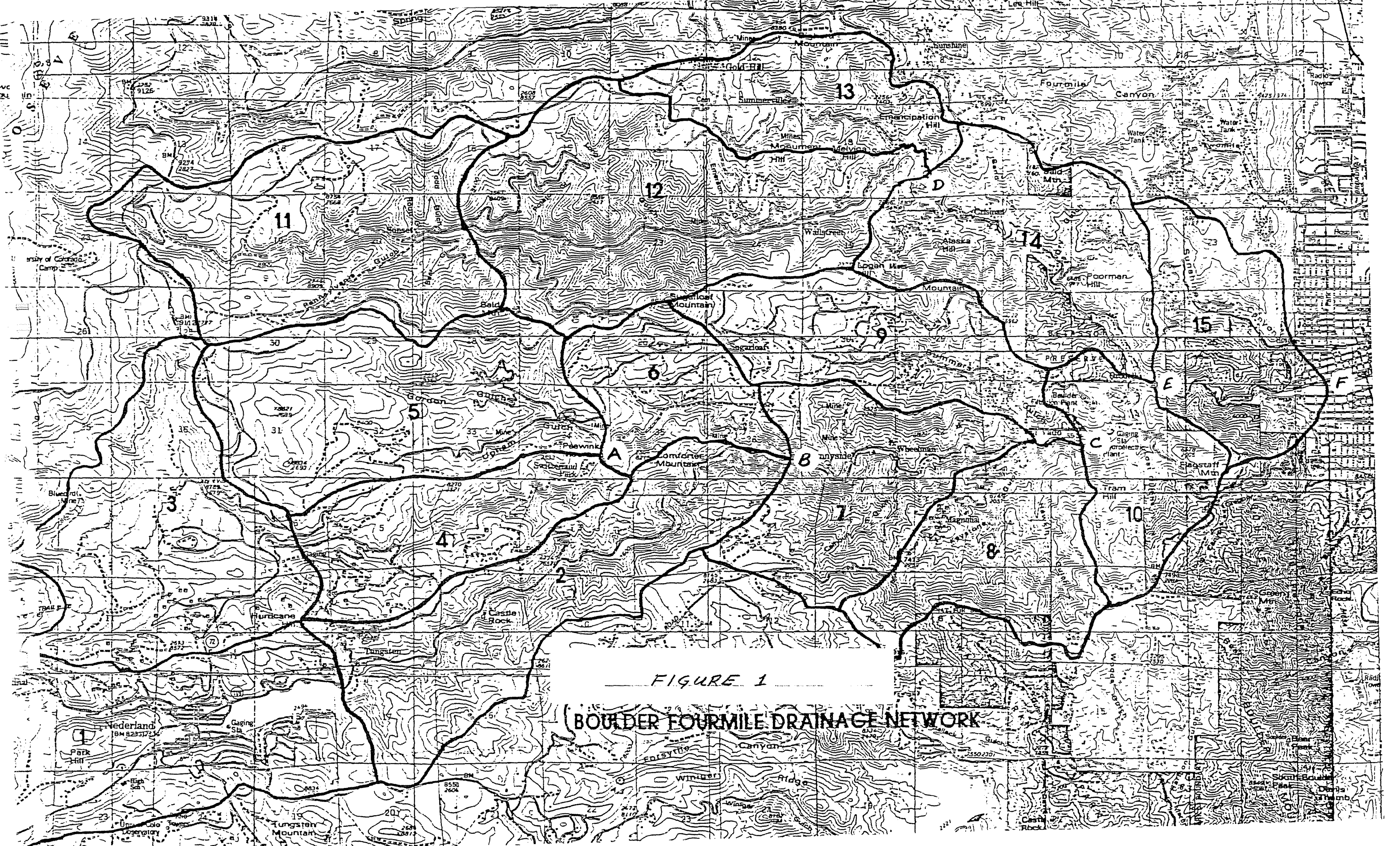

FIGURE 1

BOULDER FOURMILE DRAINAGE NETWORK

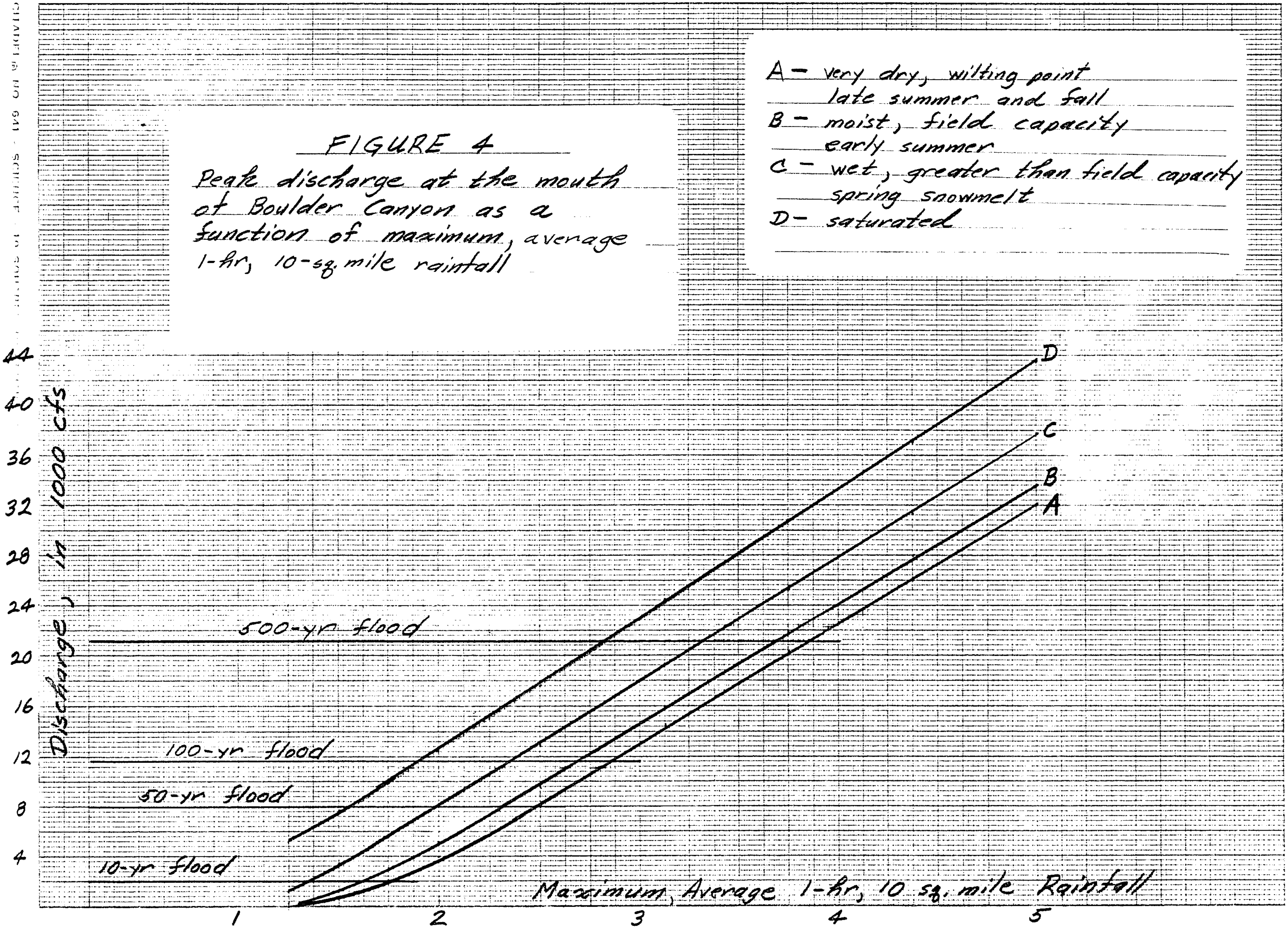
FIGURE 4
Peak discharge at the mouth of Boulder Canyon as a function of maximum, average 1-hr, 10-sq. mile rainfall
A – very dry, wilting point
late summer and fall
B – moist, field capacity
early summer
C – wet, greater than field capacity
spring snowmelt
D – saturated
500-yr flood
100-yr flood
50-yr flood
10-yr flood
Discharge, in 1000 cfs
44
40
36
32
28
24
20
16
12
8
4
Maximum, Average 1-hr, 10 sq. mile Rainfall
1
2
3
4
5
A
B
C
D

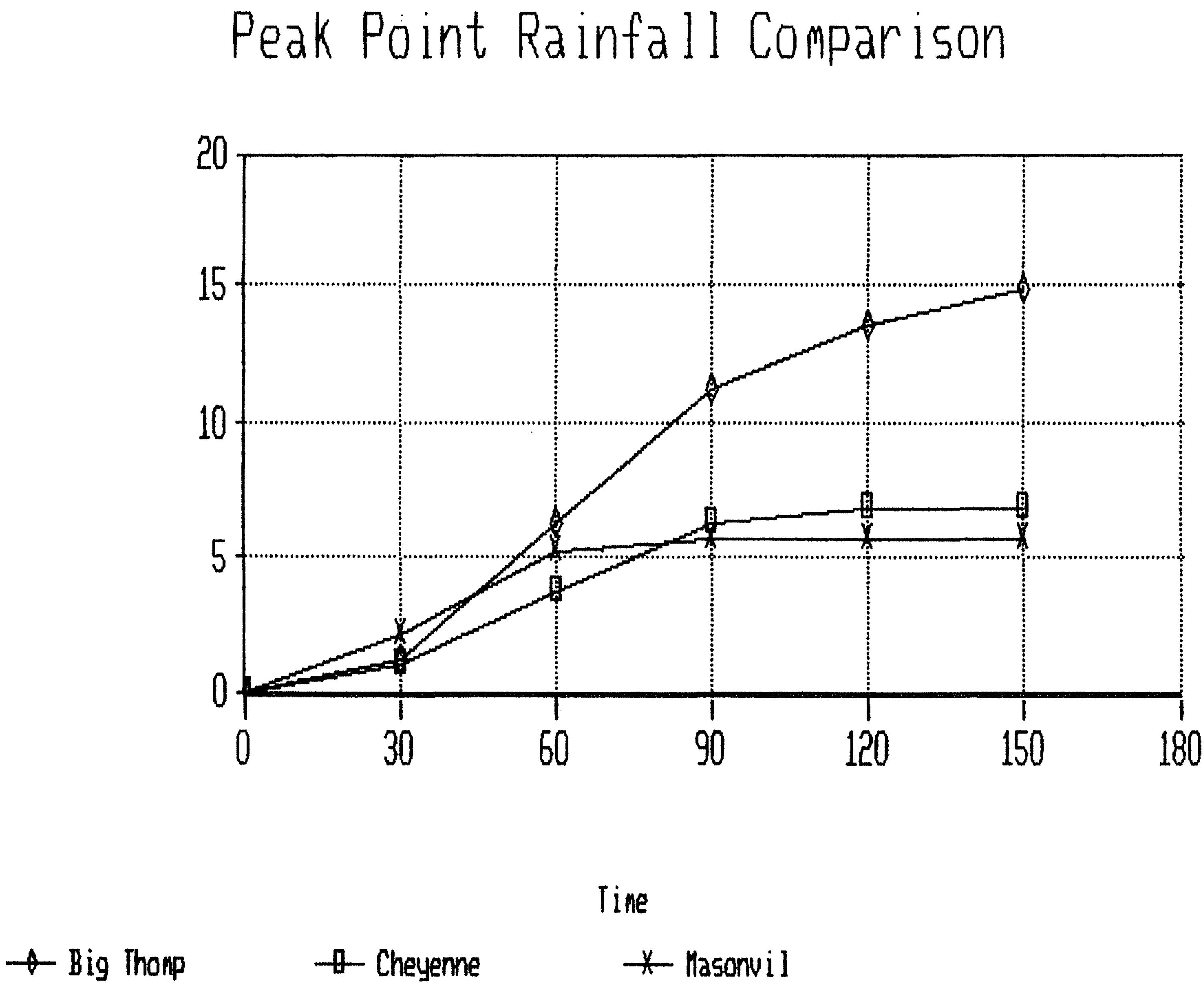

FIGURE 5
Rainfall Mass Diagrams

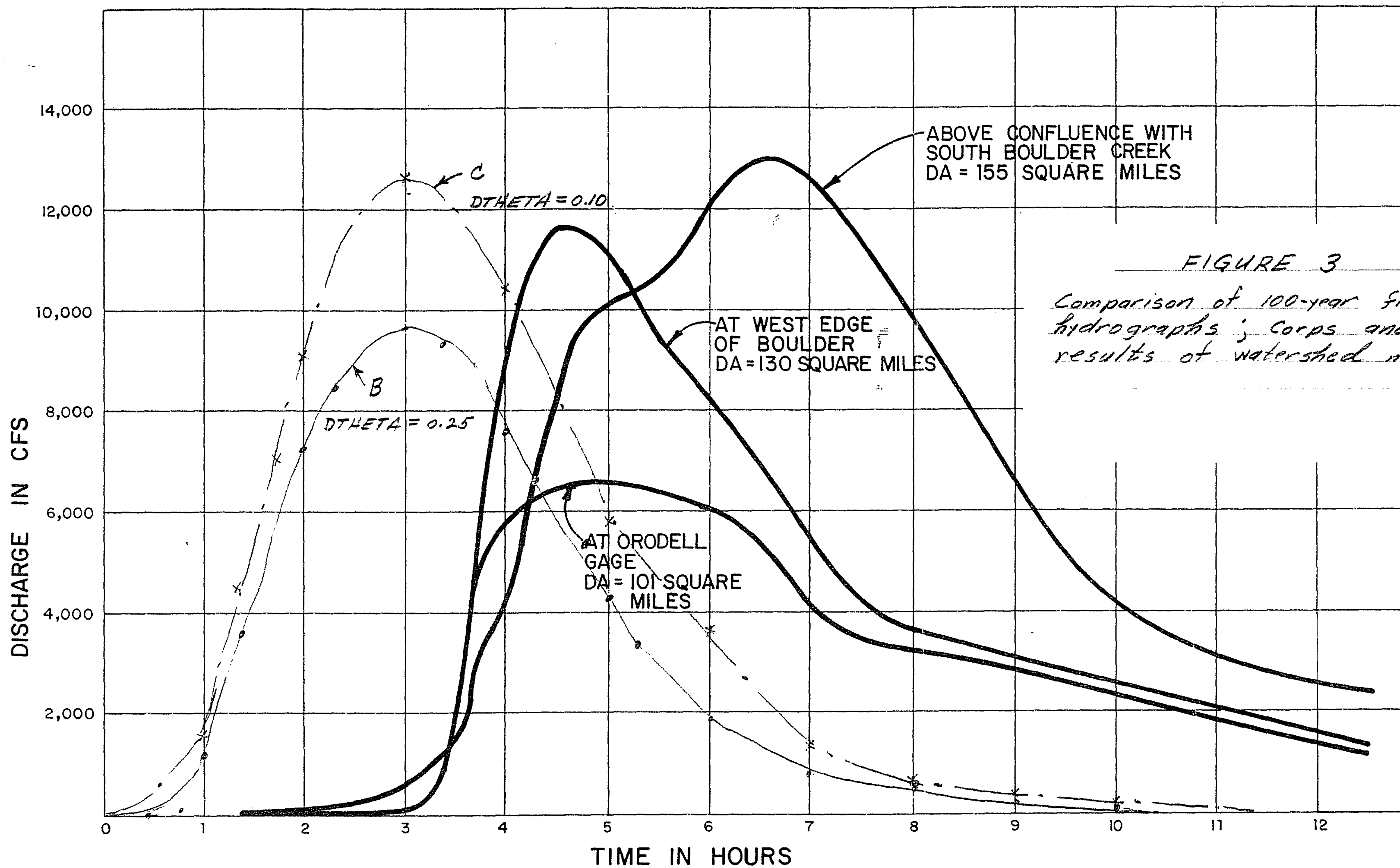

FIGURE 3

Comparison of 100-year flood hydrographs; Corps and results of watershed model

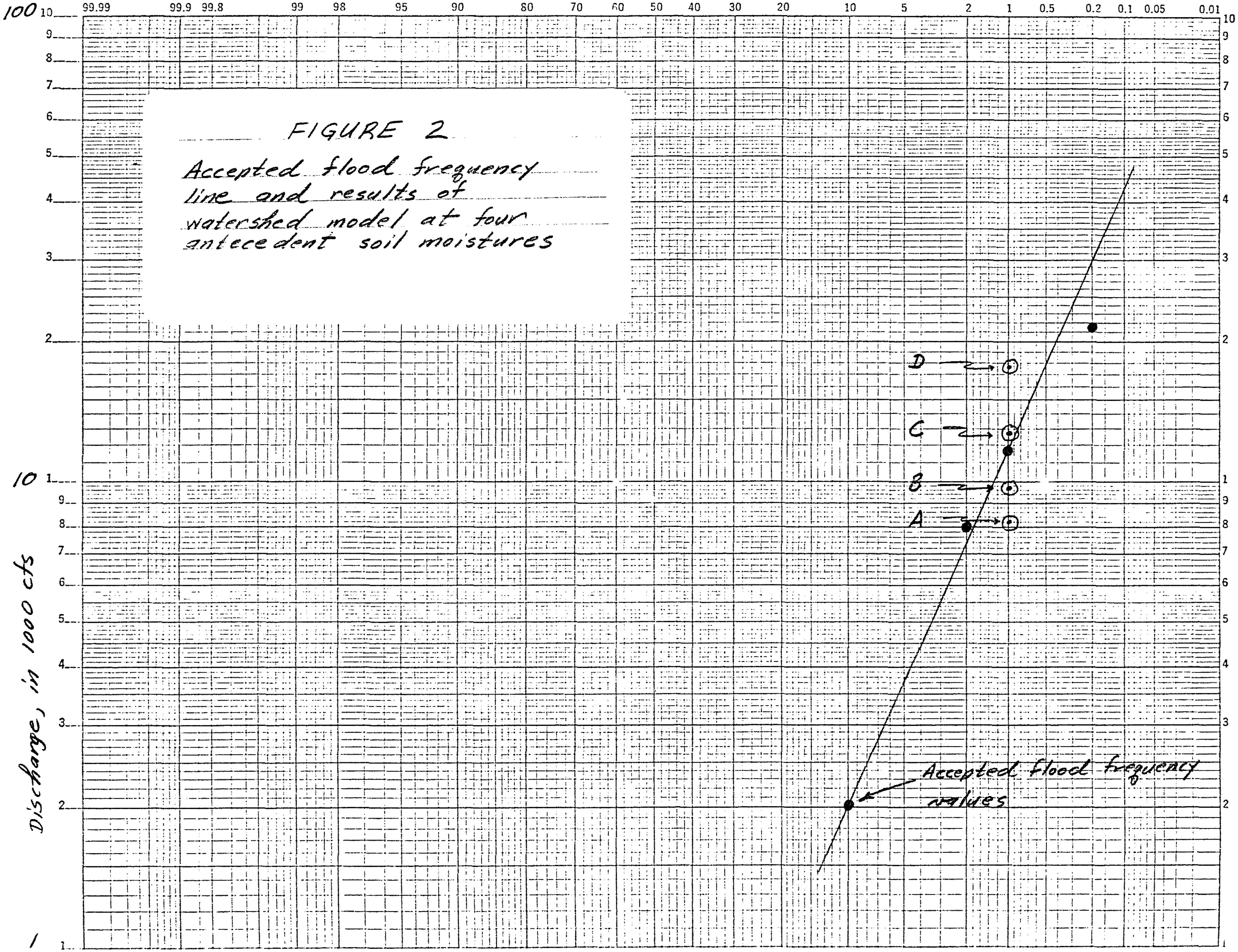

FIGURE 2
Accepted flood frequency line and results of watershed model at four antecedent soil moistures

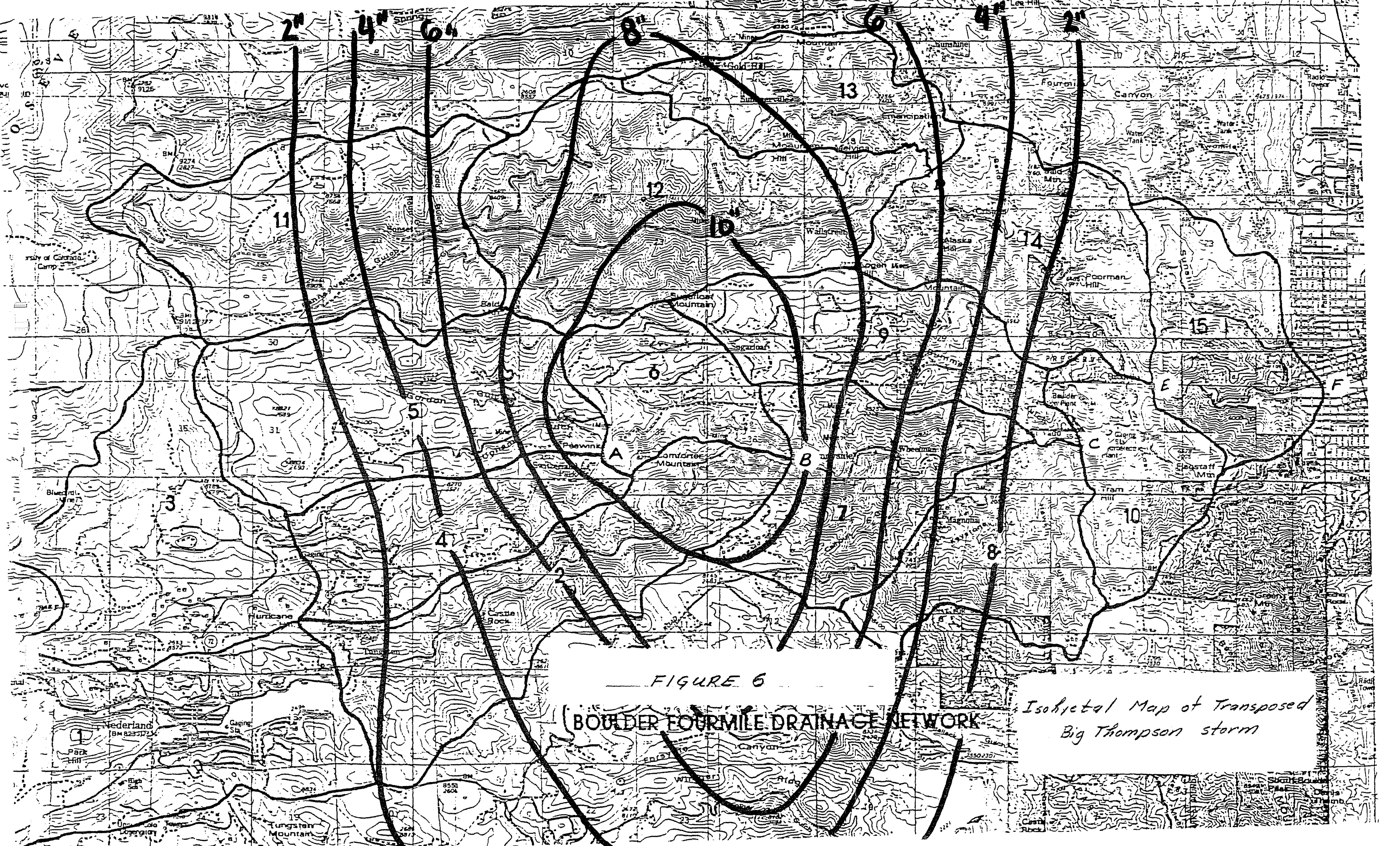

FIGURE 6

BOULDER FOURMILE DRAINAGE NETWORK

Isohyetal Map of Transposed Big Thompson storm

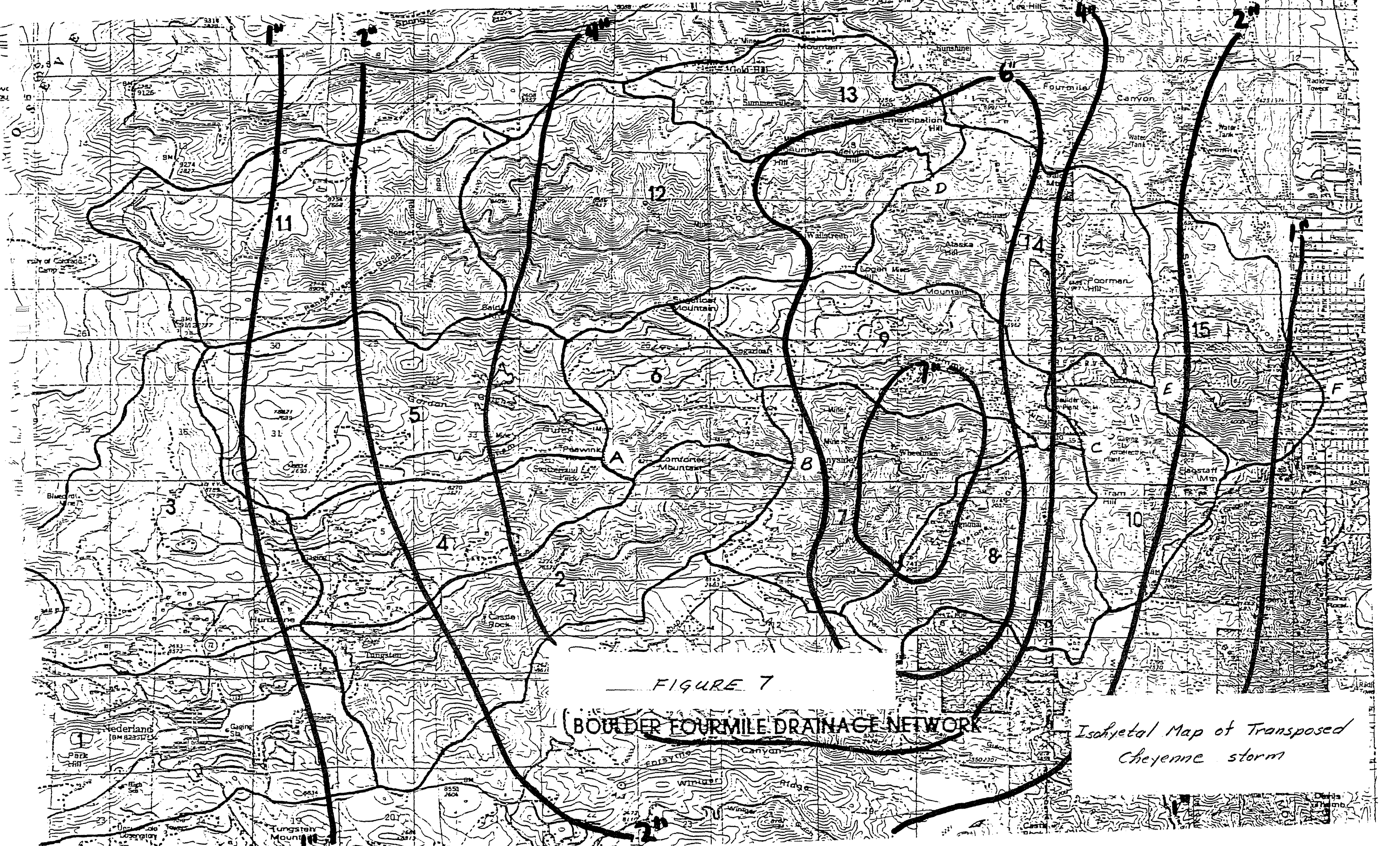

FIGURE 7

BOULDER FOURMILE DRAINAGE NETWORK

Isohyetal Map of Transposed Cheyenne storm

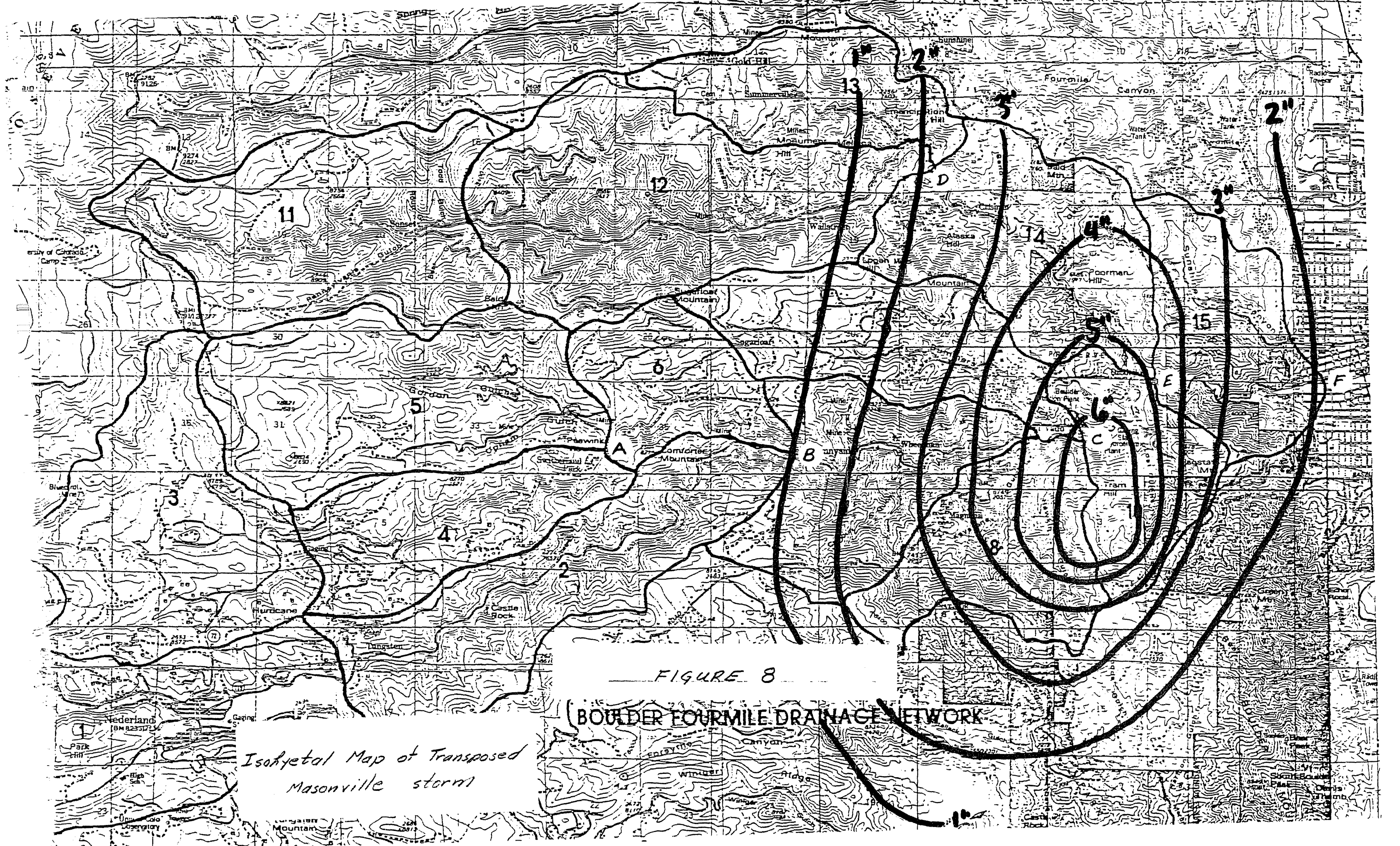

FIGURE 8

BOULDER FOURMILE DRAINAGE NETWORK

Isohyetal Map of Transposed Masonville storm