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The Buffalo Creek Flash Flood of 1996

A reconstruction of rainfall and meteorology

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

1.0 Introduction

The town of Buffalo Creek, Colorado was struck by a deadly flash flood about 900PM on the night of July 12, 1996. The flash flood killed two residents and produced several hundred thousand dollars of damage to the town. The cruel irony of the flash flood is that it followed a massive forest fire which burned 12,000 acres of nearby forest land during May 1996. The combined hardships associated with both of these disasters and the continuing threat of additional flash flooding has produced serious concerns for the remaining residents of Buffalo Creek.

The town of Buffalo Creek is located in southern foothills of Jefferson County about 35 miles southwest of downtown Denver (see **Figure 1**). The elevation of the town of Buffalo Creek is about 7,200 feet but it is flanked by 10,421 ft Green Mountain to the south, 11,588 ft Buffalo Peak to the west-southwest and 11,970 ft Windy Peak to the west (See **Figure 2**). The average elevation of the watershed is about 8,500 feet. The Buffalo Creek basin extends roughly 15 miles to the southwest from the town of Buffalo Creek and varies from 2 to 5 miles wide. The basin covers about 55 square miles of drainage area. It is easy to imagine that orographic influences on precipitation exist in the basin.

Henz (1974) identified fourteen areas along the Colorado Front Range which he referred to as orogenic thunderstorm "hot spots" or preferred orographic locations for thunderstorm generation. He observed that over 2.5 times as many thunderstorms formed over these "hot spots" as the neighboring terrain at elevations above 5,000 feet during the radar survey periods of the summers of 1970 and 1971. He identified the orographic characteristics of these hot spots were very similar and supportive of an **enhanced mountain-valley breeze circulation** which appeared to be related to the observed increase in storm formation over these areas. He recently observed (Henz, 1996) that most of the significant flash floods which have occurred since 1976 along the Colorado Front Range at elevations above 6,000 feet have occurred in one of these "hot spots". The Buffalo Creek watershed is located within the southern half of his Conifer "hot spot".

Many have suggested that the burn areas of the basin produced a significant increase to the runoff from the rains of July 12th which acerbated the flash flood. Others have suggested that the burn area has been responsible for thunderstorm intensification and formation over the Buffalo Creek basin. This report will not address those concerns directly. Rather, it will present a coherent presentation of the timing, aerial coverage and intensity of the rainfall which produced the Buffalo Creek flash flood. Discussions on the use of radar data and standard surface and upper air observations to produce precipitation mapping will be presented.

Figure 1 Location of the town of Buffalo Creek

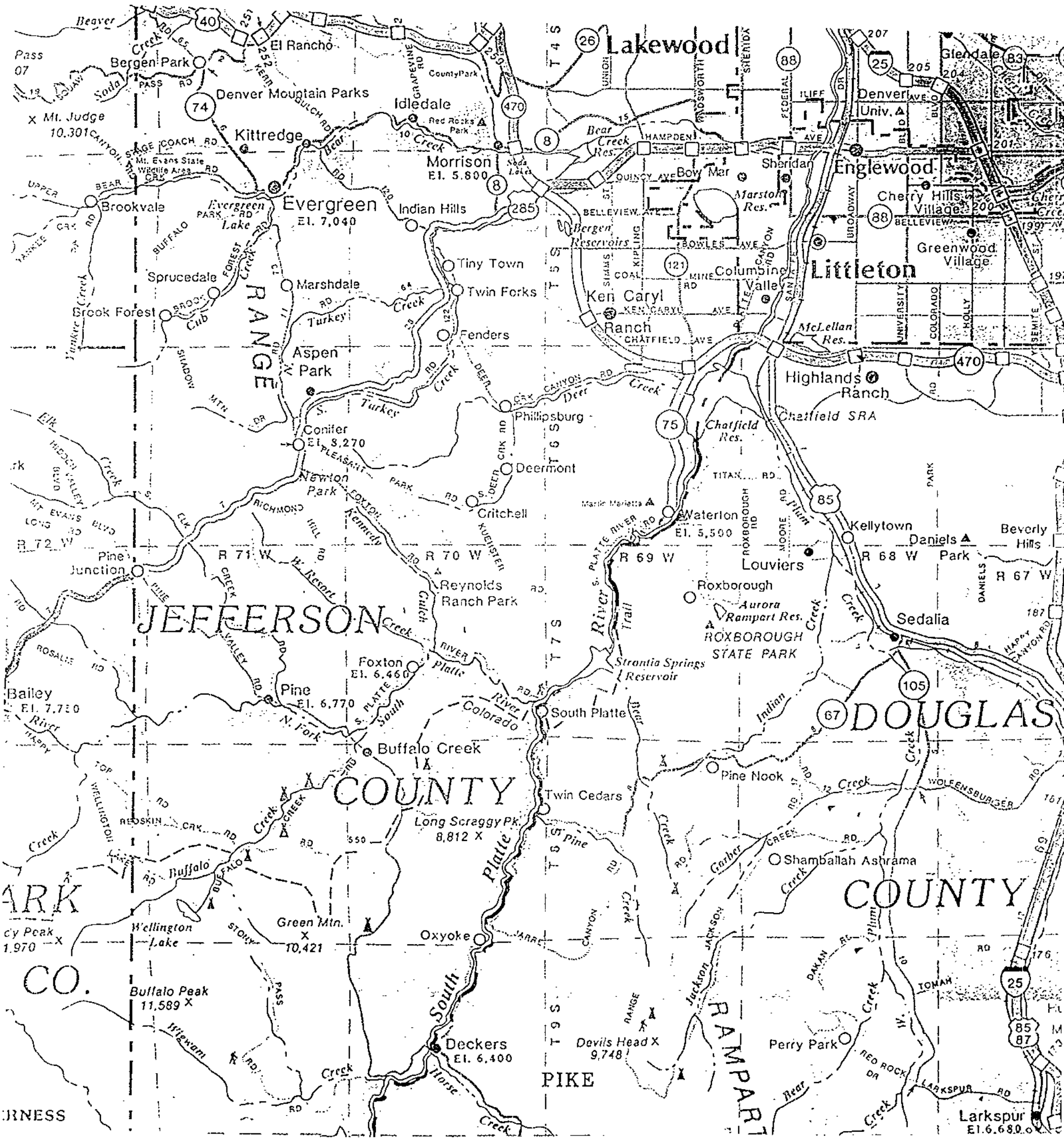
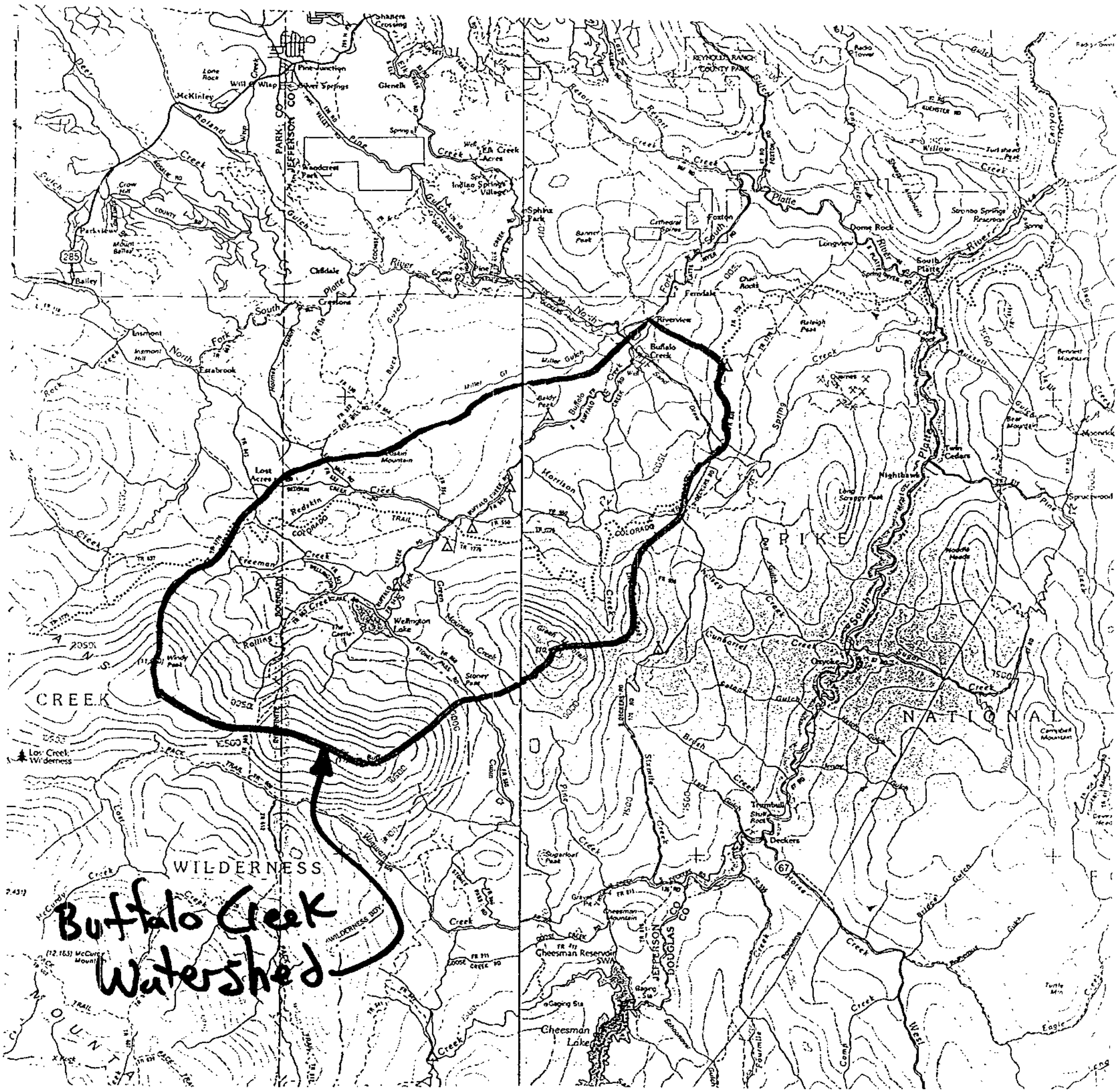


Figure 2 Map of Buffalo Creek Watershed



Additionally, it will present a detailed reconstitution of the rainfall on July 12^{th} and contrast it to the rainfall associated with several additional storm events which occurred over the Buffalo Creek basin during the post-fire period of 1996. Finally, the report will present information on the meteorological causes of the primary July 12^{th} flash flood event and contrast it to the causes of the other lessor events which occurred.

2.0 Use of radar to describe storm rainfall

The ability to use radar to obtain a map of current rainfall has been pursued for over 30 years by engineers, meteorologists and hydrologists. In general, most current radar-rainfall techniques rely an assumed relationship between the strength of the radar reflectivity and the intensity of the rainfall rate. This relationship is described by the equation below:

$$\text{(1)} \qquad \mathbf{Z = A\, R^{b}}$$

where, **Z** is the radar reflectivity, **R** is the rainfall rate, **A** is an empirically derived co-efficient related to the cloud physics of the storm cloud water droplets and **b** is another empirical co-efficient related to the type of storm cloud present. This relationship has proven to produce highly variable results. Since the values of both A and b must be assumed to allow the equation to be solved correctly, many opportunities for errors in the calculation are possible.

The algorithms used to estimate the rainfall are standard for use around the country and have not proven to be responsive to local cloud variations. The r-squared or "goodness" correlation factor of the rain to radar reflectivity statistical relationship has varied from 0.15 to 0.90 on a daily basis and for most storm seasons has been about 0.60. The good "r's" (values >0.75) have been achieved for the low volume and low intensity rain events, generally those of less than 0.25"/hr accumulation rates. The high intensity, high volume, "front-end dumper" thunderstorms have produced r-values of 0.15 to 0.45. Thus the standard products appear to be unreliable at this point. The storm rainfall has been both overestimated and underestimated for periods of less than three hours for storms within 25 miles of each other.

Finally, hail "pollution" of the equation has proven to be a troublesome problem. The strength of the radar return signal is related objectively to the diameter of the rain droplet size. The strong radar return signal produced by wet hail stones frequently causes an over-estimation of the rainfall rate. Attempts have been made to reduce this over-estimation by adjusting the coefficients A and b in Equation 1. A satisfactory solution to this problem continues to prove quite elusive.

The HMS methodology to relating radar reflectivity to rainfall approaches the solution of this problem from another direction. In over 90 percent of the operational heavy rain days in the Urban Drainage & Flood Control District since 1985, **HMS has observed that the heaviest rainfall has occurred when the strongest radar reflectivity field of a thunderstorm passes over the rain gauges**. The HMS method uses the radar reflectivity **to locate** the portion of the cloud where **the heaviest rainfall** is located rather than using its strength to calculate a rainfall rate. Given the validity of this assumption, the next step is to calculate the peak rainfall rate associated with the storm which can in turn be related to the strongest radar reflectivity values.

HMS has predicted the quantitative precipitation associated with thunderstorms since 1979 in the Urban Drainage & Flood Control District. Since late 1981, it has used a combination of surface weather station data, upper air soundings plotted on a Skew T, Log P diagram and a 2-D cloud methodology to predict the peak rainfall rate associated with thunderstorms. HMS has found that the depth of a thunderstorm's updraft which is warmer than freezing is directly related to the rain-making potential of the cloud. Henz (1995) describes this process in detail and a copy of the paper is included in Appendix A. When the warm depth of the updraft exceeds 1.5 km in Colorado, for instance, the rain-making potential of the cloud doubles.

Equations 2 to 4 below show simplified forms of this relationship:

(2) Peak 60-minute rainfall = PWI times $\left(\frac{\textbf{Depth of updraft warm layer}}{\textbf{1.5km}}\right)$ **times 2***

(3) Peak 30-minute rainfall = 0.70(Peak 60-min rain)

(4) Peak 10-minute rainfall = 0.60(Peak 30-min rain)

*** Note that the doubling occurs only if the depth of warm layer exceeds 1.5 km**

where the Precipitable Water Index (PWI) is a measure of the amount of water in the air from the surface to about 20,000 feet. In effect, the calculated **peak 60-,30-,10- minute rainfall rates** are assumed to occur in the grids covered by the **50 dBZ or greater radar reflectivity in the thunderstorm** with appropriate time apportionment. Lower rain rates are logarithmically down-stepped to the lower radar reflectivity values.

HMS generates a matrix of rainfall rates which are derived from surface temperature and dew point fields used to initialize the 2-D model output. For each set of surface temperature-dew point combinations, HMS creates a unique radar-rainfall relationship for precipitation mapping. A weather station network provides information on observed surface temperature/dew point values in the District. For the night of July 12th, HMS used the PROFS mesonet of automated weather stations and the District ALERT weather station at Evergreen to calculate and assign a radar-rainfall relationships to the Buffalo Creek basin.

Figure 3 shows the HMS-plotted surface weather observations for the PROFS mesonet for 805PM PM (0205Z) on July 12. Note the strong moist, northeasterly winds flowing into Jefferson County. Next, HMS plotted the surface weather station observations from the mesonet on a Skew-T, Log P thermodynamic diagram (**Figure 4**) on which the evening Denver upper air sounding had already been plotted. The vertical plotting of the surface weather observations is called by HMS a mesosound and is used as a means of calculating the changes in the stability and moisture content of the air over the District.

Note on **Figure 4** points A and B. Point A is where the cloud base has been calculated using the surface weather observations from the mesonet and point B is the point where the thunderstorm updraft cools to 0C. The calculated PWI is 1.31" adjusted for an elevation of 7,000 feet while the **depth of the warm updraft layer is** point B (5.4km) minus point A (2.6 km) or **2.8 km**. The next step is to solve Equations 2 to 4 for the peak rainfall rates.

Next insert the values for PWI (1.31") and the depth of the warm layer (2.8 km) into Equation 2 and solve for the peak 60-minute rainfall rate which is 4.90". Using this value in Equation 3 and solving the equation, the peak 30-minute rainfall rate is calculated to be 3.43 inches. These rainfall rates are assigned to the grid squares covered by radar reflectivity values of 5 level or greater. The rainfall rates assigned to lower reflectivity values are found in Table 1. Note that the peak 10-minute rain rates are not calculated to allow for the reduction of rainfall by hail production in the storm.

Table 1 Relationship between peak 60-minute and peak 30-minute rainfall rates and radar reflectivity levels.

Radar Z - Level	Peak 60-min 4.90"	Peak 30-min 3.43"	Peak 10-min 2.05"(Hail)
2	0.10"/5min	0.22"/5min	
3	0.22"/5min	0.30"/5min	
4	0.30"/5min	0.41"/5min	
5	0.40"/5min	0.57"/5min	* Hail
6	0.40"/5min	0.57"/5min	* Hail

HMS routinely archives 6 minute radar observations from the National Weather Service (NWS) WSR-88D located at Watkins, Colorado. This radar is located less than 60 miles from the Buffalo Creek basin and provides very accurate radar reflectivity observations. The resolution of the radar reflectivity

Figure 3 Surface observations for 805PM (0205Z), July 12, 1996

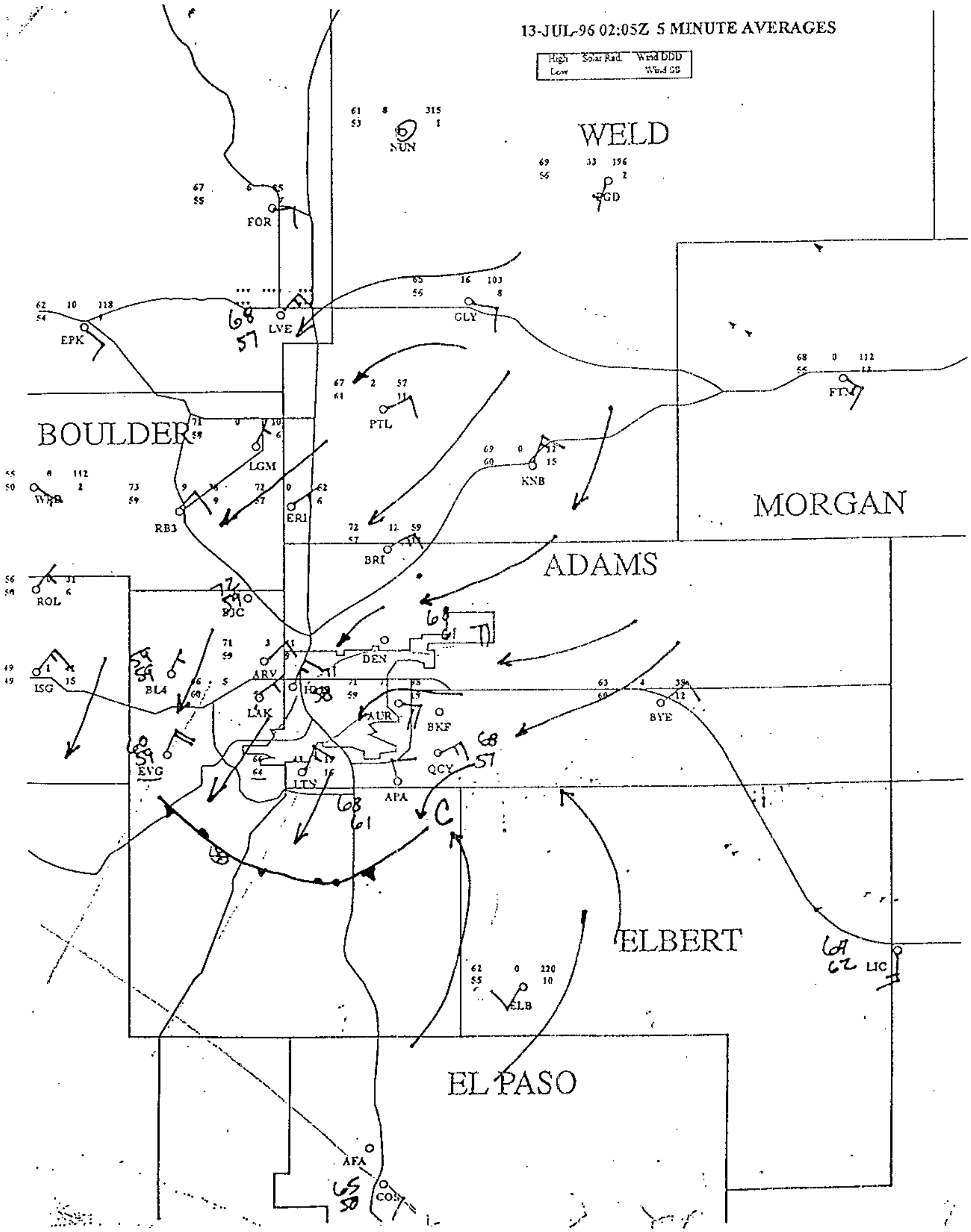
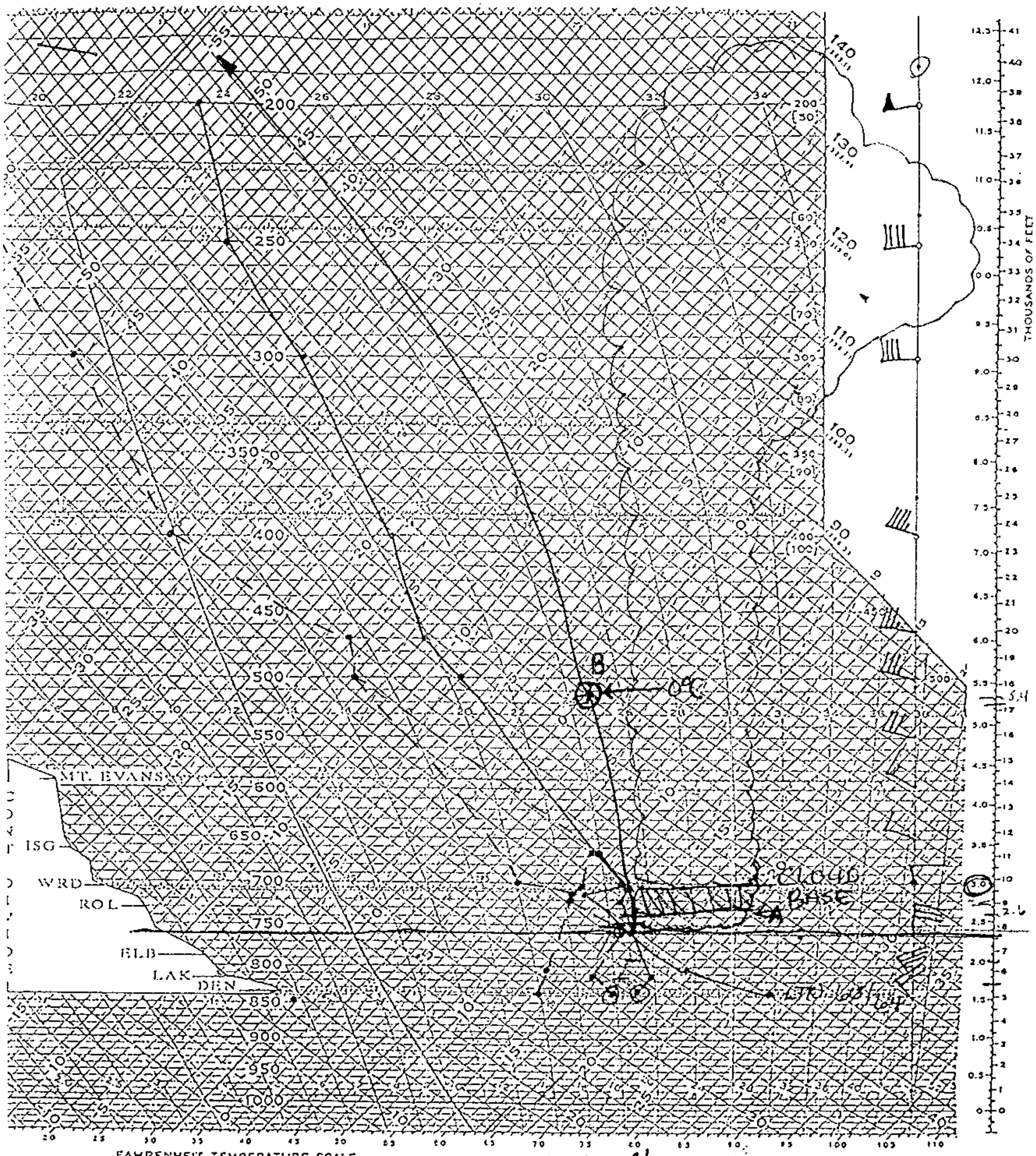


Figure 4 SkewT, LogP diagram of 600PM Denver sounding



STATION:	DEN
NUMBER:	
TIME (GCT):	∅Z
DATE (GCT):	7-13-96

0205Z

PRECIPITABLE WATER PWI = 1.34 > 7,000 ft

LYR	MR	CONV	PWI
820	14.5	0.044	.64
750	13.8	0.133	1.83
650	10.0	0.154	1.54
555	4.5	0.182	.82
TOTAL:			/3.2 = 1.51"

5% PWI

STABILITY DATA

	T	Td	DelT	DelZ	PF
1.	66	64			3.5
2.	70	61			2.3
3.					
4.	60	59			
5.					

QPF

60 min.	30 min.	10 min.
7.04	4.90	2.45
6.64	4.65	3.25
4.90"	3.43"	2.05"

data allows it to define the radar reflectivity for 0.5 by 0.5 square mile areas over the Buffalo Creek watershed.

An example of the Table 1 relationship applied to observed radar reflectivity from the NWS WSR-88D Watkins radar is shown in **Figure 5**. The top map of the basin shows the observed radar reflectivity while the bottom map shows the associated rainfall. Each of these "maps" is really a Microsoft Excel 7.0 spreadsheet in a storm workbook. HMS has made copies of each spreadsheet on 1.44" disk which are included with the copy of the report for each of the organizations sponsoring this project. Additionally, HMS has included a hard copy of each data plot for each radar observation period of the four storm periods which occurred on the July 12, 1996 in Appendix B.

Additionally, HMS has calculated the rainfall for storms which hit the Buffalo Creek basin on June 12, July 12, August 7, August 8, August 23 and September 14. The basic data and spreadsheets for these storms is included on 1.44" disk with the report to major sponsors. Please note that HMS did not have archived data for an early afternoon storm on June 12, 1996 which produced flooding in Buffalo Creek. The HMS storm calculations for this date are for storms which occurred later during the afternoon. HMS will include information on this early June 12, 1996 storm in the Phase 2 report of this project. The radar data required has been ordered from the National Climate Data Center and was not available in time to complete the analysis for inclusion in this report. The remainder of this report presents the results of applying the described technique to the storms identified earlier in this section.

3.0 The Buffalo Creek Flash Flood of July 12, 1996

The Buffalo Creek Flash Flood of July 12, 1996 occurred on one of the most weather active days of the summer of 1996. Two tornadoes, 11 damaging hail reports and numerous wind damage reports were logged by the NWS in Denver as shown in **Figure 6**. The Buffalo Creek Flash Flood reached the town of Buffalo Creek about 900PM or just after a round of severe weather had buffeted the Denver metro area with a tornado and numerous wind and hail damage reports.

It is interesting to note from Figure 6 that the most active weather period of the day in the Denver metro area occurred from about 700PM until 900PM which provided a significant challenge to area meteorologists. We will not discuss the operational implications of the other severe weather events which preceded the flash flood. In effect, Mother nature was serving notice that July 12th would be a day of very severe weather.

Figure 5 Example of radar and rainfall maps

Buffalo Creek Watershed Flash Flood
July 12/13 1996
Storm 3 - 0220Z

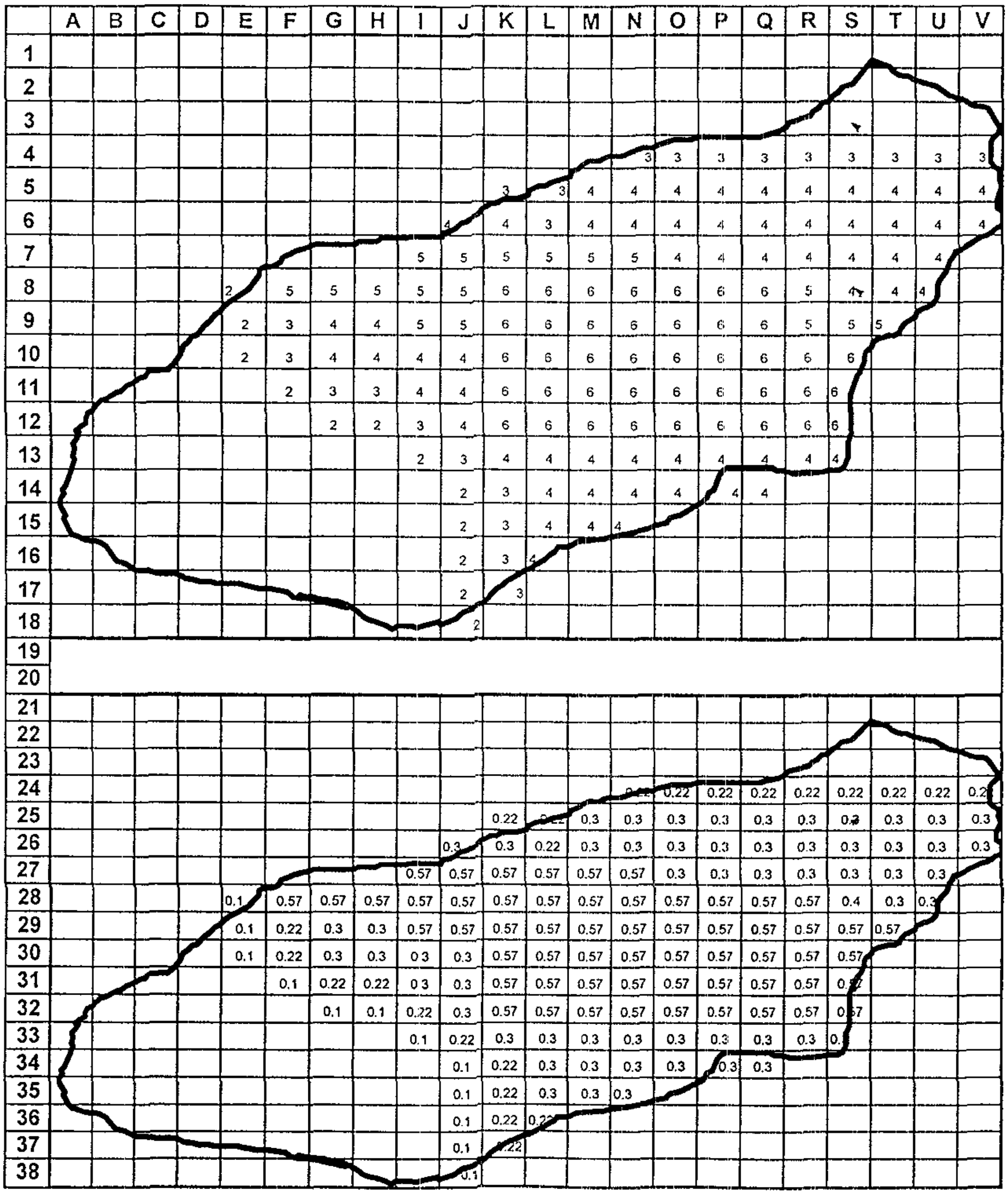


Figure 6 Severe storm log of NWS for July 12, 1996

LOCAL STORM REPORT
NATIONAL WEATHER SERVICE DENVER CO
450 AM MDT SATURDAY JULY 13 1996

TIME(MDT)	.....CITY LOCATION..... ....COUNTY LOCATION....	STATE	...EVENT/REMARKS...
217 PM 7/12/96	3E ENGLEWOOD DOUGLAS	CO	BRIEF TORNADO TOUCHDOWN 3 E OF ARAPAHOE COUNTY AIRPORT BY FAA TOWER PERSONNEL
346 PM 7/12/96	2E DIA AIRPORT ADAMS	CO	1.5 INCH DIAMETER HAIL HAM RADIO SPOTTER
542 PM 7/12/96	15S BRUSH MORGAN	CO	1.75 INCH DIAMETER HAIL PUBLIC REPORT
550 PM 7/12/96	8S BRUSH MORGAN	CO	1.75 INCH DIAMETER HAIL HAM RADIO SPOTTER
554 PM 7/12/96	IN CARR WELD	CO	1.75 INCH DIAMETER HAIL MOUNTAIN STATES WEATHER
610 PM 7/12/96	IN NUNN WELD	CO	WIND GUST 50KT MESONET OBSERVATION SYSTEM
702 PM 7/12/96	EVERGREEN JEFFERSON	CO	1.25 INCH DIAMETER HAIL HENZ METEOROLOGICAL SERVICE
719 PM 7/12/96	3S MORRISON JEFFERSON	CO	1.5 INCH DIAMETER HAIL MARTIN MARIETTA PERSONNEL
722 PM 7/12/96	LAKEWOOD JEFFERSON	CO	1.0 INCH DIAMETER HAIL HAM RADIO SPOTTER
747 PM 7/12/96	ENGLEWOOD ARAPAHOE	CO	1.0 INCH DIAMETER HAIL HAM RADIO SPOTTER
813 PM 7/12/96	7NE BOULDER BOULDER	CO	1.25 INCH DIAMETER HAIL RESEARCH METEOROLOGIST
830 PM 7/12/96	LOUISVILLE BOULDER	CO	ESTIMATE WIND GUST 52KT FENCE BLOWN DOWN OFF DUTY NWS FORECASTER
840 PM 7/12/96	BROOMFIELD/WESTMINSTER WESTMINSTER/ADAMS	CO	TORNADO SEVERAL PUBLIC REPORTS CONFIRMED BY BROOMFIELD POLICE TRAMPOLINE BLOWN THRU WINDOW TREES DOWN IN MANY PLACES
844 PM 7/12/96	BROOMFIELD JEFFERSON	CO	WIND DAMAGE WITH LARGE TREE BRANCHES DOWN AT 120TH AND MAIN ST BY HAM RADIO SPOTTER
845 PM 7/12/96	BROOMFIELD BOULDER	CO	0.75 INCH DIAMETER HAIL REPORTED BY SPOTTER
845 PM 7/12/96	BROOMFIELD JEFFERSON	CO	WIND GUST 70KT AT JEFFERSON COUNTY AIRPORT BY OBSERVER
846 PM 7/12/96	BROOMFIELD JEFFERSON	CO	1.25 INCH DIAMETER HAIL HAM RADIO SPOTTER

BOODA

HMS radar records indicated that four storm periods occurred across the Buffalo Creek watershed on July 12, 1996:

1. **Storm Period 1: 210PM until 228PM**, a light shower across the lower third of the basin.

2. **Storm Period 2: 612PM until 710PM**, rain showers and two moderate thunderstorms across the western third of the basin.

3. **Storm Period 3: 739PM until 913PM**, a line of severe thunderstorms cross and go stationary over the watershed producing the flash flood.

4. **Storm Period 4: 918PM until 1023PM**, post-flash flood thundershowers and showers cross the lower half of the watershed.

The first storm period produced only minor rainfall accumulations of 0.18" to 0.24" over the lower third of the basin from light rain showers. No radar indication of thunderstorm activity over the basin was noted. The radar echoes of these showers appeared to form over the burn area of the May 1996 fire. These showers failed to develop further because of a strong inversion capping their development above 25,000 feet. Further east on the plains of Arapahoe and Douglas Counties, warmer temperatures and the converging winds of a Denver Cyclone spawned a brief tornado southeast of Centennial Airport during this time period.

The **second storm period** was more vigorous and preceded the line of storms which produced the flash flooding by about one hour. These storms formed over the higher terrain of Buffalo and Windy Peaks in the far western portion of the watershed. Rain accumulation from these storms reached about 0.15" to 0.65" in the western third of the basin. The storms moved quickly from west to east at almost 25 mph and cleared the basin shortly after 700PM. No hail was reported with these storms but is quite possible that small hail of up to 0.75 inches in diameter could have occurred with these storms.

The low rainfall totals produced by these early storms did not reflect the true potential of the atmosphere. **Table 2** shows a comparison of the peak 30-minute rainfall rates, the depth of the warm layer of the thunderstorm updrafts and the Precipitable Water Index (PWI) from 530PM until 910PM. This temporal variation in rainfall rates and PWI is quite common and underscores the problems in using standard radar reflectivity-rainfall relationships. Note the dramatic increase in the PWI by 805PM and the nearly doubling of the peak 30-minute rainfall rates from the earlier second period of storms which concluded shortly after 700PM.

Table 2 **Comparison of radar reflectivity/rainfall rates from 530PM to 910PM on July 12, 1996 over the Buffalo Creek watershed.**

GMT/PM	2330Z/530PM	0025Z/625PM	0205Z/805PM	0310Z/910PM
Radar	Peak 30-min	Peak 30-min	Peak 30-min	Peak 30-min
Z - Level	2.25"	1.75"	3.43"	2.79"
2	0.17"/5min	0.11"/5min	0.22"/5min	0.17"/5min
3	0.23"/5min	0.15"/5min	0.30"/5min	0.24"/5min
4	0.32"/5min	0.20"/5min	0.41"/5min	0.33"/5min
5	0.45"/5min	0.29"/5min	0.57"/5min	0.47"/5min
6	0.45"/5min	0.29"/5min	0.57"/5min	0.47"/5min
Warm Layer	**2.7km**	**1.7km**	**2.8km**	**2.4km**
PWI	**0.90"**	**1.02"**	**1.31"**	**1.24"**

Shortly after the second wave of storm ended, a group of severe thunderstorms formed about 10 miles to 20 miles north of the basin near Golden and Evergreen in central Jefferson County. These storms produced several reports of 1.00-1.50 inch in diameter hail over central Jefferson County and brief heavy rainfall as they rapidly moved east. Rainfall estimates in North Turkey Creek Canyon were made by John Henz using a 4" diameter can which equaled about 1.50 inches of rain in 22 minutes while the ground was covered by 1.25 inch in diameter soft hail. The NWS in Denver issued a severe thunderstorm warning for this storm about 705PM.

While this storm was very intense, it moved east-southeastward at about 25 mph and cleared the Jefferson County foothills about 725PM. This storm produced additional severe weather in western Arapahoe and northern Douglas Counties between 730PM and 800PM. More importantly it produced a gust front boundary of very humid northeasterly winds of 20-30mph which moved southward into the Buffalo Creek watershed by about 800PM. **This gust front provided the meteorological mechanism which caused the Buffalo Creek thunderstorm to go stationary over the watershed producing the flash flood**. The gust front acted as a focussing boundary for converging air masses from the south and north. Both air masses were very humid and unstable and provided the moisture for the flash flooding rainfall. The gust front is clearly visible in the WSR-88D radar imagery and extended from Castle Rock in eastern Douglas County westward to Buffalo Creek from 800PM until 900PM.

As the central Jefferson County storm moved north of Buffalo Creek, additional storms were forming to the west. The Buffalo Creek thunderstorm complex appears to have formed about 715PM along the slopes of Mount Blaine and the Twin Cone Peaks in Park County 15-20 miles west of the basin. The storm complex moved steadily eastward and into the central part of the Buffalo

Creek watershed by 808PM according the NWS WSR-88D radar data. Unfortunately, its arrival and that of the gust front from the earlier storm in central Jefferson County coincided. **Figure 7** shows the path of the storm complex from 715PM to 900PM. It is very possible that the storm would not have gone stationary if the gust front had not provided a focus for a strong inflow of moist, unstable air into the storm complex.

The radar-rainfall maps in **Appendix B** should be consulted for the incremental rainfall by time for the flash flooding period. Review of these maps suggests that the peak rainfall production occurred from 815PM until 900PM over the lower third of the basin. During this period over 3.00 inches of rain fell over the lower third of the basin. The rain was accompanied by hail at times, especially before 830PM. By 913PM the core of the storm had moved eastward over the Spring Creek watershed which experienced the same amounts of rain as the lower third of Buffalo Creek between 900PM and 945PM.

Figure 8 shows the HMS radar-estimated storm rainfall from 739PM until 913PM across the Buffalo Creek basin. The **basin average rainfall** during this period was **2.16 inches** of rain with a **peak 0.5 square mile rainfall of 5.13 inches**. During this period, an 18 square mile area of the lower third of the basin received over 3.25 inches of rain while a **core area of 6 square miles just above the town of Buffalo Creek was inundated by over 4 inches of rain** and hail. HMS removed hail contamination from its rainfall estimates by not including the peak 10 minute rainfall estimates in its precipitation mapping. In effect, this process eliminated just over an inch of rain from the mapping which may have been used for hail production by the storm.

Figure 9 shows the July 12, 1996 storm total rainfall over the basin for the entire period from 210PM until 1023PM when the last showers of consequence cleared the basin. **The basin average rain increases to 2.49 inches while the peak 0.5 square mile increases to 6.29 inches**. The lower third of the basin shows an average rainfall of just over 4.00 inches. **Clearly, this thunderstorm rainfall was focussed by the stationary movement of the storm over the basin for about 30-45 minutes.**

Another contributing factor to the flash flood may have been the **slow movement down the basin of the rainfall core** which could have aided in producing a runoff maximum that traveled with the storm. This storm was the only one which went stationary over northeastern Colorado. All the other storm complexes moved at speeds of 25 to 40 mph while producing severe weather. It appears that **the gust front** which aided storm intensification and inhibited storm motion **was a major contributing weather feature** to the storm's severity **along with the very moist condition of the atmosphere**.

Figure 7 Track of 5 level or greater echo area for Buffalo Creek storm from 715PM to 900PM

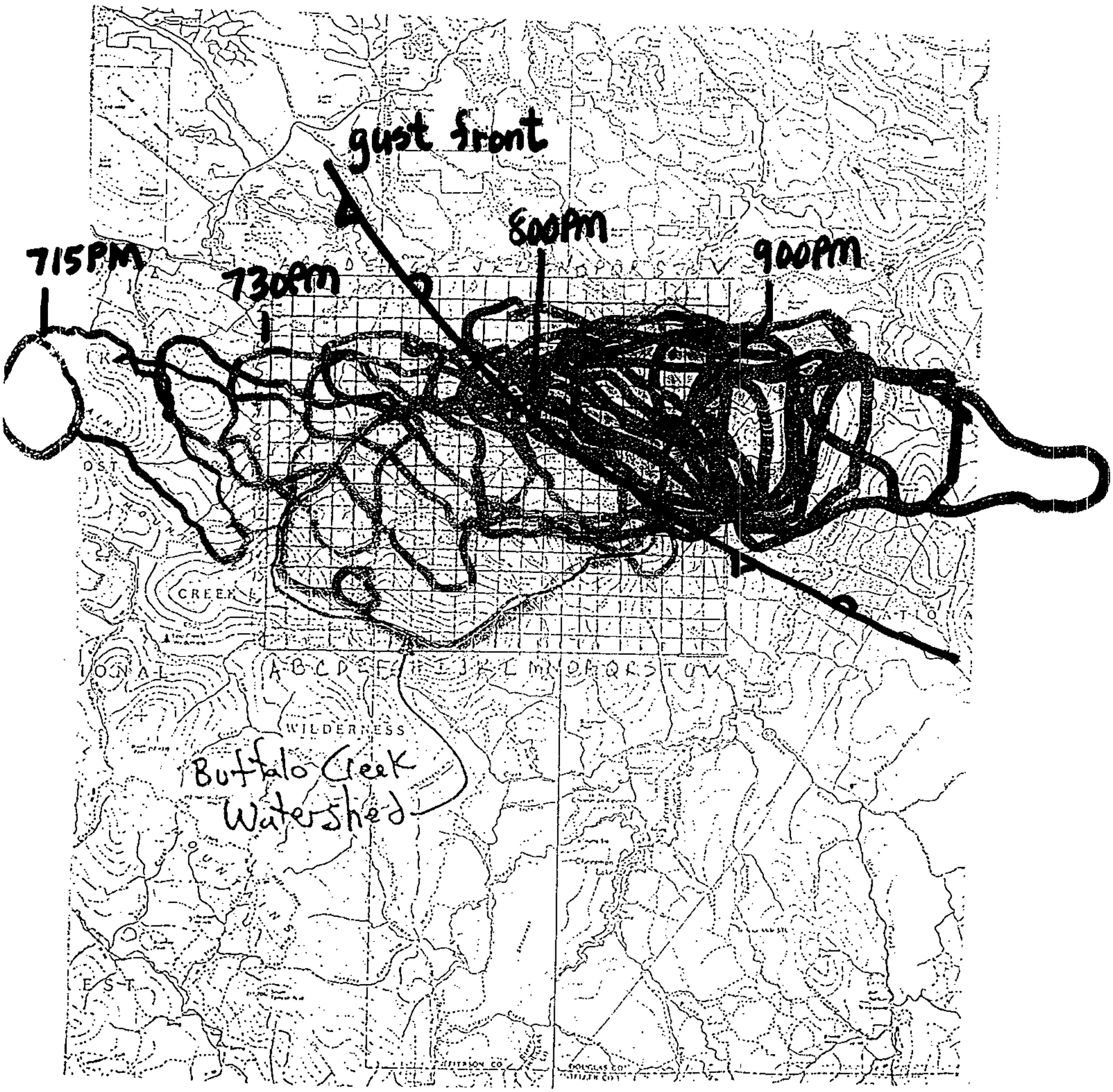


Figure 8 Storm 3 total rainfall from 739PM to 913PM, the Buffalo Creek Flash Flood

BUFFALO CREEK DRAINAGE BASIN RAINFALL

July 12, 1996 (Storm 3 Totals, 0139Z - 0313Z)

																							Row TTL	Cells/Row	Row Avg.
																			2.15	2.25	2.3[illegible]		6.77	3	2.26
																		2.23	2.15	2.25	2.37	2.37	11.37	5	2.27
														1.55	1.75	2.58	3.06	2.94	3.10	3.09	3.05	3.0[illegible]	24.17	9	2.69
												1.29	2.09	3.08	3.45	3.83	3.61	3.51	3.60	3.76	4.15	4.23	36.60	11	3.33
										1.18	1.82	2.36	2.74	3.28	3.68	4.40	4.23	4.13	4.32	4.46	4.41	3.9[illegible]	44.93	13	3.46
						1.00	1.27	2.01	2.90	2.97	3.43	3.30	3.58	3.45	3.78	4.32	4.13	4.13	4.32	4.78	4.6[illegible]	2.63	56.69	17	3.33
					1.50	1.97	2.41	2.41	3.00	3.32	3.48	3.08	3.11	3.27	3.61	4.30	4.38	4.67	4.77	5.13	4.56		58.97	17	3.47
				0.42	1.60	1.72	2.14	2.14	3.00	2.98	3.28	3.35	3.37	3.69	4.17	3.85	3.93	4.02	4.31	4.7[illegible]			52.71	17	3.10
			0.45	0.87	1.60	1.72	2.31	2.09	2.36	2.60	2.95	3.13	3.03	3.39	3.77	3.06	3.14	2.94	3.22				42.63	17	2.51
		0.10	0.62	0.82	1.67	1.37	1.88	1.93	2.01	2.38	2.75	2.83	3.03	3.10	2.98	2.98	2.71	2.26	1.95				37.37	18	2.08
	0.[illegible]7	0.57	1.16	0.96	1.64	1.45	1.37	1.42	1.54	2.01	2.16	1.99	2.11	2.23	2.03	2.11	2.11	2.01	2.81				31.45	19	1.66
	0.27	0.67	0.86	0.96	1.56	1.37	1.19	1.24	1.52	1.49	1.45	1.55	1.67	1.52	1.86	1.8[illegible]	[illegible]	1.27	1.17				25.12	19	1.32
	0.57	0.57	1.04	1.14	1.44	1.37	1.19	1.24	1.19	1.25	1.37	1.45	1.55	1.44	1.24	0.52							18.57	16	1.16
	0.20	0.20	0.40	0.30	0.82	0.82	1.04	1.21	1.21	1.37	1.19	1.37	1.47	[illegible]	0.32								13.04	15	0.87
		0.22	0.10	0.10	0.32	0.32	0.54	0.59	0.59	0.91	1.03	0.91											5.63	11	0.51
				0.10	0.10	0.10	[illegible]	0.59	0.59	0.91	0.91												3.84	8	0.48
								0.15	0.37	0.25													0.77	3	0.26
Totals:																							470.63	218	
Col. TTL :	1.31	2.33	4.63	5.67	12.25	13.21	15.88	17.02	20.28	23.62	25.82	26.61	27.75	31.12	32.64	33.81	32.94	34.11	37.37	30.48	25.60	16.20			
Cells/Col	4	6	7	9	10	11	11	11	11	12	12	12	11	12	12	11	10	11	12	8	7	5			
Col. Avg	0.33	0.39	0.66	0.63	1.23	1.20	1.44	1.55	1.84	1.97	2.15	2.22	2.52	2.59	2.72	3.07	3.29	3.10	3.11	3.81	3.66	3.24			

Basin 1/2-Square Mile Average:	2.16
Basin 1/2-Square Mile Max:	5.13
% of Basin > 1.00":	79%
% of Basin > 0.50":	90%
% of Basin > 0.25":	95%
Peak 30-minute Basin 1/2-Square Mile Rainfall:	3.42
Peak 12-minute Basin 1/2-Square Mile Rainfall:	1.14

Figure 9 Storm total rainfall in Buffalo Creek basin on July 12, 1996

BUFFALO CREEK DRAINAGE BASIN RAINFALL
July 12, 1996 (Storm 1-4 Totals)

																							Row TTL	Cells/Row	Row Avg.
																			2.15	2.25	[illegible]		6.77	3	2.26
																		2.23	2.15	2.25	2.37	2.37	11.37	5	2.27
														1.55	1.91	2.74	3.22	3.10	3.26	3.25	3.21	3.2	25.45	9	2.83
												1.54	2.50	3.77	4.25	4.54	4.15	3.97	4.21	4.37	4.70	4.78	42.78	11	3.89
										1.26	2.15	2.85	3.48	4.05	4.62	5.18	4.99	4.92	5.34	5.32	5.21	4.72	54.09	13	4.16
						1.00	1.27	2.01	2.98	3.29	3.92	3.95	4.48	4.38	4.96	5.43	5.06	4.92	5.51	5.97	5.57	3.27	67.97	17	4.00
					1.50	1.97	2.41	2.49	3.16	3.64	3.80	3.57	3.77	3.98	4.55	5.07	5.35	5.75	5.85	6.29	5.58		68.73	17	4.04
				0.42	1.60	1.72	2.14	2.14	3.00	3.06	3.44	3.51	3.69	4.15	4.86	4.54	4.76	5.01	5.38	[illegible]			59.23	17	3.48
			0.45	0.87	1.60	1.72	2.31	2.09	2.36	2.60	3.03	3.21	3.19	3.61	4.30	3.67	3.81	3.93	4.29				47.04	17	2.77
		0.10	0.62	0.82	1.67	1.37	1.88	1.93	2.01	2.38	2.75	2.83	3.03	3.16	3.43	3.35	3.16	2.70	[illegible]				39.58	18	2.20
	[illegible]	0.70	1.29	1.02	1.70	1.51	1.43	1.48	1.60	2.07	2.16	1.99	2.11	2.23	2.09	2.17	2.25	2.15	[illegible]				32.80	19	1.73
	0.53	1.00	1.19	1.22	1.82	1.63	1.25	1.36	1.74	1.77	1.67	1.77	1.85	1.70	2.04	1.86	1.78	1.41	1.31				28.90	19	1.52
	0.83	0.90	1.37	1.34	1.64	1.57	1.19	1.46	1.59	1.59	1.65	1.79	1.80	1.76	1.56	0.72							22.76	16	1.42
	0.33	0.40	0.60	0.57	1.15	1.15	1.37	1.68	1.80	1.84	1.72	1.89	1.71	[illegible]	0.43								17.94	15	1.20
		[illegible]	0.23	0.37	0.59	0.59	0.81	1.00	1.12	1.51	1.70	1.52											9.79	11	0.89
				0.37	0.37	[illegible]	0.81	0.78	0.84	1.23	1.17												5.94	8	0.74
								0.15	0.57	0.57													1.29	3	0.43
																						Totals:	542.43	218	
Col TTL:	2.09	3.45	5.75	7.00	13.64	14.60	16.87	18.57	22.77	26.81	29.16	30.42	31.61	35.64	39.00	39.27	38.53	40.09	44.29	35.51	29.01	18.35			
Cells/Col:	4	6	7	9	10	11	11	11	11	12	12	12	11	12	12	11	10	11	12	8	7	5			
Col. Avg.:	0.52	0.58	0.82	0.78	1.36	1.33	1.53	1.69	2.07	2.23	2.43	2.54	2.87	2.97	3.25	3.57	3.85	3.64	3.69	4.44	4.14	3.67			

Basin 1/2-Square Mile Average: 2.49

Basin 1/2-Square Mile Max: 6.29

% of Basin > 1.00": 84%

% of Basin > 0.50": 94%

% of Basin > 0.25": 99%

Peak 30-minute Basin 1/2-Square Mile Rainfall: 3.42

Peak 12-minute Basin 1/2-Square Mile Rainfall: 1.14

4.0 Comparison with other Buffalo Creek storms in 1996

HMS has prepared a comparison of the key rainfall and weather features of several other important storms which crossed the Buffalo Creek basin during 1996. An Excel 7.0 spreadsheet workbook has been completed for each of these storms which includes observed radar reflectivity and associated rainfall for each observation period. This information has been included on 1.44" disk with the report. Other readers can obtain a copy of this data by written request to the author.

The **June 12, 1996 storm** (**Figure 10**) was related to a weak cool front which pushed into northeast Colorado during the early morning hours. Weak easterly flow developed behind the front creating moisture and wind convergence into the foothills of Jefferson County which helped to initiate strong to, possibly, severe storms.. Two thunderstorms moved over portions of the Buffalo Creek drainage basin. The first was between 130PM and 245PM and the second was between 400PM and 515PM. Storm movement was to the east/northeast at 10-15 mph. HMS has analyzed the data for the second storm from 400PM to 500PM but has radar data on order for the first storm which will be included in the Phase 2 portion of this project.

On **August 7, 1996** (**Figure 11**) a northeast to southwest oriented wind convergence line developed across western Douglas and southern Jefferson counties. It is estimated that 20-30 mph southeast winds converged with 10-15 mph northerly winds, creating the convergence line. A weak mid-level disturbance pushed over northeast Colorado during the middle to late afternoon hours. One thunderstorm, developing on the convergence line, moved over portions of the Buffalo Creek basin between 215PM and 315 PM. Storm movement was to the east/southeast at 12-18 mph.

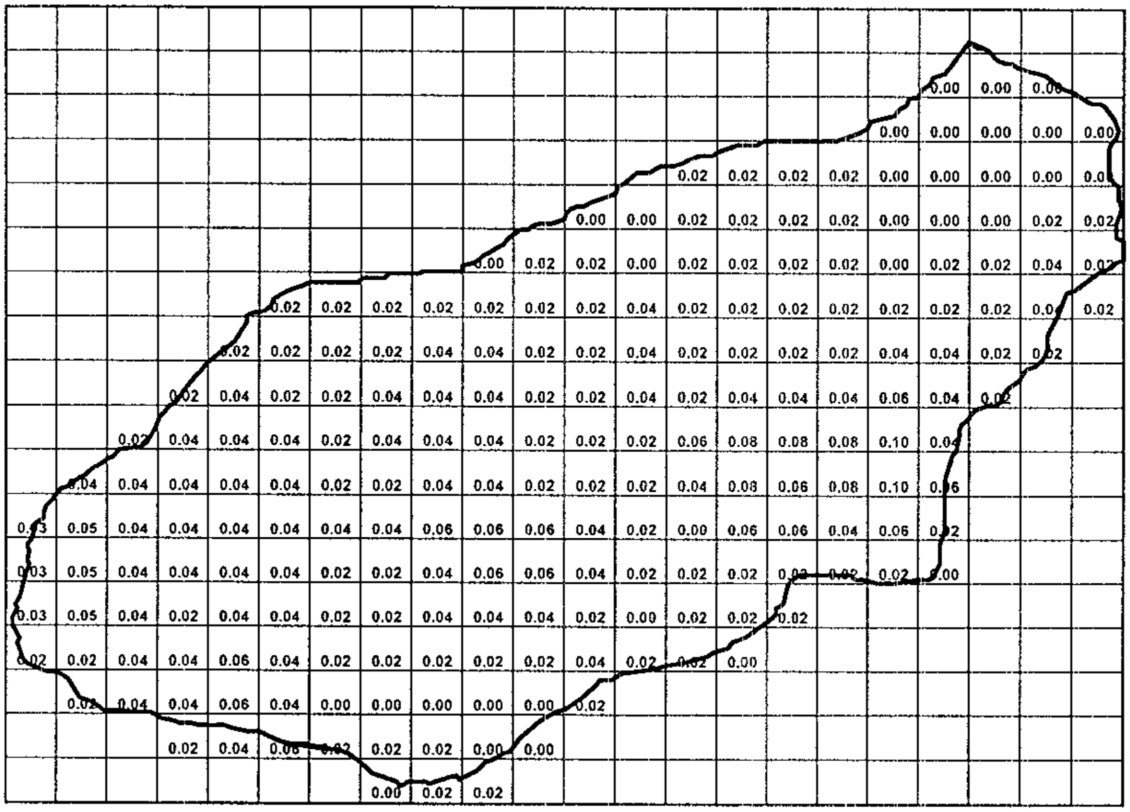
On **August 8, 1996** (**Figure 12**) weak easterly low level flow combined with a 500 mb circulation helped in the initiation of a moderate to strong thunderstorm that affected portions of the Buffalo Creek drainage basin. The thunderstorm crossed the basin between 245PM and 350 PM. Storm movement was to the north at 08-12 mph.

On **August 23, 1996** (**Figure 13**) weak easterly low level flow combined with a 700 mb and 500 mb circulation helped in the initiation of **two strong thunderstorms** that affected portions of the Buffalo Creek drainage basin. The thunderstorms crossed the basin between 255PM and 509 PM. Storm movement was to the northeast at 04-08 mph.

Finally on **September 14, 1996** (**Figure 14**) tropical moisture from ex-Hurricane Fausto was being pumped into Colorado via southwesterly flow aloft. It acted in concert with a cut-off low at all levels of the atmosphere to initiate

Figure 10 Storm total rainfall for July 12, 1996 storm

BUFFALO CREEK DRAINAGE BASIN RAINFALL
June 12, 1996 (2216Z to 2309Z)



Row TTL	Cells/Row	Row Avg.
0.00	3	0.00
0.00	5	0.00
0.08	9	0.01
0.12	11	0.01
0.22	13	0.02
0.38	17	0.02
0.44	17	0.03
0.56	17	0.03
0.78	17	0.05
0.80	18	0.04
0.80	19	0.04
0.60	19	0.03
0.46	16	0.03
0.40	15	0.03
0.22	11	0.02
0.18	8	0.02
0.04	3	0.01
Totals: 6.08	218	

Col. TTL:	0.11	0.23	0.26	0.30	0.42	0.40	0.22	0.26	0.38	0.38	0.30	0.28	0.22	0.28	0.40	0.38	0.36	0.40	0.24	0.08	0.12	0.06
Cells/Col:	4	6	7	9	10	11	11	12	12	13	12	12	11	12	12	11	10	11	12	8	7	5
Col. Avg.:	0.03	0.04	0.04	0.03	0.04	0.04	0.02	0.02	0.03	0.03	0.03	0.02	0.02	0.02	0.03	0.03	0.04	0.04	0.02	0.01	0.02	0.01

Basin 1/2-Square Mile Average: 0.03

Basin 1/2-Square Mile Max: 0.10

% of Basin > 1.00": 0%

% of Basin > 0.50": 0%

% of Basin > 0.25": 0%

Peak 30-minute Basin 1/2-Square Mile Rainfall: 0.06

Peak 12-minute Basin 1/2-Square Mile Rainfall: 0.05

Figure 11 Storm total rainfall for August 7, 1996 storm

BUFFALO CREEK DRAINAGE BASIN RAINFALL
August 7, 1996 (2031Z to 2143Z)

																							Row TTL	Cells/Row	Row Avg.
																			0.33	0.33	0.3[illegible]		0.98	3	0.33
																		0.31	0.34	0.34	0.36	0.35	1.70	5	0.34
														0.25	0.26	0.15	0.33	0.33	0.34	0.34	0.36	0.3[illegible]	2.72	9	0.30
												0.11	0.19	0.27	0.16	0.21	0.27	0.30	0.33	0.34	0.36	0.36	2.90	11	0.26
										0.25	0.22	0.23	0.19	0.15	0.15	0.07	0.25	0.29	0.33	0.34	0.35	0.24	3.06	13	0.24
						0.12	0.12	0.15	0.29	0.27	0.25	0.20	0.14	0.09	0.09	0.08	0.09	0.14	0.14	0.12	0.1[illegible]	0.11	2.53	17	0.15
					0.06	0.17	0.17	0.14	0.25	0.20	0.22	0.20	0.13	0.07	0.09	0.11	0.10	0.14	0.14	0.12	0.06		2.37	17	0.14
				0.00	0.05	0.08	0.12	0.06	0.11	0.03	0.07	0.04	0.07	0.07	0.10	0.10	0.09	0.06	0.11	0.10			1.26	17	0.07
			0.00	0.00	0.05	0.12	0.08	0.11	0.07	0.07	0.07	0.06	0.09	0.06	0.09	0.09	0.04	0.04	0.08				1.12	17	0.07
		0.02	0.02	0.00	0.00	0.05	0.04	0.04	0.08	0.06	0.04	0.06	0.09	0.11	0.09	0.09	0.04	0.08	0.[illegible]7				1.08	18	0.06
	0.[illegible]0	0.02	0.04	0.02	0.00	0.00	0.00	0.00	0.02	0.02	0.00	0.03	0.07	0.08	0.09	0.08	0.06	0.09	0.[illegible]9				0.71	19	0.04
	0.02	0.03	0.02	0.00	0.00	0.03	0.03	0.03	0.05	0.07	0.07	0.04	0.06	0.09	0.08	0.05	0.05	0.08	0.07				0.87	19	0.05
	0.02	0.03	0.02	0.00	0.00	0.00	0.02	0.00	0.05	0.06	0.07	0.07	0.07	0.11	0.09	0.04							0.65	16	0.04
	0.02	0.02	0.02	0.00	0.00	0.00	0.00	0.00	0.04	0.05	0.06	0.10	0.07	0.1[illegible]	0.06								0.57	15	0.04
		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.04	0.03	0.04	0.10											0.21	11	0.02
				0.00	0.00	0.00	0.00	0.00	0.04	0.06	0.04												0.14	8	0.02
								0.00	0.02	0.01													0.03	3	0.01
																						Totals:	22.90	218	
Col. TTL :	0.06	0.12	0.12	0.02	0.16	0.57	0.58	0.53	1.06	1.18	1.15	1.24	1.17	1.48	1.35	1.07	1.32	1.86	2.47	2.03	1.94	1.42			
Cells/Col :	4	6	7	9	10	11	11	12	12	13	12	12	11	12	12	11	10	11	12	8	7	5			
Col. Avg :	0.02	0.02	0.02	0.00	0.02	0.05	0.05	0.04	0.09	0.09	0.10	0.10	0.11	0.12	0.11	0.10	0.13	0.17	0.21	0.25	0.28	0.28			

Basin 1/2-Square Mile Average:	0.11
Basin 1/2-Square Mile Max:	0.36
% of Basin > 1.00":	0%
% of Basin > 0.50":	0%
% of Basin > 0.25":	13%
Peak 30-minute Basin 1/2-Square Mile Rainfall:	0.32
Peak 12-minute Basin 1/2-Square Mile Rainfall:	0.24

Figure 12 Storm total rainfall for August 8, 1996 storm

BUFFALO CREEK DRAINAGE BASIN RAINFALL
August 8, 1996 (2049Z to 2148Z)

																							Row TTL	Cells/Row	Row Avg.
																			0.01	0.00	0.0[illegible]		0.01	3	0.00
																		0.01	0.01	0.00	0.00	0.00	0.02	5	0.00
														0.02	0.01	0.00	0.00	0.00	0.00	0.03	0.00	0.0[illegible]	0.06	9	0.01
												0.05	0.05	0.02	0.01	0.00	0.00	0.00	0.03	0.03	0.00	0.00	0.19	11	0.02
										0.01	0.06	0.08	0.05	0.08	0.10	0.12	0.06	0.03	0.03	0.03	0.03	0.03	0.71	13	0.05
						0.15	0.25	0.15	0.15	0.15	0.12	0.10	0.12	0.17	0.19	0.18	0.15	0.12	0.12	0.09	0.06	0.00	2.27	17	0.13
					0.15	0.30	0.27	0.16	0.14	0.16	0.15	0.16	0.15	0.17	0.15	0.19	0.16	0.13	0.12	0.09	0.06		2.71	17	0.16
				0.21	0.28	0.31	0.27	0.27	0.20	0.24	0.17	0.15	0.12	0.18	0.09	0.17	0.18	0.13	0.12	0.0[illegible]			3.18	17	0.19
			0.10	0.26	0.34	0.32	0.31	0.27	0.29	0.29	0.31	0.28	0.23	0.25	0.13	0.21	0.18	0.16	0.12				4.05	17	0.24
		0.23	0.28	0.31	0.36	0.30	0.30	0.37	0.23	0.31	0.36	0.24	0.20	0.23	0.16	0.14	0.16	0.10	0.06				4.34	18	0.24
	0.20	0.23	0.27	0.31	0.35	0.36	0.33	0.22	0.31	0.31	0.28	0.26	0.10	0.27	0.22	0.22	0.22	0.16	0.09				4.61	19	0.24
	0.13	0.16	0.29	0.28	0.33	0.46	0.42	0.27	0.36	0.30	0.33	0.39	0.28	0.25	0.14	0.22	0.12	0.09	0.09				4.91	19	0.26
	0.10	0.16	0.19	0.24	0.25	0.30	0.24	0.21	0.32	0.32	0.26	0.21	0.21	0.14	0.07	0.07							3.29	16	0.21
	0.10	0.12	0.18	0.18	0.19	0.22	0.08	0.07	0.23	0.23	0.21	0.17	0.09	0.07	0.00								2.14	15	0.14
		0.06	0.08	0.06	0.11	0.10	0.06	0.01	0.07	0.17	0.07	0.09											0.88	11	0.08
				0.06	0.10	0.0[illegible]	0.01	0.00	0.00	0.00	0.00												0.21	8	0.03
								0.00	0.00	0.00													0.00	3	0.00
																						Totals:	33.58	218	
Col. TTL :	0.43	0.96	1.39	1.91	2.46	2.86	2.54	2.00	2.30	2.49	2.32	2.18	1.60	1.85	1.27	1.52	1.23	0.93	0.80	0.36	0.15	0.03			
Cells/Col :	4	6	7	9	10	11	11	12	12	13	12	12	11	12	12	11	10	11	12	8	7	5			
Col. Avg :	0.11	0.16	0.20	0.21	0.25	0.26	0.23	0.17	0.19	0.19	0.19	0.18	0.15	0.15	0.11	0.14	0.12	0.08	0.07	0.05	0.02	0.01			

Basin 1/2-Square Mile Average: 0.15

Basin 1/2-Square Mile Max: 0.46

% of Basin > 1.00": 0%

% of Basin > 0.50": 0%

% of Basin > 0.25": 22%

Peak 30-minute Basin 1/2-Square Mile Rainfall: 0.42

Peak 12-minute Basin 1/2-Square Mile Rainfall: 0.16

Figure 13 Storm total rainfall for August 23, 1996 storm

BUFFALO CREEK DRAINAGE BASIN RAINFALL

August 23, 1996 (2055Z to 2309Z)

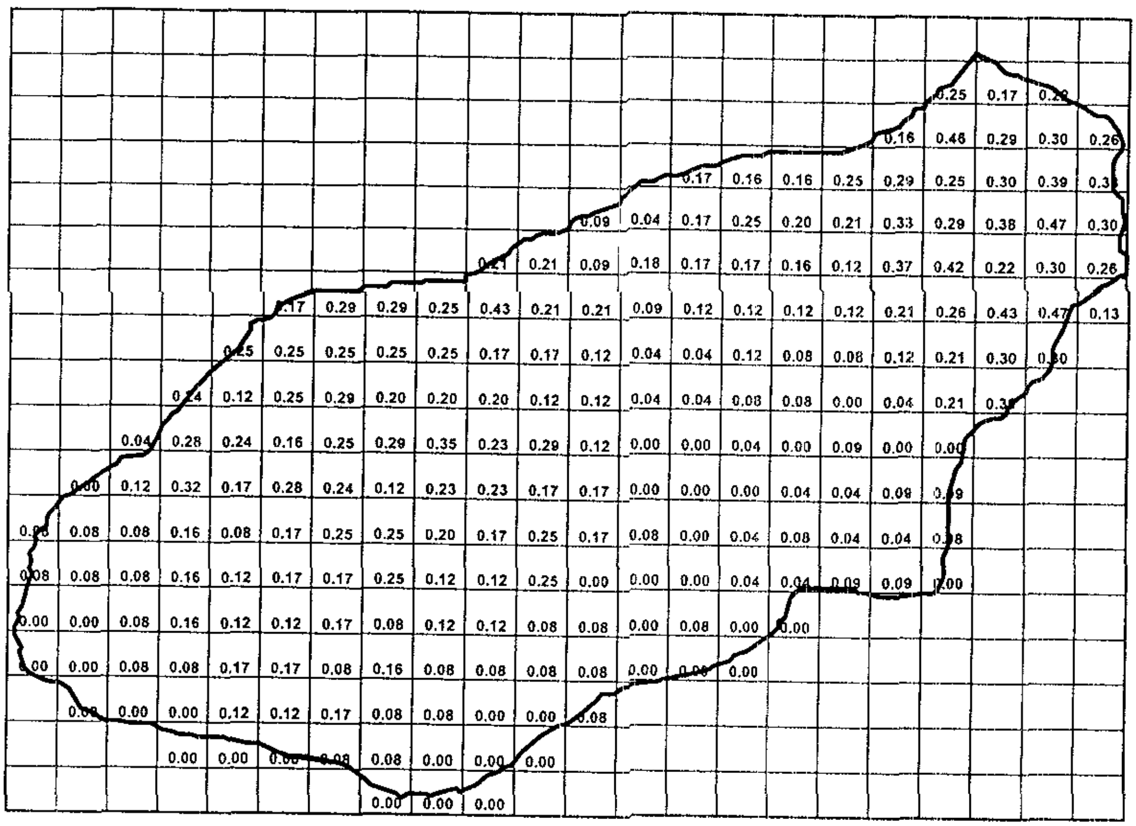
																							Row TTL	Cells/Row	Row Avg.
																			0.98	1.41	1.4[illegible]		3.80	3	1.27
																		1.33	1.69	1.41	1.31	1.41	7.15	5	1.43
														1.04	1.37	1.26	1.50	1.47	1.25	1.14	1.31	1.3[illegible]	11.70	9	1.30
												1.13	1.69	1.48	1.20	1.15	1.25	1.33	1.19	1.14	1.37	1.37	14.30	11	1.30
										.87	1.33	1.31	1.75	1.41	1.35	1.15	1.20	1.15	0.98	1.08	1.42	1.4[illegible]	16.42	13	1.26
						0.60	0.87	1.44	1.54	1.50	1.44	1.31	1.31	1.14	1.03	0.82	0.87	0.76	1.08	1.02	1.47	0.93	19.13	17	1.13
					.11	0.76	0.92	1.14	1.39	1.45	1.44	1.31	1.25	1.14	0.98	0.77	0.71	0.60	0.65	0.81	1.[illegible]5		16.68	17	0.98
				0.11	0.22	0.71	0.87	0.98	1.15	1.15	1.17	1.15	1.09	1.19	0.82	0.76	0.71	0.60	0.75	0.6[illegible]			14.07	17	0.83
			0.00	0.22	0.44	0.66	0.82	0.98	0.98	0.98	0.98	0.98	1.15	1.08	0.97	0.86	0.70	0.70	0.69				13.19	17	0.78
		0.00	0.11	0.22	0.44	0.55	0.60	0.71	0.87	0.82	0.87	0.92	0.70	0.75	0.75	0.97	0.75	0.64	0.[illegible]9				11.36	18	0.63
	0.[illegible]0	0.00	0.11	0.22	0.22	0.22	0.33	0.55	0.71	0.82	0.77	0.82	0.71	0.76	0.59	0.81	0.59	0.43	0.[illegible]3				9.09	19	0.48
	0.00	0.00	0.00	0.22	0.22	0.22	0.22	0.44	0.54	0.76	0.76	0.81	0.86	0.55	0.43	0.60	0.38	0.38	0.27				7.66	19	0.40
	0.00	0.00	0.00	0.11	0.11	0.11	0.11	0.22	0.37	0.75	0.59	0.80	0.70	0.70	0.48	0.38							5.43	16	0.34
	0.00	0.00	0.00	0.11	0.11	0.11	0.11	0.27	0.37	0.58	0.59	1.02	0.74	0.7[illegible]	0.21								4.96	15	0.33
		0.0[illegible]	0.00	0.11	0.11	0.11	0.22	0.27	0.42	0.53	0.70	0.92											3.39	11	0.31
				0.00	0.00	0.1[illegible]	0.16	0.21	0.37	0.48	0.48												1.81	8	0.23
								0.22	0.37	0.16													0.75	3	0.25
																						Totals.	160.89	218	
Col. TTL :	0.00	0.00	0.22	1.32	1.98	4.16	5.23	7.43	9.08	10.85	11.12	12.48	11.95	11.98	10.18	9.53	8.66	9.39	10.65	8.65	9.54	6.49			
Cells/Col :	4	6	7	9	10	11	11	12	12	13	12	12	11	12	12	11	10	11	12	8	7	5			
Col. Avg. :	0.00	0.00	0.03	0.15	0.20	0.38	0.48	0.62	0.76	0.83	0.93	1.04	1.09	1.00	0.85	0.87	0.87	0.85	0.89	1.08	1.36	1.30			

Basin 1/2-Square Mile Average:	0.74
Basin 1/2-Square Mile Max:	1.75
% of Basin > 1.00":	30%
% of Basin > 0.50":	67%
% of Basin > 0.25":	77%
Peak 30-minute Basin 1/2-Square Mile Rainfall:	1.36
Peak 12-minute Basin 1/2-Square Mile Rainfall:	0.52

Figure 14 Storm total rainfall for September 14, 1996 storm

BUFFALO CREEK DRAINAGE BASIN RAINFALL

September 14, 1996 (0122Z to 0226Z)



Row TTL	Cells/Row	Row Avg
0.64	3	0.21
1.47	5	0.29
2.35	9	0.26
2.73	11	0.25
2.88	13	0.22
3.92	17	0.23
3.00	17	0.18
2.53	17	0.15
2.38	17	0.14
2.31	18	0.13
2.30	19	0.12
1.86	19	0.10
1.21	16	0.08
1.06	15	0.07
0.65	11	0.06
0.16	8	0.02
0.00	3	0.00
Totals: 31.45	218	

Col TTL :	0.16	0.16	0.48	1.40	1.39	1.86	2.24	2.05	1.88	1.96	1.83	1.33	0.47	0.79	1.02	0.96	1.04	1.74	2.52	2.39	2.45	1.33
Cells/Col :	4	6	7	9	10	11	11	12	12	13	12	12	11	12	12	11	10	11	12	8	7	5
Col. Avg :	0.04	0.03	0.07	0.16	0.14	0.17	0.20	0.17	0.16	0.15	0.15	0.11	0.04	0.07	0.09	0.09	0.10	0.16	0.21	0.30	0.35	0.27

Basin 1/2-Square Mile Average:	0.14
Basin 1/2-Square Mile Max:	0.47
% of Basin > 1.00":	0%
% of Basin > 0.50":	0%
% of Basin > 0.25":	15%
Peak 30-minute Basin 1/2-Square Mile Rainfall:	0.43
Peak 12-minute Basin 1/2-Square Mile Rainfall:	0.35

strong thunderstorms. Portions of the Buffalo Creek drainage basin were affected by a thunderstorm between 720PM and 825 PM. Storm movement was to the east northeast at 07-11 mph.

Of the additional storms studied only the strong storms of August 23, 1996 produced significant flooding on the basin. A quick review of **Figures 10-14** shows that most of the storms did not produce significant aerial coverage or depth of rainfall in the basin. Clearly, the storms of August 23, 1996 were the most notable of the group. The first storm of June12, 1996 which has not yet been analyzed may also offer additional insight into the factors which determine which storm is capable of producing flooding on the basin.

The meteorological characteristics of the storms is summarized in **Table 3** and shows significant differences in the structure of the atmosphere for the other storms dates compared to July 12, 1996. Note the highlighted conditions associated with the August 23 storm comes the closest to matching the intensity of storm updraft and depth of the warm layer in the updraft. Both storms moved slowly in a very moist atmosphere. The initial review of these conditions suggests that the following three factors may be useful in predicting basin flash flood watches by the National Weather Service:

1. **PWI is greater than 1.00" and**
2. **Storm updraft warm layer is greater than 1.5 km and**
3. **Cloud layer winds favor movement less than 15 mph**
4. **Predicted peak 30-minute rain rate is greater than 1.00"**

Table 3 Comparison of meteorological characteristics of Buffalo Creek storms

DATE (1996)	PWI	STORM UPDRAFT WARM LAYER	STORM UPDRAFT ΔT	STORM SPEED OF MOTION/DIRECTION	PEAK 1/2 sq. MI. 12 MIN. RAINFALL	PEAK 1/2 sq. MI. 30 MIN. RAINFALL
JUNE 12*	1.04"	0.7 km	3.5 °C	14-19 MPH/NE	0.05"	0.06"
JULY 12	**1.39"**	**2.8 km**	**5.0 °C**	**5-10 MPH E**	**1.14"**	**3.42"**
AUGUST 7	0.91"	0.9 km	3.5 °C	12-18 MPH/E-SE	0.24"	0.32"
AUGUST 8	0.92"	1.1 km	4.5 °C	08-12 MPH/N	0.16"	0.42"
AUGUST 23	**1.14"**	**1.7 km**	**3.5 °C**	**04-08 MPH/NE**	**0.52"**	**1.36"**
SEPTEMBER 14	1.00"	1.5 km	2.0 °C	07-11 MPH/E-NE	0.35"	0.43"

*Second of two storms that moved over portions of the basin

A further comparison of the rainfall characteristics of the storms sheds additional light on the differences which may help determine which storms are capable of flash flooding the Buffalo Creek basin. **Table 4** shows comparisons of the basin average rainfall and the aerial coverage of rainfall in the basin. Clear differences appear between all storms and the July 12 storm. The storms of August 23 are also notable for their extensive aerial coverage and intensity compared to the other storms.

Table 4 Comparison of rainfall characteristics of Buffalo Creek storms

DATE (1996)	PEAK 1/2 SQ. MI.. TOTAL RAINFALL	BASIN AVG. RAINFALL	% OF BASIN RECEIVING >1.00" OF RAINFALL	% OF BASIN RECEIVING >0.50" OF RAINFALL	% OF BASIN RECEIVING >0.25" OF RAINFALL
JUNE 12	0.10"	0.03"	0	0	0
JULY 12	**6.29"**	**2.43"**	**99%**	**94%**	**84%**
AUGUST 7	0.36"	0.11"	0	0	13%
AUGUST 8	0.46"	0.15"	0	0	22%
AUGUST 23	**1.75"**	**0.74"**	**30%**	**67%**	**77%**
SEPTEMBER 14	0.47"	0.14"	0	0	15%

Based on the comparison of rainfall characteristics of the storms, HMS suggests that the following quantitative characteristics of the storms radar signature could be used to assist in the issuance of flash flood warnings by the National Weather Service:

1. **When > 60 % of the basin will be covered by 5-level or greater radar reflectivity capable of producing 0.50" of rain in 60 minutes or less**

2. **When > 30 % of the basin will be covered by 5-level or greater radar reflectivity capable of producing 1.00" of rain in 60 minutes or less**

The combination of the observed meteorological and radar conditions may provide quantitative guidelines to the National Weather Service which will assist in the issuance of flash flood watches and warnings in the basin. These guidelines will have to be evaluated within the context of the results of basin hydrological studies and the flexibility of NWS policy. The results of this study are considered preliminary but should provide an active opportunity for further discussion.

5.0 Conclusions

The town of Buffalo Creek, Colorado was struck by a deadly flash flood about 900PM on the night of July 12, 1996. The flash flood killed two residents and produced several hundred thousand dollars of damage to the town. The cruel irony of the flash flood is that it followed a massive forest fire which burned 12,000 acres of nearby forest land during May 1996

This report presents a coherent presentation of the timing, aerial coverage and intensity of the rainfall which produced the Buffalo Creek flash flood. Use of radar data and standard surface and upper air observations was made to produce precipitation mapping of the rainfall on July 12th and contrast it to the rainfall associated with several additional storm events which occurred over the Buffalo Creek basin during the post-fire period of 1996. Finally, the report presented information on the meteorological causes of the primary July 12th flash flood event and contrasted it to the causes of the other lessor events which occurred.

The Buffalo Creek Flash Flood of July 12, 1996 occurred on one of the most weather active days of the summer of 1996. Two tornadoes, 11 damaging hail reports and numerous wind damage reports were logged by the NWS in Denver. The flash flood producing rainfall occurred simultaneously with severe weather, tornadoes and hail, in the Denver metro area.

HMS radar records indicated that four storm periods occurred across the Buffalo Creek watershed on July 12, 1996:

1. **Storm Period 1: 210PM until 228PM**, a light shower across the lower third of the basin.

2. **Storm Period 2: 612PM until 710PM**, rain showers and two moderate thunderstorms across the western third of the basin.

3. **Storm Period 3: 739PM until 913PM**, a line of severe thunderstorms cross and go stationary over the watershed producing the flash flood.

4. **Storm Period 4: 918PM until 1023PM**, post-flash flood thundershowers and showers cross the lower half of the watershed.

A severe thunderstorm which formed in central Jefferson County produced severe weather in central Jefferson, western Arapahoe and northern Douglas Counties between 655PM and 800PM. More importantly it produced a gust front boundary of very humid northeasterly winds of 20-30mph which moved southward into the Buffalo Creek watershed by about 800PM. **This gust front provided the meteorological mechanism which caused the Buffalo Creek**

thunderstorm to go stationary over the watershed producing the flash flood. The gust front acted as a focussing boundary for converging air masses from the south and north.

The Buffalo Creek thunderstorm complex appears to have formed about 715PM along the slopes of Mount Blaine and the Twin Cone Peaks in Park County 15-20 miles west of the basin. The storm complex moved steadily eastward and into the central part of the Buffalo Creek watershed by 808PM according the NWS WSR-88D radar data. Unfortunately, its arrival and that of the gust front from the earlier storm in central Jefferson County coincided. Radar shows the storm going stationary over the lower half of the basin from about 815PM until about 900PM. It is very possible that the storm would not have gone stationary if the gust front had not provided a focus for a strong inflow of moist, unstable air into the storm complex. **No impact of the fire burn areas on the formation of this storm can be detected.**

the peak rainfall production occurred from 815PM until 900PM over the lower third of the basin. During this period over 3.00 inches of rain fell over the lower third of the basin. The rain was accompanied by hail at times, especially before 830PM. By 913PM the core of the storm had moved eastward over the Spring Creek watershed which experienced the same amounts of rain as the lower third of Buffalo Creek between 900PM and 945PM.

The HMS radar-estimated storm rainfall from 739PM until 913PM across the Buffalo Creek basin shows the **basin average rainfall** during this period was **2.16 inches** of rain with a **peak 0.5 square mile rainfall of 5.13 inches**. During this period, an 18 square mile area of the lower third of the basin received over 3.25 inches of rain while a **core area of 6 square miles just above the town of Buffalo Creek was inundated by over 4 inches of rain** and hail.

The July 12, 1996 storm total rainfall over the basin for the entire period from 210PM until 1023PM shows **the basin average rain increases to 2.49 inches while the peak 0.5 square mile increases to 6.29 inches**. The lower third of the basin shows an average rainfall of just over 4.00 inches. **Clearly, this thunderstorm rainfall was focussed by the stationary movement of the storm over the basin for about 30-45 minutes**.

Another contributing factor to the flash flood may have been the **slow movement down the basin of the rainfall core** which could have aided in producing a runoff maximum that traveled with the storm. **This storm was the only one which went stationary over northeastern Colorado**. All the other storm complexes moved at speeds of 25 to 40 mph while producing severe weather. It appears that **the gust front** which aided storm intensification and inhibited storm motion **was a major contributing weather feature** to the storm's severity **along with the very moist condition of the atmosphere**.

The initial review of the meteorological conditions suggests that the following three factors may be useful in addition to standard criteria in predicting Buffalo Creek basin flash flood watches by the National Weather Service:

1. **PWI is greater than 1.00" and**
2. **Storm updraft warm layer is greater than 1.5 km and**
3. **Cloud layer winds favor movement less than 15 mph**
4. **Predicted peak 30-minute rain rate is greater than 1.00"**

Based on the comparison of rainfall characteristics of the storms, HMS suggests that the following quantitative characteristics of the storm's radar signature could be used to assist in the issuance of flash flood warnings by the National Weather Service:

1. **When > 60 % of the basin will be covered by 5-level or greater radar reflectivity capable of producing 0.50" of rain in 60 minutes or less**

2. **When > 30 % of the basin will be covered by 5-level or greater radar reflectivity capable of producing 1.00" of rain in 60 minutes or less**

The combination of the observed meteorological and radar conditions may provide quantitative guidelines to the National Weather Service which will assist in the issuance of flash flood watches and warnings in the basin. These guidelines will have to be evaluated within the context of the results of basin hydrological studies and the flexibility of NWS policy.

Finally, it is the opinion of HMS meteorologists that the Buffalo Creek flash flood was primarily a product of coincident meteorological factors which significantly overwhelm other possible weather-related impacts of the fire burn area. The strong thunderstorms of July 12, 1996 were the product of a very volatile atmospheric structure which is repeated annually over eastern Colorado. The co-incident arrival of the strong outflow boundary and the thunderstorm complex from the west into the basin within the context of this atmospheric structure is the dominant controlling factor on the cause of the flash flood.

Clearly this thunderstorm rainfall was focused by the stationary movement of the storm over the basin for about 30-45 minutes.

It is appears that the gust front which aided storm intensification and inhibited storm motion was a major contributing weather feature to the storms severity along with the very moist condition of the atmosphere.