THE 1993 FLASH FLOOD PREDICTION PROGRAM (F2P2) ANNUAL OPERATIONS REPORT HMS REPORT No. 94-1

to

Urban Drainage and Flood Control District
Denver, Colorado

by

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1.0 Introduction

Urban Drainage & Flood Control District (UDFCD or District) has funded a Flash Flood Prediction Program (F2P2) since May 1979. The F2P2 was established as a response to the disastrous Big Thompson Flash Flood of July 31, 1976 in Larimer County. The F2P2 contracts the value-added weather forecasts of a Private Meteorological Service (PMS) to augment the traditional forecast services of the National Weather Service (NWS) for the six county District region. The forecast area supported is shown in Figure 1 and includes over 80 per cent of Colorado's population in roughly a 1600 square mile area. Terrain in the region varies from the rolling populated prairies of Arapahoe and Adams Counties to highly urbanized Denver County to the rugged plains-foothills-mountain interfaces of Jefferson, Boulder and Douglas Counties.

In recent years the area serviced by the District has increased to the east and the south to meet the needs of new population growth associated with the new Denver International Airport and in Arapahoe and Douglas Counties. The increased population has been especially noticed in the DIA construction areas of Denver County. Special services were provided to this area through the Denver Office of Emergency Preparedness during 1993.

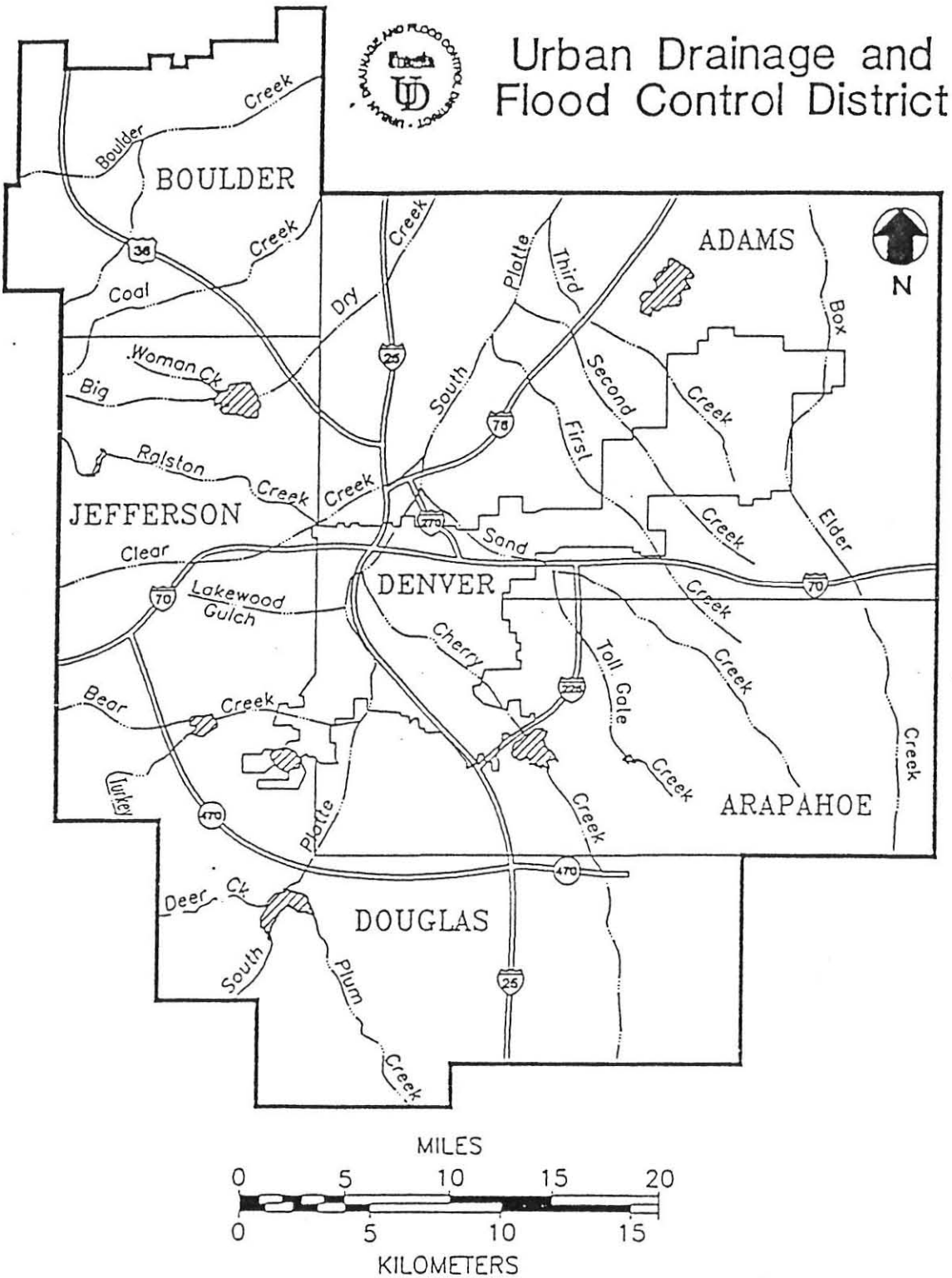
Henz Meteorological Services (HMS) of Denver was selected as the 1993 F2P2 Private Meteorological Service. HMS provided similar services for the 1990 - 1992 F2P2's. HMS forecast services were prepared by John Henz, Bryan Rappolt and Michael Mc Carter during the 1993 season. Significant communications improvements were made by Robert Hirsekorn, the business manager of HMS. Two meteorological technicans were employed mid-May to mid-September to assist the HMS meteorologists, Jon Henz and Pamela Bates. Jon is a student at University of Colorado-Denver with an astronomy major. Pamela is a recent graduate of the Univeristy of Colorado - Boulder with a degree in geography and is currently pursuing a meteorology degree at Metro State College.

The F2P2 season began on 15 April 1993 and continued through 15 September 1993 for 154 operations days. Normal operational hours were from 0700L to 2200L and covered 2,310 hours. Overnight operations conducted during the period from 1000PM to 700AM added **an additional 283 hours** for a total of 2,593 hours of F2P2 activity. The overnight hours were especially active during May and July for both John Henz and Bryan Rappolt. A trend toward more active overnight periods has now been evidenced in both 1992 and 1993. The last time overnight hours exceeded 200 hours due to storm activity was during the 1979 and 1980 F2P2's.

The F2P2 required a continuous Metwatch of the District for the entire period using radar, satellite, conventional surface and upper air observations and local ALERT and mesonet networks. These observations were used to prepare predictions and specialized F2P2 products. These products included daily Heavy Precipitation Outlooks (HPO), MESSAGE 1, 2,3 and 4's, update statements, Quantitative Preciptiation Forecasts (QPF), Storm-Traks and special forecast requests from District members.

FIGURE 1

URBAN DRAINAGE AND FLOOD CONTROL DISTRICT
FLASH FLOOD PREDICTION PROGRAM (F2P2)
BACKGROUND INFORMATION HANDOUT



VICINITY MAP

While no formal interaction was requested or funded, HMS provided extensive special forecasts to both the Denver and Arapahoe County F2P2 upon request during the Pope's Visit to World Youth day activities during August. Additional special forecasts related to rescue/fire actions were fulfilled for F2P2 participants upon request. The remainder of the report will outline the operations of the 1993 F2P2, the results of its predictions, identification of significant storm events and recommendations for the 1994 season.

2.0 F2P2 Operations Products

The F2P2 is designed to offer a supplementary weather information source concerning heavy precipitation, urban flooding and flash flooding threat to the six participating District Counties and the cities within those counties. Additionally direct basin specific support is rendered to the seven District basin warning plans which exist. Four specific F2P2 products exist in addition to voice support.

Direct basin specific support is rendered to the following seven District basin warning plans listed below:

1. **Boulder Creek Warning Plan:** Supports Boulder, South Boulder and Left Hand Creek and additional tributaries to each creek basin.

2. **Ralston Creek Warning Plan:** Supports Ralston and Van Bibber Creek basins as they flow across northwestern Jefferson County

3. **Lena Gulch Warning Plan:** Supports the Lena Gulch basin in central Jefferson County

4. **Bear Creek Warning Plan:** Supports the large Bear Creek basin and tributaries in southwestern Jefferson County

5. **Westerly Creek Warning Plan:** Supports Westerly Creek as it flows through the Cities of Denver and Aurora and Denver and Arapahoe Counties

6. **Goldsmith/Harvard Gulch Warning Plan:** Supports Goldsmith Gulch and Harvard Gulch Basins in Denver County

7. **Toll Gate Creeks Warning Plan:** Supports east and west Toll Gate Creek basins as they flow across Aurora and Arapahoe County

The primary forecast products are Heavy Precipitation Outlooks (**HPO**), Internal Message Status Statements (**IMS**), Quantitative Precipitation Forecasts (**QPF**) and HMS StormTrack Predictions (**FAX Map**). A brief description of each product is presented next as it was recently described by UDFCD. Please note that the use of EBB refers to the District's Electronic Bulletin Board and FAX refers to the transmission of a product by either the HMS internal fax card or fax machine as used in the program.

HMS Heavy Precipitation Outlook (HPO)

HPO's are available every day by 11:00AM and updated by 4:00PM when appropriate. This forecast information can be obtained by either EBB or FAX communications. The daily outlook will typically include a descriptive header and a single paragraph summarizing the weather forecast. This paragraph will be followed by a table providing a county-specific prediction of flash flood potential, expected rainfall and other associated weather.

HMS Internal Message Status (IMS)

IMS's will be communicated via FAX and EBB when internal alerts, flash flood watches or flash flood warnings are issued to local governments within the District (i.e. MESSAGE 1, MESSAGE 2, MESSAGE 3 and MESSAGE UPDATES). All users of this information should be familiar with current F2P2 procedures including the issuance of "RED FLAG" messages. The purpose of the IMS report is to keep local officials updated regarding the active message status for the entire District. The IMS will typically include a descriptive header and paragraph summarizing the weather situation. This will be followed by a table indicating the specific messages issued for each F2P2 contact point. The table will also list each area's valid and prime times for storm activity along with anticipated problems.

HMS Quantitative Precipitation Forecast (QPF)

QPF's will be communicated via FAX and EBB when the potential exists for point rainfall accumulations to exceed 1.5 inches in one hour or less. The QPF product is designed primarily for technical personnel familiar with the hydrologic procedures and the regional major drainage system of the District. EBB users require a separate login to obtain this detailed forecast. It should be noted that both the HPO and IMS bulletins generally contain quantitative predictions of rain but, in limited detail. The purpose of the QPF product is to provide more information in terms of predicted rainfall intensities and storm duration, storm total estimates, probabilities of occurrence for specific drainage basins, storm classification, etc.

HMS StormTrack Prediction (FAX Map)

Storm track predictions will only be available to FAX users on MESSAGE days. The FAX Map will show the predicted storm tracks and associated zones of storm influence. The predicted storm movement timing will also be indicated on the map. When appropriate, this product will be updated 30-60 minutes prior to flooding occurrence to show refined predictions and specific basins affected.

The EBB and FAX products are not intended to replace voice communications between HMS and dispatchers. The major advantages of hard copy products are: 1) daily weather forecasts are available; 2) written information can be quickly obtained and re-disseminated if desired; 3) the FAX Map can be easily interpreted ; 4) early communications with HMS and NWS can be initiated by local authorities before situations develop; and 5) lead times for implementing emergency action plans will be increased.

Each of these four products were delivered to local government entities particpating in the District's F2P2. In turn many of them further transmit these products to internal focal points for action. During 1993 season HMS delivered 7,070 routine HPO faxes to these groups. It is estimated that on a daily basis the 22 primary HPO reception points fax these HPO's to an additional 200 plus locations. Clearly the program has a more far reaching extent than the numbers alone imply.

Additionally HMS originated over 5,860 IMS, QPF and StormTrack products via FAX to participating agencies. Each of these products were followed up by a telephone verification of reception and discussion of the product. HMS logged over 2,300 storm-related telephone interactions during the program emphasizing the strong technical "touch" of the program in the local community. In anticipation of these numerous communications HMS installed three dedicated telephone lines: two for voice and one for fax and data communication into its re-designed weather center. Examples of some of these products can be found in a paper written on F2P2 communications found in Appendix B.

Several projects were initiated by HMS staff to improve the operational products of the F2P2 during the Winter 1992/1993. The projects, brief descriptions and the project investigator are listed below:

- A overhaul of the communications system for the production and transmission of F2P2 products via fax and an updating of the software templates and procedures for internal HMS use for F2P2 products. Project investigator: Bob Hirsekorn.

- Investigation of the relationship of the Denver Cyclone circulation features to the occurrence of heavy precipitation events and severe weather in the District. Project investigators: Bryan Rappolt and John Henz.

- Verification of the 1990 to 1993 StormTraks issued by HMS and the development of an objective forecast technique. Project investigator: John Henz

Each of these projects made major contributions to the success of the 1993 F2P2 and generated papers which were presented at the 17th Severe Local Storms Conference sponsored by the American Meteorological Society and held in October, 1993. Copies of each paper can be found in Appendix B. Additionally John Henz authored another paper for the Severe Storms Conference on the updraft characteristics used by HMS to predict flash flood potential in the District F2P2. This paper is also found in Appendix B.

The next section of this report will deal with the operational results of the 1993 program as compared with prior seasons. Verification will be presented for MESSAGES issued to each county and city for all MESSAGE days. Information is presented on District-wide forecasts for the 15 year period 1979 - 1993.

3.0 1993 F2P2 Operations Results

The primary service rendered by the F2P2 to participating local governments is the issuance of value added weather forecasts of urban and stream flooding and locally heavy rainfall. HMS indicates the potential for these events in a series of MESSAGES issued directly to the users by phone, FAX and EBB. The criteria for MESSAGE issuance is shown in Figure 2. These criteria were developed with the District to identify rainfall criteria directly related to the production of flooding events. Evaluations of program performance are based on rainfall and event occurrences which verify these criteria. An effort has been made to verify all program forecasts by these criteria and the results are presented in Table 1.

A comparison is presented in Table 1 of all F2P2 seasons since 1979. The table shows the number of days MESSAGES were issued each season (a MESSAGE day) , the number of MESSAGE days which recorded a heavy rain event (> 1"/hour) or flooding event and the number which did not record an event in the District. The accuracy indicates the percentage of correct MESSAGE day forecasts while the false alarm rate indicates the number of days incorrectly identified as a MESSAGE day. The probability of detection indicates the percentage of days which experienced a heavy rainfall or flooding event and had appropriate MESSAGES issued.

The 1993 season was again below average in the number of MESSAGE days and the intensity of thunderstorm activity noted on MESSAGE days as compared to 15 year averages. Only 25 MESSAGE days were observed in 1993 compared to the average of 28 MESSAGE days. HMS correctly forecasted the occurrence of all these days which experienced a MESSAGE-level rainfall or flooding event. However, 3 days were over forecasted, with no reports of flooding or heavy rainfall. On 2 of the 3 days, active thunderstorms crossed the District but produced no flooding problems.

It should be noted during the 7 year period from 1981 to 1987 the observed number of MESSAGE days averaged 32 while in the 6 year period from 1988 to 1993 the observed number of MESSAGE days averaged 26. During the 1981-87 period severe weather in the form of tornadoes and hail frequently accompanied heavy rainfall and flooding events. Severe weather has been less frequently observed during heavy rain events especially in the past two years. A consideration of those two observations seems to support the "feeling" that the drought of the 1990's expected by many meteorologists has begun to reduce both the intensity and number of heavy thunderstorm events. However a note of caution is due.

While the 1980's were every active in producing numerous minor urban flooding events in the District, no significant life threatening flash flood events such as a repeat of the 1965 Denver, 1976 Big Thompson or 1985 Cheyenne flash floods were observed in the District. It has been exactly 100 years since the Big Boulder 1894 Flash Flood. It may be that just as the number of urban events decreases the opportunity for a devasting flash flood within the District's foothills may be increasing.

FIGURE 2

UDFCD FLASH FLOOD PREDICTION PROGRAM
MESSAGE CRITERIA

Message 1: Issued primarily to alert local governments to the threat of nuisance street flooding due to thunderstorm rainfall when storm total rainfall is 0.50" -1.00" in one hour or less. When rainfall is 1.00" to less than 3.00" in one hour or more urban and rural street and stream flooding becomes a more significant problem. M-1 leadtimes of 1 hour or more are desireable.

Rainfall intensity criteria: any of the intensities below should prompt a Message 1 issuance

1.00"/ 60 minutes

0.75"/ 30 minutes

0.50"/ 10 minutes

Message 1, RED FLAG: Issued whenever rainfall rates will exceed 1.00"/30 and the storm is considered imminent.

Message 2: Issued to local governments when the threat of potential life threatening urban street and stream flooding is predicted. A M-2 is the equivalent of a Flash Flood Watch.

M-2 Rainfall intensity criteria: 3.00" /hour

Message 3: Issued to local governments whenever a life-threatening flash flood is imminent. M-3's are issued in accordance with basin-specific warning plans if available or at the discretion of the meteorologist.

Quantitative Precipitation Forecasts(QPF) are issued whenever a M-1 is issued and rainfall rates will predicted to equal or exceed 1.50"/hour or 1.00"/30minutes.

Table 1

UDFCD F2P2 **DISTRICT-WIDE** MESSAGE DAY VERIFICATION: 1979 - 1992

Year	Message 1 Days	Verified Hits	Verified Misses	Accuracy	False Alarm	Probability of Detection
GRD Weather Center (District Era)						
1979	26	17	9	65%	35%	85%
1980	35	23	12	66%	34%	100%
1981	40	31	9	77%	23%	100%
1982	42	34	8	81%	19%	100%
	143	105	38	73%	27%	97%
Henz, Kelly & Associates (County Era)						
1983	37	32	5	86%	14%	100%
1984	38	32	6	84%	16%	100%
1985	28	25	3	89%	11%	100%
1986	35	30	5	86%	14%	97%
1987	47	40	7	85%	15%	100%
1988	28	24	4	86%	14%	100%
1989	31	26	5	84%	16%	100%
	244	209	35	86%	14%	99.5%
Henz Meteorological Services (Red Flag Era)						
1990	30	26	4	87%	13%	93%
1991	42	31	11	74%	26%	100%
1992	29	25	4	86%	14%	100%
1993	28	25	3	89%	11%	100%
	129	107	22	83%	17%	98%
Total	516	421	95	82%	18%	98.8%

Message Day = Issuance of a Message 1: Stream of Urban Flooding Forecast anywhere in District usually due to 1"/hour or more

Hit = Verification of Message in issued County

Miss = No verifications

Customer support levels can best be judged by reviewing the individual MESSAGE verification statistics. Table 2 shows a comparison of individual MESSAGE statistics for the 1987, 1991, 1992 and 1993 F2P2 seasons. The verification of MESSAGES on a county and city basis was begun experimentally in 1987 when the first ALERT Flood Detection Networks(FDN) were made operationally available to the PMS. Note that less than 50 percent as many MESSAGES were issued in 1992 and 1993 as in the other two operational seasons. Part of this drop can be attributed to a decrease in the number of heavy thunderstorms while part of it is due to an effort to improve "basin-level" forecasting by HMS meteorologists.

It is important to note the continuing decrease in the number of individual MESSAGES since 1987 while accuracy increased 10 percent. The 1987 F2P2 season was very representative of the 1980's F2P2 forecasting skills. HMS suggests that the increase in individual MESSAGE accuracy while the number of MESSAGES issued has decreased is an indication that new forecast techniques developed from 1990 to 1991 have improved F2P2 products and services.

A comparison of the MESSAGE verification on the county and city basis can be found in Table 3 which shows 60 percent of the county MESSAGES verified while 26 per cent of the city MESSAGES hit. The combined individual MESSAGE verfications was about 54% or 35% less than the 89% District-wide MESSAGE day accuracy. As noted last year overforecasting of MESSAGES on a county/city basis appeared related to days when the Denver Cyclone (DC) was present.

HMS initiated a research program in Winter 1992-93 to investigate the relationship of the DC to heavy rainfall events. The purpose of the study was to determine if a reliable relationship existed between the DC and heavy rainfall events and if such a relationship could be used to improve the issuance of F2P2 MESSAGES. The complete results of this study are presented in Appendix B along with several other papers presented at the 17th Annual Severe Storms Conference in October 1993. In essense HMS verified that heavy rainfall events were not reported in the cool, backwash western quadrants of the DC. During a three year period no events had been reported in the northwestern portion of the DC circulation. HMS developed a forecasting technique which related the convective instability to the location of the DC's circulation to the issuance of a MESSAGE. HMS began applying the results of this study to its F2P2 forecasts from 16 July to 15 September.

Prior to the application of this forecasting technique the statistics for the combined county/city MESSAGE verification from 15 April to 15 July was 53% accuracy. Verification from 16 July to 15 September after the technique was applied to forecasts improved to 57 per cent. Before judging the relatively small improvement, it must be noted that poor forecasts on August 21 and 27 by a part-time HMS weekend meteorologist did not use the new forecast technique from the study. If the study

Table 2

Annual Verification Comparison for UDFCD (District)

Year	M-Days	Hits	Misses	Percent Accuracy	Percent False Alarm	Probability of Detection	Total M-1's	Hits	Misses	Percent Accuracy
1987	47	40	7	85%	15%	100%	353	153	200	44%
1991	42	31	11	74%	26%	100%	293	155	138	53%
1992	29	25	4	86%	14%	100%	143	81	62	57%
1993	28	25	3	89%	11%	100%	123	66	57	54%

Table 3

County / City Message-1 Verification

	Total County and City			County Verification			City Verification		
Year	Number of M-1's	Hits	Percent Hit	County M-1's	Hits	Percent Hit	City M-1's	Hits	Percent Hit
1991	293	155	53%	185	98	53%	108	57	53%
1992	143	81	57%	109	66	61%	34	15	44%
1993	123	66	54%	100	60	60%	23	6	26%

Table 4

Red Flagged M-1's (RF)

Year	Total M-1's	RF's	RF Hits	% RF Hits	% RF's
1991	293	171	156	91%	58%
1992	143	85	81	95%	59%
1993	123	12	12	100%	10%

Year	Number of RF's	RF Hits	Percent RF Hits	County RF's	County RF Hits	Percent Hit	City RF's	City RF Hits	Percent Hit
1992	85	81	95%	69	66	96%	16	15	94%
1993	12	12	100%	8	8	100%	2	2	100%

technique had been applied to both days, **no MESSAGES would have been issued either day! By dropping the bad forecasts on these two days the combined MESSAGE verification for 16 July to 15 September would have increased to 69% accuracy or a 16% improvement.** Application of the forecast technique to the entire operational season would have improved county/city verification to almost 70%. It is encouraging to note this change and significant improvement is anticipated for the 1994 F2P2 in the issuance of the county/city MESSAGE product.

It should be noted that the use of the terms county and city could be misleading when used in a verification process. UDFCD includes less than 25 percent of Boulder County, 50 percent of Jefferson County, 40 percent of Adams County, 35 percent of Arapahoe County and 25 percent of Douglas County on an area basis. It does cover all of the City and County of Denver. A county MESSAGE can be verified as a "hit" only if it verifies in the District portion of that county, not just anywhere in the county. Since the size of each District county area is much smaller than the entire county, consideration of the verification statistics should take this fact into account.

While only 54% of the total county/city MESSAGES verified, their utility to the users was improved by the use of a MESSAGE Red Flag issuance. A MESSAGE indicates to the user that the potential exists for a flooding event later during the day somewhere in the District support portion of the county or city. A Red Flagged MESSAGE indicates that the potential of an operationally important flooding event will be realized in the next 30-60 minutes. In other words the **RED FLAG means action is needed.**

Red Flags were issued on only 6 days during the 1993 F2P2 compared to 22 days during the 1992 F2P2. All Red Flag MESSAGES issued verified and all events requiring Red Flags were issued appropriately. The 75 % decrease in Red Flagged events appears to be yet another indication that a drought period may be in progress locally. Table 4 shows the verification for the Red Flagged MESSAGES. While only about 10 percent of the MESSAGES were Red Flagged, 100 percent verified. This high accuracy rate for the Red Flags indicates why the MESSAGE program is such a success with the users.

An exception this year occurred on August 5th when a MESSAGE 1, Red Flag was issued for Aurora concurrent with the event. While a MESSAGE 1 had been issued earlier for Arapahoe County, the Red Flag issuance was prompted by heavy rainfall noted in the Toll Gate Flood Detection Network. The Red Flag came at a very awkward time just prior to the rush hour. The storm which prompted the Red Flagged event developed directly over the western half of Aurora.

HMS has noted the need for an automated weather station in Aurora between the Quincy Reservoir weather station and the NWS mesonet station at Stapleton. It is very likely that the information on local temperature, dew point and winds could have allowed a more timely issuance of the MESSAGE 1 and Red Flag on August 5. The frequent location of the City of Aurora within the circulation of the Denver Cyclone makes MESSAGE

issuance more difficult. The addition of weather stations strategically placed to define the circulation's influence on the city would be an important improvement.

A summary of the individual MESSAGES and Red Flags by day, county and city are presented in Table 5. Flash Flood Watches(MESSAGE 2's) and Flash Flood Warnings (MESSAGE 3's) issued by the National Weather Service were also included in Table 5 but were not included in the HMS statistical verification in Tables 1-4.

Please note that the coordination and cooperation between the NWS and HMS within the F2P2 has remained at a very high level of interaction for the past two years. HMS faxes all F2P2 products to the NWS to assist coordination of forecasts. One of the best examples of this cooperation was found during the heavy rainfall and flooding events on August 20, 1993. All NWS statements and HMS MESSAGES verified to the users' benefit. While interaction is not perfect it has become mutually beneficial and productive.

Quantitative Precipitation Forecasts (QPF)

An important operational product in the F2P2 has been quantitative precipitation forecasts (QPF) issued to technical program participants. While a general form of QPF is offered for each county daily in the HPO's, the basin-specific QPF's are only issued when rainfall is forecast to equal or exceed 1.50"/hour or 1.00"/30 minutes. During the 1993 F2P2, QPF's were issued on only 13 days compared to 15 days in 1992. Examples of 1993 QPF basin-specific verification are presented in Appendix A. Since strong storms avoided hitting the FDN's the data in Appendix A is not as dramatic as last year.

QPF's were issued on all Red Flag and NWS Flash Flood watch days and for 13 of the 28 MESSAGE 1 days. The QPF's correctly identified the basins affected by the Red Flag rainfall events with at least a 60% probability of occurrence. The only non-verification of a QPF occurred on June 6, 1993 when a new weekend meteorologist made an overly conservative forecast. No events were missed which required a QPF issuance.

Heavy rainfall events occurred in Douglas County near Parker on July 19 and August 10 which were radar estimated at 2-3 inches in less than 90 minutes. On August 20 1.50 - 2.25 inches in an hour was measured in southern Jefferson, western Douglas and western Arapahoe Counties outside active FDN's. While no specific time-intensity rainfall data was available for these storms to verify the QPF, the QPF storm totals were within 0.35 inches of the observed rainfall.

HMS began the QPF verification and forecast effort in a detailed manner during the 1988 F2P2. As the number of ALERT FDN's increased from one to seven, the ability to verify QPF's has understandably improved. Prior to 1990 the spotty distribution of FDN's limited QPF verification. HMS is in the process of completing a detailed verification of the QPF's since 1990 and will publish its results at the conclusion of the 1993 season. At this time this verification is deemed too technical for inclusion in this report.

Table 5: Daily Message Verification by County and City for 1993 Denver F2P2

MESSAGE DAYS FOR THE 1993 FLASH FLOOD PREDICTION PROGRAM																	
DATE	FORMS ISSUED						MESSAGE VERIFICATION BY DISTRICT, COUNTY, AND CITY										
	HPO	M1	M2	M3	IMS	QPF	DISTRICT	BOCO	ARAPCO	DENCO	DOUGCO	ADCO	JEFFCO	AURORA	WHTRDGE	LKWD	ARVADA
5/16/93	X	X			X	X	●		●		●			●			
5/24/93	X	X			X		●		●	●	●			●			
5/31/93	X	X			X		●					●					
6/2/93	X	X			X		●		●	●			●	●			
6/3/93	X	X			X		●		●	●	●	●	●	●			
6/6/93	X	X			X	X	●	●	●	●	●	●	●	●	●	●	●
6/17/93	X	X			X		●		●	●	●		●	●			
6/18/93			N		X	X	⌘	⌘	⌘	⌘	⌘	⌘	⌘	⌘	⌘	⌘	⌘
6/21/93	X	X			X		●		●		●	●		●			
6/23/93	X	X			X	X	●		●	●	●	●		●			
7/11/93	X	X			X		●	●					●				
7/12/93	X	X			X		●	●	●	●		●	●	●			
7/13/93	X	X			X	X	●	●	●	●◆	●◆	●◆	●◆	●			
7/14/93	X	X			X	X	●	●	●	●	●	●	●	●	●	●	●
7/15/93	X	X			X		●		●	●		●	●	●			
7/17/93	X	X			X	X	●	●					●				
7/19/93	X	X			X	X	●		●		●◆						
8/5/93	X	X			X	X	●	●	●◆			●		●◆			
8/10/93	X	X	N		X	X	●⌘		●⌘	●	●⌘◆	●⌘	●	●			
8/12/93	X	X			X	X	●				●		●				
8/18/93	X	X			X		●		●		●			●			
8/19/93	X	X			X		●			●		●					
8/20/93	X	X			X	X	●	●	●◆	●	●◆	●	●◆				
8/21/93	X	X			X		●	●	●	●	●		●				
8/27/93	X	X			X		●	●			●		●				
9/2/93	X	X			X		●				●						
9/5/93	X	X			X	X	●		●	●				●◆			
9/6/93	X	X			X		●		●					●			
9/7/93	X	X			X		●	●	●	●		●	●	●			
TOTAL:	28	28	2	0	29	13	29	12	23	17	19	16	17	18	3	3	3

X=HMS ISSUED

N=NWS ISSUED

◆ = Red Flag

● = Potential Forecasted by HMS

⌘ = Potential Forecasted by NWS

= Hit or Correct Forecast

4.0 Significant 1993 Storms

The 1993 thunderstorm season featured a dramatic decrease in the number of significant thunderstorm events. Low intensity, short duration storms and the flare-up of nocturnal storms during May and July were key notes of the season. The F2P2 remained on the west edge of the severely flooded central section of the country throughout the summer. Many of the thunderstorm systems which flooded portions of Nebraska, Kansas, Iowa and Missouri could be followed from inception in eastern Colorado to the east by satellite.

The most significant thunderstorm event days of 1993 are be highlighted below:

June 2: A mid-day severe thunderstorm formed over Lakewood and moved due east across the District producing hail and a small tornado which touched down briefly in southeast Denver. Minor street flooding was noted.

July 13: A squall line pounded Boulder, Jefferson, Adams , Denver and Douglas Counties dropping 0.71" in 10 minutes at HMS and 0.75"-1.50" in 30 - 45 minutes producing wide-spread minor street flooding.

July 19: A rapidly forming thunderstorm was enhanced by the Denver cyclone into an intense storm near Parker. Radar estimated 1-2 inches of rain.

August 20: Strong monsoonal thunderstorms erupted over Highlands Ranch and moved northwestward out of Douglas County between 4:30PM and 7:00PM. Intense lightning and 1.5"- 2.12/30-60 minute rainfall accompanied the core of the storm in Jefferson and Aaraphoe Counties.

In past operational years none of these storms would have been worthy of mention as significant since their impact was minimal on the populated portions of the District. An exception could possibly be made of the August 20th storm complex which impeded travel during a Friday rush hour on the far south side. A growing concern exists both within the District and the HMS staff that we have been overly fortunate to avoid the flooding problems experienced around us for the past 15 years and that our system will be tested to the maximum soon. Since a history exists which supports the occurrence of severe foothills flash floods during drought periods, the recent decrease in storm intensity and coverage may be Mother Nature's clarion call to a heightened sense of awareness of the threat.

5.0 Concerns and Recommendations

HMS utilizes this portion of the report to identify operational problem areas or matters of concern which became apparent during the operational season and need to be addressed. The primary concern areas during the 1992 season were related to communications, training, and weather radar data availability. The communications and radar data

availability and display issues were both resolved during the 1993 season but the training concerns continue.

Communication Concerns

In the 1992 F2P2 season annual report HMS indicated the following communications issues needed to be addressed:

- Overloading of telephone lines slowed transmission of fax products which became an operational problem

- Telephone interaction with county focal points, routine weather data ingest needs and fax needs have become too much for one dedicated, unlisted telephone line

- Use of the UDFCD cellular phone makes remote communications cumbersome at best.

The problem was addressed by Bob Hirsekorn of HMS during the latter portion of the 1992 F2P2 and during May and June of the 1993 F2P2. A paper written by Bob appears in Appendix B which describes the problems and solutions in considerable detail. In short he addressed the problem through the addition of new software and an internal fax card in the HMS weather workstation. He utilized Microsoft Word for Windows 2.0 to create MESSAGE form templates for the HMS forecasters to use in issuing MESSAGES. He used WinFax Pro2.0 software to transmit the completed templates through an internal fax/modem to the user communication points. By simultaneous use of both the fax card and the fax machine, HMS noted a significant reduction in the fax "log jam" problem. Additionally users reported very favorable comments on the reception of a MESSAGE hard copy for use by dispatchers. It eliminated most misunderstandings of MESSAGE content and eliminated the need to search for a blank MESSAGE form.

HMS installed three unlisted lines for program use during 1993 F2P2; one line for fax communication, one line for voice communication and one line for weather data ingest (mesonet). The inclusion of Broadcast Fax network in the 1993 F2P2 greatly eased both the fax logjams and the phone line overloads. HMS believes the communications bottleneck has been removed for the paresent. Except for a brief Broadcast Fax network paralysis experienced the afternoon of Pope John Paul's arrival in August and occasional F2P2 meteorologist problems with the new software no problems were experienced.

HMS utilizes a UDFCD transportable cellular phone within the F2P2 for several purposes. Most importantly, it allows an HMS meteorologist to provide direct storm observations by vehicle. Each year, mobile observation is made by HMS of 10-15 storms. Next, it allows the HMS meteorologist to leave the weather center and make direct observation of storms from the HMS roof-top observation site while still manning program phones. This process occurs on most MESSAGE days several times and facilitates invaluable observation input.

The original transportable phone was purchased by UDFCD in the mid 1980's, and was a very progressive step at the time. However, cellular phone technology has passed the old phone by. Two factors are especially important, connectability issues and unit weight. The old phone tips the scales at over eight pounds and relies on obsolescent battery technology. This weight factor discourages the use of the phone.

More importantly, connectability and battery technology issues are developing. The current battery in the UDFCD phone decreases the field flexibility of the phone, and constrains the use time between charges. There is no connectability between the UDFCD phone and laptop computers. Recent advances in cellular phone technology allow lap top computers to connect directly to newer cellular phones. A new phone could allow a mobile HMS meteorologist to connect directly to the ALERT base station, Radac 2100 and the mesonet to provide valuable input. With the existing phone no such connectibility exists.

Radar Data Availibility and Display

The District purchased a new Kavouras RADAC 2100 unit which consolidated the reception and display of radar and satellite data into one unit. The installation of the unit was delayed and no formal field tests of the new RADAC unit were accomplished during the 1993 F2P2. However, the new unit has demonstrated the ability to display both conventional and new NWS WSR-88D doppler data and satellite data to the satisfaction of HMS meteorologists in the past three months. While the final verdict will be out until intensive field use of the system in 1994 the radar problem appears to be solved.

Training Concerns

- User understanding of F2P2 products and their utility in flood warning programs continued to be a concern.

HMS has noted **a continuing need for training** of both dispatchers and other emergency response personnel in the understanding and utilization of F2P2 products within Flood Warning Plans and in emergency situations. These factors have become apparent when working with dispatchers and other emergency response personnel on message days during the 1990 -1993 F2P2 seasons. It is obvious that even if a flood forecast is perfect and the flooding rainfall and stream flow are measured that a system failure could still result by an ineffectively carried out plan or poor communication.

Recommendations

1. HMS recommends that the 1994 F2P2 program maintains the US WEST Broadcast Fax service as a source of eliminating the fax "log jam" problem as demonstrated during the 1993 F2P2.

2. HMS recommends that it purchase its own cellular phone and charge back to the F2P2 program the fees for all calls related to the F2P2 program during the next season that HMS participates in. Today's cellular phones are very lightweight with most phones weighing less than two pounds. Newer battery technology will increase the use time of the phone by several factors of time. Additionally, the opportunity to connect a laptop computer to a cellular phone through a modem will allow HMS to connect a laptop to its existing ALERT base station during storms to enhance support to users under severe conditions.

3. HMS recommends that an expanded F2P2 training program be developed cooperatively between the District and HMS. The training program would encompass the following elements.

    - The development and implementation of effective, seasonal flash flood exercises in each of the District warning plan basins.

    - Training in the proper utilization of ALERT base stations

    - The development of effective flood warning systems, plans, and communications.

    - The development of a training session to increase the understanding of the F2P2 products.

4. HMS recommends that the District continue to add surface weather stations in the southern and western portions of the District to assist in more accurate county and city specific MESSAGES and Red Flags issuance.

APPENDIX A

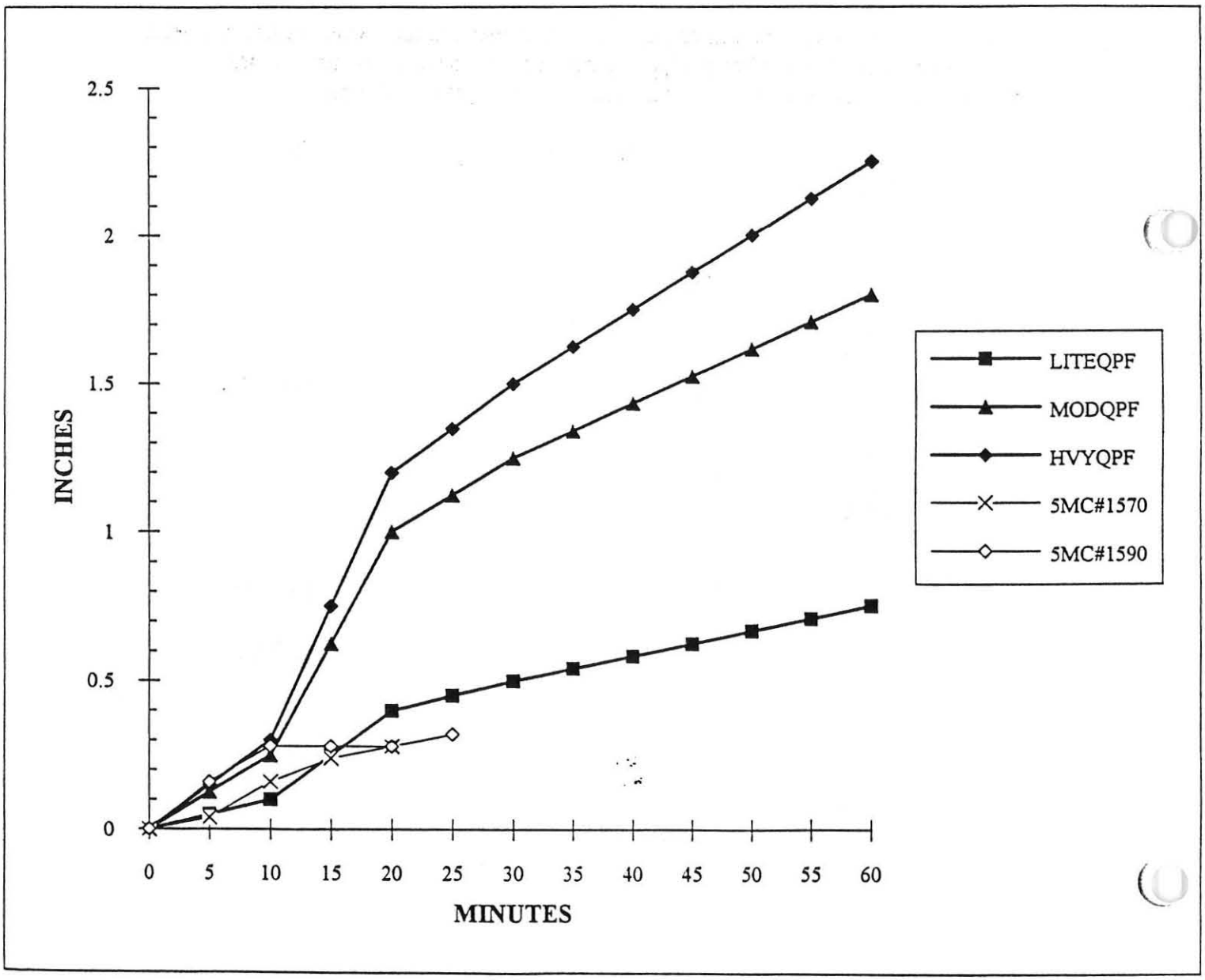
1993 Quanitiative Preciptiation Forecast (QPF) Verification versus Flood Detection Network (FDN) Observed Rainfall

The information provided in this appendix represents only a small portion of the rainfall data used by HMS to verify both MESSAGES and QPF products. It is included since the FDN data is an important part of the F2P2 and it provides a continuing climatological data base for the basis of comparison of the time distribution of rainfall in the basins and the District. Please note that the District's FDN's were missed in 1993 by most, if not all, of the strong thunderstorm systems which crossed the District. A list of the dates when QPF's had been issued and FDN precipitation was observed for the 1993 F2P2 is presented below. An asterisk identifies dates and sensor numbers when sensor problems are suspected. HMS recommends that the raw data be consulted on these dates and judgment used before accepting the amounts plotted on the verification.

Date	Suspect data	Sensor
5-16-93		
5-31-93		
6-2-93		
6-3-93		
6-17-93		
6-18-93		
6-23-93	*	**5MC#30**
7-11-93		
7-12-93		
7-13-93		
7-15-93		
8-5-93	*	**5MC#720**
9-5-93	*	**5MC#720**

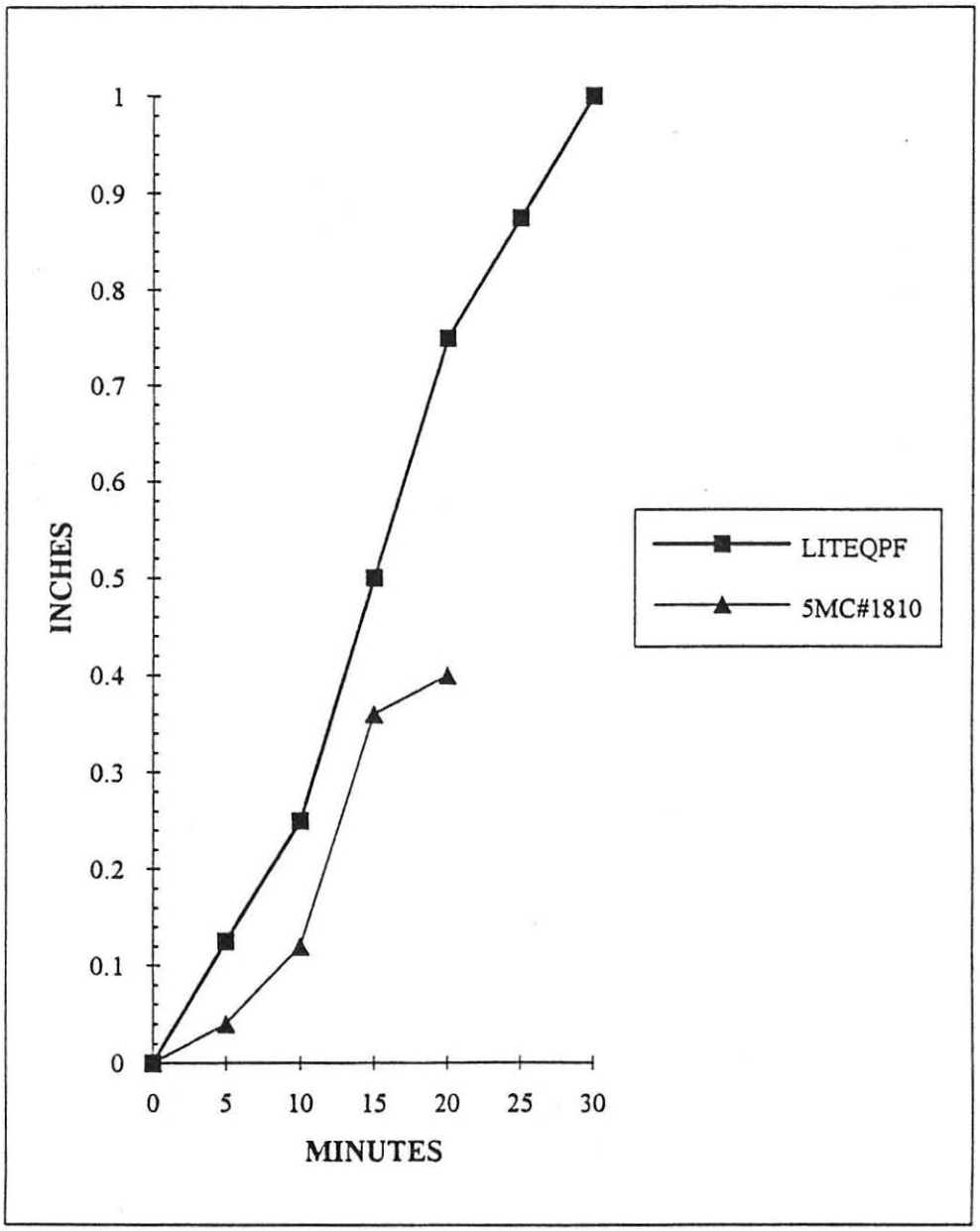
MAY 16, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5M#1570	5MC#1570	5M#1590	5MC#1590
0	0	0	0	0	0	0	0
5	0.05	0.13	0.15	0.04	0.04	0.16	0.16
10	0.10	0.25	0.30	0.12	0.16	0.12	0.28
15	0.25	0.63	0.75	0.08	0.24	0.00	0.28
20	0.40	1.00	1.20	0.04	0.28	0.00	0.28
25	0.45	1.13	1.35			0.04	0.32
30	0.50	1.25	1.50				
35	0.54	1.34	1.63				
40	0.58	1.43	1.75				
45	0.63	1.53	1.88				
50	0.67	1.62	2.00				
55	0.71	1.71	2.13				
60	0.75	1.80	2.25				



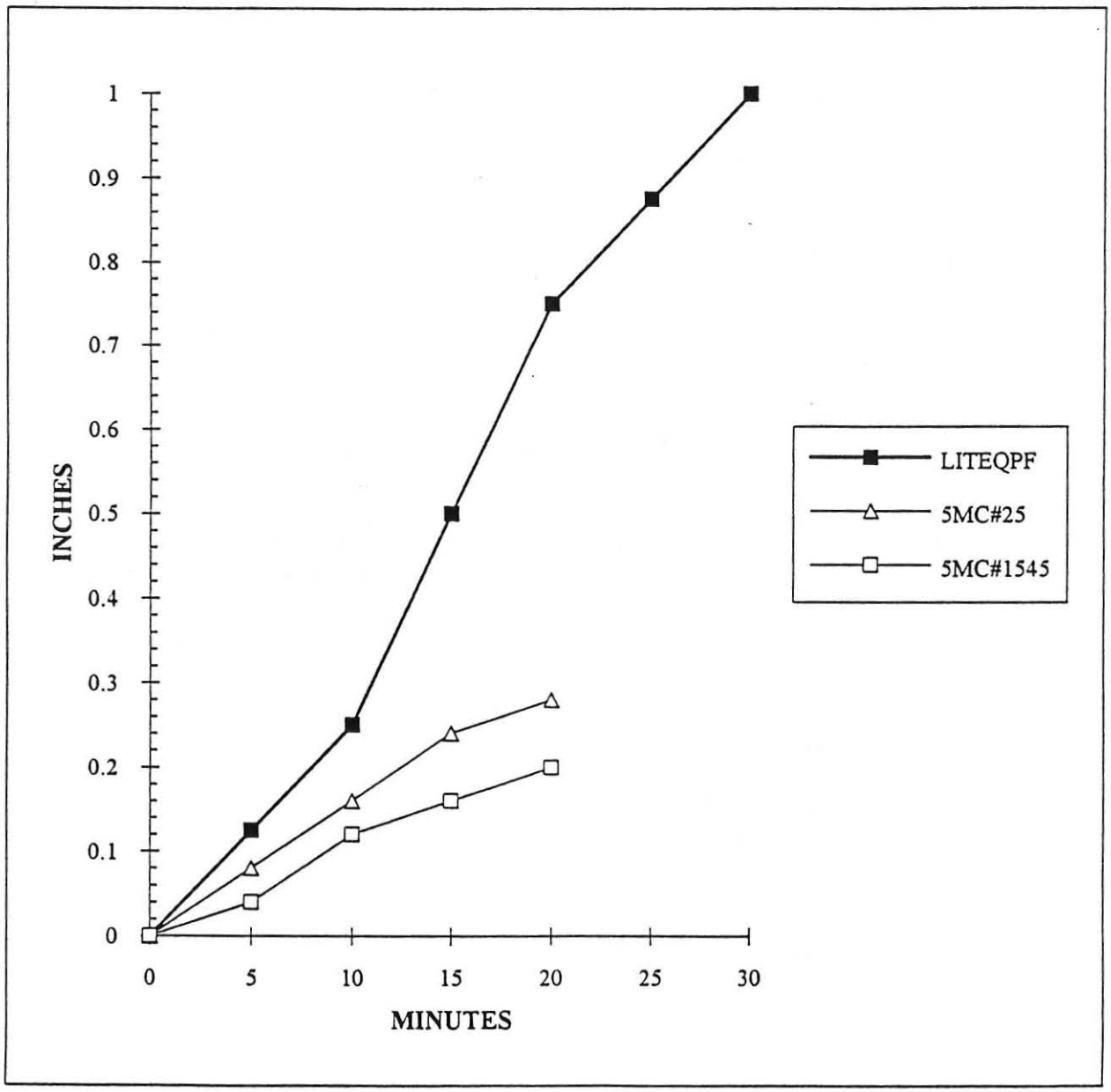
MAY 31, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	5M#1810	5MC#1810
0	0	0	0
5	0.13	0.04	0.04
10	0.25	0.08	0.12
15	0.50	0.24	0.36
20	0.75	0.04	0.40
25	0.88		
30	1.00		



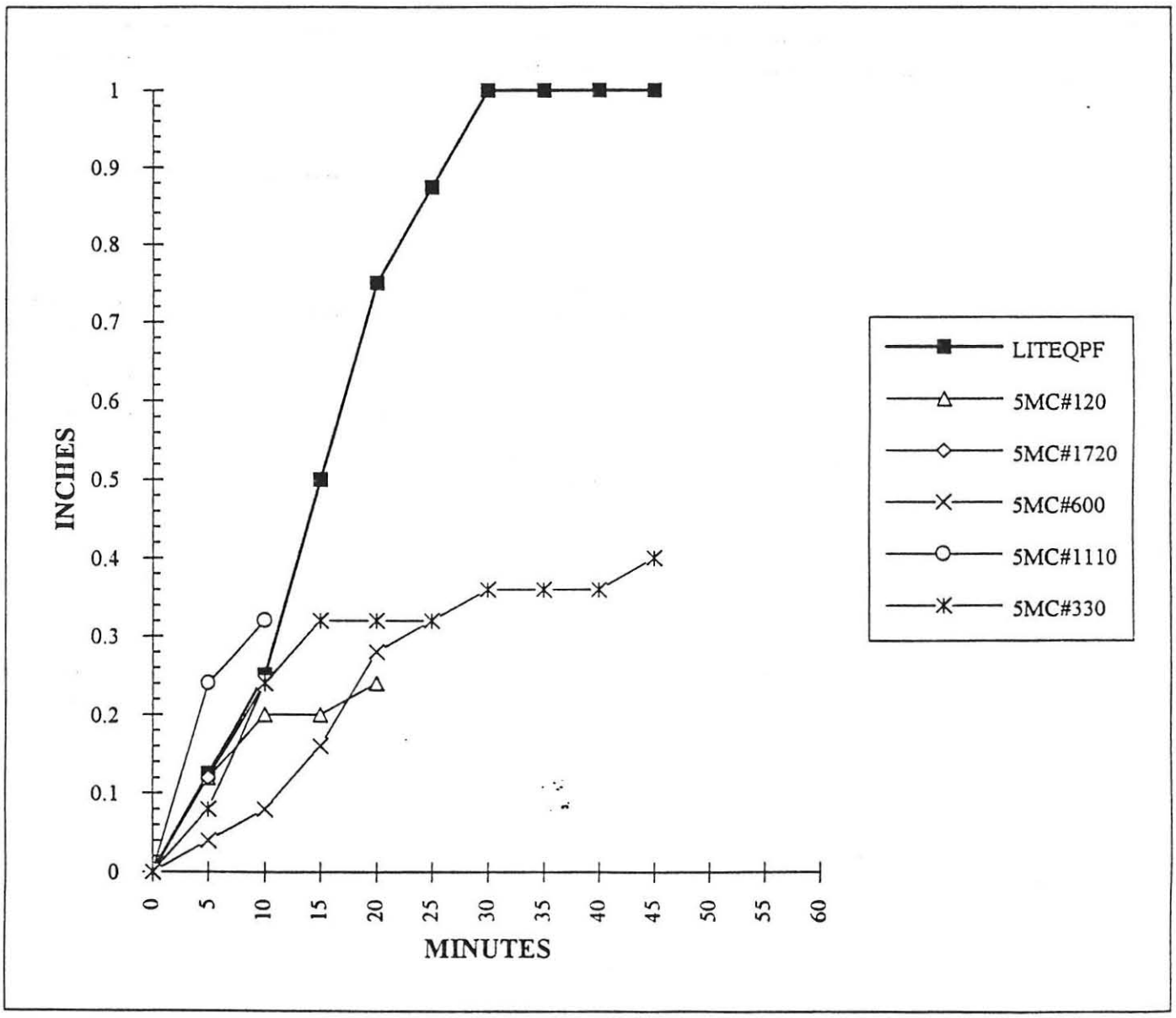
JUNE 2, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	5M#25	5MC#25	5M#1545	5MC#1545
0	0	0	0	0	0
5	0.13	0.08	0.08	0.04	0.04
10	0.25	0.08	0.16	0.08	0.12
15	0.50	0.08	0.24	0.04	0.16
20	0.75	0.04	0.28	0.04	0.20
25	0.88				
30	1.00				



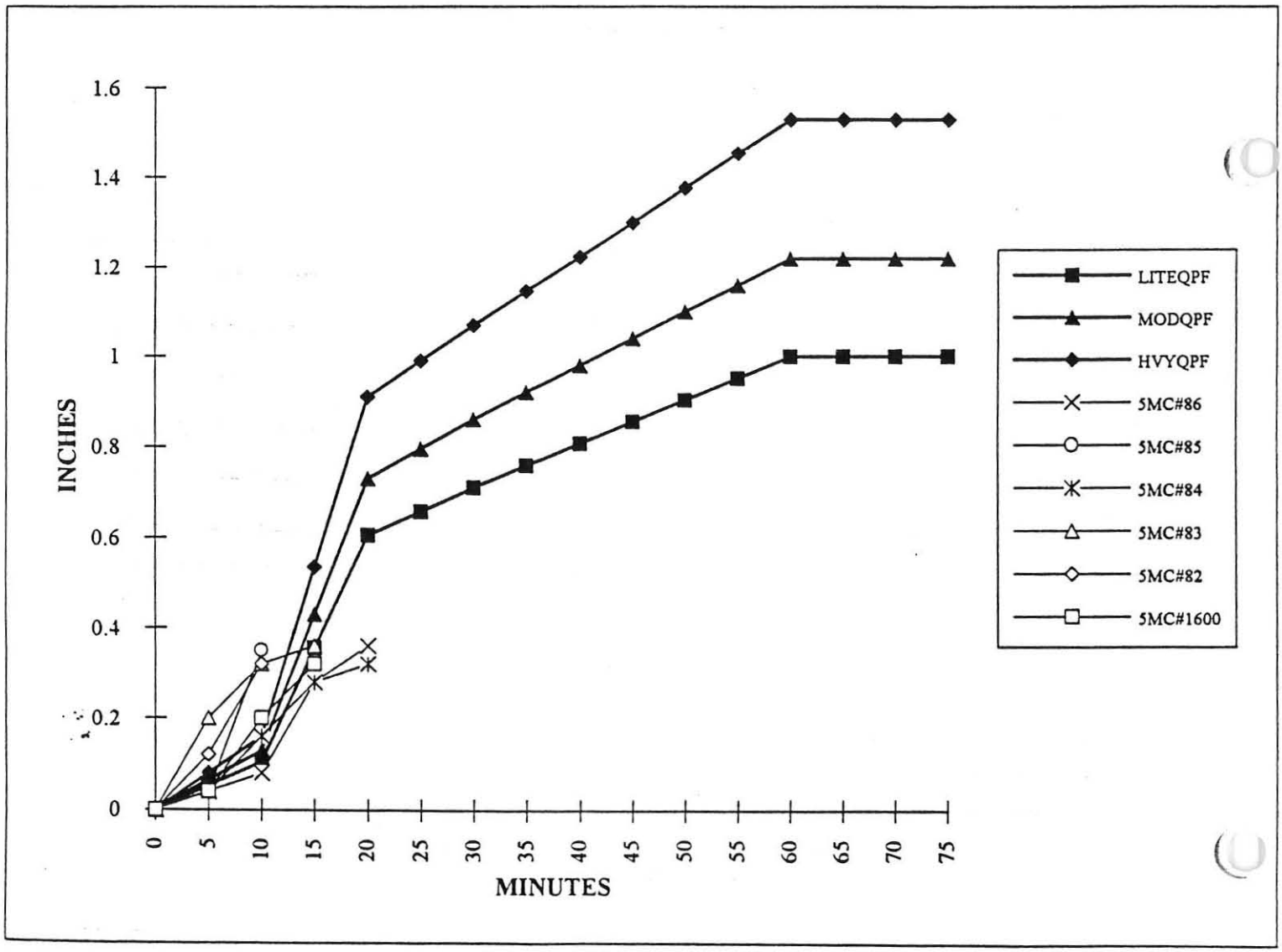
JUNE 3, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	5MC#120	5MC#1720	5MC#600	5MC#1110	5MC#330
0	0	0	0	0	0	0
5	0.13	0.12	0.12	0.04	0.24	0.08
10	0.25	0.20	0.24	0.08	0.32	0.24
15	0.50	0.20		0.16		0.32
20	0.75	0.24		0.28		0.32
25	0.88			0.32		0.32
30	1.00					0.36
35	1.00					0.36
40	1.00					0.36
45	1.00					0.40
50						
55						
60						



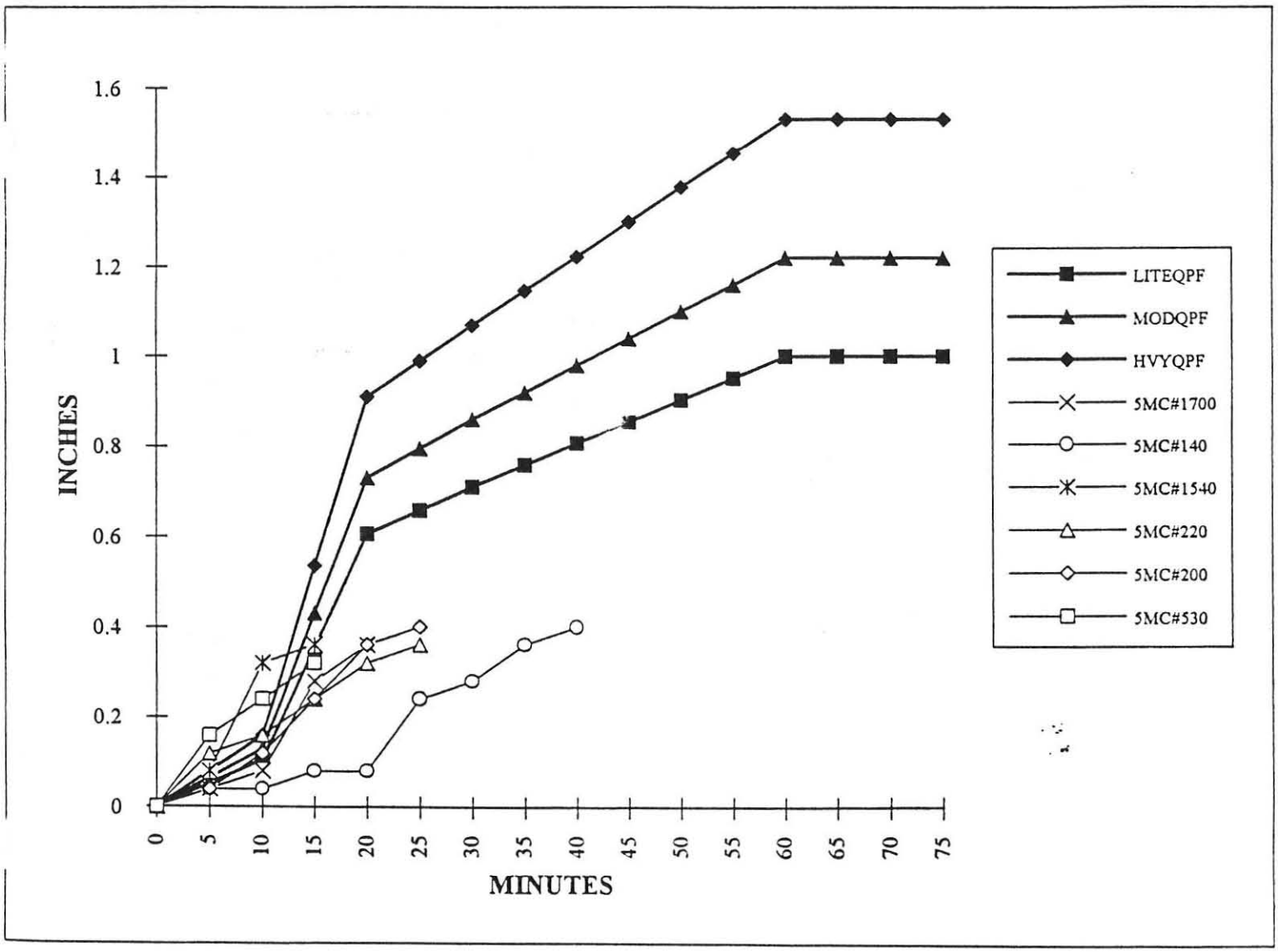
JUNE 17, 1993 AFTERNOON THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#86	5MC#85	5MC#84	5MC#83	5MC#82	5MC#1600
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.04	0.04	0.04	0.20	0.12	0.04
10	0.11	0.13	0.16	0.08	0.35	0.16	0.32	0.32	0.20
15	0.36	0.43	0.54	0.28		0.28	0.36		0.32
20	0.61	0.73	0.91	0.36		0.32			
25	0.66	0.80	0.99						
30	0.71	0.86	1.07						
35	0.76	0.92	1.15						
40	0.81	0.98	1.22						
45	0.86	1.04	1.30						
50	0.90	1.10	1.38						
55	0.95	1.16	1.45						
60	1.00	1.22	1.53						
65	1.00	1.22	1.53						
70	1.00	1.22	1.53						
75	1.00	1.22	1.53						



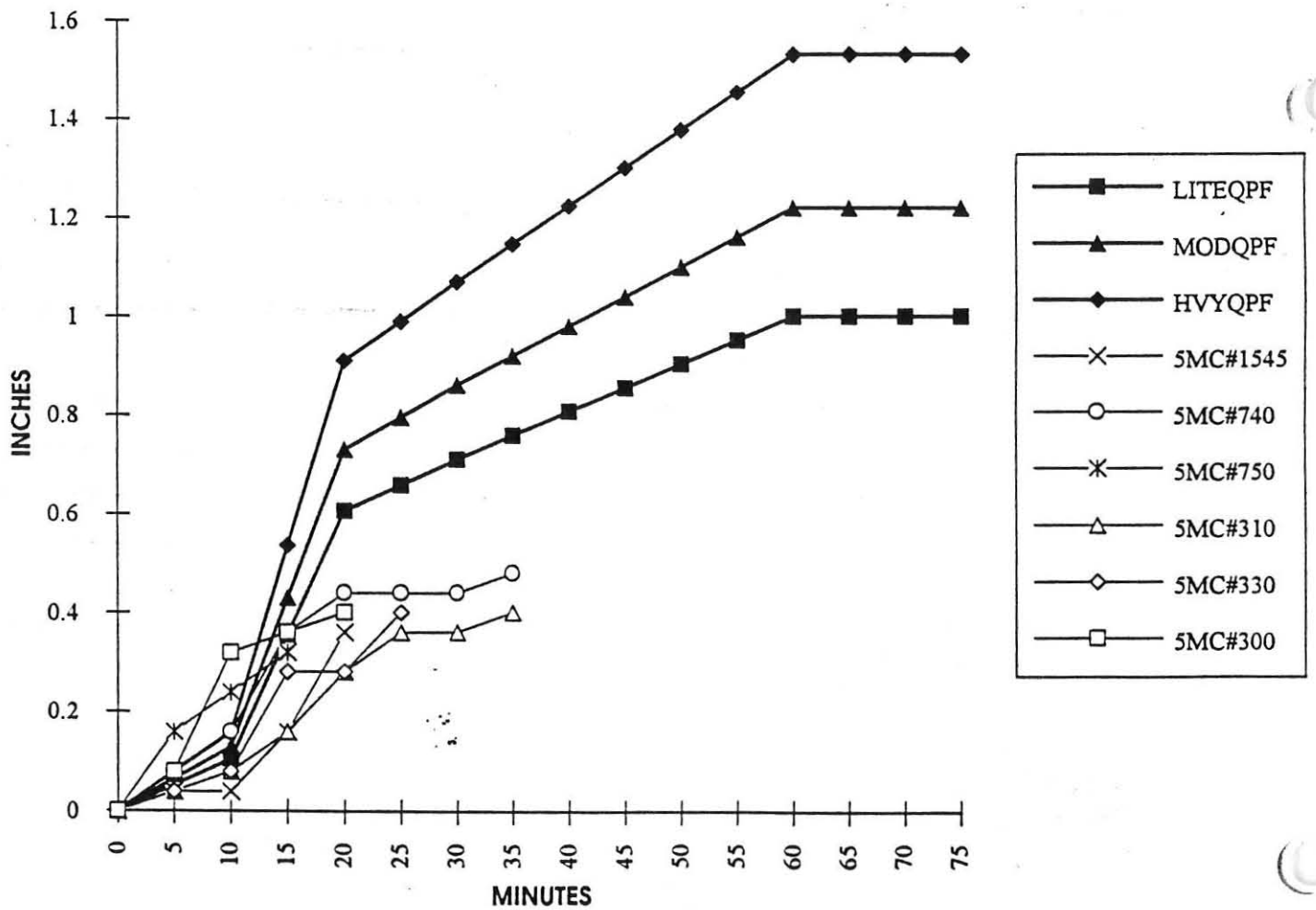
JUNE 17, 1993 AFTERNOON THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#1700	5MC#140	5MC#1540	5MC#220	5MC#200	5MC#530
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.04	0.04	0.08	0.12	0.04	0.16
10	0.11	0.13	0.16	0.08	0.04	0.32	0.16	0.12	0.24
15	0.36	0.43	0.54	0.28	0.08	0.36	0.24	0.24	0.32
20	0.61	0.73	0.91	0.36	0.08		0.32	0.36	
25	0.66	0.80	0.99		0.24		0.36	0.40	
30	0.71	0.86	1.07		0.28				
35	0.76	0.92	1.15		0.36				
40	0.81	0.98	1.22		0.40				
45	0.86	1.04	1.30						
50	0.90	1.10	1.38						
55	0.95	1.16	1.45						
60	1.00	1.22	1.53						
65	1.00	1.22	1.53						
70	1.00	1.22	1.53						
75	1.00	1.22	1.53						



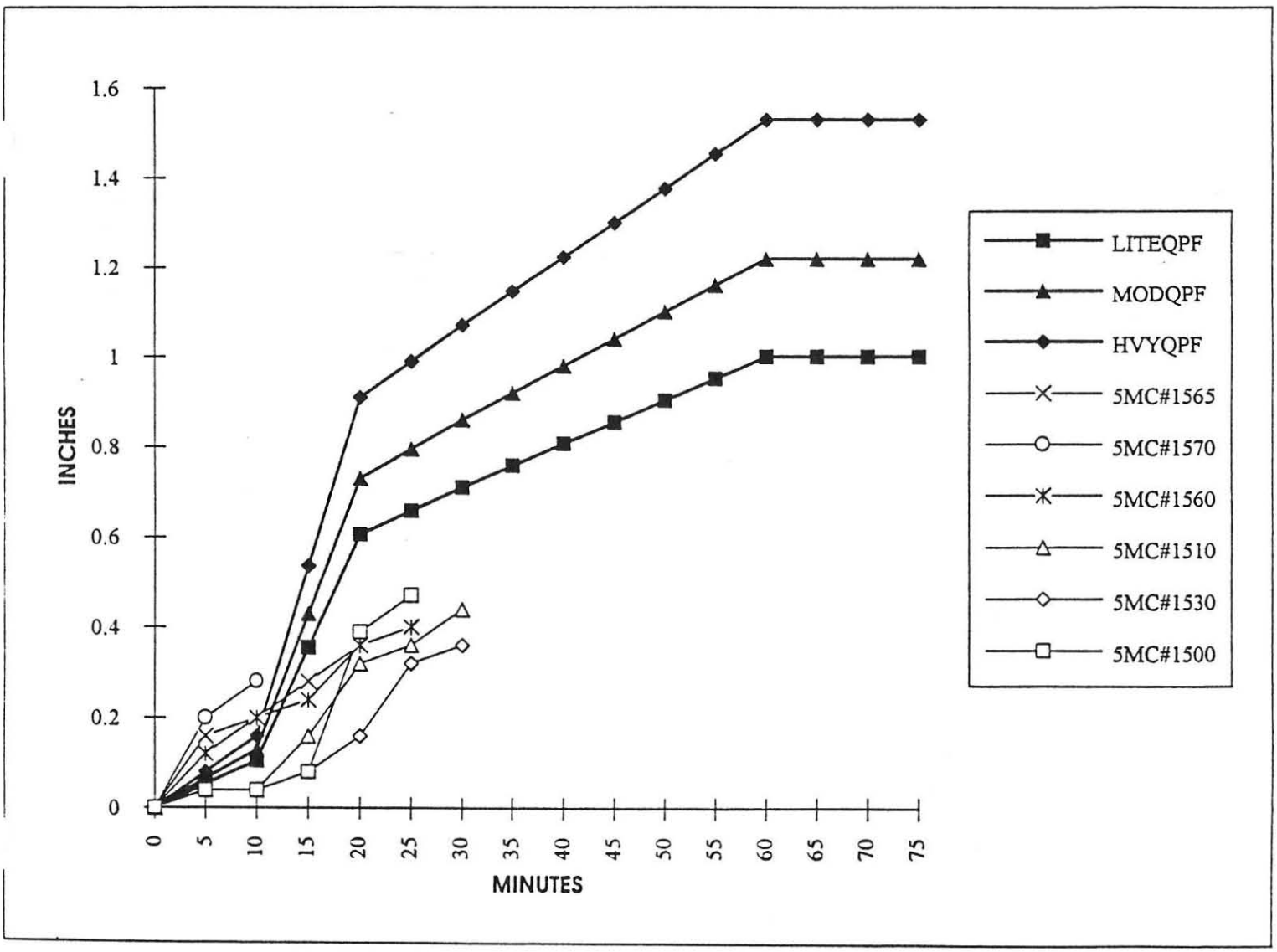
JUNE 17, 1993 AFTERNOON THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#1545	5MC#740	5MC#750	5MC#310	5MC#330	5MC#300
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.04	0.08	0.16	0.04	0.04	0.08
10	0.11	0.13	0.16	0.04	0.16	0.24	0.08	0.08	0.32
15	0.36	0.43	0.54	0.16	0.36	0.32	0.16	0.28	0.36
20	0.61	0.73	0.91	0.36	0.44		0.28	0.28	0.40
25	0.66	0.80	0.99		0.44		0.36	0.40	
30	0.71	0.86	1.07		0.44		0.36		
35	0.76	0.92	1.15		0.48		0.40		
40	0.81	0.98	1.22						
45	0.86	1.04	1.30						
50	0.90	1.10	1.38						
55	0.95	1.16	1.45						
60	1.00	1.22	1.53						
65	1.00	1.22	1.53						
70	1.00	1.22	1.53						
75	1.00	1.22	1.53						



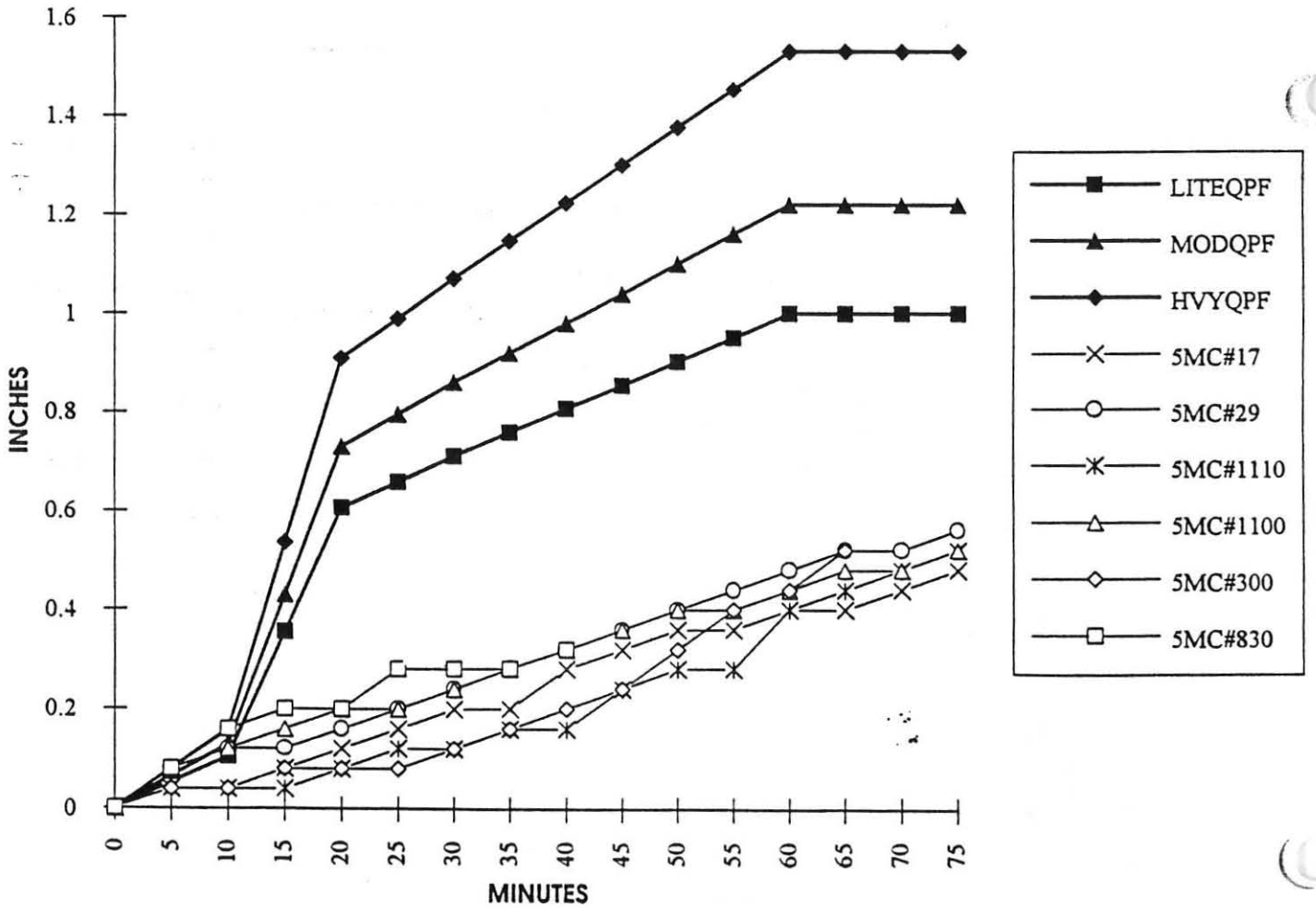
JUNE 17, 1993 AFTERNOON THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#1565	5MC#1570	5MC#1560	5MC#1510	5MC#1530	5MC#1500
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.16	0.20	0.12	0.04	0.04	0.04
10	0.11	0.13	0.16	0.20	0.28	0.20	0.04	0.04	0.04
15	0.36	0.43	0.54	0.28		0.24	0.16	0.08	0.08
20	0.61	0.73	0.91	0.36		0.36	0.32	0.16	0.39
25	0.66	0.80	0.99			0.40	0.36	0.32	0.47
30	0.71	0.86	1.07				0.44	0.36	
35	0.76	0.92	1.15						
40	0.81	0.98	1.22						
45	0.86	1.04	1.30						
50	0.90	1.10	1.38						
55	0.95	1.16	1.45						
60	1.00	1.22	1.53						
65	1.00	1.22	1.53						
70	1.00	1.22	1.53						
75	1.00	1.22	1.53						



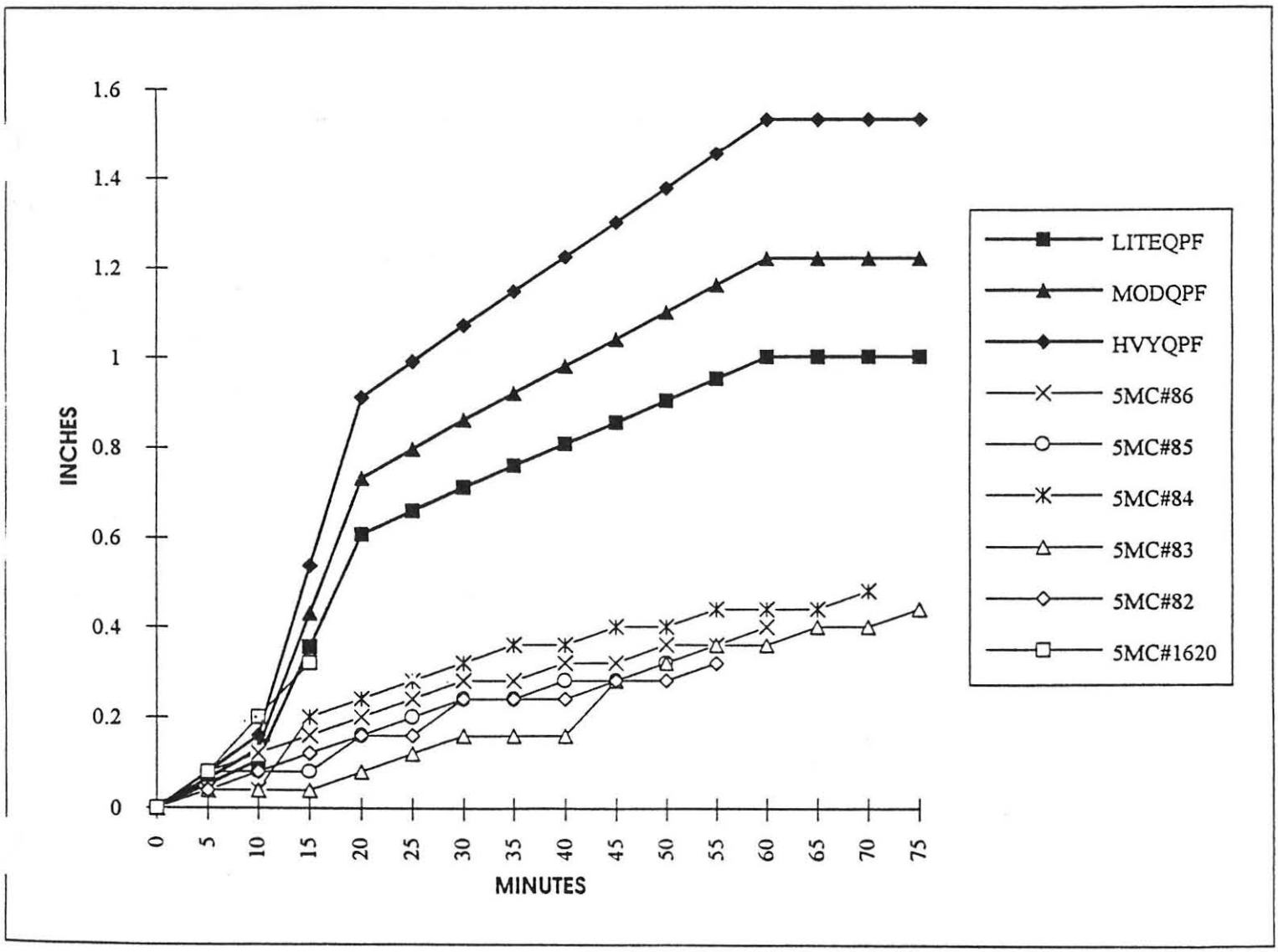
JUNE 17, 1993 LATE EVENING THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#17	5MC#29	5MC#1110	5MC#1100	5MC#300	5MC#830
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.04	0.08	0.04	0.08	0.04	0.08
10	0.11	0.13	0.16	0.04	0.12	0.04	0.12	0.04	0.16
15	0.36	0.43	0.54	0.08	0.12	0.04	0.16	0.08	0.20
20	0.61	0.73	0.91	0.12	0.16	0.08	0.20	0.08	0.20
25	0.66	0.80	0.99	0.16	0.20	0.12	0.20	0.08	0.28
30	0.71	0.86	1.07	0.20	0.24	0.12	0.24	0.12	0.28
35	0.76	0.92	1.15	0.20	0.28	0.16	0.28	0.16	0.28
40	0.81	0.98	1.22	0.28	0.32	0.16	0.32	0.20	0.32
45	0.86	1.04	1.30	0.32	0.36	0.24	0.36	0.24	
50	0.90	1.10	1.38	0.36	0.40	0.28	0.40	0.32	
55	0.95	1.16	1.45	0.36	0.44	0.28	0.40	0.40	
60	1.00	1.22	1.53	0.40	0.48	0.40	0.44	0.44	
65	1.00	1.22	1.53	0.40	0.52	0.44	0.48	0.52	
70	1.00	1.22	1.53	0.44	0.52	0.48	0.48		
75	1.00	1.22	1.53	0.48	0.56	0.52	0.52		



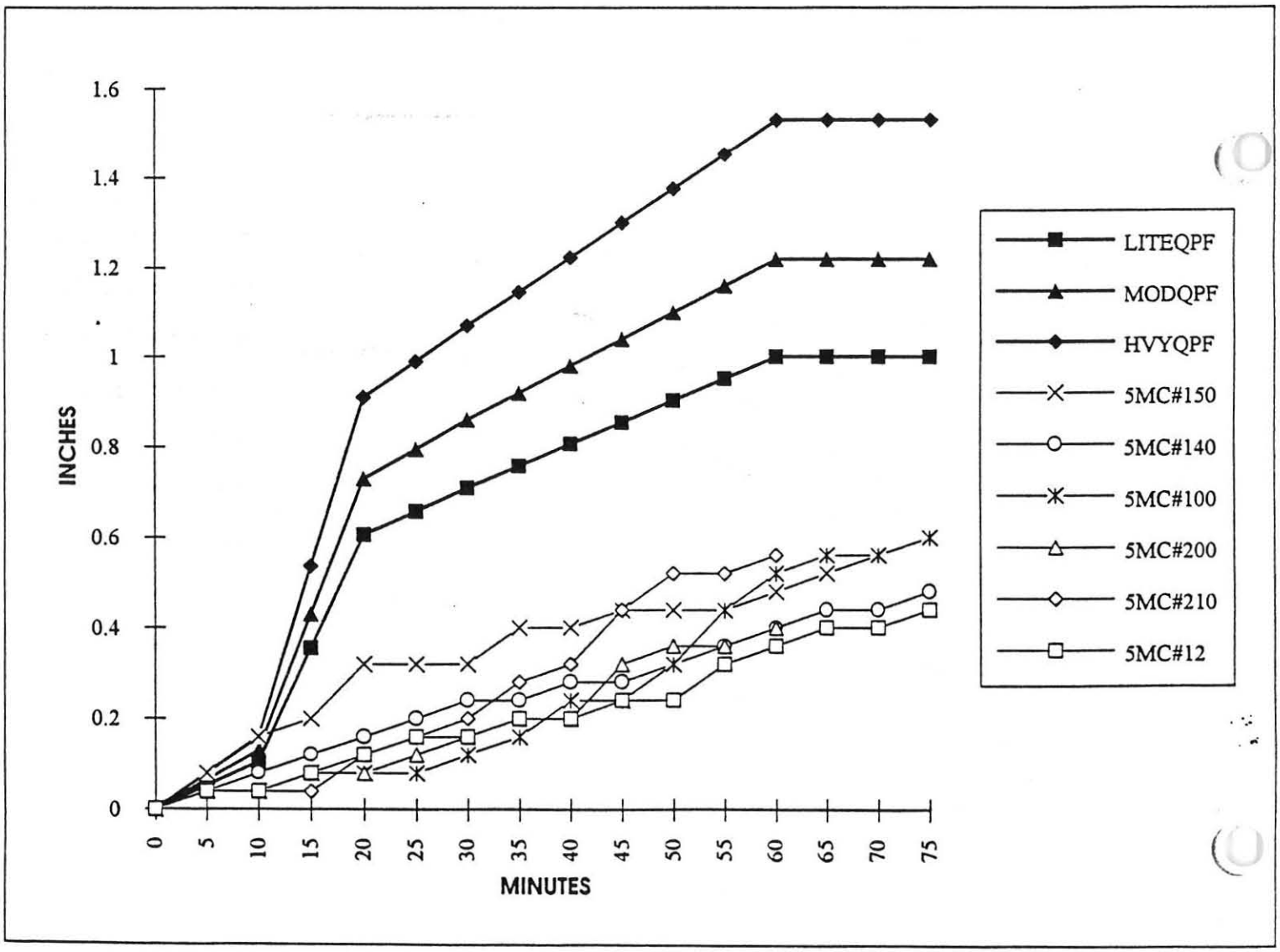
JUNE 17, 1993 LATE EVENING THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#86	5MC#85	5MC#84	5MC#83	5MC#82	5MC#1620
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.08	0.08	0.04	0.04	0.04	0.08
10	0.11	0.13	0.16	0.12	0.08	0.04	0.04	0.08	0.20
15	0.36	0.43	0.54	0.16	0.08	0.20	0.04	0.12	0.32
20	0.61	0.73	0.91	0.20	0.16	0.24	0.08	0.16	
25	0.66	0.80	0.99	0.24	0.20	0.28	0.12	0.16	
30	0.71	0.86	1.07	0.28	0.24	0.32	0.16	0.24	
35	0.76	0.92	1.15	0.28	0.24	0.36	0.16	0.24	
40	0.81	0.98	1.22	0.32	0.28	0.36	0.16	0.24	
45	0.86	1.04	1.30	0.32	0.28	0.40	0.28	0.28	
50	0.90	1.10	1.38	0.36	0.32	0.40	0.32	0.28	
55	0.95	1.16	1.45	0.36		0.44	0.36	0.32	
60	1.00	1.22	1.53	0.40		0.44	0.36		
65	1.00	1.22	1.53			0.44	0.40		
70	1.00	1.22	1.53			0.48	0.40		
75	1.00	1.22	1.53				0.44		



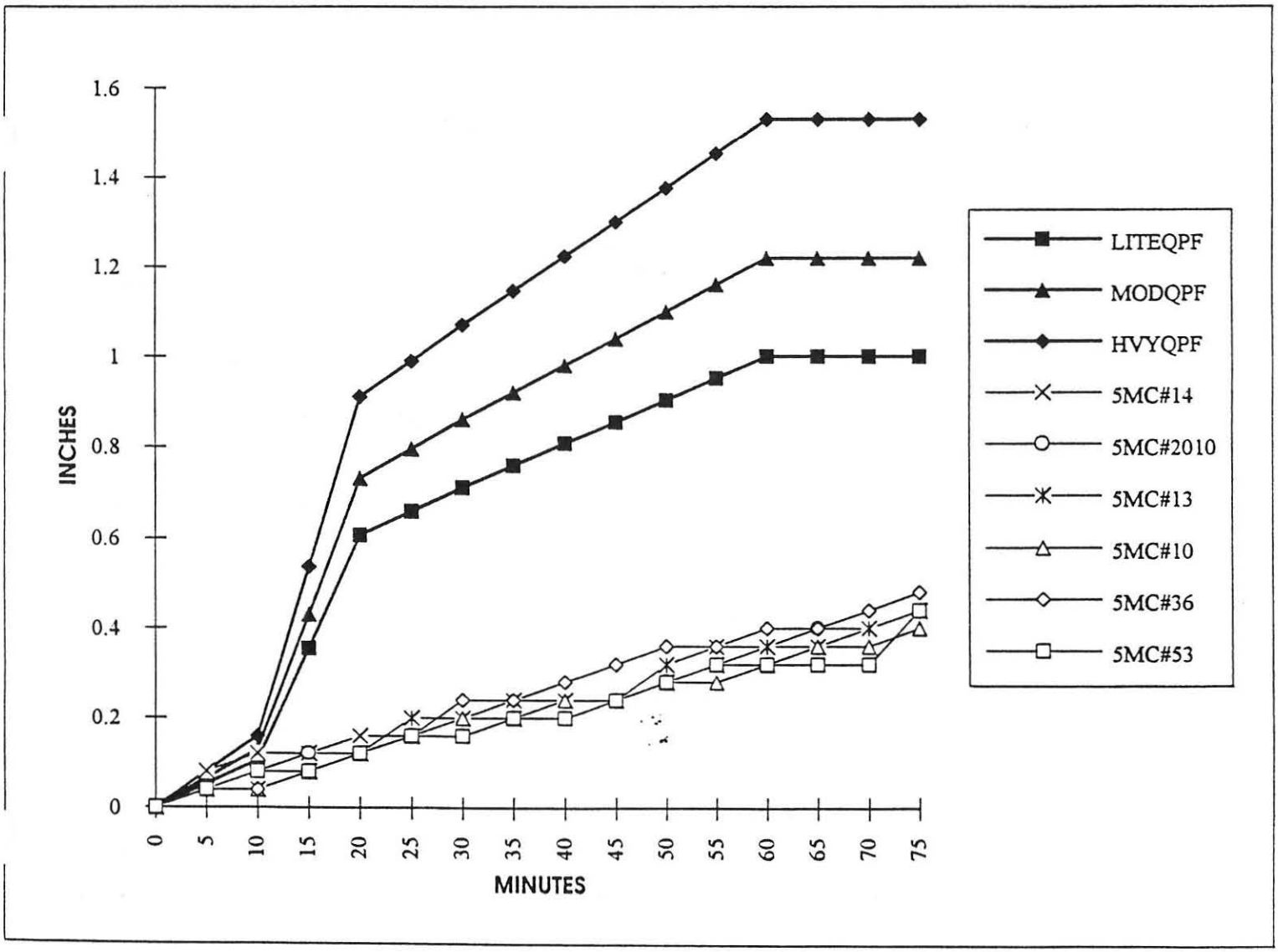
JUNE 17, 1993 LATE EVENING THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#150	5MC#140	5MC#100	5MC#200	5MC#210	5MC#12
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.08	0.04	0.04	0.04	0.04	0.04
10	0.11	0.13	0.16	0.16	0.08	0.04	0.04	0.04	0.04
15	0.36	0.43	0.54	0.20	0.12	0.08	0.08	0.04	0.08
20	0.61	0.73	0.91	0.32	0.16	0.08	0.08	0.12	0.12
25	0.66	0.80	0.99	0.32	0.20	0.08	0.12	0.16	0.16
30	0.71	0.86	1.07	0.32	0.24	0.12	0.16	0.20	0.16
35	0.76	0.92	1.15	0.40	0.24	0.16	0.20	0.28	0.20
40	0.81	0.98	1.22	0.40	0.28	0.24	0.20	0.32	0.20
45	0.86	1.04	1.30	0.44	0.28	0.24	0.32	0.44	0.24
50	0.90	1.10	1.38	0.44	0.32	0.32	0.36	0.52	0.24
55	0.95	1.16	1.45	0.44	0.36	0.44	0.36	0.52	0.32
60	1.00	1.22	1.53	0.48	0.40	0.52	0.40	0.56	0.36
65	1.00	1.22	1.53	0.52	0.44	0.56			0.40
70	1.00	1.22	1.53	0.56	0.44	0.56			0.40
75	1.00	1.22	1.53	0.60	0.48	0.60			0.44



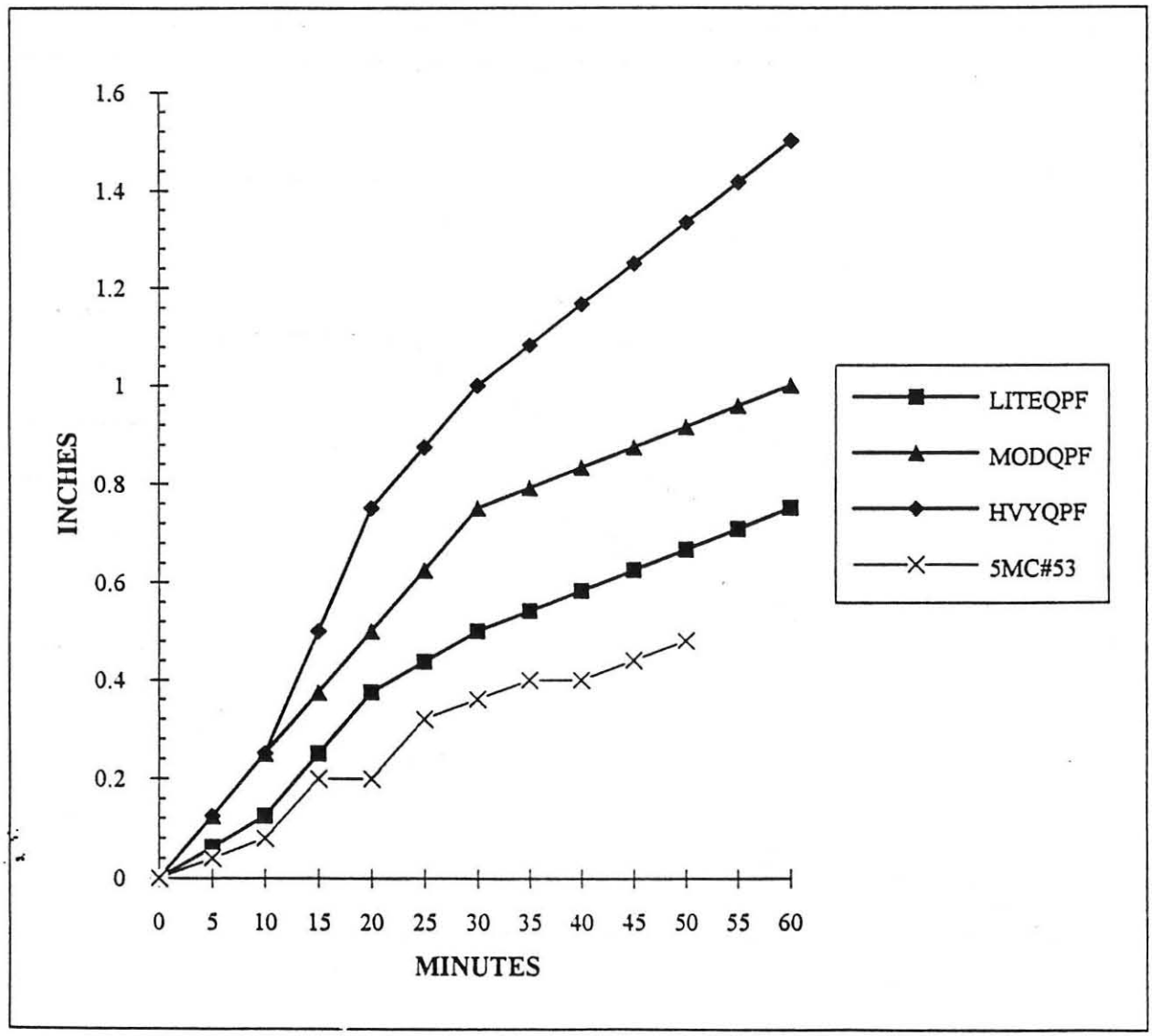
JUNE 17, 1993 LATE EVENING THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#14	5MC#2010	5MC#13	5MC#10	5MC#36	5MC#53
0	0	0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.08	0.04	0.04	0.04	0.04	0.04
10	0.11	0.13	0.16	0.12	0.08	0.04	0.04	0.04	0.08
15	0.36	0.43	0.54	0.12	0.12	0.08	0.08	0.08	0.08
20	0.61	0.73	0.91	0.16	0.12	0.12	0.12	0.12	0.12
25	0.66	0.80	0.99	0.16	0.16	0.20	0.16	0.16	0.16
30	0.71	0.86	1.07	0.20	0.16	0.20	0.20	0.24	0.16
35	0.76	0.92	1.15	0.20	0.20	0.24	0.20	0.24	0.20
40	0.81	0.98	1.22	0.24	0.20	0.24	0.24	0.28	0.20
45	0.86	1.04	1.30	0.24	0.24	0.24	0.24	0.32	0.24
50	0.90	1.10	1.38	0.28	0.28	0.32	0.28	0.36	0.28
55	0.95	1.16	1.45	0.32	0.32	0.36	0.28	0.36	0.32
60	1.00	1.22	1.53	0.36	0.36	0.36	0.32	0.40	0.32
65	1.00	1.22	1.53	0.36	0.40	0.36	0.36	0.40	0.32
70	1.00	1.22	1.53	0.40	0.40	0.40	0.36	0.44	0.32
75	1.00	1.22	1.53		0.44	0.44	0.40	0.48	0.44



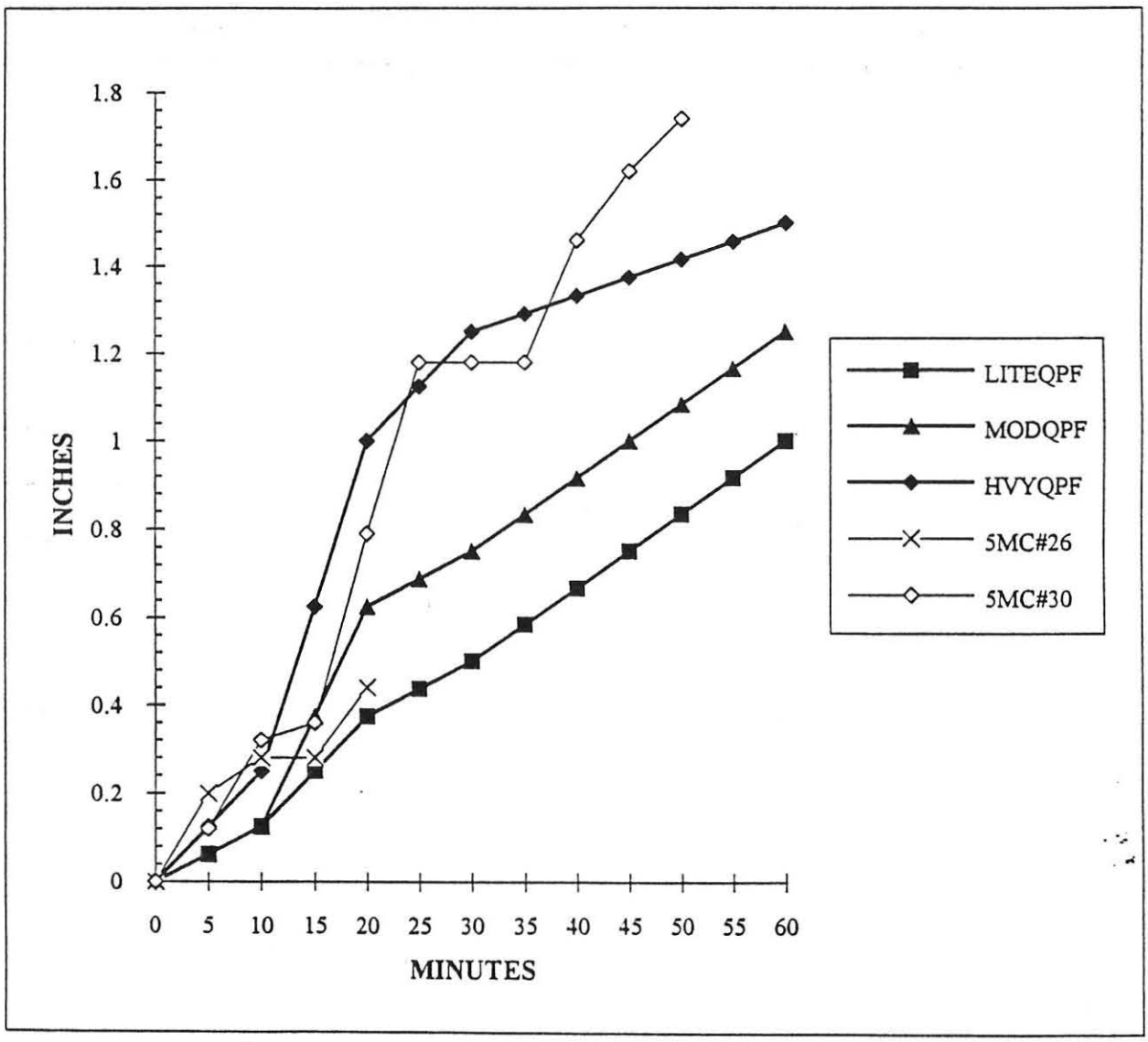
JUNE 18, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5M#53	5MC#53
0	0	0	0	0	0
5	0.06	0.13	0.13	0.04	0.04
10	0.13	0.25	0.25	0.04	0.08
15	0.25	0.38	0.50	0.12	0.20
20	0.38	0.50	0.75	0.00	0.20
25	0.44	0.63	0.88	0.12	0.32
30	0.50	0.75	1.00	0.04	0.36
35	0.54	0.79	1.08	0.04	0.40
40	0.58	0.83	1.17	0.00	0.40
45	0.63	0.88	1.25	0.04	0.44
50	0.67	0.92	1.33	0.04	0.48
55	0.71	0.96	1.42		
60	0.75	1.00	1.50		



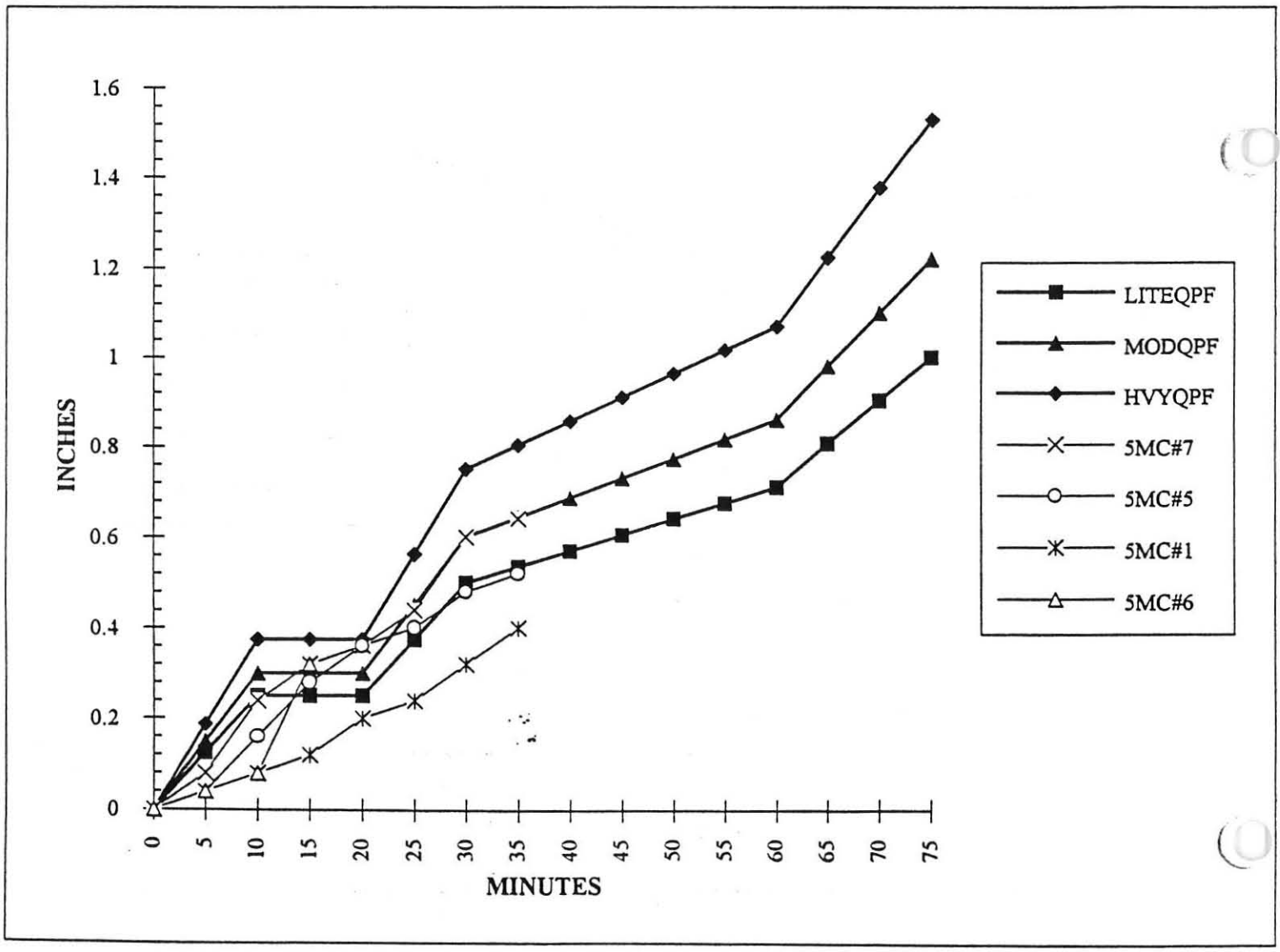
JUNE 23, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5M#26	5MC#26	5M#30	5MC#30
0	0	0	0	0	0	0	0
5	0.06	0.06	0.13	0.20	0.20	0.12	0.12
10	0.13	0.13	0.25	0.08	0.28	0.20	0.32
15	0.25	0.38	0.63	0.00	0.28	0.04	0.36
20	0.38	0.63	1.00	0.16	0.44	0.43	0.79
25	0.44	0.69	1.13			0.39	1.18
30	0.50	0.75	1.25			0.00	1.18
35	0.58	0.83	1.29			0.00	1.18
40	0.67	0.92	1.33			0.28	1.46
45	0.75	1.00	1.38			0.16	1.62
50	0.83	1.08	1.42			0.12	1.74
55	0.92	1.17	1.46				
60	1.00	1.25	1.50				



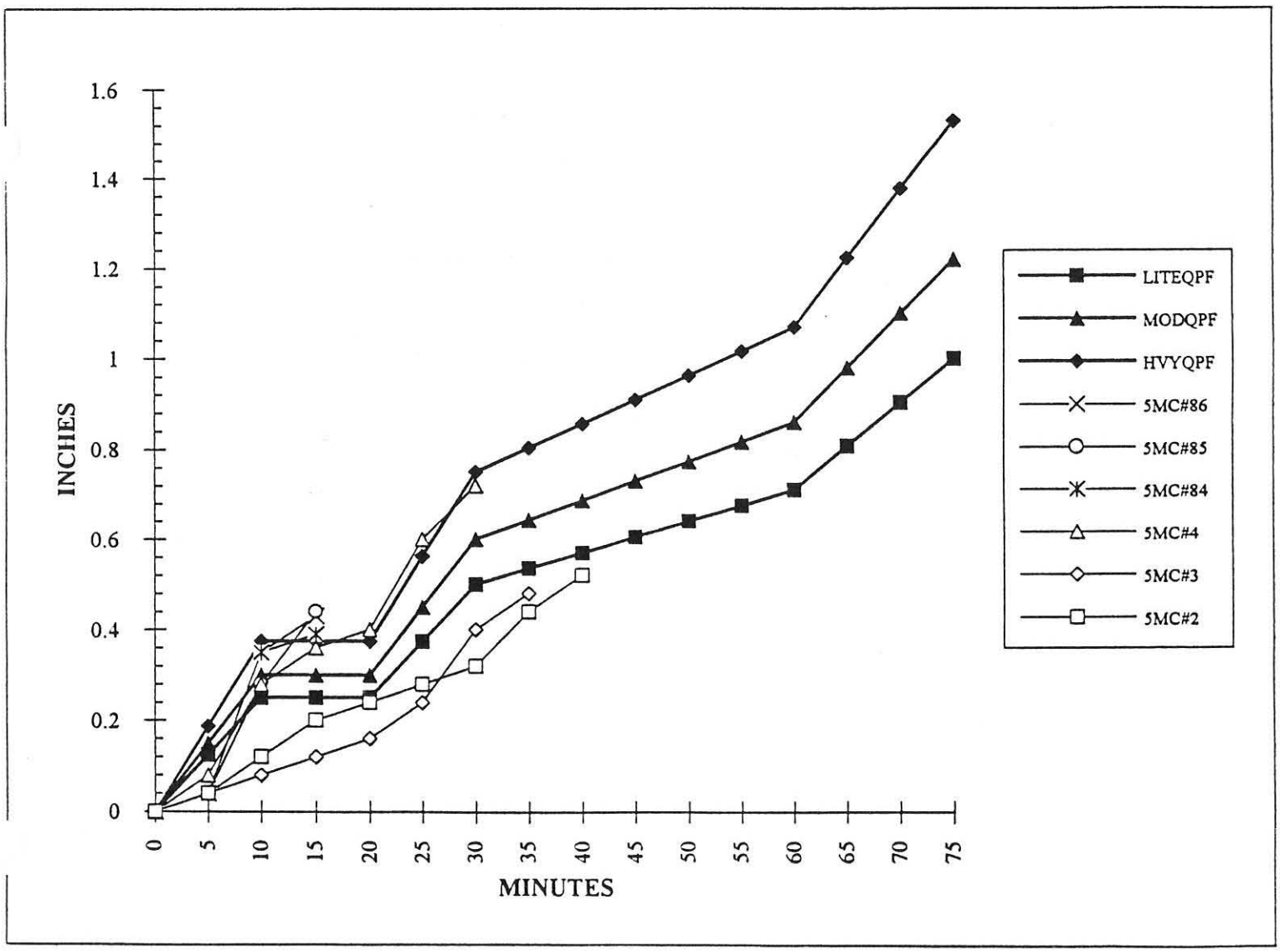
JULY 11, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#7	5MC#5	5MC#1	5MC#6
0	0	0	0	0	0	0	0
5	0.13	0.15	0.19	0.08	0.04	0.04	0.04
10	0.25	0.30	0.38	0.24	0.16	0.08	0.08
15	0.25	0.30	0.38	0.32	0.28	0.12	0.32
20	0.25	0.30	0.38	0.36	0.36	0.20	
25	0.38	0.45	0.56	0.44	0.40	0.24	
30	0.50	0.60	0.75	0.60	0.48	0.32	
35	0.54	0.64	0.80	0.64	0.52	0.40	
40	0.57	0.69	0.86				
45	0.61	0.73	0.91				
50	0.64	0.77	0.96				
55	0.68	0.82	1.02				
60	0.71	0.86	1.07				
65	0.81	0.98	1.22				
70	0.90	1.10	1.38				
75	1.00	1.22	1.53				



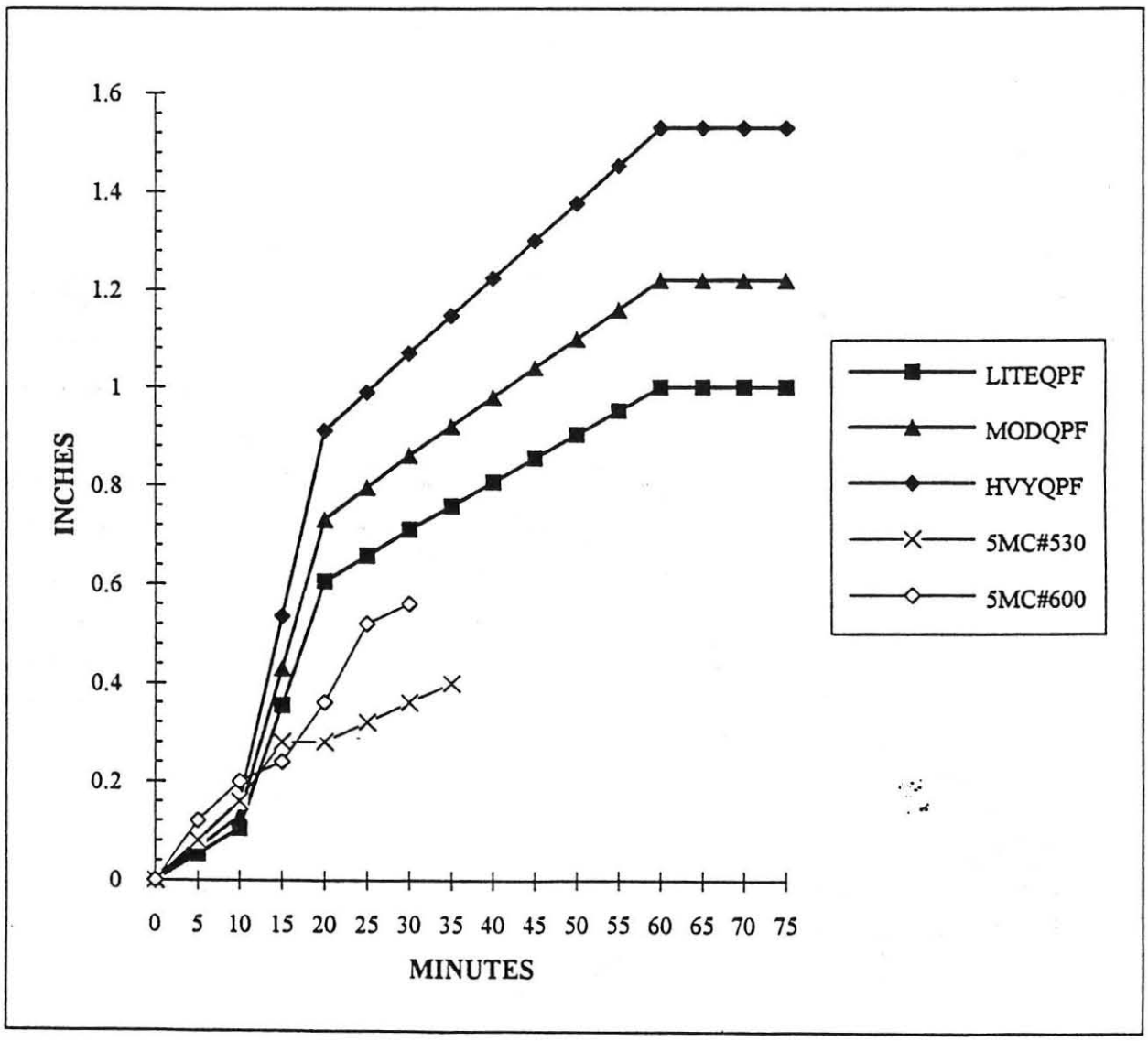
JULY 11, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#86	5MC#85	5MC#84	5MC#4	5MC#3	5MC#2
0	0	0	0	0	0	0	0	0	0
5	0.13	0.15	0.19	0.04	0.04	0.04	0.08	0.04	0.04
10	0.25	0.30	0.38	0.35	0.28	0.35	0.28	0.08	0.12
15	0.25	0.30	0.38	0.43	0.44	0.39	0.36	0.12	0.20
20	0.25	0.30	0.38				0.40	0.16	0.24
25	0.38	0.45	0.56				0.60	0.24	0.28
30	0.50	0.60	0.75				0.72	0.40	0.32
35	0.54	0.64	0.80					0.48	0.44
40	0.57	0.69	0.86						0.52
45	0.61	0.73	0.91						
50	0.64	0.77	0.96						
55	0.68	0.82	1.02						
60	0.71	0.86	1.07						
65	0.81	0.98	1.22						
70	0.90	1.10	1.38						
75	1.00	1.22	1.53						



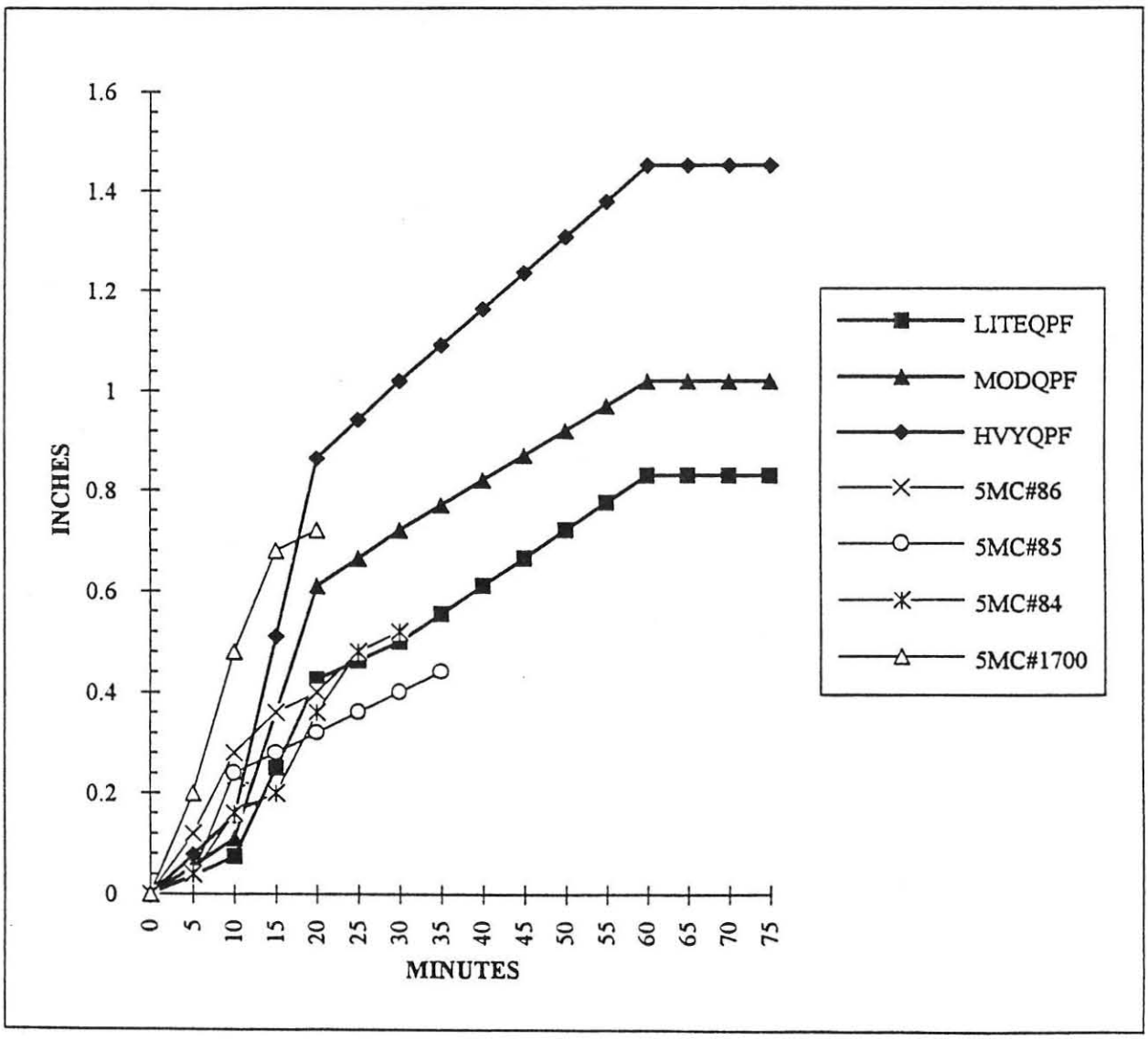
JULY 12, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5M#530	5MC#530	5M#600	5MC#600
0	0	0	0	0	0	0	0
5	0.05	0.07	0.08	0.08	0.08	0.12	0.12
10	0.11	0.13	0.16	0.08	0.16	0.08	0.20
15	0.36	0.43	0.54	0.12	0.28	0.04	0.24
20	0.61	0.73	0.91	0.00	0.28	0.12	0.36
25	0.66	0.80	0.99	0.04	0.32	0.16	0.52
30	0.71	0.86	1.07	0.04	0.36	0.04	0.56
35	0.76	0.92	1.15	0.04	0.40		
40	0.81	0.98	1.22				
45	0.86	1.04	1.30				
50	0.90	1.10	1.38				
55	0.95	1.16	1.45				
60	1.00	1.22	1.53				
65	1.00	1.22	1.53				
70	1.00	1.22	1.53				
75	1.00	1.22	1.53				



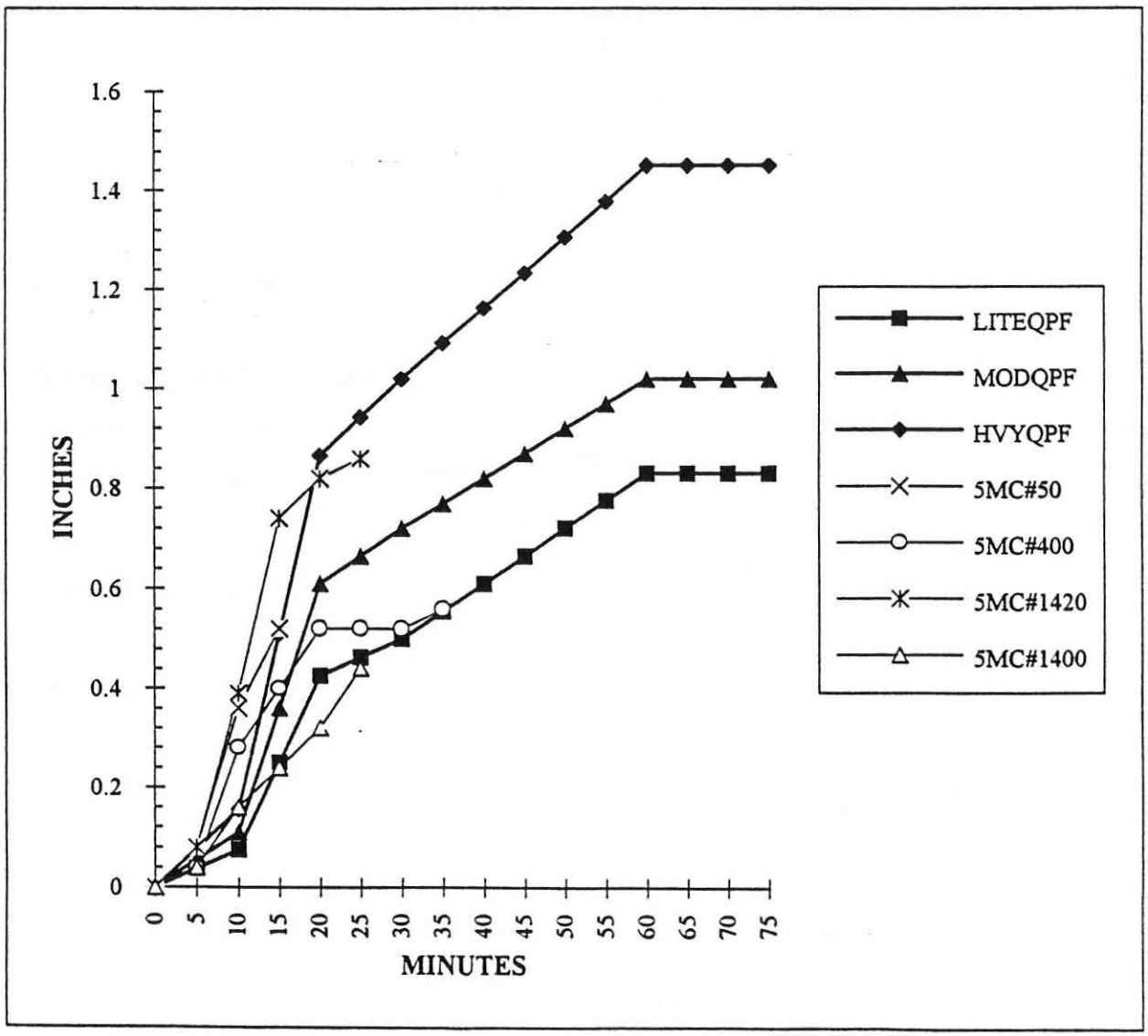
JULY 13, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#86	5MC#85	5MC#84	5MC#1700
0	0	0	0	0	0	0	0
5	0.04	0.06	0.08	0.12	0.04	0.04	0.20
10	0.08	0.11	0.16	0.28	0.24	0.16	0.48
15	0.25	0.36	0.51	0.36	0.28	0.20	0.68
20	0.43	0.61	0.87	0.40	0.32	0.36	0.72
25	0.46	0.67	0.94	0.48	0.36	0.48	
30	0.50	0.72	1.02		0.40	0.52	
35	0.56	0.77	1.09		0.44		
40	0.61	0.82	1.16				
45	0.67	0.87	1.24				
50	0.72	0.92	1.31				
55	0.78	0.97	1.38				
60	0.83	1.02	1.45				
65	0.83	1.02	1.45				
70	0.83	1.02	1.45				
75	0.83	1.02	1.45				



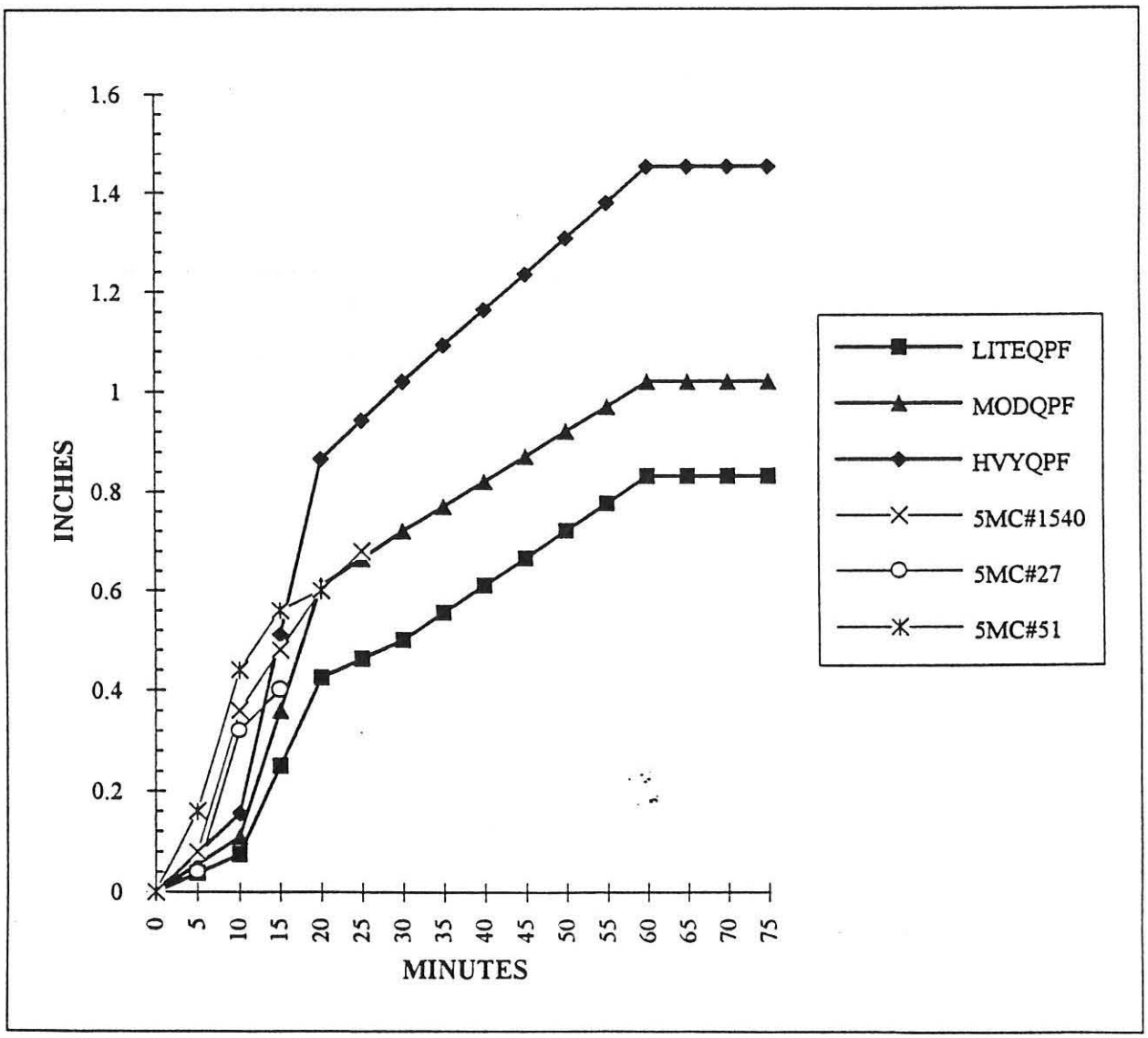
JULY 13, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#50	5MC#400	5MC#1420	5MC#1400
0	0	0	0	0	0	0	0
5	0.04	0.06	0.08	0.08	0.04	0.08	0.04
10	0.08	0.11	0.16	0.36	0.28	0.39	0.16
15	0.25	0.36	0.51	0.52	0.40	0.74	0.24
20	0.43	0.61	0.87		0.52	0.82	0.32
25	0.46	0.67	0.94		0.52	0.86	0.44
30	0.50	0.72	1.02		0.52		
35	0.56	0.77	1.09		0.56		
40	0.61	0.82	1.16				
45	0.67	0.87	1.24				
50	0.72	0.92	1.31				
55	0.78	0.97	1.38				
60	0.83	1.02	1.45				
65	0.83	1.02	1.45				
70	0.83	1.02	1.45				
75	0.83	1.02	1.45				



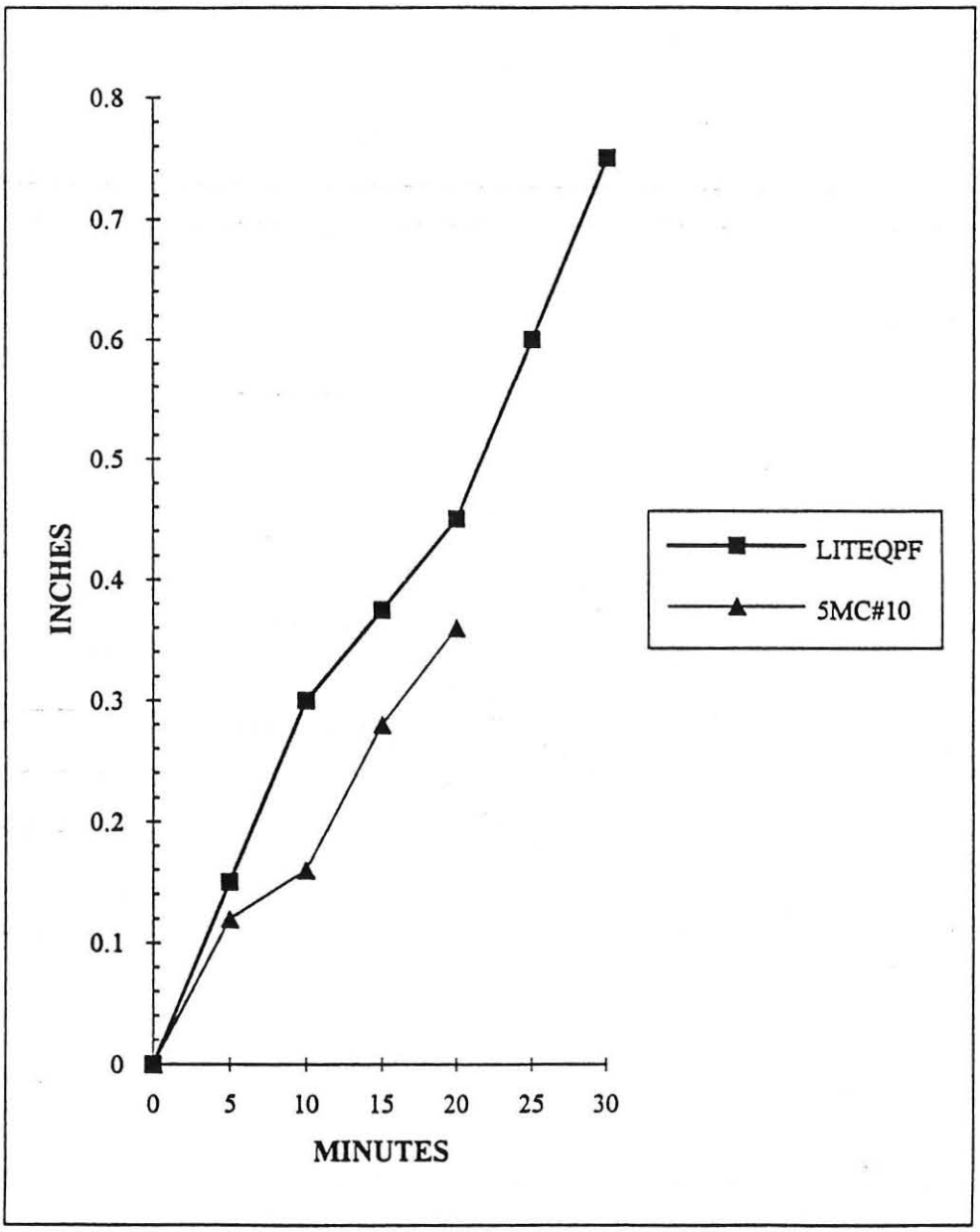
JULY 13, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	HVYQPF	5MC#1540	5MC#27	5MC#51
0	0	0	0	0	0	0
5	0.04	0.06	0.08	0.08	0.04	0.16
10	0.08	0.11	0.16	0.36	0.32	0.44
15	0.25	0.36	0.51	0.48	0.40	0.56
20	0.43	0.61	0.87	0.60		0.60
25	0.46	0.67	0.94	0.68		
30	0.50	0.72	1.02			
35	0.56	0.77	1.09			
40	0.61	0.82	1.16			
45	0.67	0.87	1.24			
50	0.72	0.92	1.31			
55	0.78	0.97	1.38			
60	0.83	1.02	1.45			
65	0.83	1.02	1.45			
70	0.83	1.02	1.45			
75	0.83	1.02	1.45			



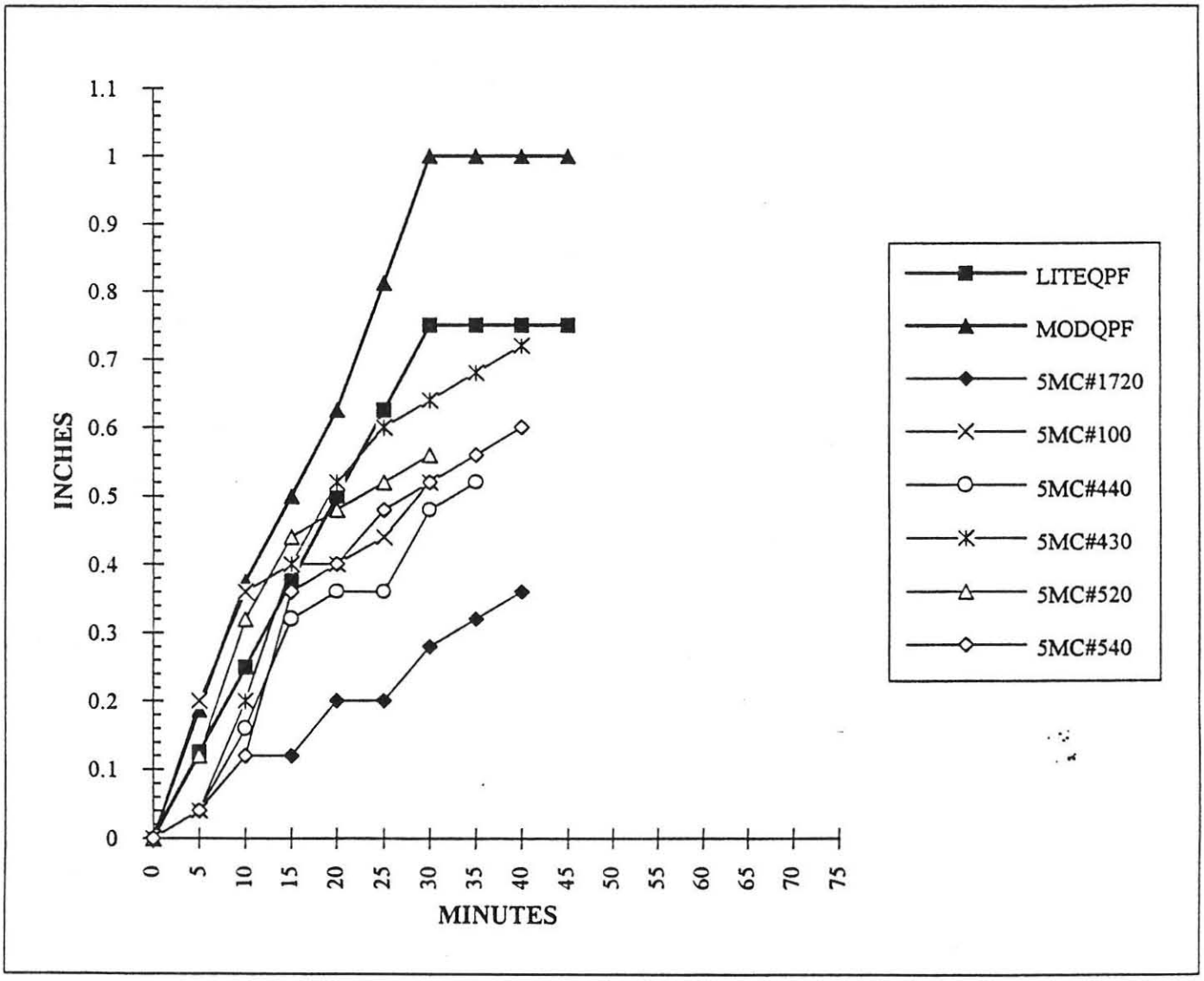
JULY 15, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	5M#10	5MC#10
0	0	0	0
5	0.15	0.12	0.12
10	0.30	0.04	0.16
15	0.38	0.12	0.28
20	0.45	0.08	0.36
25	0.60		
30	0.75		



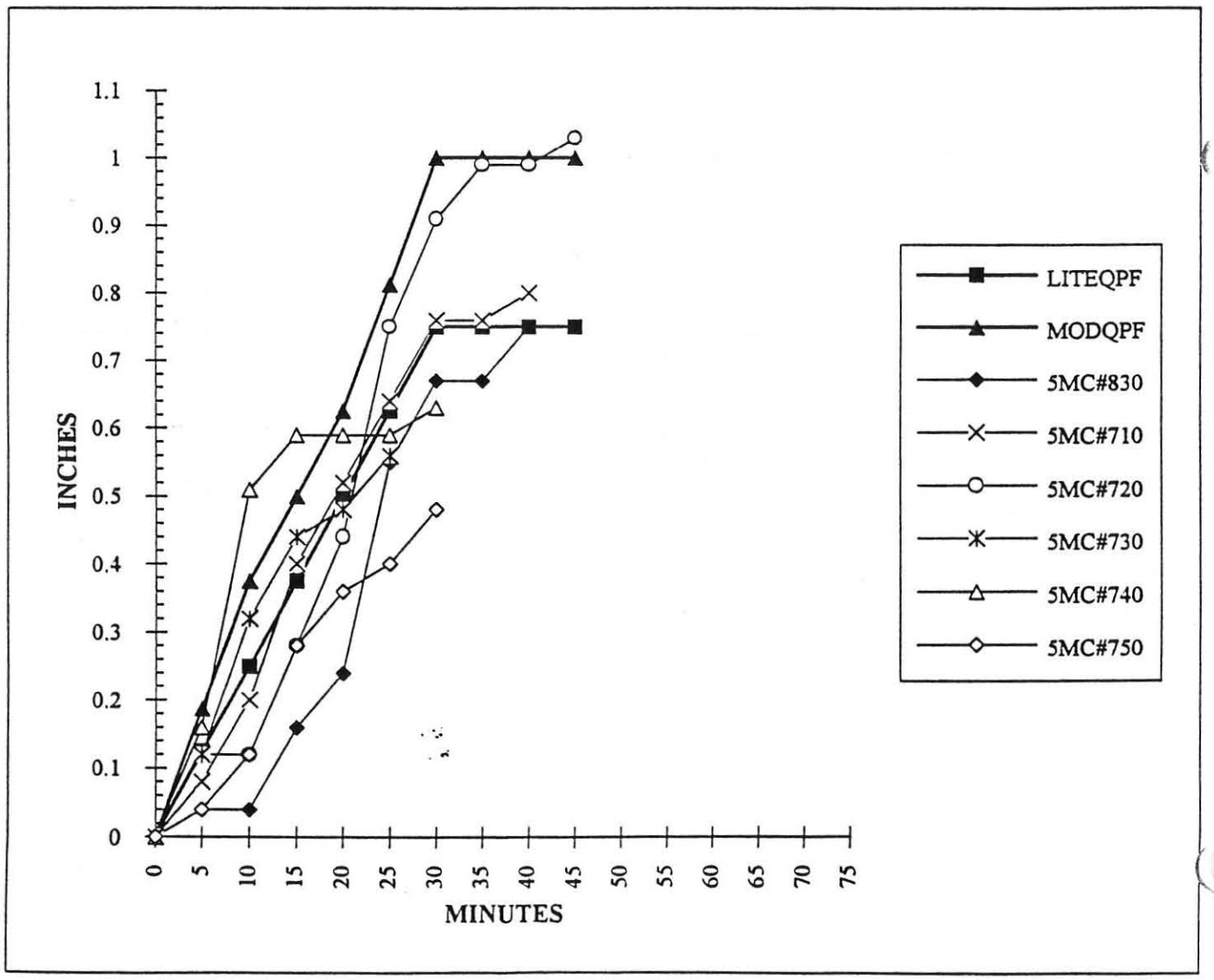
AUGUST 5, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	5MC#1720	5MC#100	5MC#440	5MC#430	5MC#520	5MC#540
0	0	0	0	0	0	0	0	0
5	0.13	0.19	0.04	0.20	0.04	0.04	0.12	0.04
10	0.25	0.38	0.12	0.36	0.16	0.20	0.32	0.12
15	0.38	0.50	0.12	0.40	0.32	0.40	0.44	0.36
20	0.50	0.63	0.20	0.40	0.36	0.52	0.48	0.40
25	0.63	0.81	0.20	0.44	0.36	0.60	0.52	0.48
30	0.75	1.00	0.28	0.52	0.48	0.64	0.56	0.52
35	0.75	1.00	0.32		0.52	0.68		0.56
40	0.75	1.00	0.36			0.72		0.60
45	0.75	1.00						
50								
55								
60								
65								
70								
75								



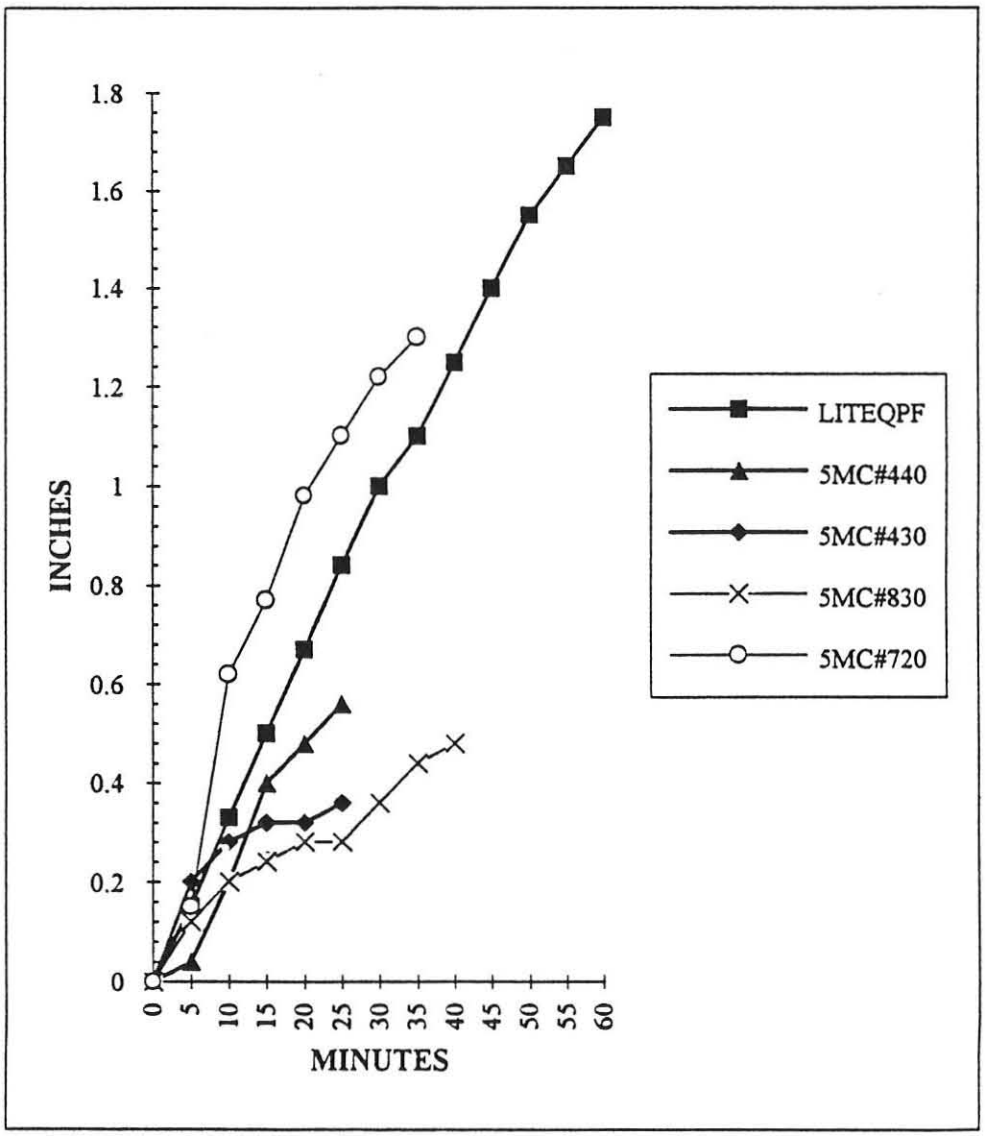
AUGUST 5, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	MODQPF	5MC#830	5MC#710	5MC#720	5MC#730	5MC#740	5MC#750
0	0	0	0	0	0	0	0	0
5	0.13	0.19	0.04	0.08	0.12	0.12	0.16	0.04
10	0.25	0.38	0.04	0.20	0.12	0.32	0.51	0.12
15	0.38	0.50	0.16	0.40	0.28	0.44	0.59	0.28
20	0.50	0.63	0.24	0.52	0.44	0.48	0.59	0.36
25	0.63	0.81	0.55	0.64	0.75	0.56	0.59	0.40
30	0.75	1.00	0.67	0.76	0.91		0.63	0.48
35	0.75	1.00	0.67	0.76	0.99			
40	0.75	1.00	0.75	0.80	0.99			
45	0.75	1.00			1.03			
50								
55								
60								
65								
70								
75								



SEPTEMBER 5, 1993 THUNDERSTORM
QPF VERSUS OBSERVED RAINFALL

CUMETIME	LITEQPF	5MC#440	5MC#430	5MC#830	5MC#720
0	0	0	0	0	0
5	0.15	0.04	0.20	0.12	0.15
10	0.33	0.20	0.28	0.20	0.62
15	0.50	0.40	0.32	0.24	0.77
20	0.67	0.48	0.32	0.28	0.98
25	0.84	0.56	0.36	0.28	1.10
30	1.00			0.36	1.22
35	1.10			0.44	1.30
40	1.25			0.48	
45	1.40				
50	1.55				
55	1.65				
60	1.75				



APPENDIX B

THE USE OF OFF-THE-SHELF SOFTWARE AND TECHNOLOGY TO IMPROVE COMMUNICATION OF URBAN FLOODING/SEVERE WEATHER STATEMENTS

Robert D. Hirsekorn

Henz Meteorological Services
Denver, Colorado

1. INTRODUCTION

One of the three basic components to a flash flood prediction and early warning system is the timely dissemination of information and warnings to the public at risk. This information may include weather guidance, severe weather statements, and or flash flood messages. In the case of the Flash Flood Prediction Program (F2P2) of the Urban Drainage & Flood Control District (UDFCD) in Denver, Colorado, this information is communicated by the UDFCD's Private Meteorological Service (PMS) to the appropriate Emergency Management Officials throughout the District. Since 1990 the PMS for the UDFCD of Denver has been Henz Meteorological Services (HMS). During the April 15 to September 15 operational season HMS disseminates over 10,000 voice and fax transmissions through its five main products:

a. Heavy Precipitation Outlook (HPO)
b. Message Alert
c. Internal Message Status (IMS)
d. Quantitative Precipitation Forecast (QPF)
e. StormTrak Prediction

A significant communication "logjam" became evident during the 1990 and 1991 F2P2 seasons as the number of basin specific warning plans increased from 3 to 7, more users within each basin plan requested the products, and user contacts increased. The "logjam" was further amplified by increased production time as an effort was made to increase the information available within each product. This meant that if the products were to get out to all users in a timely manner, modifications needed to be made. The goals of the modifications were to:

1. Streamline the product production process.
2. Reduce the time required in disseminating the products to the end users.
3. Reduce errors in communicating weather information.

2. THE PRODUCTS AND THEIR "LOGJAM" CONTRIBUTION

2.1 Heavy Precipitation Outlook (HPO)

The HPO is a daily outlook that usually includes a descriptive header and one or two key paragraphs summarizing the weather forecast. These paragraphs are followed by a table that provides a county-specific prediction of expected rainfall amounts and probabilities along with other associated weather. The HPO is available every day by 11:00 a.m. and updated by 4:00 p.m. when appropriate. It is available to the end users via the District's Electronic Bulletin Board (EBB) or FAX communications.

The production and dissemination process used during the 1991 F2P2 season is outlined in Figure 1. As shown, the HPO was typed using Sidekick, a basic text editor, and then placed into the EBB via modem. Since not all agencies had remote computer communications capabilities, the HPO was also faxed out to 24 users. The production and transmission process took a combined total of 65 minutes. Although the HPO was available by 11:00 a.m. for EBB users, some agencies would not receive the forecast until 11:40 a.m.. This also tied up the fax machine at HMS on many days when thunderstorms were developing by 12:00 p.m.. Trying to fax out an update during the afternoon when Denver thunderstorms were developing and other critical weather information needed to be communicated became a lesson in futility.

2.2 Messages

Messages are internal alerts, flash flood watches, flash flood warnings and updates communicated verbally to the specific communication centers throughout the District. Whenever possible, the message forms are faxed to the centers immediately prior to the required voice contact. The HMS meteorologist then verifies receipt of the fax, reviews the contents with the dispatcher, and answers any questions. The use of the faxed message form has essentially eliminated the need of the dispatcher to write down the weather information therefore reducing the potential for misunderstanding the meaning of the verbal weather communication.

Figure 1 shows that in 1991, messages were handwritten on each form and then faxed out to the various communication centers of the District. Since each message is county specific, new forms were required for each county. Times, locations, problem areas, and expected rainfall amounts needed to be carefully written on each form. This process took approximately 7 minutes per county.

2.3 Quantitative Precipitation Forecast (QPF)

The QPF, like the HPO is a fax disseminated EBB product that is used when the potential exists for point rainfall accumulations to exceed 1.5 inches in one hour or less or 1.0 inch in 30 minutes or less. While the HPO generally contains quantitative predictions of rain in limited detail, the QPF product provides more information in terms of predicted rainfall intensities and storm duration, storm total estimates, probabilities of occurrence for specific drainage basins, and storm classifications. For that reason, the QPF product is disseminated only to those users with technical personnel familiar with the hydrologic procedures and the regional major drainage system of the District.

As seen in Figure 1, the production and transmission process for the QPF was primarily the same. Although the number of end users receiving the QPF was about half that of the HPO, the criteria for QPF's indicated that messages were being issued at the same time. This created a bottleneck at the fax machine and many times, the faxed messages could not be sent due to time constraints presented by the oncoming storms. The messages were then only communicated verbally, creating the possibility for misunderstandings and errors in communication.

2.4 StormTraks (ST)

The StormTrak product contains an area map showing where a single storm or multiple storms are expected to cross the district along with their predicted impact zones and estimated size. Travel speeds of the storms are also forecast and depicted on the map. Appropriate text is added to briefly summarize conditions and the estimated magnitude of the flood threat. The StormTrak is only issued on "Message Days", and lead times may vary from 1 to 3 hours according to the flood potential and the availability of current meteorological data. The F2P2 users rely heavily upon this product.

StormTraks were entirely handwritten in 1991 and then placed into the fax machine for dissemination. Since StormTraks are communicated to all F2P2 users, the transmission time needed to reach everyone was 40 minutes. There was no prioritization of the end users. Again the fax machine was tied up and the "logjam" was amplified. Furthermore, the handwritten text required the meteorologist to be precise in his handwriting during emergency situations.

2.5 Internal Message Status (IMS)

The IMS is prepared only when messages have been issued in the District, and is disseminated as soon as possible after those messages have been issued. The intent of the IMS is to keep all users throughout the District updated concerning the message status for the entire six-county area. Like the HPO and the QPF, the IMS is available both through the EBB or FAX communications.

From Figure 1, it can be seen that the production and dissemination process used during the 1991 F2P2 season for the IMS was identical to that used by the HPO. The same problems existed for the IMS as for the HPO, with one exception. Since the IMS was used during an alert situation, the time factors involved in its production and dissemination created more of a logistical logjam. Relative to the other products, the IMS has a lower priority. Therefore, when the other higher priority products had to be disseminated, it was sometimes impossible to update the IMS.

3. MODIFICATIONS AND CHANGES

As discussed in section 2, each product used during the 1991 F2P2 had time elements associated with it for production and dissemination which contributed to the communication "logjam". The problem became critical when more than one product needed to be communicated in a short period of time or at the same time.

During the 1992 and 1993 F2P2 seasons, HMS has made modification and changes to its F2P2 products to improve the communication of weather information

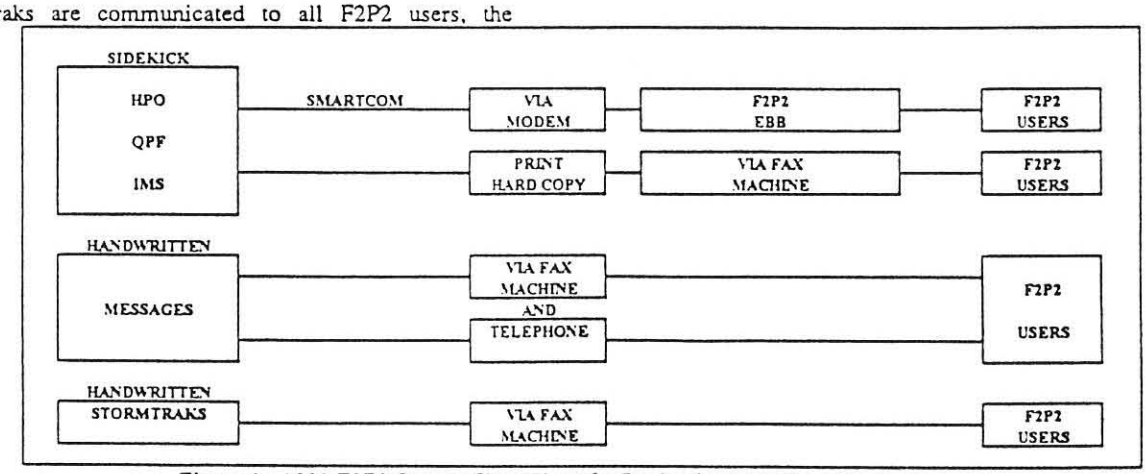


Figure 1: 1991 F2P2 Season Flow Chart for Production and Dissemination

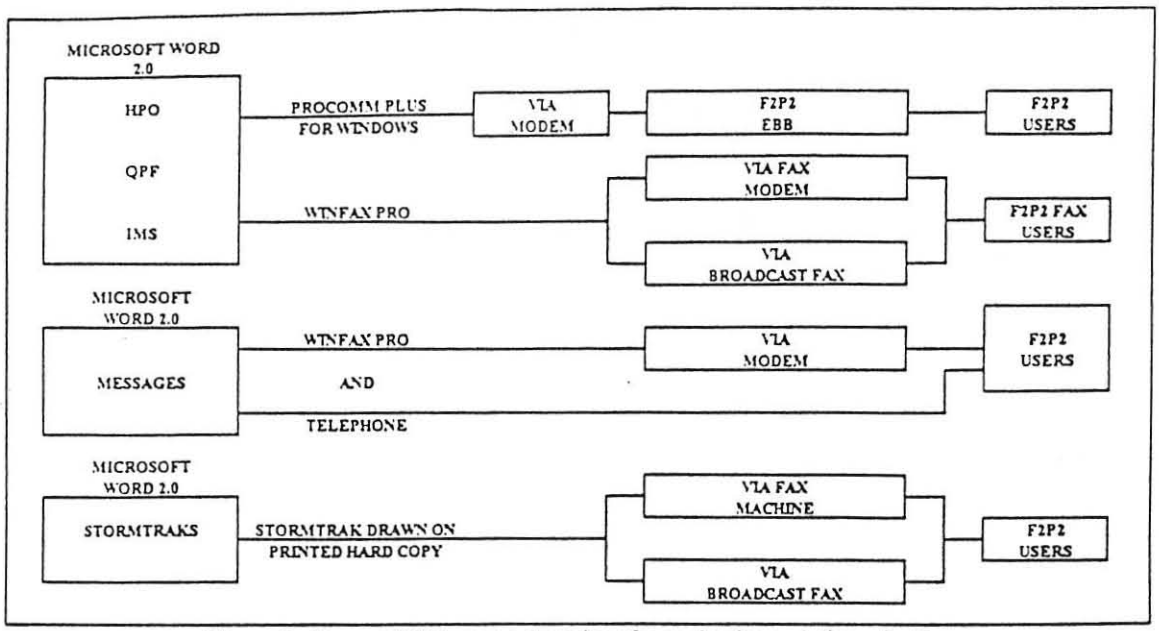


Figure 2: Current F2P2 season flow chart for production and dissemination

to the end users. These modifications and changes were accomplished using off-the-shelf software and technology such as existing Windows-based software, a fax machine, an internal modem, an internal fax/modem card, and most recently, US West's Broadcast Fax product. The remainder of section 3 will summarize how the software and technology has been used to affect the changes. Figure 2, shown below, is a flow chart of the 1993 F2P2 production and dissemination.

3.1 HPO

Using Microsoft Word 2.0 for Windows, an HPO template was created. This gives the meteorologist a standard professional looking form to use for each HPO with the date and time built in and the ability to use a sophisticated spell checker. Once completed, the HPO is transmitted to the EBB using ProComm Plus for Windows and a standard modem. While the HPO is being transmitted to the EBB, it can be sent simultaneously to the F2P2 fax users. This is accomplished with WinFax Pro and an internal fax card. To further cut down the transmission time, half of the users receive their fax from the standard fax machine. This process is outlined in Figure 2 above.

3.2 Messages

For the message forms, HMS developed an on-line form through Word 2.0 for Windows, that prompts the meteorologist with the critical questions. The answers are typed in and appear on the form in the appropriate places. After the form is completed, the spell checker is used, and the message form can be immediately faxed to the specific communication center through the internal fax card using WinFax Pro. An example of this message form is shown in figure 3. The production and dissemination time for the first message has now been cut to 2 minutes. The production time for subsequent messages is cut even further since the meteorologist needs to only change any information that is different for each county or communication center. The new production and dissemination process is shown in figure 2.

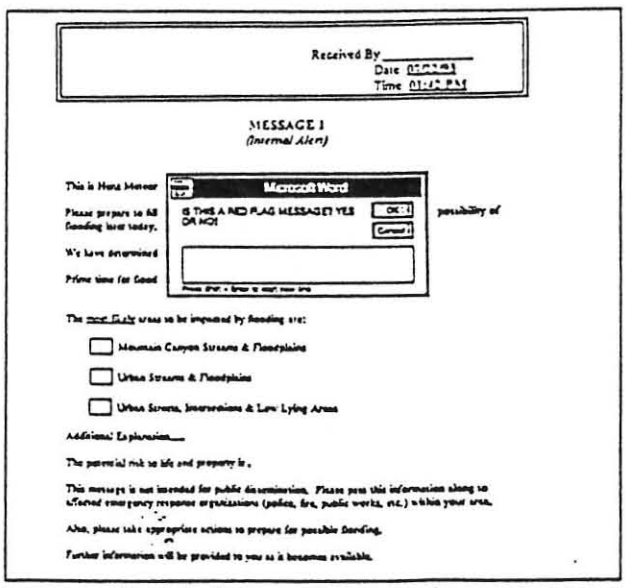


Figure 3: Current on-line message form

3.3 QPF

The changes to the QPF product are basically the same as those for the HPO as shown in figure 2. A new form was created in Word for Windows and the dissemination process matches that of the HPO with one exception. The QPF is sent out only during an alert status, therefore time is of the essence and it was necessary to find a way to reduce the 20 minutes needed to fax the QPF to all of the users. HMS found a service through U.S. West, Broadcast Fax, that allows the QPF to be received by all users within 2 minutes.

3.4 StormTraks

The written portion of StormTrak as seen in figure 4, is now produced in Word for Windows and printed out so that the StormTrak can be drawn on the form. This has made the form more legible and easier to read. Figure 2 shows that the StormTrak form is also sent by way of Broadcast Fax, cutting the 40 minute dissemination time to 2 minutes.

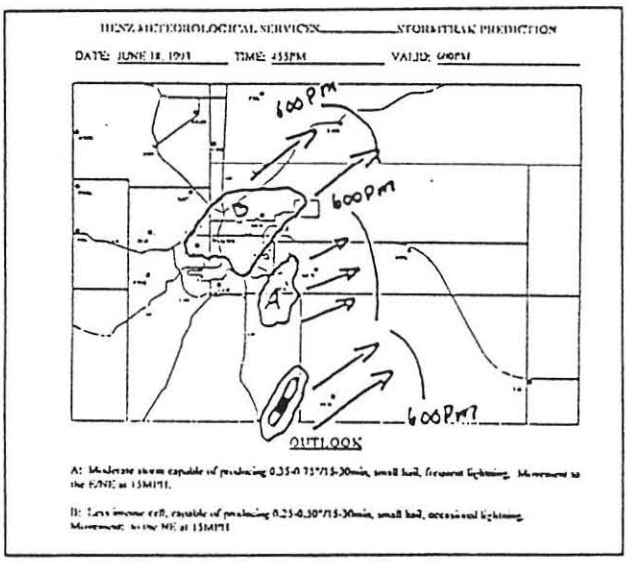


Figure 4: Current StormTrak form

3.5 IMS

The modifications to the IMS are similar to those for the HPO and QPF, see Figure 2. As with the QPF and StormTrak, the IMS is also sent via Broadcast Fax when time is critical.

4. CONCLUSIONS

PRODUCT	OLD	NEW	TIME SAVINGS
HPO	25 min	15 min	10 min
IMS	25 min	15 min	10 min
QPF	20 min	10 min	10 min
MESSAGES	5 min	1 min	4 min
ST	10 min	8 min	2 min

Table 1: Production Time Savings

PRODUCT	OLD	NEW	BR'DC'ST FAX	TIME SAVINGS
HPO	40 min	25 min	2 min	15 min
IMS	40 min	25 min	2 min	15 min
QPF	20 min	15 min	2 min	5 min
MESSAGES	2 min	1 min	N/A	1 min
ST	40 min	40 min	2 min	0 min

Table 2: Transmission Time Savings

Tables 1 and 2 depict the time savings that were derived by the modifications and changes made to the production and dissemination processes of the five F2P2 products. The time savings calculated in table 2 do not include the extra time savings that have been accomplished through the use of U.S. West's Broadcast Fax services since those services are only used if necessary. If those savings are added to the already derived savings, an additional 13 to 38 minutes of savings can be accomplished depending upon the product.

Furthermore, the savings derived in the sending of messages is multiplied by the number of areas that messages need to be issued for. The dissemination of 7 messages at one time results in a 35 minute time saving for the meteorologist during an alert situation. This time coupled with the additional savings from the QPF, StormTrak, and IMS allows the meteorologist to spend adequate time in analysis, thus assuring more timely and precise weather information. Since all of the products have been standardized in a professional format, the users are able to interpret the weather information in a more accurate and timely manner.

All of these modifications and changes were accomplished using of the shelf software and technology. The total cost for this software and technology including Word for Windows, WinFax, ProComm Plus for Windows, external modem, and internal fax card was less than $1,000. For a $1,000 dollar investment, HMS has developed a delivery system that gets weather information into the end users hands quickly, accurately and easy to understand.

OPERATIONAL APPLICATIONS OF THE DENVER CYCLONE CONVERGENCE-VORTICITY ZONE TO PREDICT SEVERE WEATHER/HEAVY PRECIPITATION EVENTS

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1.0 Introduction

The prediction and timely warning of severe weather and heavy precipitation events is a major concern to the operational meteorologist. When the forecast district includes a heavily populated area, the meteorologist has added pressures to perform in an accurate manner.

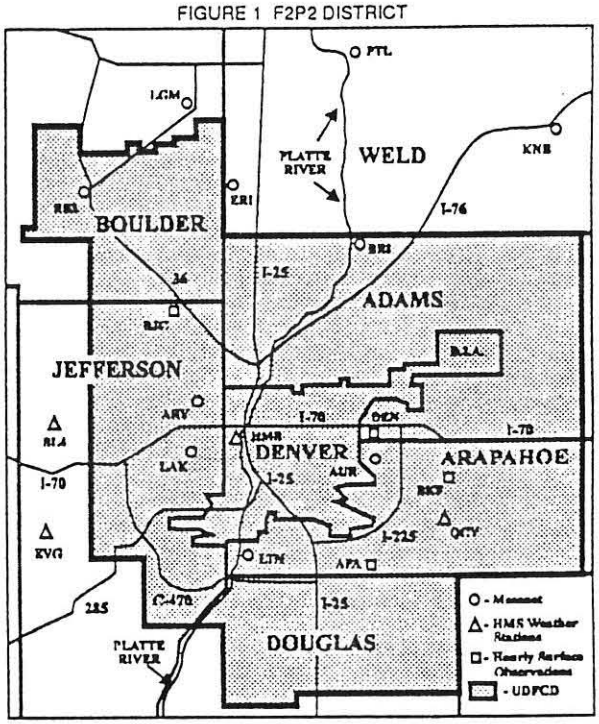
Weather forecasting of this magnitude is done every day across the world and Denver, Colorado is no exception. Urban Drainage & Flood Control (UDFCD) has put together and operated a Flash Flood Prediction Program (F2P2) in the Metro Denver area since 1979. The F2P2 provides drainage basin specific quantitative precipitation forecasts (QPF) to local emergency response agencies in order to alert them of a heavy rain threat. These agencies use these forecasts to prepare in the event of a flooding situation.

Henz Meteorological Services (HMS) has provided these precipitation forecasts since 1990 in cooperation with the National Weather Service. In preparing these forecasts HMS meteorologists carry out daily intensive convective atmospheric analyses to determine the daily flooding potential.

The F2P2 (Fig 1.0) covers a 1,600 square mile area, and includes six counties around the Denver metro area. These counties include Denver, eastern Jefferson, northern Douglas, western Arapahoe, western Adams, and east and south central Boulder. Some of the major cities include Denver, Aurora, Boulder, Lakewood, Englewood and Commerce City. Other significant areas located in the district include Stapleton International Airport, the new Denver International Airport, Lowry Air Force Base, Buckley Air National Guard Base, Centennial Airport, Broomfield Jefferson County Airport, along with Chatfield and Cherry Creek reservoirs. The forecast period runs from the 15th of April through the 15th of September, and is extended if the flooding potential exists beyond the set date.

The district has a population of over 1.8 million people, which is nearly 65% of Colorado's population. It is located on the western edge of the tornado belt and is annually subjected to severe weather and heavy rainfall events. While most of the tornadoes observed within the district have been of the weaker variety (F_0 to F_1) their persistent occurrence within such a heavily populated area make them a significant concern to emergency response agencies.

FIGURE 1 F2P2 DISTRICT



Heavy rain events that produce nuisance flooding of low lying streets and small steams is a common occurrence within the district. Occasionally more serious flooding occurs when larger streams or basins overflow and create a threat to life and property.

HMS is also contracted by Arapahoe County, Colorado to forecast severe weather, including hail, high winds, lightning, and tornadoes. This is the second operational season HMS has provided severe weather forecasting to Arapahoe County.

In July of 1990 a supercell thunderstorm caused intense hail damage to a large portion of the district, creating an estimated 625 million dollars worth of damage, and caused personal injuries to about sixty people. This event peaked the awareness of damage that can result from large hail. Private business became aware of this and since contracted HMS for hail forecasting, hail track prediction, and hail storm reconstruction.

A low level circulation or Convergence Zone, otherwise known as the "Denver Cyclone" or "Denver Convergence Zone", frequently operates within the district on days when severe weather or heavy rainfall is observed. This circulation and/or convergence zone often sets up over the Denver Metro area acting to initiate and/or enhance thunderstorms.

2.0 The Denver Cyclone\Convergence Zone

2.1 What is it?

The Denver Cyclone develops frequently when the low level flow is from the southeast, south or southwest (130°-240°). It's circulation can be very small, four to eight kilometers in diameter, or very large covering most of northern and central portions of eastern Colorado. Most of the time, its counterclockwise circulation is centered over the County of Denver. The circulation begins near the surface and is very shallow, but often grows vertically, reaching to as high as 700 mb (Wilczak & Christian, 1990). Wind speeds associated with it usually vary between 2 m/s and 10 m/s, but sometimes reach as high as 15 m/s.

The Denver Cyclone will sometimes take on the form of an elongated area of wind and moisture convergence, usually oriented in a north-south or east-west line. This form is known as the Denver Convergence Zone.

2.2 How often is it present?

It was present on 33% of the days during the convective season (May-August) for a 9-year sample period from 1981-1989 (Szoke, 1991). HMS carried out its own research on the Denver Cyclone/Convergence Zone during the convective seasons of 1990 to 1992, and discovered that the Cyclone or its associated Convergence Zones initiated or enhanced 65% of the storms that produced severe weather and/or heavy rainfall events.

2.3 What effect does it have on thunderstorms?

The cyclonic circulation produces a region of low level moisture and wind convergence, as well as a compact region of cyclonic vorticity. The combination of these variables help to enhance thunderstorm updrafts if the storm moves into one of the favorable quadrants of the circulation. Thunderstorms can also develop within one of these favorable quadrants if certain criteria are met.

According to Wakimoto (1989), low level horizontal vorticity, produced by the circulation and converging winds, is lifted vertically by the storms updraft. The horizontal vorticity then stretches from near the surface, up into or near the cloud base. This causes the updraft to rotate, enhancing the horizontal vorticity within the updraft. The strengthening of the vorticity causes an acceleration of the upward moving air. As the updraft becomes accelerated, it allows more moisture be drawn into the storm. The storm then grows vertically as well as horizontally.

The stronger updraft will be capable of drawing moister air, if present around the storm, up into it. The base of the cloud then lowers, causing the depth of the cloud to increase. With the decreased cloud base comes an increased warm layer (area above 0°C). The larger warm layer combined with condensation of the moist air allows coalescence to take place more easily. Rain production increases, thus causing heavy rainfall and potential flooding.

When these large coalescence drops are carried up into the cold region of the cloud by the updraft they freeze and eventually grow into hail stones. Once the hail is too large to be supported by the updraft it falls to the ground.

Short lived "land spout" tornadoes occasionally are spawned by storms within favored quadrants of the Cyclone, as well. The accelerated updraft takes on rotation from the stretching of the horizontal vorticity being lifted up from the cyclones circulation (Brady & Szoke, 1989).

2.4 "Key" Denver Cyclone research points.

Various studies and research have been carried out on the Denver cyclone and its associated Convergence zones over the past nine years. Some important observations and discoveries have been made in these studies. The research utilized in this paper include:

- A Decade of Tornado Occurrence Associated with a Surface Mesoscale Flow Feature-the Denver Cyclone (Szoke & Augustine, 1990).
- A Case Study of Nonmesocyclone Tornado Development in Northeast Colorado: Similarities to Waterspout Formation (Brady & Szoke, 1989).
- Observations of a Colorado Tornado. Part II: Combined Photogrammetric and Doppler Radar Analysis (Wakimoto & Martner, 1992).
- Case study of an Orographically Induced Mesoscale Vortex (Wilczak & Christian, 1990).
- A Subsynoptic Analysis of the Denver Tornadoes of 3 June 1981(Szoke, Weisman, Brown, Caracena & Schlatter, 1984).
- Non-Supercell tornadoes (Wakimoto & Wilson, 1989).

Although a lot of useful points were derived from these research papers, they were all mainly qualitative and based on specific case studies. Two "key" points that could be deduced by an operational forecaster are listed below:

1. As the circulation of the Denver Cyclone increases in strength, so does the frequency of severe weather (Szoke and Augustine, 1990).

2. When a thunderstorm cell meets or exceeds severe weather criteria and moves over the top of the Denver Cyclone's circulation, it increases the chances for updraft generated tornadoes (Wakimoto & Wilson, 1989).

Six "key" points HMS uses when forecasting severe weather and heavy rain events, when the Denver Cyclone or Denver Convergence Zone is operating within the F2P2 district are:

1. Backwash flow in the northwest quadrant of the Cyclone has a very low probability of initiating or enhancing thunderstorms capable of producing heavy rain or severe weather.

2. The northeast quadrant of the Cyclone has a higher probability of tornado occurrences than the other three quadrants combined.

3. The Denver Convergence Zone is more likely to produce heavy rain events than the Denver Cyclone.

4. The Denver Convergence Zone is more likely to produce severe weather events than the Denver Cyclone.

5. A strong Cyclone tends to inhibit occurrences of heavy rain or severe weather within the district, except when cloud layer winds are out of the south (160°-220°).

6. Hail tends to occur with a Denver Convergence Zone more frequently than with a Denver cyclone or any other surface features combined.

When applying these points, certain severe weather and/or heavy rain criteria must be met. This criteria will be covered later. These points were deduced from research performed by HMS on the convective seasons of 1990 and 1991. A detailed look at the results will follow.

3.0 Data

The research was performed on the convective season (May-August) for the years 1990 and 1991 (dependent data) and 1992 (independent data). All the severe weather and heavy rain events that occurred within the F2P2 district were verified using Storm Data, the UDFCD's 109 automated rain gauges, and HMS's own records. Each event was characterized as being influenced by the Denver Cyclone, the Denver Convergence Zone, or other low level features. The other low level features include large scale frontal boundaries with non-southeast flow, diurnal or synoptically enhanced upslope flow, and development due to diurnal heating with non-southeast flow. Severe weather events include hail 0.75" in diameter or larger and tornadoes F_0 in intensity or greater. Heavy rain events were based on criteria set forth by the UDFCD, which includes rainfall amounts greater or equal to 0.50"/10 min., 0.75"/30 min., and 1.00"/hr. High wind events associated with thunderstorms were omitted from the study because of the lack of relevance to heavy precipitation forecasting.

HMS meteorologists applied the following severe weather and heavy rain criteria to all the events. These criteria were developed by HMS using over 10 years of severe weather and heavy rain research. The criteria are listed below:

<u>Severe weather forecasting criteria.</u>

Mean surface-lifted parcel environmental temperature deviation $\geq +6.0°$ C.
Mean cloud depth ≥ 7.0 km
Cloud layer vertical shear ≥ 3.0 m/s/km.
Jet streak 45 knots or greater 200 nm upstream

<u>Heavy rain forecasting criteria.</u>

Mean surface-lifted parcel environmental temperature deviation $\geq +3.5°$C.
Mean cloud depth ≥ 7.0 km.
Cloud layer vertical shear ≤ 2.0 m/s/km.
Updraft layer > 0° C 1.5 km or greater. (Henz, 93).

HMS meteorologists utilized the PROFS meso-network (Mesonet) to refine the space and time occurrence for each event. Each one met or exceeded the established severe or heavy rainfall criteria. It must be noted that on some days the criteria was met and a Denver Cyclone, Denver Convergence Zone or some other low level feature was present, and no severe weather or heavy rainfall was reported within the district. These cases were considered null events.

Mesonet was utilized during the 1990 and 1991 convective season (dependent data set) in order to recognize the criteria, in the following manner. Mesonet data was plotted to identify surface flow

features. Temperature and dew point values of surface and mountain mesonet stations were plotted on a Skew-T, Log P diagram overlaid on the Denver upper air sounding. By analyzing the "new" sounding it was then determined if the severe and/or heavy rainfall criteria was met.

4.0 Results and Conclusions

The dependent data set (1990 and 1991) and independent data set (1992) derived from the research were entered into three separate tables. The results are shown in Table 1 for the dependent data and in Table 2 for the independent data. The combined data for the period 1990-1992 is presented in Table 3. "Key" points can be deduced from each table and compared.

The tables all show the number of observed occurrences of hail, tornadoes, and heavy rainfall events in relation to the analyzed position of the Denver Cyclone or Denver Convergence Zone. The four quadrants of the Cyclone are listed along with the number of events occurring in each, and the percentage of total occurrences of that particular event. Zones of each Convergence Zone, as well as the events that occurred in each and the percentage of total occurrences are also listed. North and south zones are associated with an east-west Convergence Zone, and east-west zones are associated with a north-south Convergence Zone. All the Cyclone and Convergence Zone induced events fall into one of three categories: Weak (1-5 m/s), moderate (6-10 m/s), and strong (11 m/s or greater). These are based on average wind speeds observed, using mesonet data.

Table 1 shows the following "key" points derived from the dependent data set:

a) Of the nine observed tornadoes 56% of them occurred within the NE quadrant of the Cyclone, and all of these were associated with a moderate circulation. The NW and SW quadrants produced no tornadoes.

b) The most hail events, 40 (32%) were associated with the convergence zone, with the western zone of the N-S convergent zone experiencing the most events, 18 (20%). Hail associated with "other" low level flows (most being diurnal upslope flow causing storms to develop over the foothills and then move over onto the plains) ranked second ahead of the cyclone, 32% to 22%. Only 1 hail event was reported in the NW quadrant.

c) Of the 280 heavy rainfall events, 116 (43%) were associated with the Convergence Zone, most being associated with a N-S convergence zone, 82 (30%). Ninety four (34%) of the events were associated with "other" low level features. The Cyclone ranked third with 70 (25%) of the events.

Table 2 shows the following key points derived from the 1992 independent data set:

a) The NW quadrant or "backwash" area contained only 1 or 1% of the heavy rainfall events, and no hail was reported.

b) The Cyclone only initiated 30 severe or heavy rainfall events compared to the average of 48 events in 1990 and 1991.

c) The Convergence Zone only initiated 26 events compared to the average of 79 events in 1990 and 1991.

d) "Other" features accounted for 42% of all the events, compared to 33% in 1990 and 1991.

In comparison, the independent data set supports three of the six "key" points deduced by HMS research. The three that were substantiated include Number 1: backwash flow in the northwest quadrant of the Denver Cyclone having a very low probability of initiating or enhancing thunderstorms capable of producing heavy rain or severe weather, Number 4: The Denver Convergence Zone being more likely to produce severe weather events than the Denver Cyclone , and Number 5: a strong Denver Cyclone tends not to initiate or enhance heavy rain or severe weather within the district, except when cloud layer winds are out of the south (160°-210°). Number 2 could not be tested due to the fact that no tornadoes were reported within the district in 1992. The two that were not substantiated include Number 3: the Denver Convergence Zone being more likely to produce more heavy rainfall events than the Denver Cyclone, and Number 6: hail tending to occur with a Denver Convergence Zone more frequently than with a Denver Cyclone and "other" surface features combined.

The "key" points deduced from the papers of Szoke & Augustine, and Wakimito & Wilson were also applied to the 1992 field test. Point number one was not substantiated by the test, as a moderate or weak Cyclone was found to be present more frequently during severe weather events than a strong Cyclone. This point is rather subjective depending on the researchers' criteria on Cyclone strength. The second point relative to tornado enhancement by the Denver Cyclone could not be tested do to a lack of tornado occurrences during the 1992 F2P2 season. These results could change when the 1993 F2P2 season data is reported at the conference.

Table 1 Dependent Data Set From the Convective Seasons 1990 & 1991

Events	Cyclone				Convergence Zone				Cyclone			Convergence Zone			Other	Total
	NE Cy.	NW Cy.	SW Cy.	SE Cy.	N CZ	S CZ	E CZ	W CZ	Wk. Cy.	Mo. Cy.	St. Cy.	Wk. CZ	Mo. CZ	St. CZ		
Heavy Rain	6 (2%)	9 (6%)	30 (8%)	25 (9%)	10 (4%)	24 (9%)	49 (18%)	33 (12%)	29 (10%)	31 (11%)	10 (4%)	35 (13%)	61 (22%)	20 (7%)	94 (34%)	280 (100%)
Tornado	5 (56%)	0 (0%)	0 (0%)	1 (11%)	0 (0%)	1 (11%)	1 (11%)	0 (0%)	0 (0%)	6 (67%)	0 (0%)	0 (0%)	2 (22%)	0 (0%)	1 (11%)	9 (100%)
Hail	3 (3%)	1 (1%)	9 (10%)	7 (8%)	3 (3%)	6 (7%)	13 (15%)	18 (20%)	0 (0%)	20 (23%)	0 (0%)	24 (27%)	14 (16%)	2 (2%)	28 (32%)	88 (100%)

Table 2 Independent Data Set From the Convective Season 1992

Events	Cyclone				Convergence Zone				Cyclone			Convergence Zone			Other	Total
	NE Cy.	NW Cy.	SW Cy.	SE Cy.	N CZ	S CZ	E CZ	W CZ	Wk. Cy.	Mo. Cy.	St. Cy.	Wk. CZ	Mo. CZ	St. CZ		
Heavy Rain	12 (15%)	1 (1%)	3 (4%)	7 (9%)	1 (1%)	4 (5%)	11 (14%)	2 (3%)	14 (18%)	9 (11%)	0 (0%)	6 (8%)	12 (15%)	0 (0%)	39 (49%)	80 (100%)
Tornado	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)	0 (0%)
Hail	5 (28%)	0 (0%)	0 (0%)	2 (11%)	0 (0%)	0 (0%)	7 (39%)	1 (6%)	3 (17%)	4 (22%)	0 (0%)	2 (11%)	5 (28%)	1 (6%)	3 (17%)	18 (100%)

Table 3 Combined Data Set From the Convective Seasons 1990 - 1992

Events	Cyclone				Convergence Zone				Cyclone			Convergence Zone			Other	Total
	NE Cy.	NW Cy.	SW Cy.	SE Cy.	N CZ	S CZ	E CZ	W CZ	Wk. Cy.	Mo. Cy.	St. Cy.	Wk. CZ	Mo. CZ	St. CZ		
Heavy Rain	18 (5%)	18 (5%)	25 (7%)	32 (9%)	11 (3%)	28 (8%)	60 (17%)	35 (10%)	43 (12%)	40 (11%)	10 (3%)	41 (11%)	73 (20%)	20 (6%)	133 (37%)	360 (100%)
Tornado	5 (56%)	0 (0%)	0 (0%)	1 (11%)	0 (0%)	1 (11%)	1 (11%)	0 (0%)	0 (0%)	6 (67%)	0 (0%)	0 (0%)	2 (22%)	0 (0%)	1 (11%)	9 (100%)
Hail	8 (8%)	1 (1%)	9 (8%)	9 (8%)	3 (3%)	6 (6%)	20 (19%)	19 (18%)	3 (3%)	24 (23%)	0 (0%)	26 (25%)	19 (18%)	3 (3%)	31 (29%)	106 (100%)

Table 3 presents the combined independent and dependent data sets. The differences derived by grouping the data in this manner were readily apparent. Sixty per-cent fewer hail events, and 43% fewer heavy rain events were observed within the district in 1992 compared to the average of 1990 and 1991. When a Cyclone was present in 1992 and induced an event, a weak circulation dominated, compared to 1990 and 1991 when a moderate circulation dominated. When a Convergence Zone was present and induced an event, moderate convergence dominated all three years

Because of the lack of severe weather and heavy rain events, and the occurrences of the Denver Cyclone and the Denver Convergence Zone in 1992, the independent data set is not a good representation of the "average" convective season within the F2P2 district.

Clearly additional research will be needed to quantitatively unravel the applications of the Denver Cyclone and the Denver Convergence zone to local forecasters. However this study has put forward several promising qualitative considerations which have been used to improve F2P2 forecasts. HMS would like to prepare additional operational research based on utilization of the new NWS WSR-88D, soon to be commissioned at Watkins Colorado. The proposed research will be described at the conference.

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REFERENCES

Brady, R.H. and E.J. Szoke, 1989: A Case Study of Nonmesocyclone Tornado Development In Northeast Colorado: Similarities to Waterspout Formation. *Mon. Wea. Rev.*, 117, 843-856.

Henz, J.F., 1993: Operationally Predictable Characteristics of Heavy Precipitation Producing Thunderstorms. Proceedings, 17th Conference on Severe Local Storms. Amer. Meteor. Soc. October, 1993, St. Louis, MO.

Szoke, E.J. and JA. Augustine, 1990: A Decade of Tornado Occurrence Associated with a Surface Mesoscale Flow Feature-The Denver Cyclone. Proceedings, 16th Conference on Severe Local Storms. Amer. Meteor. Soc., 554-559.

Szoke E.J., M.L. Weisman, J.M. Brown, F. Caracena, and T.W. Schlatter, 1984: A Subsyoptic Analysis of the Denver Tornadoes of June 3 1981. *Mon. Wea. Rev.*,112, 790-808

Wakimoto R.M. and B.E. Martner, 1992: Observations of a Colorado Tornado. Part II. *Mon. Wea. Rev.*, 120, 522-543.

Wakimoto R.M. and J.W. Wilson, 1989. Non-supercell Tornadoes. *Mon. Wea. Rev.*, 117, 1113-1140.

Wilczak J.M. and T.W. Christian, 1990. Case Study of an Orographically Induced Mesoscale Vortex (Denver Cyclone). *Mon. Wea. Rev.*, 118, 1082-1102.

AN OPERATIONAL EXPERIMENT IN THUNDERSTORM TRACK PREDICTION IN THE 0-3 HOUR PREDICTION WINDOW

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1. INTRODUCTION

The prediction of the track which a severe or non-severe thunderstorm will take over a period of 0 to 3 hours presents a difficult challenge to an important operational problem. If the track can be successfully estimated it can be used to improve the spatial and temporal specificity of the related severe weather forecasts and warnings. In effect the issuance of severe weather and urban flooding statements for a large urban area could be made in a more specific manner to both the emergency response community and the public. If the forecasts are accurate they should improve the user community's acceptance and utilization of severe weather and other forecast products.

Recently Wilson and Mueller, 1993 and Mueller, et al., 1993 have elaborated on the difficulties and limitations inherent in the short-term prediction of thunderstorm initiation, movement and weather production in northeastern Colorado based on tests conducted during 1989 and 1990. In general the thunderstorm initiation nowcasts issued during these tests were between 50 and 61 percent correct in storm placement. Better accuracy was noted in the extrapolation of existing thunderstorm movement or interaction with existing sub-cloud layer boundaries with accuracy of 55 to 81 percent correct nowcasts. The verification period covered time periods of 30 minutes and verified the occurrence of greater than 30 dBZ echoes in the nowcast polygons. While these tests were rigorously verified and conducted, a series of somewhat similar operational forecasts of thunderstorm tracks was made operationally in the southwestern quarter of their test area.

An operational experiment in predicting the storm track of heavy precipitation and severe weather producing thunderstorms crossing the Urban Drainage & Flood Control District (UDFCD) was conducted for the period of 15 April to 15 September 1990 to 1992. The UDFCD is located in the Denver, Colorado metropolitan area which contains over 70 per cent of the state's population and is shown in Figure 1. The UDFCD covers an area of approximately 1800 square miles in a n area which stretches 30 miles from the foothills of Jefferson and Boulder Counties on the west into the rolling plains of Adams and Arapahoe Counties on the east. The northern portion of the District is located on the plains of western Adams County and stretches 60 miles southward through the City of Denver into the foothills of northern Douglas County.

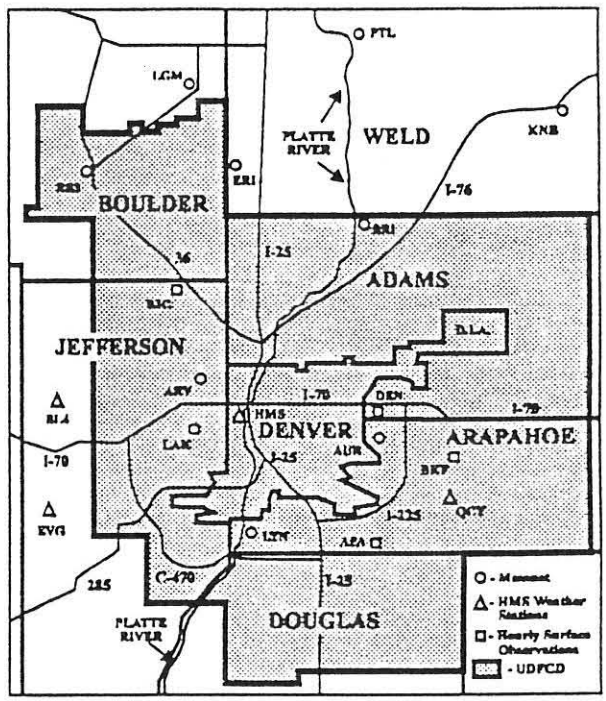

Figure 1

Since 1979 the UDFCD has sponsored a flash flood prediction program (F2P2) which complements the National Weather Service's flash flood watch and warning program with a county/city specific hydrometeorological service program. The F2P2 utilizes a private meteorological service to produce county/city/basin specific quantitative precipitation forecasts, internal urban street and stream flooding alerts and refinements to NWS flash flood products. The F2P2 has been described in preceding papers (Stewart et al, 1993 and Henz et al, 1985). One unique aspect of the F2P2 is its ability to respond to local emergency response team requests for special products.

The experiment began in late June 1990 after local police officials asked if the verbal storm motion statements issued by HMS since 1979 could be prepared as a hard copy, graphic forecast. HMS responded to their request by preparing experimental storm track forecasts for five days during June and July 1990 while testing the format, content and communication of the storm track forecasts.

After discussions with F2P2 users on the content of the storm track product the following information was settled upon as most important to assist in decision-making:

- Location of storm initially and identification of the track it will follow over the next 30-90 minutes
- Time hacks identifying the time the storm arrives at various points along the predicted storm track
- Identification of those portions of the storm track most likely to produce heavy rainfall and severe weather events
- Identification of prime problem areas

Each of the HMS storm tracks included this information. Individual meteorologists were given the option on how to present the information based on the situation.

The predicted storm tracks were faxed to the emergency response community in the Denver, Colorado metropolitan area served by the UDFCD's Flash Flood Prediction Program (F2P2) and to the National Weather Service Forecast Office at Stapleton International Airport. These initial storm track predictions were so well received that storm tracks were issued for all thunderstorm complexes capable of producing urban street or stream flooding for the 1991, 1992 and the 1993 F2P2 seasons. This paper will focus on the results for the 1990 to 1992 F2P2's but additional results for the 1993 season will be presented at the conference.

2. STORMTRACK PRODUCTION

The storm track forecasts were prepared as a means of alerting emergency response agencies to the predicted track of thunderstorms capable of producing point/basin total rainfalls of at least 1.00"/30 minutes in a time frame which provided at least a 30 to 90 minute lead-time of the storm's arrival. Additionally the operational meteorologist was encouraged to predict severe weather events likely to occur concurrently with the urban street or stream flooding which could impact emergency response efforts.

The predicted storm tracks showed most "tracks" as a rectangle or polygon which were from 1 to 8 miles wide and from 5 to 40 miles long. Time hacks were included along the track to indicate the progression of the storm along the track in roughly 30 minute intervals for periods of 30 minutes to 3 hours. Additionally attempts were made to identify those portions of the storm track where the production of heavy rain, hail and, in some cases, tornadoes were at high risk to form or occur.

The storm tracks were produced using input from conventional surface and upper air observations, surface mesonet observations, satellite loops and radar observations. Visual observations of the developing thunderstorm complexes were a significant asset to the operational forecast but were not relied upon due to forecaster time limitations. In general the storm track forecast procedure required several steps to achieve a product. These steps began with the morning convective and heavy precipitation outlook preparation and concluded during the "nowcast" period 30-90 minutes before the storm produced flooding or severe weather occurred.

Storm track forecasts were only made for those days meeting the criteria for the issuance of an internal alert for urban street and stream or foothills flooding due to thunderstorm rainfall. Thus unlike the earlier described tests these operational forecasts were made on a very special set of days which favored the development and intensification of thunderstorms. No doubt this criteria had a positive influence on the verification statistics which will be presented.

2.1 STEP 1: Convective - Severe Weather Forecast

The first step in the storm track forecast was the prediction of the ability of the atmosphere to support deep convection supportive of heavy rainfall and severe weather. The surface mesonet, morning radiosonde data, satellite loops and conventional upper air data were used to predict the wind and stability fields in the sub-cloud and cloud layers. Mean winds were predicted for the sub-cloud region and for the predicted cloud layer to produce an anticipated mean cloud vector motion for the next 12 hour period. Sounding and mesonet surface data was used in a 2-D cloud model to identify the key surface temperature and dew point combinations supportive of thunderstorm development. These key values were then monitored every 30 minutes using the surface mesonet to identify areas in the F2P2 operations area which would support deep convective updrafts if ingested by an approaching storm.

A set of companion papers in this conference proceedings, Henz, 1993 and Rappolt and Henz, 1993, describe the unique atmospheric characteristics associated with both heavy convective rainfall and severe weather in northeastern Colorado. In general heavy rainfall is favored in an atmosphere which will support convective clouds at least 7 km deep with average surface parcel lifted updrafts that are at least + 4.5 °C warmer than the ambient atmosphere through the cloud depth. The updraft should have a layer of warmer than 0 °C at least 1.5 km deep with a perceptible water index of 1.90 cm (0.75") or more. The use of the sounding analysis to determine the critical values of surface temperature and dew point needed to support a thunderstorm updraft capable of heavy rainfall or severe weather

production was the crucial first step in the storm track prediction process.

Surface mesonet plots were used to identify if sufficient low level moisture existed or was forecast into the District boundaries to support updraft development sufficient to support the sounding derived values. Thus the sounding analysis was rooted into the sub-cloud layer moisture fields through the mesonet values of surface temperature and dew point. As pointed out in Mueller, et al 1993 the depth of the moist layer in northeastern Colorado is a critical factor in determining storm development. To assist in this evaluation "Me(so)unds" were plotted every 30 minutes using the mesonet stations which varied in altitude from the plains surface to just over 700 mb to give an estimate of the vertical distribution of moisture and temperature relative to atmospheric stability and moisture content. Unlike soundings which provide this information every 12 hours, a me(so)und can be plotted every 5 minutes though in practice a new one is typically plotted every 30 - 60 minutes during the late morning through evening hours.

Additionally sub-cloud layer winds were monitored for changes which would effect the forecast storm steering wind vector. The cloud layer winds were monitored by using visible satellite photo loops of middle and high cloud motion and orphan anvil blowoff from cumulonimbi forming to the west of the District. An updated cloud motion vector was estimated every 2 hours to assist in the storm track predictions if the satellite-derived motion vectors differed significantly from the morning cloud motion vectors.

2.2 Step 2: Preparation of the Storm Track

After the surface mesonet analysis indicated that sub-cloud layer instability was approaching critical storm supportive values, the storm track prediction process began. First, the surface mesonet analysis was analyzed for estimates of instability areas and streamline convergence regions in the sub-cloud layer. Next, the radar was used to indicate areas where thunderstorm development was already under way. Thunderstorms were considered to be in existence where 30 dBZ or greater reflectivity were located. Next, the cloud motion vectors were used to draw the downstream motion track anticipated from the thunderstorm location over the next 30-90 minutes.

Attention was placed on how the motion vectors would cross areas of stable and unstable air masses in the sub-cloud region and areas of confluence and diffluence in the pattern of the sub-cloud streamline field. Storm tracks were constructed for those storms which would have the forecast **potential** to produce either heavy rainfall and/or severe weather. The storm track prediction was altered to direct the thunderstorm paths into regions most supportive of continued storm development, i.e., favorable convective temperatures, focused areas of convergence, etc. Severe right motions of the storm were predicted based on the ability of the sub-cloud layer and cloud layer structures to support the formation of a tornado, locally heavy rainfall or, in some cases, large hail. Placement of the storm vector over an existing Denver cyclone was a strong indicator of increased tornado formation potential in the preferred eastern quadrants while placement over the unfavorable northwestern quadrant led to a dissipation forecast.

The purpose of the storm track forecast was to identify in a more specific manner the area of influence or corridor that would be impacted by a thunderstorm capable of producing urban street and stream flooding rainfall and associated severe weather. Many traditional NWS severe thunderstorm warnings or urban flooding statements describe areas the size of entire counties for varying periods of time. The storm track allows the emergency response groups the opportunity to apply space and timing factors into their decision-making based on the forecast storm movement and size. The HMS meteorologist was instructed to prepare storm tracks only for those storms capable of producing the flooding rainfall or severe weather and to ignore other storms nearby unless they felt these other storms could be of concern to local emergency response groups.

An example of a recent storm track forecast and verification is presented in Figures 2 and 3 for June 2, 1993. On this date the preparation of the storm track was quite simple meteorological. Low level sub-cloud layer winds were moist and easterly while cloud layer winds were from a west - southwest direction resulting an almost direct west to east cloud motion vector. The mesonet indicated that an inversion capped the low level moist layer. Forced upslope motion of the "capped layer" released the instability along the Jefferson County foothills in the form of a rapidly developing thunderstorm over Lakewood at about 1815 UMT (1215MDT) as indicated by "A" on Figure 2. An 1800 UMT mesonet indicated favorable temperature/dew point values in the downstream corridor for the storm. The "A" area represents the approximate size of the 30 dBZ area while the forecast corridor allows for some storm widening due to development. Time hacks along the corridor indicate the forecast arrival time of the storm centroid. A narrative is placed by hand in the space below the track to relay vital storm information. The same process is followed for another storm "B" which was developing in northeastern Douglas County. The storm track was issued at 1820 UMT (1220 MDT) or in 5 minutes and disseminated to 26 emergency response groups in less than 2 minutes using US West's Broadcast Fax network. The entire process of storm track production and dissemination required less than 10 minutes.

Verification of the storm track for June 2, 1993 is presented in Figure 3. Storm A marched right down the center of the predicted storm track and produced a swath of damaging hail which stretched from Lakewood to Aurora. Heavy rainfall produced street flooding in portions of Lakewood, Denver and Aurora. Storm B produced damaging hail across Parker and portions of northeastern Douglas County. Storm direction and speed errors were less than 10 percent. The track presented represents the swath created by the 40-55 dBZ radar echoes created by the storm. A more complete

verification for the test period is presented in the next section.

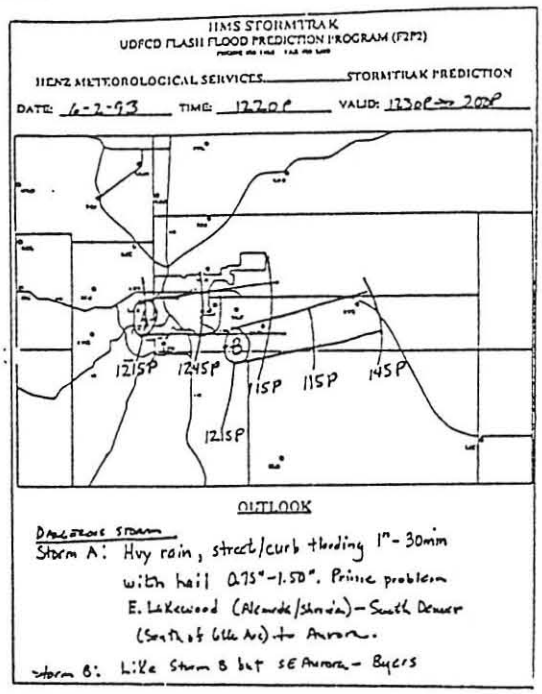

Figure 2

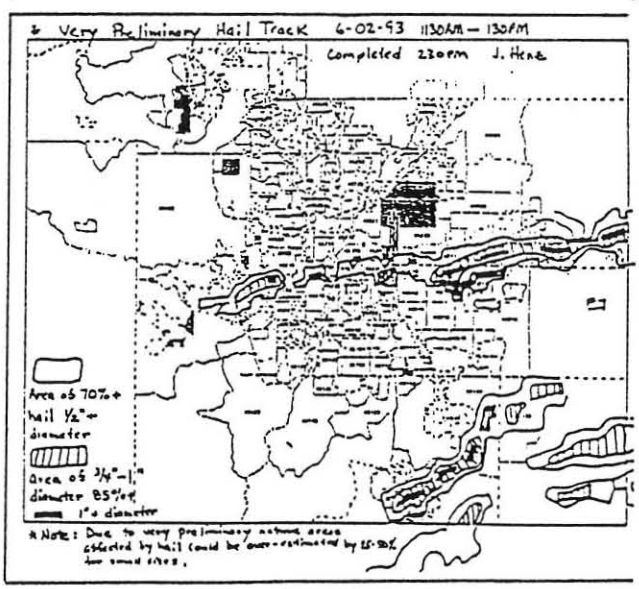

Figure 3

3.0 VERIFICATION OF STORM TRACK FORECASTS

The verification of the storm tracks was accomplished for each of the storm tracks issued from 1990 to 1993 in the manner previously described for the storm of June 2, 1993. Table 1 presents a summary of the number and types of storm tracks issued for each of the years. Since 1990 storm tracks have been issued on only 16 percent of the operational days. However, storm tracks were only issued for a portion of the 1990 and 1993 seasons. A more accurate representation should be the 25 percent daily issuance during 1991 and 1992. The remainder of the comments will consider the entire 1990 - 1993 period.

Table 1. Annual Statistics of Storm Track Forecasts for the 1990-1993 Operational Seasons

Year	Days	No.	%	#ST	#IST	#TS	#LN
1990 *	154	5	3	5	10	10	0
1991	154	26	25	40	80	69	11
1992	154	28	25	38	99	83	16
1993 *	77	3	4	3	5	5	0
Total	539	62	16	86	194	167	27

#ST = The number of storm track forecast sheets faxed
#IST = The number of individual storm tracks prepared
#TS = The number of thunderstorm storm tracks issued
#LN = The number of storm tracks issued for lines of thunderstorms
* = Partial season

While 86 storm track documents were faxed to F2P2 users, a total of 194 storm tracks were issued: 167 for thunderstorm complexes and 27 for lines of thunderstorms. The most active year was observed in 1992 when almost 100 storm tracks were issued. The verification of the individuals storm tracks is summarized in Table 2 and the following paragraph.

Table 2. Accuracy of individual thunderstorm and line storm tracks forecasts of heavy rainfall and severe weather for 1990 - 1993.

Total	Fcst 1	% Fcst	# Correct	% Right
167 TS	134 HR	80%	107	90%
167 TS	52 SVR	30%	47	90%
167 TS	50 HAIL	29%	45	90%
167 TS	5 TORN	5.2%	4	80%
27 LN	25 HR	93%	22	88%
27 LN	10 SVR	40%	8	80%
27 LN	9 HAIL	33%	8	89%
27 LN	1 TORN	4%	0	0%

HR = Heavy Thunderstorm Rainfall
SVR = Severe Weather Forecast
HAIL = Severe Weather Hail Forecast
TORN = Severe Weather Tornado Forecast
TS = Thunderstorm Track Forecast
LN = Line of Thunderstorms Forecast

Of the 167 individual thunderstorm storm tracks issued 134 thunderstorms were forecast to produce a heavy rainfall event. Of these 134 storms 107 or 80 percent actually produced a heavy rainfall event in the F2P2 operational area and within the storm track envelope. In general the heavy rain storm tracks were very reliable and over 80 percent of

the storms arrived within 15 minutes of their forecast arrival time. Over 70 percent of the storms moved within 15 degrees of their forecast motion vector while another 20 percent of the storms moved within 15 - 30 degrees of the forecast motion vector. The storms which varied the most from the forecast motion vector were typically storms encountering the Denver cyclone or a strongly inverted boundary layer.

An additional 33 storms which do not show up in Table 2 did not produce a heavy rain event but were issued storm tracks. Four of these storms were predicted to produce some form of severe weather while the other 29 storms were issued storm tracks in an effort to differentiate them from their stronger companion storms. Twenty of these storms were forecast to form at a later time and a track was predicted based on their anticipated position. Only 11 of the forecast storms actually formed indicating less skill at forecasting storm formation location than the track of an existing or developing storm.

The identification of severe weather producing thunderstorms was of great interest to most F2P2 users. These storms were only issued storm tracks on days when the severe weather potential was perceived as a complicating factor to heavy rainfall prediction. In each case severe weather forecasts were coordinated with the local National Weather Service office.

Only 52 storms of the 167 (30 percent) issued storm tracks were forecast to produce some form of severe weather. Of these 52 forecast severe storms 47 storms or 90 percent actually did produce a severe weather event. Most (45) of the storms produced large hail while 4 storms produced a tornado. The initial success at predicting the track of severe thunderstorms is very encouraging but should be viewed with a degree of caution.

Since the primary purpose of the F2P2 is to predict urban street and stream flooding events, many severe weather producing thunderstorms occurred on non-heavy rain days. No attempt was made to predict storm tracks for the severe thunderstorms which occurred on non-heavy precipitation days limiting the evaluation presented. Nonetheless it was encouraging that reasonably accurate forecasts were issued for both severe and heavy rain producing storms. Similar results were attained for the 27 thunderstorm lines which were issued storm tracks.

4.0 DISCUSSION AND CONCLUSIONS

The prediction of operational storm tracks for both heavy rain and severe weather producing thunderstorms in northeastern Colorado has met with reasonable success. The application of these results to other portions of the country may present other considerations. As noted in Mueller, et al, 1993, thunderstorm forecasting in northeastern Colorado is highly dependent on the anticipation of moisture depth and the diurnal mixing of the boundary layer. Other portions of the country which experience similar atmospheric conditions, such as the desert Southwest and the High Plains from Montana to western Texas, may find the reported results of direct use.

However, those portions of the country which experience a dominantly unmixed and inversion-capped boundary layer should consider additional factors in forecasting storm tracks for active storms. In those cases the approach used in this paper may be of limited value. It is encouraging that the simple approach used did bear operationally usable results. The prediction of storm tracks should be assisted by the use of doppler-derived low level and storm environmental winds. HMS will gain access to these types of products late in the 1993 F2P2 season as the NWS WSR-88D located at Watkins, Colorado comes on-line. If any of the WSR-88 products are used in production of 1993 storm tracks or if applications can be anticipated comments will be presented at the conference.

In conclusion the operational storm tracks issued during the periods from 1990 to 1993 have been enthusiastically received by the local emergency response community. The storm tracks provided them with a space-time planning tool for thunderstorm weather production which aided in decision-making. The production of the storm tracks was aided by the effective use of mesonet observations and detailed atmospheric sounding analysis. To this point less skill has been achieved in predicting the pre-storm formation location of thunderstorms and their subsequent storm tracks. This factor is being studied and points to the difficulty faced by many forecasters in other parts of the country which do not enjoy the advantage of forecasting the motion of pre-existing thunderstorms.

REFERENCES

Henz, John F., 1993: Operationally Predictable Characteristics of Heavy Precipitation Producing Thunderstorms. Proceedings, 17th Conference on Severe Local Storms. Amer. Meteor. Soc. October, 1993, St Louis, MO.

Henz, John F. and R. Kelly, 1985: The Denver Flash Flood Prediction Program: A Joint Hydrometeorological Effort. Proceedings, 14th Conference on Severe Local Storms, Amer. Meteor. Soc., October , 1985, Indianapolis IN, 8pp.

Mueller, Cynthia, J.W. Wilson and N.A. Crook, 1993: The Utility of Sounding and Mesonet Data to Nowcast Thunderstorm Initiation. Wea. Forecasting, 8, 132-146.

Rappolt, Bryan and J.F. Henz, 1993: Operational Applications of the Denver Cyclone Convergence-Vorticity Zone to Predict Severe Weather/ Heavy Precipitation Events. Proceedings, 17th Conference On Severe Local Storms. Amer. Meteor. Soc. October, 1993, St. Louis, MO.

Stewart K. and L. S. Tucker, 1993: Flash Flood Prediction and Early Warning. Presented at the United States - Republic of China Workshop on Natural Disaster Reduction, Taipei, Taiwan, June 24-26,1993, 9pp. (Available from Urban Drainage & Flood Control District, 2480 W. 26th Ave, Suite 156B, Denver CO).

Wilson, J.W., and C.K. Mueller, 1993: Nowcasts of Thunderstorm Initiation and Evolution. Wea Forecasting, 8, 113-131.

OPERATIONALLY PREDICTABLE UPDRAFT CHARACTERISTICS OF HEAVY PRECIPITATION PRODUCING THUNDERSTORMS

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1. INTRODUCTION

A significant problem facing operational meteorologists on the local level is the refinement of regional quantitative precipitation forecasts (QPF) into a local product. This problem is especially troublesome when thunderstorms are the source of the precipitation over small urban or stream basins of less than 2,500 square miles.

The problem is frequently compounded in urban areas by the rapid runoff response of highly impervious areas to high intensity rainfall associated with thunderstorms. In these areas a premium is placed on the ability of the operational meteorologist to identify a potential flash flood situation as soon as it is possible. In these situations even the enhanced heavy precipitation detection and display capabilities of the WSR-88D may be too slow to allow response rather than reaction by local officials to a flash flood situation.

Considerable research effort was directed at researching the meso-synoptic structure of the atmosphere associated with flash flooding events after the tragic Big Thompson, Colorado flash flood of July 31 and August 1, 1976. Maddox, et al 1977, 1979 provided numerous pattern recognition techniques, composite soundings and kinematic forecast techniques to assist the operational meteorologist in identifying the presence of the flash flooding threat. These techniques have provided invaluable operational insights into the successful prediction of flash flooding potential across most of the country.

Another operational step which must be addressed once the flash flood potential has been detected is the quantification of the heavy precipitation forecast. Simply stated: **How much rain can be produced by a thunderstorm or thunderstorm complex over a given period of time?** While the pattern recognition techniques reported have provided insight into predicting the potential heavy rain situation another key insight relates to the amount of rainfall that can be expected.

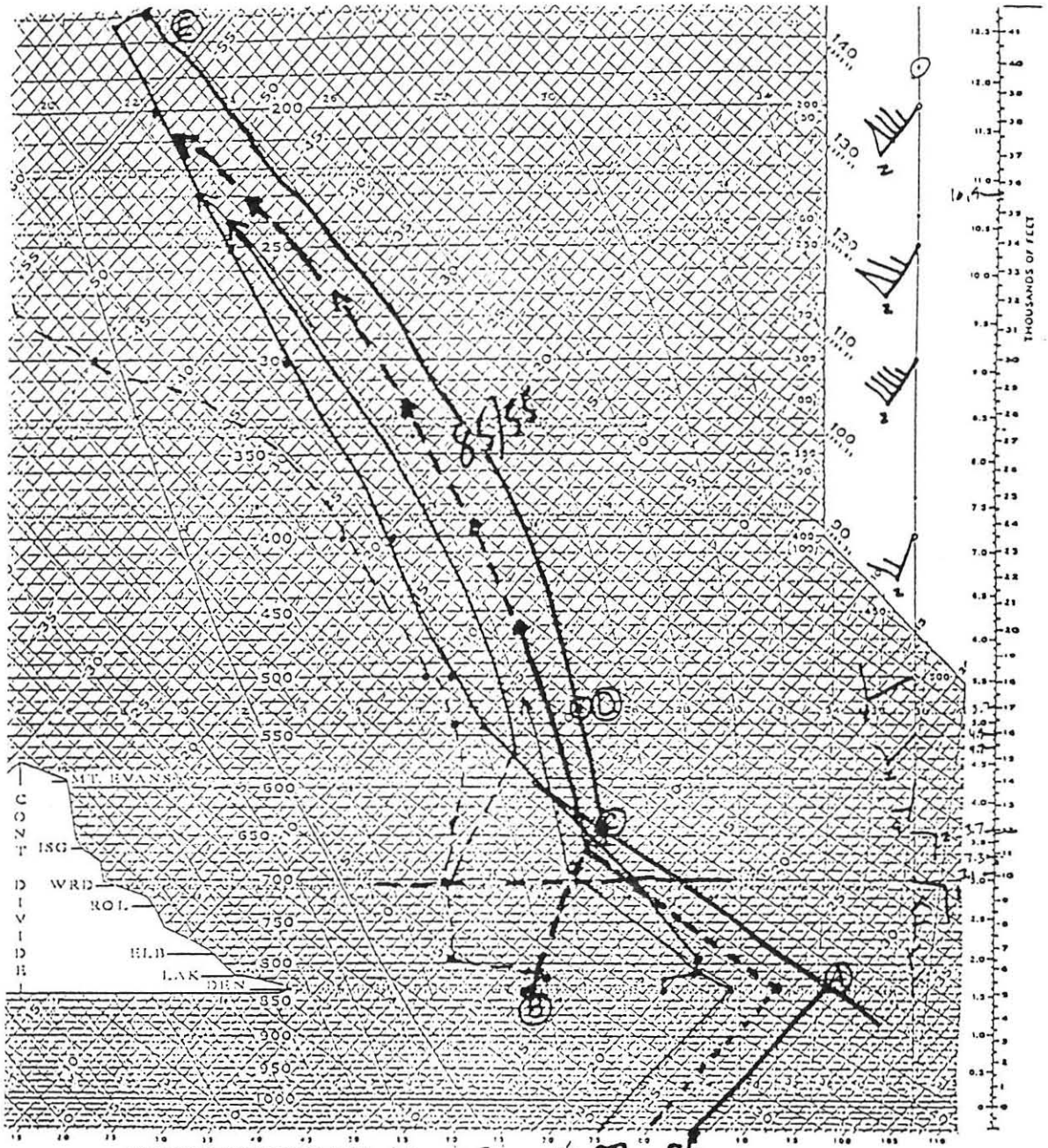
A step in answering this perplexing question in the quantification prediction can be accomplished through the analysis of implied thermal characteristics of the predicted thunderstorm updraft on Skew T, Log P diagrams. The remainder of this paper will share the author's experience with the technique and discuss some of its applications and possible physical interpretations.

2.0 Updraft Analyses - Skew T, Log P

The Flash Flood Prediction Program (F2P2) sponsored by the Urban Drainage & Flood Control District of Denver, Colorado (UDFCD) has afforded the author an opportunity to produce daily flash flood potential predictions since 1979 for the period from 15 April to 15 September for a 1,600 square mile area surrounding the Denver, Colorado metropolitan area. An integral part of the daily analyses program is directed at the kinematic analysis of the vertical structure of the atmosphere as it is depicted on a Skew T, Log P diagram through the use of both forecast and observed atmospheric soundings.

The daily sounding analysis routine is rather detailed and is conducted on a standard Skew T, Log P diagram which has been modified by Henz Meteorological Services (HMS) for use in the QPF process. The modified diagram is presented in Figure 1. Note the following differences in the modified form:

- A schematic presentation of the vertical profile of the Rocky Mountains near Denver, Colorado on the lower left hand corner of the diagram.
- A precipitable water index calculation table which uses mixing ratio values and a formula to calculate the surface to 500mb precipitable water index.
- A stability data table which is used to record the temperature (T) and dew point (Td) of the surface lifted parcel, the average temperature deviation of a surface lifted parcel (DelT), the updraft depth (DelZ) and the depth of the updraft's warm layer.



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The remainder of the diagram is basically unaltered from a standard Skew T, Log P diagram. HMS plots both the 0000 GMT and the 1200GMT Denver (DEN) soundings on the diagram in the conventional manner. The temperature and the dew point for each mandatory and significant level of the sounding are plotted vertically versus pressure. The temperature is noted in the solid black line while the dew point is plotted in the dashed black line. The analyses performed using the diagram will now be described.

The precipitable water index (PWI) is calculated by estimating the mixing ratio at each of the four levels indicated in the table: 820mb, 750mb, 650mb and 550mb. This estimated mean mixing ratio for the 100 mb layer surrounding the point is multiplied times the factor opposite the appropriate level. Each layer's contribution is calculated and then added together and divided by 3.2 to get the estimated PWI. In practice then calculated PWI varies by less than 5% from the NMC calculated PWI and is available much faster.

The remainder of the analyses is based on the concept that the undiluted updraft of a strong thunderstorm can be implied by lifting a suitable surface parcel to its level of free convection (LFC) and its neutral buoyancy point. In the case of the sounding shown in Figure 1 for August 18, 1993 the surface parcel lifted has a surface temperature (A) of 85F (29C) and a dew point (B) of 56°F (13°C). If this parcel is lifted it reaches its LFC (Point C) at about 3.5 km. From this point vertically the parcel follows the moist adiabat curve to point D and then point E where it intersects the sounding line implying its neutral buoyancy point.

HMS conducts a very detailed analyses of the lifted parcel thermal trace from point C to point E. First, the thermal deviation of the surface lifted parcel temperature from that of the ambiant atmosphere is noted every 50 mb from point C to point E. This deviation is then divided by the number of 50 mb layers to calculate the DelT factor. In the case of the example the DelT is +7.8°C which implies the updraft temperature is about 7.8°C warmer than the ambient atmosphere through the updraft's vertical depth. HMS has found that this indication of the updraft's strength is superior to the standard lifted indices which terminate at 500mb or to the cumulative Convective Available Potential Energy (CAPE) index favored in some models. HMS uses the vertical variation of the DelT to calculate both the parcel's acceleration and speed.

The DelZ factor is used to describe the depth of the updraft by subtracting the lifted parcel's LFC (Point C) from its neutral point (Point E). In the example's case the DelZ is 9.2 km which implies the conservative depth of visible cloud from its base to the anvil top. Additionally HMS has found that relationships exist between this depth and the ability of the "cloud" to produce various forms of lightning and severe weather. Of more importance to this paper is the calculation of the precipitation factor or PF. The PF is calculated by subtracting the height of the LFC (Point C) from the height of the point where the updraft cools to 0°C, in this case at Point D. In the example Point D is at 5.2 km while Point C is at 3.5 km. The difference between the two points is 1.7 km. In effect this difference is used to imply the depth of the cloud's updraft which is conservatively warmer than 0°C or that portion of the cloud where coalescence precipitation formation mechanisms should be operative. The remainder of this paper will focus on the relationship of this warm layer depth to the occurrence of heavy convective rainfall.

3.0 The Updraft's Warm Layer

The updraft's warm layer (UWL) is thought to estimate the portion of the "convective cloud" which is warmer than O°C or where it is reasonable to assume that coalescence precipitation growth processes are present or operative. Warm cloud rainfall is well established as considerably more efficient than mixed or ice phase precipitation growth processes and has been linked to many of the significant flash floods of the past ten years. It is believed that the undiluted updraft profile represented by the technique in the previous section may best relate to the most intense rain production portion of the thunderstorm represented by the 5 and 6 level radar echo portion of the storm.

In 1981 the author began to measure the presence and influence that warm coalescence rain processes might have on the occurrence of heavy rainfall in the Denver metro area as part of the F2P2 program. The updraft analysis technique described in the previous section was applied each day and the depth of the warm layer was noted. In each 1981 case of rainfall equaling or exceeding 1 inch in an hour **the depth of the warm layer exceeded 1.5 km.**

Table 1. Updraft Characteristics of Significant Flash Flooding Events

Event	Date	Rain Amount	PWI (inch)	PF (km)	DelT (°C)	DelZ (km)
Big Thompson	7/31-8/1/76	10-13"	1.31	2.8	6.5	11.2
Rapid City	6/9/72	10-12"	1.38	2.5	8.5	11.5
Maddox Synoptic	composite			3.0	4.5	10.5
Mad. Frontal	composite			2.2	3.5	9.2
Mad. Meso High	composite			3.4	4.5	10.3
Mad. Western	composite			1.8	5.0	9.2
Austin ,TX	5/24/81	8"+	1.65	3.0	4.0	10.6
New Orleans, LA	11/7/89	7-13"	1.75	3.7	4.0	10.5
Minneapolis, MN	7/24/87	11"	1.42	4.3	7.8	12.1
Chicago, IL	8/4/89	6"+	1.19	4.6	7.5	12.4
Chicago, IL	8/13/87	6"+	1.25	4.0	6.0	10.7
Omaha, NE	8/8/87	4"+	1.12	3.4	2.8	10.9
Cheyenne, WY	8/1/85	6"+	0.92	2.5	8.5	9.5
Opal, WY	7/26/90	4-6"	1.22	2.3	6.0	9.6
Albuquerque, NM	7/24/89	4"+	1.17	2.0	4.3	9.0
Atlanta, GA	6/19/91	3.5"+	1.95	3.9	3.2	11.5

In many cases when PWI data was compared to a measured rainfall the **amount appeared to be roughly double the PWI for the peak point hourly rainfall** reported in the F2P2 District. This relationship between depth of warm layer, PWI and peak point hourly rainfall was not verifiable until a flood detection network of over 136 ALERT rain gages was installed by UDFCD and became operationally accessible to HMS between 1988 and 1990. HMS has verified the 1.5 km relationship to heavy rainfall since 1990.

In the four operational F2P2 years from 1990 to 1993 HMS has routinely predicted convective QPF for the F2P2 area. Daily verification of the relationship of the 1.5 km warm layer, the PWI and the peak point rainfall in the FDN have shown only three cases where the warm layer failed to equal or exceed 1.5 km. The values on those days were 1.3 km, 1.3 km and 1.4 km. Verification plots for the past four years and for 25 significant Denver storm dates from 1981 to 1989 will not be presented here due to space considerations but will be presented at the conference along with QPF verification statistics.

This warm layer criteria was tested on flash flooding event dates in Phoenix AZ, Las Vegas NV, Reno NV and on 12 significant flash flood dates in Wyoming. The 1.5 km warm layer was appropriate for all the Nevada and Wyoming events. However as the altitude dropped in Arizona below 3,500 ft. the warm layer related to flooding dates increased to 2.5 km. The 2.5 km factor was tested for the flash flooding cases presented in Table 1 and it appeared to be rather constant but deserves discussion.

Table 1 presents a summary of updraft characteristics as described in the previous section for a number of recent killer flash flood events and for the Maddox composite flash flood sounding data. The date of the flash flood, the rainfall associated with it as reported in **Storm Data**, the PWI, depth of the updraft's warm layer, the DelT and the DelZ factors as calculated in the previous section are presented for each case. In all cases the warm layer is very deep and meets or exceeds the warm updraft layer values.

In conclusion it is quite possible that the depth of the warm layer of a predicted updraft can be used to predict the maximum anticipated rainfall from a thunderstorm. More information will be presented at the conference.

REFERENCES

Maddox, R. A., C.F. Chappell, and L.R. Hoxit, 1979: Synoptic and meso-α scale aspects of flash flood events. *Bull. Amer. Soc., 60*, 115-123.

Maddox, R.A., L.R. Hoxit, C.F. Chappell, and F. Caracena, 1977: Identifying meteorological potential for flash floods along the east-slopes of the Rocky Mountains. Proceedings *Tenth Conference. on Severe Local Storms*, Amer. Meteor. Soc., Oct., 1977, Omaha, NE, 364-372.