PHOENIX FLASH FLOOD PREDICTION PROGRAM (F2-P2)

Pre-Program Documentation and Evaluation

Contract No. 38826
(Index No. ST-853143)

Property of
Flood Control District of MC Libr
Please Return to
2801 W. Durang
Phoenix, AZ 85009

May 1986

Final Report
performed for

Engineering Department
City of Phoenix, Arizona

HENZ KELLY & ASSOCIATES
Denver, Colorado 80210

808.003

HENZ KELLY & ASSOCIATES
Weather Forecasting and Consulting

FLOOD CONTROL DISTRICT
RECEIVED
JUN 19 '86

June 18, 1986

Ms. Kebba Buckley
Flood Control District
Maricopa County
3335 W. Durango
Phoenix, Arizona 85009

CH ENG	HYDRO
ASST	LMet
ADMIN	SUSP
C & O	FILE
MAL	DESTROY
FINANCE	KCB
REMARKS	

Dear Ms. Buckley:

Enclosed is a copy of Henz Kelly & Associates recent final report to the City of Phoenix entitled, " Phoenix Flash Flood Prediction Program - Pre-Program Documentation and Evaluation". The report presents background on the meteorology and predictability of Phoenix flash flooding events and the relationship of ensuing rainfall characteristics to design storm criteria. Permission to release the report was obtained last week from Phoenix.

Two sections in the report may have particular interest to you. In section 2.2 we discuss the predictability of Phoenix flash flood producing storm systems and present observed and predicted storm maximum hourly rainfall intensities and total storm rainfall derived from observation and re-constitution runs on our HKA Excessive Convective Rainfall(ECR) model. While the model is very successful in predicting pre-storm rainfall characteristics, it is also very useful in re-constituting historical storm information. The re-constitution is particulary successful when combined with the use of recorded radar information. We believe we have a break-through in our application of the model to anticipate rainfall in both the pre-storm and post event modes for obtaining areal distribution, basin intensities and temporal distributions.

Of equal interest may be section 2.3 on rainfall characteristics and design storm criteria. In our study we have identified the existence of well-defined favored and topographically forced storm tracks that cross Maricopa County. The presense of these tracks produce an uneven occurrence distribution of heavy rainfall events across both Phoenix and the county. The urban thunderstorms we studied do not conform to the typical southwestern thunderstorms reported by Osborn in Tucson. The urban storms appear to be more intense and of longer duration, especially in the longer return period storms. Additionally we have identified a "Phoenix urbanization effect" on the distribution of rainfall across the Valley. This urban effect on the re-distribution of rainfall appears to be a by-product of the temperature differences between the hot urban areas and the cooler agricultural areas across the Valley. Similar urban effects have been reported in Chicago, St. Louis, Houston and Denver. In each case their presense had a dramatic impact on the design storm criteria applied to the region.

1776 South Jackson Street • Denver, Colorado 80210 • (303) 759-1947

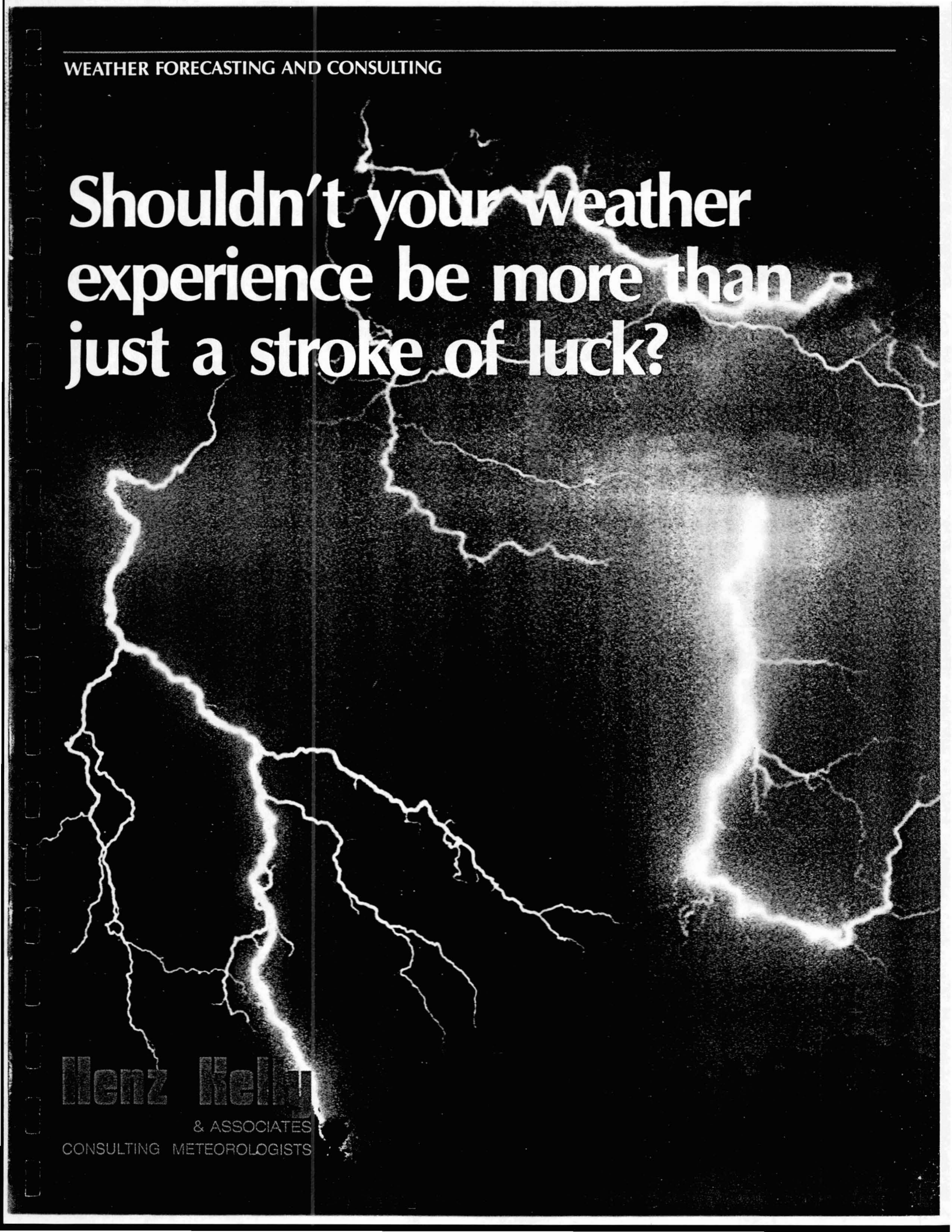
Both of these sections point out valid contributions that meteorology can make in the determination of design storm criteria revision , the definition of rainfall distributions and the re-constitution of historical storm information. We have applied our techniques very successfully to storm re-constitution in Colorado, Arizona and, recently, in Nevada. We are planning a trip to Phoenix next week and would welcome the opportunity to visit with you on contributions we feel we can provide to you and the Flood Control District of Maricopa County. Your comments and review of the report would be most welcome in our efforts to serve the region.

Very sincerely yours;

John F. Henz
Certified Consulting Meterologist

WEATHER FORECASTING AND CONSULTING

Shouldn't your weather experience be more than just a stroke of luck?



Henz Kelly

& ASSOCIATES

CONSULTING METEOROLOGISTS

"When it matters, before the fact."

Henz Kelly & Associates is a professional meteorological consulting firm focusing on life threatening and economically significant weather events. Our scope of services ranges from strategic planning to operational forecasting to post-event evaluations. Services have been provided to domestic and international clients for over 15 years.

CONTENTS

- DE JA VUE: *"I've been here before"*
- VUE JA DE: *"I've never been here before"*
- SCOPE OF SERVICES

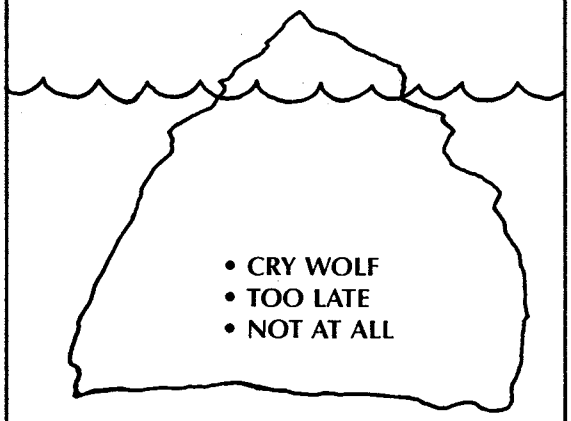
Shouldn't your weather experience be more than just a stroke of luck?

• • • • • OR • • • • •

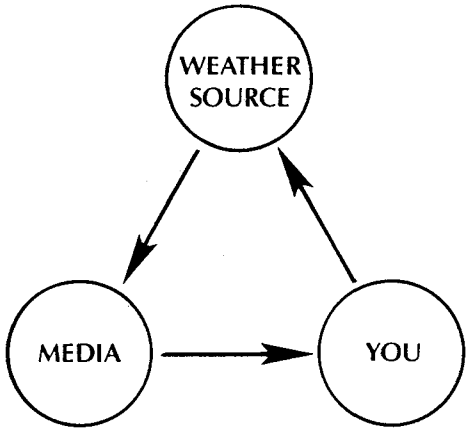
DE JA VUE—"I've been here before"

THE ICEBERG SYNDROME

- Is it your experience that most of the time when your weather service alerts you, it is crying wolf?
- Is it also your experience that most of the time when you should have been alerted, no one calls?
- Does your weather source *always* miss the big one?



THE BERMUDA TRIANGLE EXPERIENCE



- When you tune in your media source for weather, do you experience the ICEBERG SYNDROME?

DE JA VUE

- Weather can't be forecast
- Weather is an act of God
- Weather is a stroke of bad luck

"Weather is a literary specialty and no untrained hand can turn out a good article on it."
MARK TWAIN

VUE JA DE: *"I've never been here before"*

GEORGE CARLIN

"When it matters, before the fact. . . . ."

. . . . . some Henz Kelly results:

FLASH FLOOD

- Big Thompson Flashflood, Colorado—July 1976
  - National award for use of meteorological knowledge in support of the media
- Denver Flash Flood Prediction Program
  - 94% correct "Yes/No" forecast over 6 years
  - 80% of "Yes" forecasts correct

SEVERE WEATHER

- Denver Tornado Outbreak—June 3, 1981
  - Forecast on radio 23 minutes before event
- Denver Mega Hail/Rainstorm—June 13, 1984
  - Worst hail damage by single storm ($350 million) in nation's history
  - Forecast 4 hours before occurrence

WINTER STORMS

- Denver Christmas Eve Blizzard of '82
  - Paralyzed Denver and holiday travel
  - Predicted 48 hours in advance

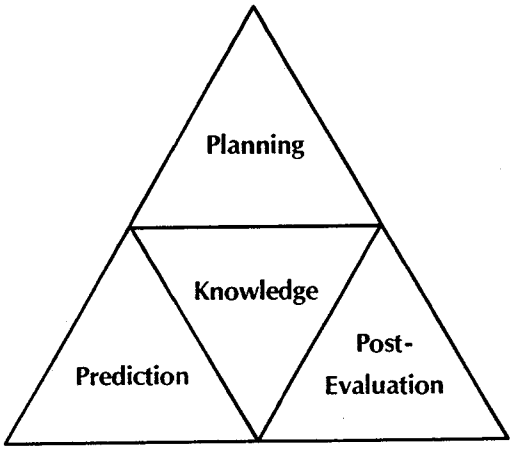
ADVENTURING

- Super Chicken Across America—October 1984
  - 1st Trans-U.S. Coast-to-Coast manned balloon flight
  - International Montgolifer Award for Ballooning, 1981
- Double Eagle V—November 1981
  - First and only manned Trans-Pacific Balloon crossing
  - Achieved on first attempt
  - Longest manned balloon flight to date

"Thunder makes all the noise. . . but lightning does all the work."

MARK TWAIN

SCOPE OF SERVICES



Our scope of services includes planning, prediction and post-evaluation phases of life threatening and economically significant events.

WEATHER FORECASTING

- Severe weather
- Precipitation
- Temperature Extremes
- Long Range
- Winter Storms

HYDRO-METEOROLOGY

- Design of flash flood prediction programs (F2-P2)
- Operation of flash flood prediction programs
- Communication design
- Post-storm analysis
- Rainfall analyses for PMP, design storm criteria and runoff simulation
- Scenario modeling
- Frequency/duration/intensity studies

LEGAL/INSURANCE

- Expert Testimony
- Risk analysis
- Weather projections
- Feasibility studies
- Event re-construction

COMMUNICATIONS

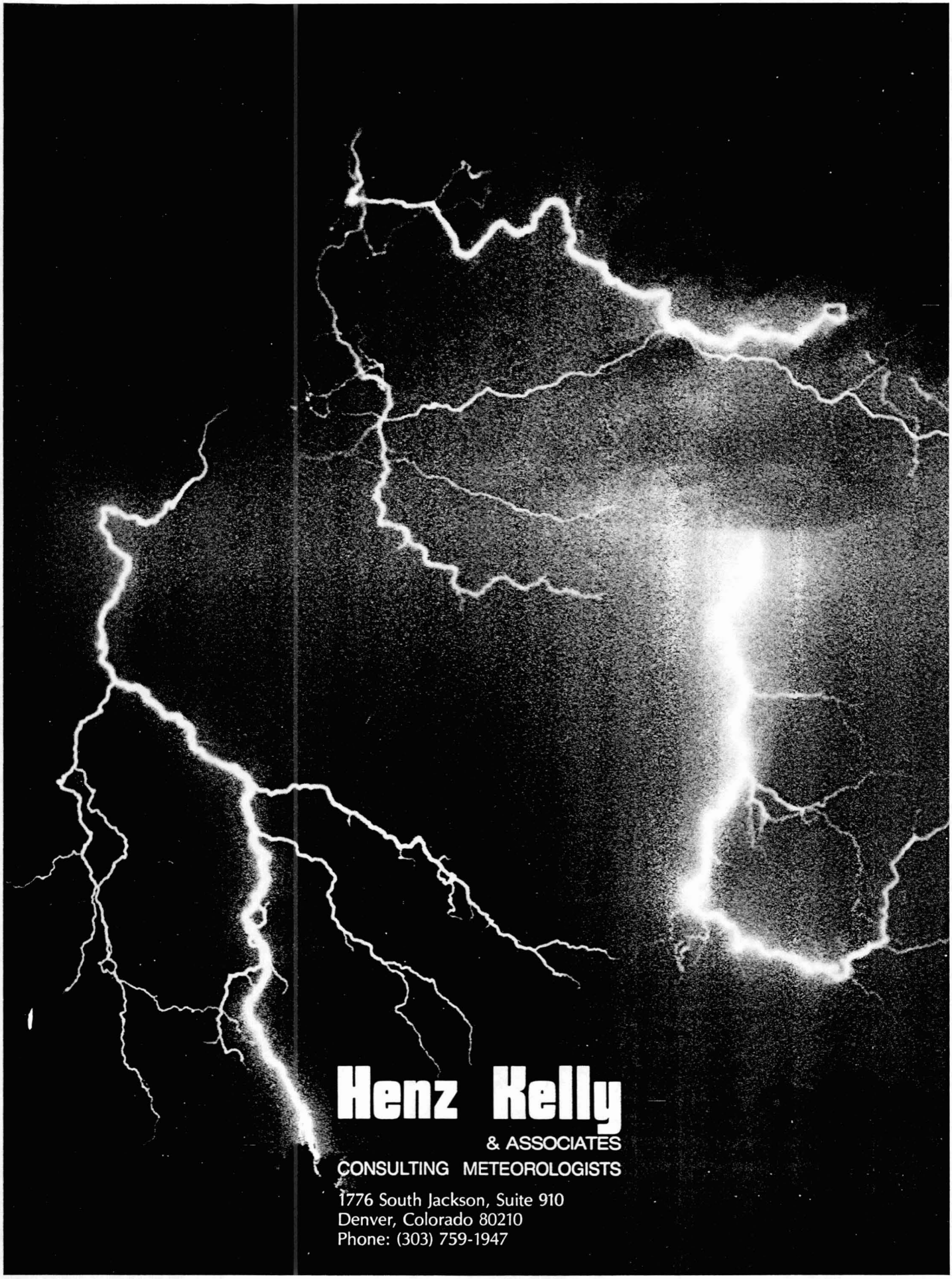
- Television
- Cable
- Radio
- Newspaper
- Electronic mail

RESEARCH

- Mesometeorology
- Weather forecasting
- Precipitation
- Artificial Intelligence
- Cyclogenesis

"No one knows your business like you do. But if you can't afford for your weather experience to be just a stroke of luck, together we can turn a costly uncertainty into a substantial benefit."

John F. Henz *Ron A. Kelly*



Henz Kelly

& ASSOCIATES

CONSULTING METEOROLOGISTS

1776 South Jackson, Suite 910
Denver, Colorado 80210
Phone: (303) 759-1947

PHOENIX FLASH FLOOD PREDICTION PROGRAM (F2-P2)

Pre-Program Documentation and Evaluation

FLOOD CONTROL DISTRICT
RECEIVED
JUN 19 '86

Performed for

Engineering Department
City of Phoenix, Arizona

Contract No. 38826
(Index No. ST-853143)

	CH ENG		HYDRO
	ASST		LMet
	ADMIN		SUCP
	C & O		FILE
	ENGR		DESTROY
	FINANCE		KCD
REMARKS			

Principal Investigators: John F. Henz
Ronald A. Kelly

HENZ KELLY & ASSOCIATES
Meteorological Consultants
1776 S. Jackson St.
Denver, Colorado 80210
May 1986

EXECUTIVE SUMMARY

INTRODUCTION

Flash flooding produced by thunderstorms poses a serious threat to life and property in Phoenix, Arizona. A joint study was conducted by Henz Kelly & Associates and Tipton and Kalmbach, Inc. of Denver, Colorado, to investigate the predictability of the flash flooding and the characteristics of the related storm rainfall as measured in the Phoenix rain gage network. The conclusions and resulting recommendations of the evaluation are summarized in the next two sections.

CONCLUSIONS

A thorough meteorological assessment was completed of the causes and predictability of flash flooding events affecting Phoenix. The characteristics of the rainfall produced by the events and the availability of resources to establish a Phoenix-based flash flood prediction program were evaluated. The conclusions of the study are listed below:

a. Thunderstorm flash flooding events in Phoenix can be accurately predicted 3-12 hours before they occur using the HKA Excessive Convective Rainfall model. All events can be forecast with a false alarm rate of less than 20 percent. Storm total rainfall, storm track and peak storm intensity can be forecast accurately.

b. Evidence exists which supports the presence of preferred thunderstorm tracks which cross the city and county. These storm tracks appear to alter the distribution and frequency of storm rainfalls across the city. The storm tracks may be caused by topographic or urban effects.

c. Apparent urban effects have altered the distribution and frequency of heavy rainfalls in Phoenix and parts of Maricopa County.

d. The existing Phoenix rain gage network is a valuable resource for performing rainfall characteristics studies.

e. A Phoenix-based flash flood prediction program can be economically established and provide timely, accurate forecasts of flash flooding events to response-based city departments before the event begins. Potential savings achieved by the program could provide a measure of fiscal stability.

These conclusions provide strong support for the establishment of a flash flood prediction program within the City of Phoenix. The program could be easily expanded to serve all of Maricopa County. Additionally the urban effects related to precipitation re-distribution appear to be caused by factors found across Maricopa County. Both of these factors could be effectively addressed by the Maricopa Association of Governments.

RECOMMENDATIONS

The study conducted provides strong support for the recommendations listed below:

a. A five year Phoenix flash flood prediction program (F2-P2) should be funded to enhance the safety of Phoenix residents and improve city services. Preliminary cost/benefit analyses suggest a potential annual $4 million savings if the F2-P2 is implemented.

b. The City of Phoenix should consider the advantages of expanding the proposed F2-P2 to include all of Maricopa County through the assistance of the Maricopa Association of Governments.

c. The existing Phoenix rain gage network should be upgraded to improve system data collection reliability. An automated weather station network should be implemented to support flash flood prediction. Rain/stream gage sites should be added to enhance revision of design storm criteria. Existing rain gage sites should not be moved to preserve their statistical significance for future studies and court case useage.

d. A radar precipitation mapping program should be initiated to identify potential urban effects and topographic influences on areal and frequency of heavy rainfall as it pertains to revision of design storm criteria and land use planning.

Additional details on the study are contained within the report and presentations can be made to develop any of the conclusions or recommendations discussed in this report. Proposal outlines for the flash flood prediction program and the radar tracking study have been prepared under separate cover.

TABLE OF CONTENTS

	Page
EXECUTIVE SUMMARY	i
Introduction	i
Conclusions	i
Recommendations	ii
1.0 INTRODUCTION	1
2.0 METEOROLOGY AND PREDICTABILITY OF PHOENIX FLASH FLOODS	2
2.1 Meteorology of Phoenix Flash Floods	2
2.2 Predictability of Phoenix Flash Flooding	12
2.3 Rainfall Characteristics and Design Storm Criteria	16
3.0 ASSESSMENT OF EXISTING COMMUNICATIONS AND DATA SOURCES	24
3.1 Communications Sources	24
3.2 Meteorological and Hydrologic Data	25
4.0 FLASH FLOOD PREDICTION PROGRAM: OPERATIONS AND RESOURCES	26
4.1 F2-P2 Operations	26
4.2 F2-P2 Resources and Investments	28
5.0 COST/BENEFIT JUSTIFICATION	29
5.1 More Efficient Structural Applications	30
5.2 Operational Flash Flood Program as Structural Alternative	30
5.3 Not Previously Realized Benefits from Forecasts	31
6.0 CONCLUSIONS AND RECOMMENDATIONS	35
REFERENCES	
APPENDIX	
A. Data Sources and Case Study Methodology	
B. Cost/Benefit Categories, Assumptions, Formulae and Results	

LIST OF TABLES

		Page
Table 1	Phoenix Flash flood Prediction study dates, & general meteorological cause	5
Table 2	Dates of Phoenix flash flooding and associated meso/synoptic atmospheric forcing features	6
Table 3	Comparison of mean atmospheric conditions for Phoenix flash flooding days to those in the Denver metro area reported by Henz, 1980 and the frontal and western mean flood cases reported by Maddox et al, 1979	9
Table 4	Date of flash flood event days studied versus reported 24 hour rainfall at each Phoenix gage site and general thunderstorm source wind	10
Table 5	Total 24 hour maximum rainfall versus thunderstorm steering wind for Phoenix event days in Phoenix rain gage network	11
Table 6	Estimated thunderstorm type, frequency, intensity, duration and total Phoenix rainfall for study flash flood event days	22
Table 7	Annual investment in a five-year flash flood prediction program for a Phoenix-based program serving either Phoenix or Maricopa County	29
Table 8	Cost-benefit summary for flash flood prediction programs	34

LIST OF FIGURES

		Page
Figure 1	City of Phoenix map with rain gage network locations.	3
Figure 2	Observed total event thunderstorm rainfall versus ECR model predicted total rainfall for summer season event days in Phoenix.	14
Figure 3	Observed peak hourly intensity versus ECR model predicted peak hourly intensity for summer season event days in Phoenix.	15
Figure 4	Annual variations in number of event days equal to or exceeding either 0.50" or 1.00" 24 hour rainfall at any site in the Phoenix rain gage network 1975-1985.	18
Figure 5	Total rainfall for study event days on Phoenix flash flooding dates in Phoenix rain gage network.	19
Figure 6	Estimated thunderstorm tracks across Phoenix.	23

1.0 INTRODUCTION

Flash flooding produced by thunderstorms poses a serious threat to life and property in Phoenix, Arizona which concerns the Engineering Department of the City of Phoenix. Meetings held with city representatives identified two primary areas of concern regarding the impact of flash flooding:

a. Can the thunderstorm systems producing Phoenix flash floods be predicted, and if so, how successful would a flash flood prediction program be?

b. Is the existing City of Phoenix rain gage network data providing information of use in identifying rainfall characteristics which impact design storm criteria used within the city?

These two areas of concern were addressed by a joint study conducted by Henz Kelly & Associates (HKA), a meteorological consulting firm and Tipton and Kalmbach (T&K), an engineering consulting firm, both from Denver, Colorado. Each group issued separate reports dealing with portions of the two concern areas in their expertise areas. This report details the results of the HKA effort. Both groups shared results and report reviews internally before issuing their respective reports.

HKA's primary task was focused on defining the predictability of the flash flood-producing thunderstorm systems and describing the configuration of Phoenix flash flood prediction program (F2-P2). HKA outlined 5 major tasks required to satisfy its study for the City of Phoenix. These tasks are outlined below and covered in detail in the subsequent report:

a. Task 1: Evaluate the meteorology of significant flash-flood producing storm systems of the past ten years with a focus on storm predictability.

b. Task 2: Evaluate the meteorological characteristics of flash-flood producing systems rainfall. (Note: T&K's report covers this topic in depth).

c. Task 3: Assess communications, data sources and requirements necessary to establish a Phoenix F2-P2.

d. Task 4: Describe the operations and resources needed to establish a Phoenix F2-P2.

e. Task 5: Prepare a report documenting the results of the study and make appropriate presentations as requested.

Conclusions from each task are reported in a separate section at the end of the report. Appropriate recommendations for future city actions to address the conclusions are also presented. A synopsis of the report is presented as an Executive Summary at the beginning of the report. In an effort to make the report more readable and useable Appendices are used for extensive reporting of data or procedural analysis descriptions.

2.0 METEOROLOGY AND PREDICTABILITY OF PHOENIX FLASH FLOODS

Flash flooding caused by warm season thunderstorms poses a significant threat to life and property in Phoenix, Arizona. The storms have an immediate impact on the operational response functions of the fire, police, streets maintenance and emergency preparedness departments. An accurate and timely flash flood prediction program could assist these departments in being more responsive to the needs of the residents of Phoenix before and during flash flooding events. Additionally, the storms exert an equally significant but less immediate impact on the Engineering Department as it uses design storm criteria to improve and build drainage systems and facilities to handle storm runoff. Concern exists that the frequency, intensity and areal distribution of heavy rain events in Phoenix has become non-uniform but no definitive evaluation has been made.

This section of the report details the meteorological characteristics of Phoenix's flash flood events as they apply to assessing the storms' predictability and investigating the need for revision of design storm criteria. The general procedure utilized in these assessments relied on detailed meteorological and rainfall case studies performed for each event date according to procedures and using data sources identified in the Appendix. Readers interested in these procedures and sources are referred to the Appendix or personal interaction with the authors. Figure 1 shows Phoenix and rain gage network locations.

2.1 Meteorology of Phoenix Flash Floods

Prior to beginning this study Henz and Kelly (1985) prepared a survey of flash flooding events and their apparent meteorological cause from 1978 to 1984 as identified in Storm Data (NOAA, 1978-84). The survey was used in a short course on Rainfall-Runoff Modeling sponsored by the Arizona Floodplain Management Association and offered in Scottsdale, February 1985. The survey noted the following flash flood characteristics:

a. Most flash flood events occurred from July through October with a secondary peak in January.

b. Most flooding events were produced by one of three causes: thunderstorm systems, general cyclonic winter storms or rapid spring snowmelt runoff situations.

c. Thunderstorm systems tended to be part of either general winter storms or sub-tropically forced outbreaks.

d. Some of the flash flood events appeared to be caused by well-organized, long duration thunderstorm systems that could be "traced" across the state over 1-2 days.

Most of these survey results were in general agreement with earlier studies by Hales (1972,1974), Corps of Engineers (1974) and Osborn and Simanton (1981). The earlier studies noted the sub-tropical moisture influences and the importance of topography and general storms but the meteorological descriptions were rather vague to assist in the predictability assessment. Additionally, each report tended to characterize southwestern thunderstorms as short duration, high intensity and highly localized events. The apparent presence of longer duration

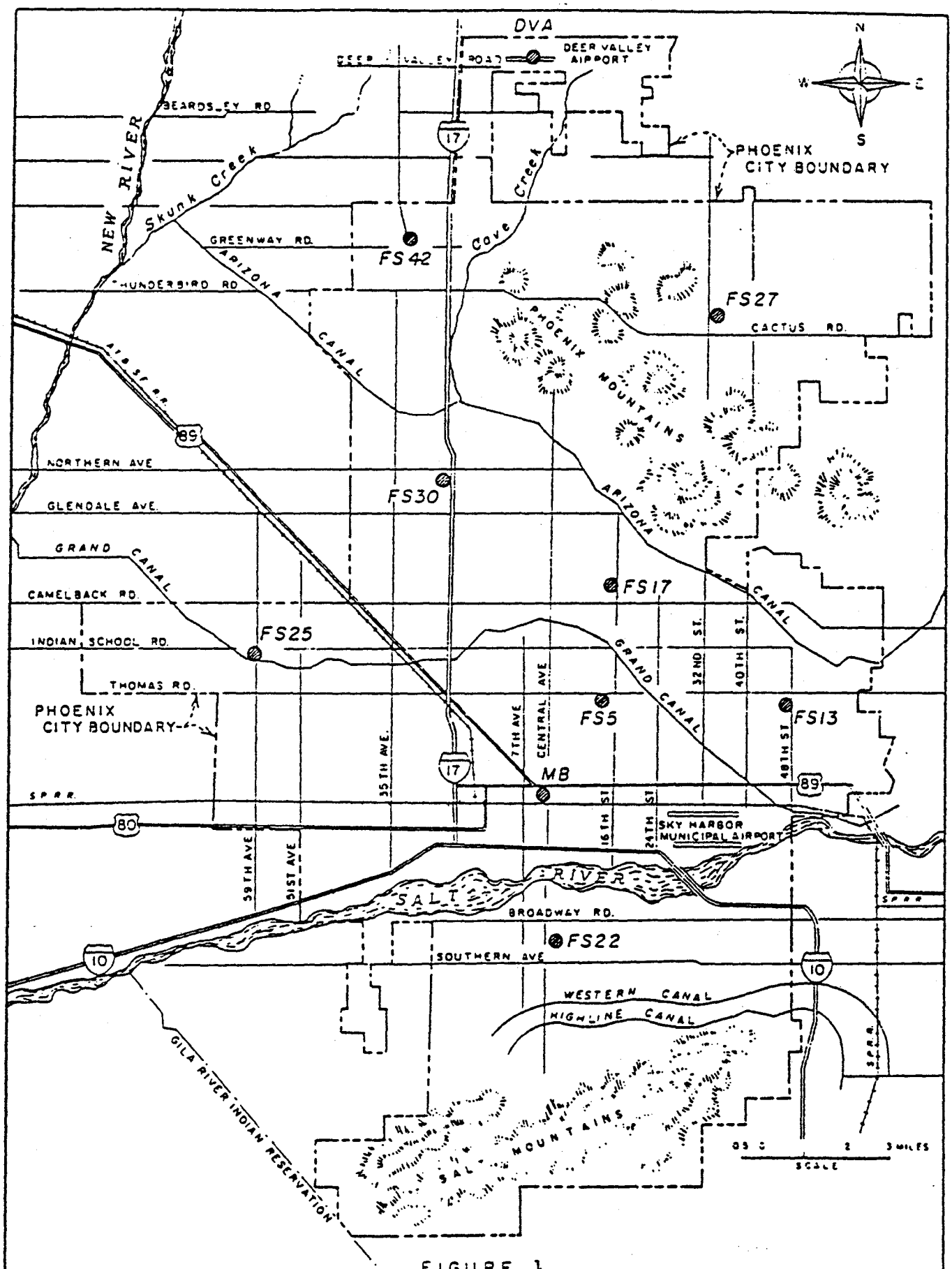


FIGURE 1

Location of City of Phoenix, Engineering Department Raingage Network

organized thunderstorm systems did not appear to be described in the earlier reports though Osborn et al (1981) expressed concern over the general applicability of the Walnut Gulch storm model over other parts of the state and suggested potential urban storm differences could exist.

In order to provide a sound framework for assessing the predictability of Phoenix flash floods, a thorough investigation of the meteorological causes of the flash-flood producing thunderstorms was conducted for each of the 30 event days identified in Table 1. The data set of 30 significant flash flooding events was selected from the period 1972-1984 based on the perceived degree of flooding severity noted in Storm Data. The sample event days were comprised of 23 general thunderstorm cases and 7 general cyclonic winter storm cases. These cases represent about a third of the flash flooding event days that occurred during the period of investigation and were the maximum number which conformed to the restraints of the study. The earlier Henz et al (1985) survey showed 80 percent of the event days caused by thunderstorm systems while the study sample showed 75 percent thunderstorm systems and 25 percent winter storms. The event cause mix is sound and provides a solid evaluation foundation.

The general atmospheric structure conducive to the spawning of flash flooding by thunderstorm rainfall has been described by Henz (1976,1977) Maddox et al (1977) and Henz (1980). The basic requirements are:

a. A deep layer of very moist air from the surface through the mid-troposphere.

b. A general light wind pattern through the atmosphere.

c. Presence of an upper level system to trigger storm development.

d. A low level feature which focuses the inflow of moist air into the storm's updraft region.

These general characteristics may take a myriad of forms which makes their prediction very difficult for the operational meteorologist.

Thorough analyses were performed for each case event day to identify the meteorological features that were present in both the pre- and flash flooding environment. The analyses were performed on the surface, planetary boundary layer (first 2000 feet above the ground), 700 MB (~10,000 feet or cloud base), 500 MB (~20,000 feet or mid-cloud layer) and jet stream levels to about 30,000 to 40,000 feet (300-200 MB). The features present on each event day are summarized in Table 2. In general the basic atmospheric requirements conducive to thunderstorm flash flooding identified are present though their form is very likely biased by Arizona's topography and climatology. A brief description of important features found in each layer are presented in the following paragraphs.

Moisture supplies are focused and instability released by several important features that vary with the season. During cold season general storms, surface cold fronts were the predominant storm triggering mechanism. This finding agrees with the Corps of Engineers (1974) as does the season of their occurrence from October through April. On the other hand frontal boundaries are rarely present during the summer season.

Table 1 Phoenix Flash Flood Prediction Study Dates and General Meteorological Cause

Date	Cause
6-21-72	Summer thunderstorms
6-22-72	Summer thunderstorms
1-10-78	Winter storm
7-24-78	Summer thunderstorms
8-3-78	Summer thunderstorms
11-10-78	Winter storms
11-11-78	Winter thunderstorms
12-17-78	Winter thunderstorms
12-18-78	Winter thunderstorms
1-18-80	Winter thunderstorms
8-7-81	Summer thunderstorms
10-1-81	Summer thunderstorms
10-2-81	Summer thunderstorms
8-23-82	Summer thunderstorms
8-24-82	Summer thunderstorms
8-8-83	Summer thunderstorms
8-16-83	Summer thunderstorms
1-10-78	Winter storm
8-19-83	Summer thunderstorms
7-14-84	Summer thunderstorms
7-21-84	Summer thunderstorms
7-27-84	Summer thunderstorms
7-28-84	Summer thunderstorms
8-8-84	Summer thunderstorms
8-9-84	Summer thunderstorms
8-14-84	Summer thunderstorms
9-1-84	Summer thunderstorms
9-10-84	Summer thunderstorms

TABLE 2 DATES OF PHOENIX FLASH FLOODING AND ASSOCIATED MESO/SYNOPTIC ATMOSPHERIC FORCING FEATURES

Case #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	6-22-72	6-21-72	7-24-78	8-3-78	11-10-78	11-11-78	12-17-78	12-18-78	1-18-80	8-7-81	10-1-81	10-2-81 00	10-2-81 12	8-23-82 12	8-23-82 00	8-24-82 12	8-8-83	8-16-83	1-10-78	3-2-78	3-3-78	8-19-83			TOTAL						
Surface																															
Fropa					X	X	X	X	X		X	X	X						X		X				10						
Gust Front		X	X								X				X		X	X							5						
Meso-Low										X	X	X	X	X	X	X	X	X				X			10						
Trough/Conv In	X		X	X	X	X				X	X	X	X	X	X	X		X		X					14						
Planetary Boundary Layer																															
LLJ	X	X	X			X	X	X			X		X			X				X					10						
Moist Tongue	X	X	X	X	X	X	X	X		X	X	X			X	X		X		X		X			16						
Convergence	X					X			X	X				X			X	X	X		X				9						
Dry Line																															
700 MB																															
Moist Tongue	X		X				X			X	X			X	X	X	X	X				X			11						
Easterly WV			X							X				X			X	X							5						
Closed Low	X		X		X	X		X	X		X				X	X	X	X	X			X			13						
Short Wave	X	X			X	X		X	X		X	X	X				X		X	X	X	X			14						
Convergence																															
500 MB																															
Easterly WV			X							X				X			X	X							5						
Short WV	X	X		X	X	X	X	X			X	X	X		X				X	X	X				14						
Closed Low		X	X		X	X		X	X							X	X		X						9						
JET LVL																															
Jet Streak				X	X	X	X	X	X		X	X	X	X					X	X	X				13						
Axis					X	X	X	X	X		X	X	X	X					X	X	X				12						
CYC/ANT Shear Axis				X	X	X	X	X	X		X	X	X	X			X	X	X	X	X				15						
Subtropical/Polar				P	S	P	S	P	P		P	P	P	S					P	P	P				13						

MAC FORM SEP 74 361 PREVIOUS EDITION WILL BE USED GENERAL PURPOSE WORKSHEET ☆ U.S. G.P.O. 1975-665-694 14

During the summer flash flooding season from June into early October thermally driven wind systems dominate focusing and triggering moist unstable air sources. These wind systems take three dominant forms:

a. Mountain-valley breeze circulations.

b. Urban effects on local wind circulations.

c. Convergence zones within weak low pressure troughs.

The valley breeze circulations tend to help release and focus the moist instability of the air over nearby foothills and mountain ranges. In turn thunderstorm systems form over and along higher terrain to the northeast through southeast and southwest of Phoenix and gradually drift across Phoenix and Maricopa County depending on cloud layer steering winds (Hales 1972). Weak low pressure troughs tend to form in the heated desert valleys and converge the moist air into developing lines of storms or showers. On occasion these troughs are really "tired fronts" that back-doored their way into Arizona by way of New Mexico with little substance other than a converging wind zone.

Of more interest is the apparent existence of a "Phoenix thunderstorm low" that is urbanly generated. This circulation was found to occur in the pre-thunderstorm environment on most flash flood event days. It may be a by-product of the rapid urbanization of Phoenix causing an urban heat island over Phoenix in contrast to the cooler irrigated air found over regions to the east. A review of daytime highs on event days found Phoenix Sky Harbor Airport 6 degrees or more warmer than Williams AFB near Chandler in the more rural area. If this temperature contrast is maintained it creates a baroclinic zone ideal for triggering thunderstorm formation or intensification over the eastern and northern parts of Phoenix. Similar urban-induced circulations were found in St. Louis and Chicago (Changnon 1980) and were responsible for downwind rainfall increases, especially on heavy rain days. In Denver similar circulations were responsible for both heavy rain and severe weather production over the southern suburban areas (Szoke et al 1985).

In the first 2,000 feet above the surface or the boundary layer the presence of low level jets (bands of stronger winds just above the surface), convergent wind flow and tongues of moist sub-tropical air were detected. At approximately 10,000 feet (700 MB) the moist tongues of sub-tropical air were noted to persist. Additionally weak easterly waves from the Gulf of Mexico and short waves of distrubed air forming over the Pacific were found to cross the flash flooding area presumably organizing and intensifying existing thunderstorm systems. Just above this region at approximately 20,000 feet (500 MB) short waves of distrubed air flowing off the Pacific were found to be crossing the region which organized and intensified the thunderstorm systems. These short waves were quite weak but compare favorably to those found in other western states flooding situations (Henz 1979, Maddox et al 1979, Randerson 1976). In general the presence of jet streaks or maxima at jet stream level or above were found to exist irregularly over the flash flooding area during the summer months. However, fall and winter storm cases noted the presence of polar jet streaks most of the time. Thus in summary the following pre-flash flooding meso/synoptic scale features appeared present:

a. A low level focusing mechanism was present at or near the ground to intensify and focus thunderstorm activity over Phoenix.

b. An ample supply of moist air from the surface into the mid-atmosphere to supply the fuel for heavy rain events.

c. Upper level triggering, organizing and intensifying features were present in the form of Pacific short waves and Gulf of Mexico easterly waves.

d. During the winter season surface cold front, polar short waves and polar jet streaks were present.

The atmospheric soundings at Tucson and Winslow were plotted and analyzed as needed for the 36 hours surrounding each event. Table 3 summarizes the average of pre-storm atmosphere at key levels over Phoenix. In turn these are compared to the averages found in pre-storm atmospheres by Henz (1979) and Maddox et al (1979). In general the atmosphere's thermal structure looks very similar in all cases. Deep convection is supported in a very moist atmosphere with generally light steering winds through the extent of the cloud layer in the presence of the triggering and focusing features described earlier.

An important consideration in both the meteorological assessment and the predictability assessment is the amount of rainfall reported in the Phoenix rain gage network on each of the 30 event days. Table 4 contains the observed total 24 hour rainfall at each city gage site and the general cloud layer steering winds for each of the 30 event days. For the seven winter event cases westerly winds in the cloud layer attended by a triggering cold front and upper level short wave were noted in all cases. Table 5 shows a comparison of the maximum 24 hour total rainfall reported in a Phoenix rain gage versus the cloud layer steering wind for the summer event cases. The following observations can be summarized:

a. For lighter rainfall ($\leq$ 0.75 inches) a distinct preference for southwesterly cloud layer winds is noted. On these days faster cloud layer winds and shear were noted and likely contributed to the lower observed totals.

b. Moderate rainfall (.76-1.25 inches) and heavy rainfall (1.26-2.00 inches) days demonstrated a distinct preference for southeasterly winds in the cloud layer. No doubt this reflects the impact of the sub-tropic air mass and attendant disturbances which accompany the "Arizona monsoon season". However it should be noted that southeasterly winds would tend to steer thunderstorms forming over high terrain features to the north and east of Tucson toward the Valley and Phoenix in particular. Preferred thunderstorm system storm tracks were evident in most of these cases.

c. On excessive rainfall days ($>$2 inches) southwesterly cloud layer winds once again appeared but in contrast to the light rainfall day winds and shear in the cloud layer tended to be quite light. These cases deserve more detailed study than the present study allows.

Table 3 Comparison of mean atmospheric conditions for Phoenix flash flooding days to those in Denver Metro area reported by Henz 1980 and the frontal and Western mean flood cases reported by Maddox et al, 1979.

Atmospheric Variable	Colorado	Frontal	Western	Arizona
Surface temperature - ^{o}F	81	70	86	99
Surface dew point - ^{o}F	49	65	56	67
Showalter Index	- 5	- 4	- 5	- 5
700mb $T/T-T_d$ - ^{o}C	9/5	7/4	7/3	10/4
500mb $T/T-T_d$ - ^{o}C	-9/5	-10/4	-10/4	-7/3
300mb T - ^{o}C	- 35	- 36	- 34	- 32
200mb T - ^{o}C	- 56	- 56	- 55	- 54
Mean Sub-Cloud Wind Direction	080°	100^{o}(SFC)	0.90^{o}(SFC)	120°
Mean sub-Cloud Wind Speed (kts)	11	9 (SFC)	9 (SFC)	8
Mean Cloud Layer Wind Direction	240°	250 (500mb)	240 (500mb)	180
Mean Cloud Layer Wind Speed (kts)	27	28 (500mb)	27 (500mb)	22
Mean Sfc-500mb Precipitable Water (In)	0.90	1.60	1.20	1.30
Stationary Surface front	Yes	Yes	No	No
Heavy rain on cool side	Yes	Yes	No	No
Wind parallel to front	Yes	Yes	No	No
Short wave trough present	60%	82%	77%	70%
Weak shear in cloud layer	Yes	Yes	Yes	Yes
Convective storms	Yes	Yes	Yes	Yes
Severe Weather Events (% of time)	80%	15%	50%	50%

TABLE 4 DATE OF FLASH FLOOD EVENT DAYS STUDIED VERSUS REPORTED 24-HOUR RAINFALL AT EACH PHOENIX GAGE SITE AND GENERAL THUNDERSTORM SOURCEWIND

PHOENIX GAGE SITES

Summer Storms

	Date		MB	South FS22	Cent West FS25	Cent FS5	Cent East FS13	Cent FS17	NW FS30	NW FS42	N DVA	NE FS27	Source Winds
1	1972	6-21											180
2		6-22											210
3	1978	1-10	.88	.77	1.13	.70	.77	.23*	1.02		.48	1.30	210
4		7-24	.23	.04	.05	.10	.35	N/A	.20		.18	.54	180
5		8-3	.36	0	.26	.74	.29*	.88	.08		.35	.20	080
6		11-10	.44	.42	M	.34	0	.53	.20		.66	.56	220
7		11-11	.60	.34	M	.68	.10	.65	.30		.83	.69	220
8		12-17	.64	.73	1.00	.68	.92	.80	1.06		.48	1.09	220
9		12-18	.61	.30	.25	.20	.85	.50	.61		.21	.79	210
10	1980	1-17/18	1.29	1.39	1.50	.66	1.27	1.11	.46		1.17	.87	240
11	1981	10-1	.15	.37	.19	.19	.65	.23	.19		.04	.28	200
12		10-2	.30	.17	.03	.25	.20	.60	.30		.46	1.45	210
13	1982	8-23	N/A	.17	.66	.44	.67	.22	1.38	1.21	.35	.34	080
14		8-24	N/A	.87	.43	.36	.11	.05	.31	.11	0	.07	120
15	1983	8-8	0	.13	0	N/A	0	.16	.82	.91	.20	N/A	120
16		8-16	.54	1.04	1.23	N/A	1.23	1.74	2.01	1.23	.70	1.45	120
17		8-19	.18	.05	0	N/A	.13	.03	0	.02	0	0	210
18	1984	7-17	.26	.58	0	.17	.75	.71	.48	.42	0	.63	110
19		7-21	1.04	.44	.50	.35	.91	1.39	.37	.58	.51	1.07	160
20		7-27	.98	1.85	.70	.28	.94	.44	1.05	.56	.65	1.10	130
21		7-28	1.71	.82	.63	1.17	.79	1.05	.96	.90	.65	1.02	170
22		8-8	0	.10	.21	0	.07	0	.18	.15	.02	0	240
23		8-9	0	.01	.06	0	.01	0	.14	1.21	.91	.07	210
24		8-14	.55	.73	.90	1.06	.75	.75	1.05	0	0	.43	110
25		9-1	.62	.63	.95	1.03	.65	2.24	2.35	1.06	.65	.60	270
26		9-10	.70	1.10	1.46	.59	.98	0	.88	.67	.58	.86	210
		Total	12.08	13.05	12.14	9.99	13.39	14.31	16.40	9.03	10.08	15.41	
		AVG/Event	.48	.48	.49	.42	.50	.55	.61	.56	.37	.59	

TABLE 5 Total 24 hour maximum rainfall versus thunderstorm steering wind for Phoenix event days in Phoenix raingage network

	RAINFALL DEPTH, IN INCHES					
	.25-.50	.51-1.00	1.01-1.50	1.51-2.00	2.00	TOTAL
Thunderstorm Sourcewind						
Summer 360-090°	0	1	1	0	0	2
091-180°	0	4	2	3	1	10
181-270°	2	2	2	0	2	8
Winter 181-270°	0	4	3	0	0	7

While these conditions and atmospheric structures are helpful in anticipating the formation of heavy thunderstorms over Arizona they do not provide the means to achieve quantitative, site-specific forecasts of flash flooding events alone. An assessment of the predictability of these events is described in the next section.

In effect the Arizona flash flood atmosphere appears to conform to the pre-flash flooding conditions found in other parts of the country. These conditions support those reported in earlier papers but offer more detail in defining the meso/synoptic scale features responsible for triggering the flash flood event in a specific, focused location. The features occur generally less than 5 percent of the time in concert over Arizona and are instrumental in producing heavy rain events when they do.

2.2 Predictability of Phoenix Flash Flooding

The prediction of flash flooding events is considered by many to be an art not a science. The most successful excessive thunderstorm rainfall and flash flooding prediction program (F2-P2) in the country is sponsored by the Urban Drainage and Flood Control District of Denver (UDFCD). The UDFCD F2-P2 is a prediction-based program that has existed since 1979. Its goal is to provide highly accurate predictions of heavy thunderstorm rainfalls and subsequent flash flooding to appropriate local government agencies for action and response before the rainfall begins. In most cases local agencies receive over 3 hour lead times and in cases of severe flooding over 6 hours of lead time to plan and put in place appropriate actions. Henz and Kelly (1985b) summarizes the successes of this program while Kelly and Henz (1985) describes the UDFCD F2-P2 response to a particularly severe heavy rainfall on June 13, 1984. In general the UDFCD F2-P2 has achieved the following degree of success:

a. Since 1979, 194 excessive convective rainfall days have been predicted with a false alarm rate of less than 20 percent.

b. The overall yes/no thunderstorm event day forecast before the first clouds have formed is 98 percent.

c. Most heavy rain events precipitation totals since 1983 have been forecast within $\pm$ 1/2 inch.

These levels of proficiency have resulted in an increased knowledge base from which to assess both in a pre-storm and post-storm mode the flash flooding potential of a given atmospheric structure. This knowledge has been assembled in the Excessive Convective Rainfall (ECR) model which is a physical/statistical model of Henz Kelly & Associates. The assessment of the predictability of Phoenix flash floods was conducted by using the data base discussed in the previous section and conducting operational assimilation runs on the ECR model.

ECR model output predictions were obtained for the following parameters for each day event listed in Table 1:

a. Thunderstorm intensity and severe weather/flash flooding potential
b. Total event rainfall
c. Peak hourly rainfall intensity

d. Likely thunderstorm duration
e. Likely path of thunderstorm systems

Using this ECR model output a comparison was made between the case study recreation of the sequence of flash flooding events in Phoenix and Maricopa County and the ECR model forecasts. Key comparisons included the accuracy of the event day forecast, peak total storm rainfall forecasts in Phoenix and Maricopa County and related peak hourly intensities of thunderstorm rainfall. Since some of the ECR model output depends on man/machine intervention, any post-storm evaluation is only an assessment of potential results. Verification of the model forecasts required the pre-evaluation establishment of what was considered an accurate forecast. Discussions with local engineers and floodplain managers suggested that short duration/high intensity events which produced total storm rainfalls of 0.50 inch or more accumulations usually led to street flooding in Phoenix. This 0.50 inch criteria was used to establish a verification for the occurrence of a flash flood event day. The remainder of the model output was verified against actual observations of the predicted parameter. In most cases objective model output was compared to actual observations of the events.

The results of the ECR model runs achieved the following verification statistics for the 30 event days studied:

a. All event days were correctly forecasted for Phoenix and Maricopa County.

b. In Phoenix on 2 days of the 30 no rainfall reports over 0.50 inch were noted leading to a false alarm rate of 6 percent.

c. In all cases the forecasts were prepared at least 5 hours, and in most cases 8 hours or more in advance of the event.

d. Storm total rainfall forecasts were ± 1/2 inch of the observed value 80 percent of the time. In one case (22 June 1972) 4 inches or more total rain were forecast and 5.25 inches observed. In 4 cases rainfall was overforecast (Figure 2).

e. Peak storm rainfall intensities were overforecast but verification was based on very limited raingage data. However, it is possible that the storm intensity estimates are more representative of storm strength than the limited ground truth (Figure 3).

These statistics are very consistent with those obtained from the operational UDFCD F2-P2 in Denver and the similarity between the Colorado and Arizona meteorological structures earlier noted. One exception to be noted is the artificially low false alarm rate of 6 percent. In practice false alarm rates tend to range from 15-20 percent. The low rate in this study was caused by the use of only known flash flood event days in the sample and many marginal days were artificially dropped. It is believed that a false alarm rate of 15-25 percent or lower would be achieved on an annual basis. The results of this evaluation strongly support that flash flood producing thunderstorms which hazard the City of Phoenix and the Greater Phoenix area can be predicted before they occur with reasonable accuracy to the benefit of the city's residents. A proposed operational configuration and related investments will be posed later

Figure 2 Observed total event thunderstorm rainfall versus ECR model predicted total rainfall for summer season event days in Phoenix

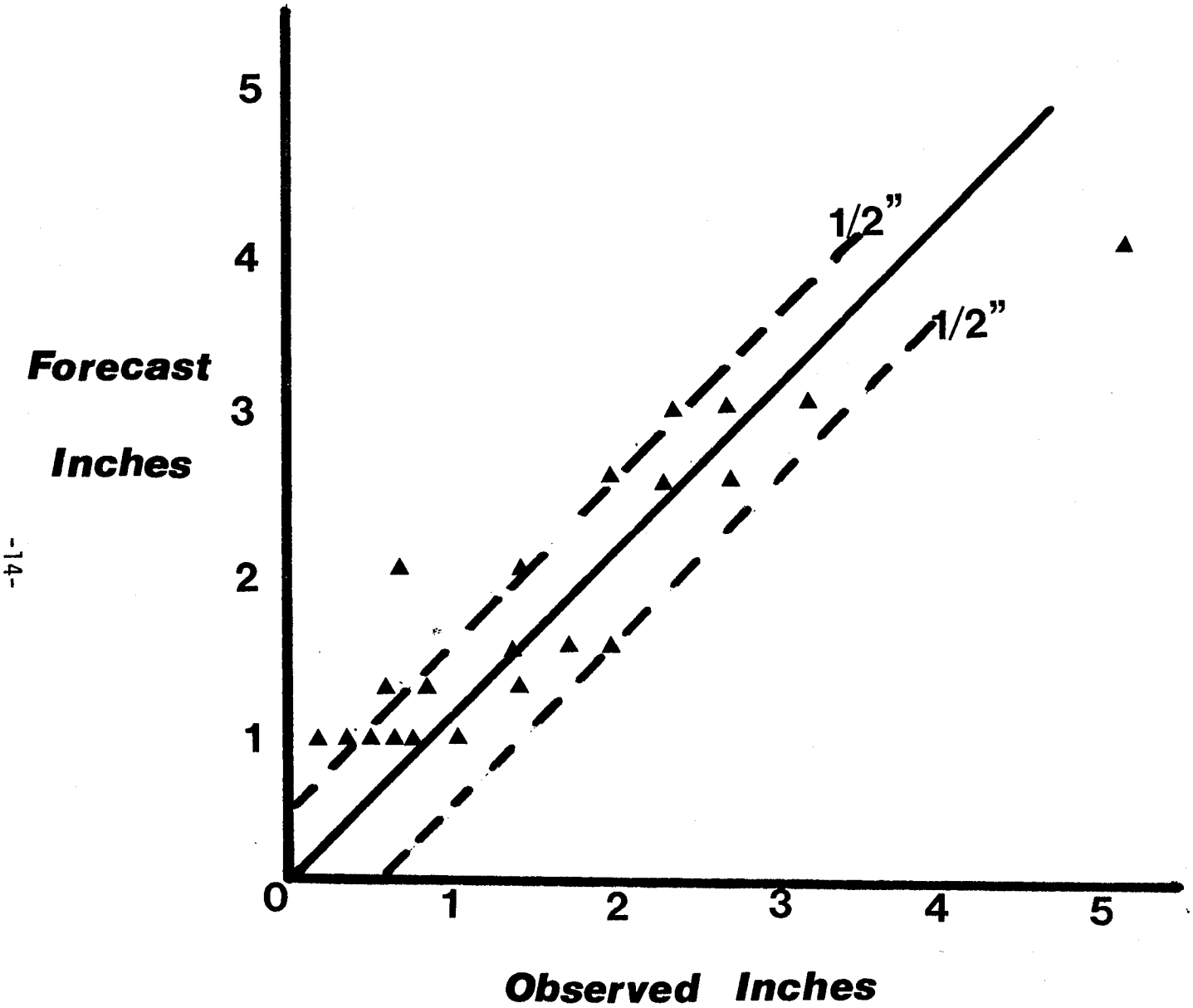
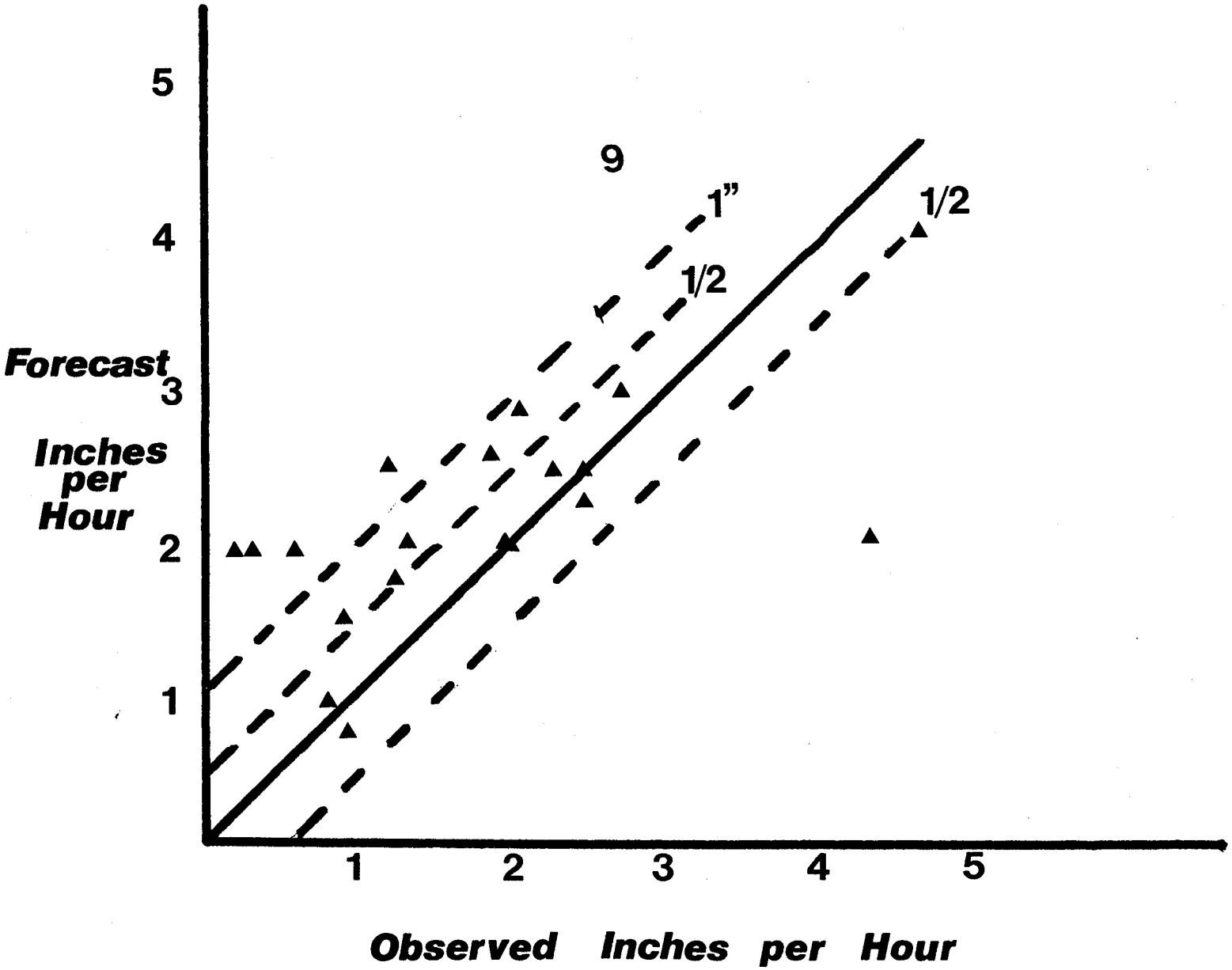


Figure 3 Observed peak hourly intensity versus ECR model predicted peak hourly intensity for summer season event days in Phoenix



in this report. Since a majority of Phoenix' heavy rainfall and flash flooding events occur at night or during the early morning hours a premium on early prediction of the storms is needed to insure adequate city response and mobilization of needed people and resources.

The key points of the predictability assessment and the anticipated results of a Phoenix flash flood prediction program are listed below:

a. 95-100% of the thunderstorm event days producing 0.50 inches or more of rain in Phoenix are predictable.

b. Four out of 5 thunderstorm rainfall forecasts will be correct within Phoenix giving an incorrect thunderstorm forecast only 1 out of 5 times or a 20 percent false alarm rate.

c. Storm total rainfall should be predicted within $\pm$ 0.50 inches 85 percent of the time for the initial forecast. Later updates should be more accurate.

d. It is anticipated that sufficient lead-times will be given for all storm situations to enable city departments to respond to the flash flooding event appropriately. Leadtime will vary from 1-3 hours for lesser events to 6-12 hours for major events.

e. The timing and duration of stormy periods should be quite accurate.

f. Storm tracks will be forecast for the majority of the days but more study is needed to improve knowledge of local variations in storm movement.

g. Basin-specific forecasts will be attempted with 1 hour to 2 hour lead times and improve in accuracy as the program progresses.

2.3 Rainfall Characteristics and Design Storm Criteria

While the primary tasks of this study were directed at the predictability of Phoenix flash floods, several key characteristics in the flash flood day rainfall become evident which directly impact the application of design storm criteria within the city. A companion report authored by Tipton and Kalmbach, Inc. (T&K) referred to as the T&K report is directed more closely at this problem. In general the important characteristics are summarized and then discussed below:

a. Heavy rainfall events occurred more frequently over the northern and eastern thirds of the city.

b. Potential urban effects, topographic effects and preferred storm tracks appear responsible for uneven rainfall distribution across the city.

c. Urban thunderstorms appear to be more intense and of longer duration than typical southwestern thunderstorms.

d. The existing city rain gage network is an invaluable resource but needs to be upgraded to provide the city maximum benefits.

Each of these characteristics, their link to meteorological influences and link to design storm criteria will be summarized in the following paragraphs.

A listing of the annual number of rainfall days occurring from 1975-1985 in the Phoenix rain gage network where at least one gage totaled 0.50 inches or 1.00 inches is given in Figure 4. The trend over the past decade is clearly toward more frequent occurrence of both category rainfalls. This increase could be a reflection of a large scale climatic trend or of an increasing role played by local urban effects on local rainfall patterns. Additionally the areal distribution of the rainfall over Phoenix is clearly non-uniform. For the 30 event days studied Figure 5 shows the total rainfall observed at each of the Phoenix gage sites. Heavier rainfall totals were observed in the northern and east central gage locations compared to the Municipal Building and southern Phoenix sites. The T&K report also indicates the unequal areal rainfall distribution.

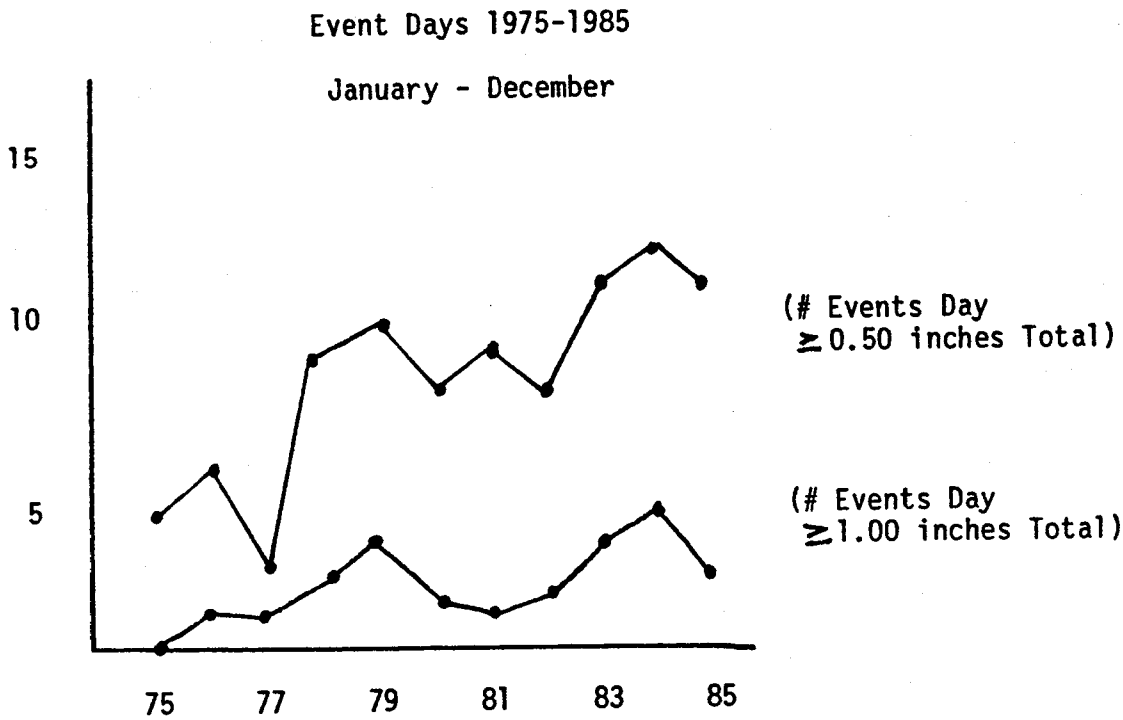
If the trend toward increasing numbers of heavier rain events is climatic in nature, a likely link could be established between the hemispheric general wind patterns for the summer season and the related occurrence of meso/synoptic atmospheric structures conducive to heavy Phoenix rains. In effect this technique boils down to sorting out how frequently thunderstorms forming over favored breeding grounds develop in a moist atmosphere and are steered by the winds down preferred tracks to affect Phoenix. A study over a longer period would likely establish statistically significant results.

On the other hand if climatic influences are not apparent a more subtle reason for increases in heavy rainfall opportunities may be the result of Phoenix's rapid urbanization and growth over the past decade. This urban effect on precipitation, especially on heavy rainfall days, has been documented over Chicago and St. Louis (Changnon 1980), Denver (Henz 1982) and is hinted at in Houston (Bouvette, et al 1982). In each case an increase in downstream rainfall from the urbanized area was noted. Each author noted that increases in the design storm criteria occurred in the 100 year, 24 hour storm in downwind areas while some decreases were noted in the highly urbanized areas. Personal communication between George Sabol of T&K and the authors strongly supports the likelihood that Phoenix is or has experienced a similar urban effect re-distribution of rainfall patterns. A more in-depth study of this effect will be needed to define its specific characteristics and effects on Phoenix' design storms.

A possible source of this potential localized urban re-distribution of rainfall patterns could be changes in localized wind circulations between the heavily irrigated, more rural areas of Maricopa County and the heavily developed, populated, urban areas. Possible sources of the apparent re-distribution of local rainfall may be found in urban effects on localized wind circulations that develop between the heavily irrigated, cool, rural areas of Maricopa County and the warmer, more populated and heavily developed Phoenix urban area. This urban rainfall effect study may be worthy of support by the Maricopa Association of Governments (MAG) because the re-distribution of rainfall and local wind

RAIN EVENT DAYS

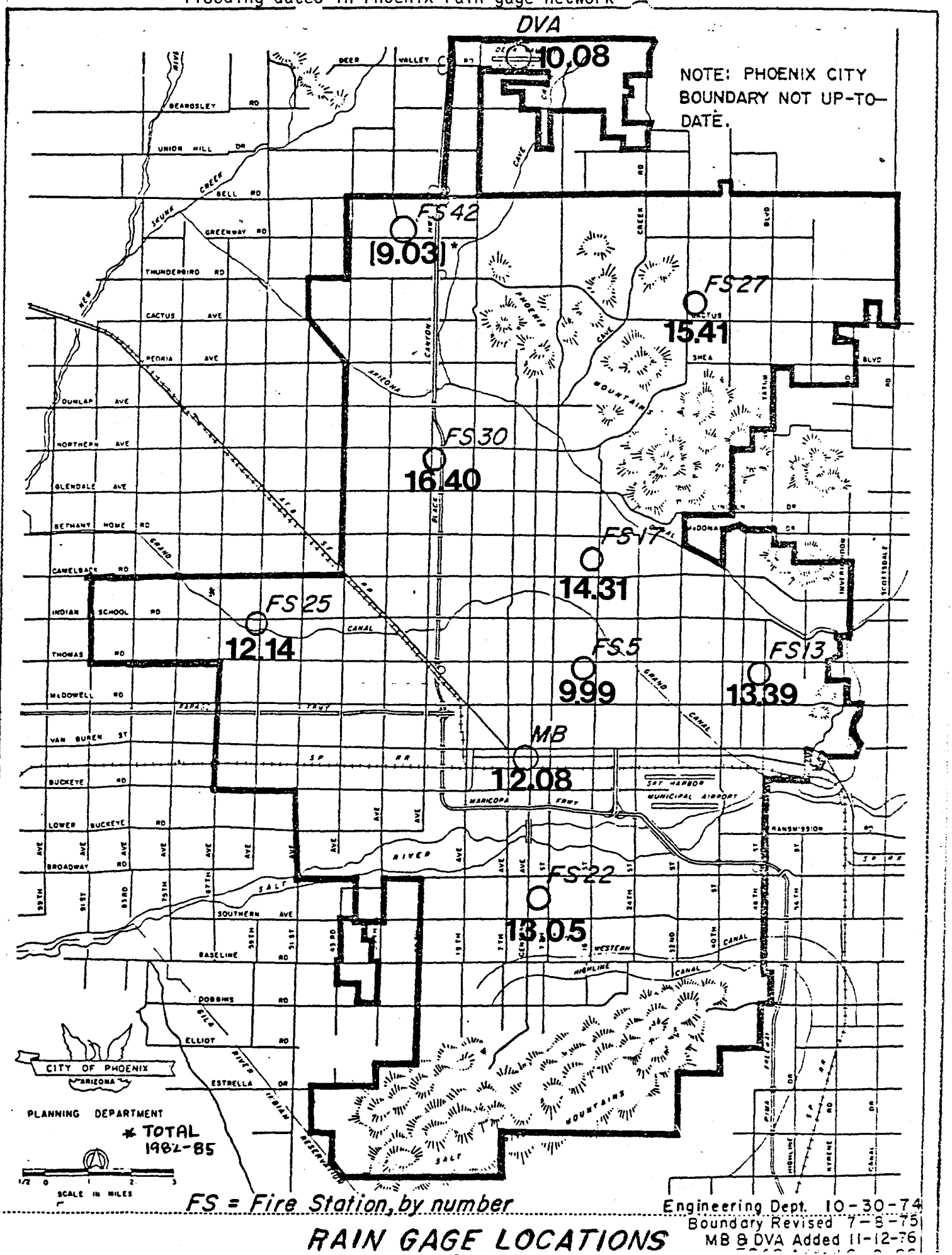
Figure 4 Annual variations in number of event days equal to or exceeding either 0.50 inches or 1.00 inches rainfall at any site in Phoenix rain gage network 1975-1985



The list of number of event days in Phoenix rain gage network with one or more stations ≥ 0.50 inches total 24 hour rainfall or ≥ 1.00 inches total 24 hours rainfall by year 1975-1985.

	0.50 inches	1.00 inches
1975	5	0
1976	6	1
1977	3	1
1978	9	3
1979	10	4
1980	8	2
1981	9	1
1982	8	2
1983	11	4
1984	12	5
1985	11	3

Figure 5 Total rainfall for study event days on Phoenix flash flooding dates in Phoenix rain gage network



circulations appear to be county-wide in scope. Because the potential causes of these circulations may be found across Maricopa County its study may be worthy of support by the Maricopa Associations of Government.

Another interesting aspect of the rainfall characteristics on the event days is that the typical urban thunderstorm systems encountered fit "text-book southwestern thunderstorm" norms only half the time. According to typical descriptions, most southwestern thunderstorms are highly localized, short duration but high intensity storms. Henz (1985) dubbed these storms "front-end dumpers" because of their high intensity rainfall production over a period of 30 minutes or less. He additionally referred to multi-cell thunderstorms or thunderstorm systems composed of two waves of storms as "double-dippers." While of lesser intensity these storm systems are characterized by longer duration and greater total rainfall than front-end dumpers. "General rain" storms refer to the winter storm type generalized rainfall of large areal coverage, low intensity but large general total rainfall. The final category is the "inverted supercell" storm that combines long duration, high intensity and large rainfall/totals into a meteorological disaster. Table 6 shows the general categorization of these four classes of storm rainfalls as they frequented Phoenix on the 30 event days studied. While front-end dumpers did make up about 50 percent of the storms, "double-dippers" or multi-cell organized storm systems made up about 20 percent of the sample. In both classes the storms fit the typical 30 minute duration at a point but only because the storms were moving. The actual storm systems appeared to persist over parts of Phoenix and Maricopa County for periods over 2 hours. In some cases radar at Luke AFB followed the apparent movement of individual storm complexes for periods over four hours. Lack of continuous radar data prevents further speculation on the origin and demise of these storms but they did tend to conform to Hales (1972) observation of initial storm formation over high terrain and subsequent movement to lower elevations within the Salt River Valley. The value of a radar storm track study to confirm the life-cycle tendencies of these storms, their development characteristics over Phoenix proper and relationship to rainfall production and design storms would be considerable.

An attempt was made to trace the movement of thunderstorm systems on each event day as they cross Maricopa County and Phoenix. Use was made of hourly and special radar summaries made by observers at Luke and Williams Air Force Bases. These radar observations were combined with hourly and surface observations of weather and rainfall to synthesize the most likely path and duration of storms in Phoenix. The methodology and results are crude compared to other parts of this study yet they support some very important concepts nonetheless. In general these concepts are listed below:

a. Three preferred thunderstorm tracks appeared:

   1. Southeast Track: This track was active on days with southeasterly thunderstorm steering winds. In general storms entered the southeastern portion of the city between the airport and Fire Station 13, intensified and exited the northwest side of the city near Fire Station 42.

   2. Southwest Track: Storms in this track entered the city in a relatively mature form on the southwest side between the Municipal Building and Fire Station 25. The storms then appeared to intensify and

split as they approached the Phoenix mountains on the city's east side.

3. Northeast Track: A less frequent storm track appeared on days with northeasterly cloud steering winds. On these days storms appeared to form or intensify over or near the northern end of the Phoenix mountains near Fire Station 27 and progressed eastward toward Fire Station 25.

b. The locus of these apparent tracks crossed a region of the northern half of the city which demonstrated heavier rains on the events days of this study.

c. If the thunderstorm characteristics can be quantified relative to rainfall production an explanation for the heavier north and central rainfall pattern can be established.

d. The reason for the apparent preference of thunderstorms for the "tracks" may be topographic causes or urban effect influences on local wind circulations or some yet undiscovered influence.

The apparent tracks are displayed in Figure 6 and they need to be studied more fully as part of a design storm criteria revision program.

Finally the entire rainfall characteristics study couldn't have been performed without the farsighted establishment of the Phoenix rain gage network in 1972. The T&K report directly addresses the importance of the network's long period of record as crucial to accurate assessments of design storm criteria. Its recommendation that the position of the gages remain unchanged is strongly supported. Movement of the gages would change the statistical validity of any data evaluation. Additionally we support the upgrading of the network telemetry for two reasons:

1. Existing telephone links and data recording severely limit the data's usefulness in an operational flash flood prediction program and downgrade the ease of analysis of the data in post-storm periods.

2. While the current positions should not be changed an additional 5-10 gages including 4-5 complete weather stations should be added to define the urban effects problems.

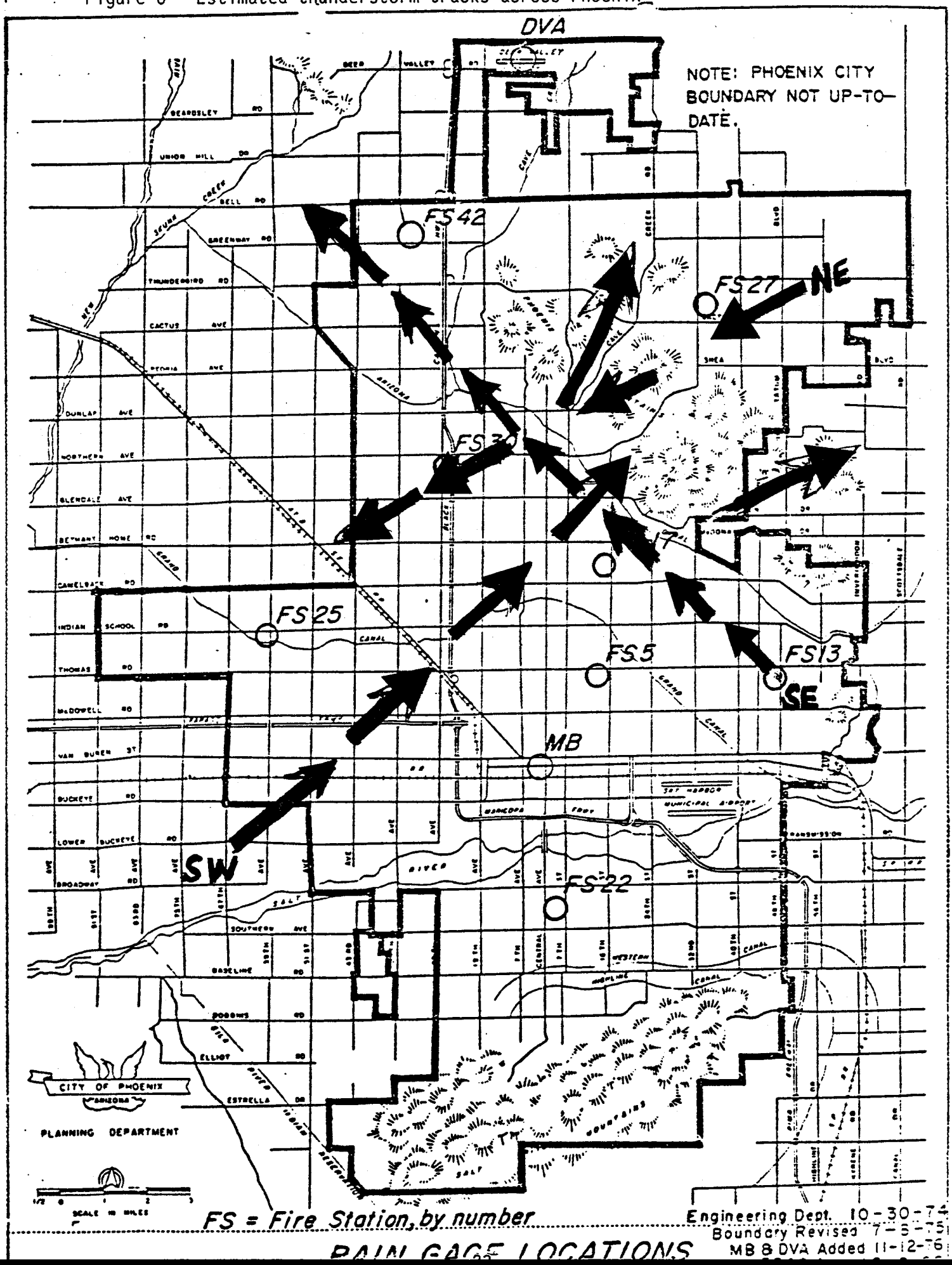
In its present state the Phoenix raingage network relies on an antiquated telephone line system to transfer data from the gages to the Municipal Building. While storm total rainfall data is quite good the current paper record files lack temporal resolution to contract accurate rainfall-time increments. Additionally during periods of heavy or sustained rainfall telephone data transmittal becomes unreliable. The upgrading of the system's data communication system is highly desireable.

As previously mentioned the current site for the rain gages should not be distrubed to preserve the integrity of each site's long term record. However the spacing between gages especially between Fire Station No. 25 and the Municipal Building and Fire Station No. 27 to the western and southwestern borders of the city is over 6 miles (see Figure 1). Many gage sites are over 4 miles apart or

TABLE 6 Estimated thunderstorm type, frequency, intensity, duration and total Phoenix rainfall for study flash flood event days.

Storm Type	Frequency	Duration	Intensity	Total
A. Front-end dumper	50%	.5 hours	1.5-3.5 inches/hr.	.50-1.5 inches
B. Double-dipper	20%	1-2.5 hours	1-2.5 inches/hr.	1.50-3.00 inches
C. General rains	25%	5-20 hours	.1-.5 inches/hr.	1.00-3.50 inches
D. Supercell	5%	2-4 hours	1.5-3.0 inches/hr.	3.00-6.00 inches

Figure 6 Estimated thunderstorm tracks across Phoenix



more. Such large distances between sites allow thunderstorm rainfalls, especially those crossing the city from either southeast to northwest or southwest to northeast, to pass between gage sites. The addition of 6-8 stations would greatly enhance the ability of the network to describe important rainfall patterns in support of both an operational flash flood prediction program and post-storm analyses.

A final recommended augmentation of the network would be the inclusion of 4-5 automated weather station/rain gage sites. These sites would measure temperature, dewpoint, wind speed and direction and rainfall in real time and sent back data to the Municipal Building by radio. The automated weather stations would be used by operational meteorologists to assess the existence of the "Phoenix thunderstorm low" and other weather patterns conducive to thunderstorm intensification and movement across the city. Additionally measurements of temperatures and dewpoint could be used during non-storm periods to assess the potential evapo-transpiration of moisture from city golf courses and parks for water conservation programs. Additional rain gage sites should be added to assist in the design storm criteria update program. A survey is needed to determine the best location for this equipment.

3.0 ASSESSMENT OF EXISTING COMMUNICATIONS AND DATA SOURCES

An important consideration in developing an operational configuration for a flash flood prediction program is the assessment of available communications services and meteorological and hydrological data sources. Information for this assessment was obtained from three sources:

a. A polling of potential city department users and their needs conducted in Phoenix during October 1985.

b. Personal interviews with department representatives conducted over the phone or in-person.

c. Follow-up polling of user resources and needs at the users meeting held in Phoenix during January 1986.

In general the appropriate communications systems are in place and adequate meteorological and hydrological data sources are available within the city to assist the program.

3.1 Communications Sources

The flash flood prediction program is dependent on the availability of reliable communication of the various forecasts and updates to the appropriate users. In general the communications services must relate to two forms of operation: pre-storm and storm environments. During the pre-storm communications phase less demanding needs must be satisfied while critical reliability should be maintained during the storm phases.

Communication during the pre-storm phase is effectively achieved by using normal telephone service and electronic mail transfer of text messages. In general flash flood potential messages will be transmitted daily to the city

department users by electronic mail at pre-arranged times. The existing OASIS system in the city will be adequate for this purpose. After the text message is sent a follow-up voice contact call will be placed by the operational meteorologist to each user to provide additional insight into the day's weather problem or concern. This personal daily contact is a very effective means of establishing trust and rapport between source and user before critical storm situations develop. Additionally the use of a text-pager system should be considered as an option to assist important decision-makers remain cognizant of the situation. The survey indicated that reliable pre-storm telephone service is available and several pager sources can be considered if the decision is made to use that technology. The electronic mail text transfer methodology should be explored in depth but discussions with city computer representatives indicates that the existing OASIS system will be more than adequate to handle the service.

During the storm environment communications must be covered by back-up capabilities which promote reliability. In most storm situations telephone and pager communications will be very useful. But lightning strikes and flash flooding can cause unreliability to become a factor in the non-communication of important messages. For this reason both radio and, possibly cable television provide alternative communications avenues. Existing radio systems used by the fire and police departments or local ham radio operators could be used in critical situations with a transmitting capability brought to or installed at the prediction site. Use of cable television as a communications option could become available by late 1987 or early 1988. A variety of visual and verbal options will exist to interact both with users and possibly the public.

3.2 Meteorological and Hydrologic Data

The acquisition and availability of crucial meteorological and hydrological data during pre-storm and storm periods is necessary for the flash flood prediction program (F2-P2) to be successful. A survey of these data sources available to a Phoenix F2-P2 indicated the necessary data was available.

The meteorological data available to the F2-P2 is listed below:

a. National Weather Service WSR-74c radar observations with a Kavorous Color Computer Radar Receiver capability is available at Sky Harbor Airport.

b) Standard upper air, surface and computer forecast charts are available via commercial satellite link-up.

c. Satellite photo information is available from several sources.

The addition of automated surface weather stations within Phoenix and Maricopa County would be very desirable to the solution of the short range prediction problem. Alternative means of adding these stations should be addressed in a later thorough study. The stations could be used, not only to support the F2-P2, but also to document the causes of "the Phoenix urban effect" or "the Valley urban effect." Additionally these stations would prove very useful in addressing the local air pollution forecast problem.

Hydrological information sources would include those listed below:

a. Phoenix rain gage and storm gage data received from the current/upgraded network.

b. Automated rain gage and stream gage data from Flood Control District of Maricopa County.

c. Automated rain gage, stream gage and weather station data from Salt River Project.

The ability to have real-time access to the above information would greatly enhance the F2-P2. Gaining access through agreement and/or cooperation should be a priority objective of any F2-P2. This data should be readily available to the City of Phoenix and plans to receive and store it should be an integral part of the F2-P2.

4.0 FLASH FLOOD PREDICTION PROGRAM: OPERATIONS AND RESOURCES

The previous two sections provide strong support for the development of a flash flood prediction program (F2-P2) in the City of Phoenix and, possibly, all of Maricopa County. A very successful F2-P2 program has been run by Henz Kelly & Associates in the Denver metropolitan area since 1979. This program is considered by many to be one of the most effective in the nation. The Denver F2-P2 has served as a model for the development of the proposed Phoenix F2-P2 as it will be presented in this report. This section will describe the operations and the resources needed to develop a similar F2-P2 in Phoenix and discuss the additional investments required to expand the program to all of Maricopa County.

4.1 F2-P2 Operations

The goal of the F2-P2 is to provide accurate site-specific forecasts of thunderstorm-produced flash flooding for use by responsive city departments in support of the public. The operations of the program consists of three active phases:

a. Regional assessment to determine the threat of locally heavy thunderstorm rains in the southern half of Arizona which could affect Phoenix within the next 48 hours.

b. Local assessment to determine the impact and potential for flash flooding events to occur in the Phoenix operating area within the next 24 hours.

c. Local support which provides direct support to city departments from 3 hours before to the conclusion of the flash flooding events.

Regional assessments focus on determining the threat that the structure of the atmosphere can produce locally heavy rains over the southern half of the state. The assessments evaluate the presence currently and over the next 48 hours of the meso/synoptic weather features identified in a previous section. If the assessment indicates that a potential for heavy thunderstorm rains is beginning to form over the region or currently exists the assessments begin to focus on impacts of the weather systems on Phoenix. Should the program be

expanded to address all of Maricopa County then analyses will be adjusted to incorporate the new areas.

The local assessment refines the regional analyses to identify the type of thunderstorms that are likely to form and the characteristics of their rainfall. These characteristics include but are not limited to the total storm rainfall, peak storm hourly rainfall intensity, the duration of rainfall, the likely threat period, and the areas of the city or county most likely to be affected by the storms. Additionally the analyses and HKA Excessive Convection Rainfall model runs will predict possible storm tracks and timing of their occurrence. The analyses will also focus on other associated weather events such as, duststorms, high winds, severe lightning, hail and tornadoes which could accompany the thunderstorm systems as they cross the area of concern. If the local assessment indicates that a potential or significant threat of flash flooding exists then the program shifts into the local support mode of operations.

After the regional and local assessments have been completed the operational meteorologist makes a decision on the operating mode of the F2-P2. The proposed modes of operation could be:

a. Mode 0: No threat of thunderstorm flash flooding in the next 24 hours. Additional comments on the opportunity for lesser rains or active thunderstorms without flooding would be mentioned.

b. Mode 1: Heavy thunderstorm rains with potential for flash flooding in the Greater Phoenix area possible later during the day. Additional information will be given on the storm type, intensity, amount and timing as predicted by the HKA ECR model.

c. Mode 2: Flash flooding potential will occur in the city of Phoenix. Additional information on the predicted impacts of the storms will be given.

d. Mode 3: Flash flooding is imminent within Phoenix within a specified period of time. Storm rainfall characteristics, path, timing and basin impact information will be given. Update messages on the storm's progress will be given as necessary.

e. Mode 4: All clear...the threat of flash flooding has cleared the city of Phoenix and a threat no longer exists.

The modes of operation would increase and decrease in response to the predicted or actual threat to the City of Phoenix or Maricopa County. Decision-response matrices should be developed for each city department which would reflect the changes in mode and operational predictions. During periods of flash flooding potential staffing would be on a 24-hour basis and otherwise would be accomplished in a mutually agreed upon manner. All forecasting would be performed by professional meteorologists.

A typical scenario of events might begin with the declaration of Mode 1 by HKA meteorologists shortly before the noon hour with appropriate notification of city departments. The mode declaration would be made after morning regional and

local flash flooding assessments have been completed. Continuous weather analyses would continue at the HKA operations center in Phoenix to pinpoint the seriousness of the flooding threat to Phoenix. After additional analyses confirm the strong likelihood of flash flooding in Phoenix a Mode 2 might be declared by 3:00 PM calling for the threat of thunderstorm-produced flash floods in Phoenix between 8:00 PM and 03:00 AM. Total storm rainfall of 2-4 inches of rain in 3 hours with peak intensity of 2 inches per hour might be forecast to occur in the northern half of the city with 0.50-1.00 inches total rainfall expected in the southern half of the city. Electronic mail messages and follow-up telephone calls to appropriate departments such as fire, police and street maintenance would be made. As the storms approach the city from the southeast update messages are issued over electronic mail and telephone between 5:00 PM and 8:00 PM detailing the storms approach and likely local impacts. A Mode 3 might be declared about 8:00 PM calling for serious thunderstorm flash flooding of 2-4 inches in 2 hours 3 miles either side of a line from Fire Station 13 to Fire Station 42 between 10PM-1AM as the storms progress from southeast to northwest. Additionally west of a line from Fire Station 25 to the Municipal Building less than 0.50 inches of rain is expected.

As the storms approach and cross Phoenix update messages detailing the storm's passage, location and predicted effects on various canals, streets and basins would be released before the storm reaches the area of effect. As the first line of storms moves north of the city, the HKA meteorologist downgrades to a Mode 2 but indicates a second line of storms is entering the valley 25 miles to the south that could reach Phoenix by 3:00 AM. As these storms approach update messages are sent to keep city departments alerted. About 2:30 AM it becomes certain that the second line of storms will pass west of Phoenix and an All-clear Mode 4 is declared. The HKA meteorologist stays on duty until sunrise and until the last storm clears the valley region. Clean-up operations continue in the flooded areas of the city and a F2-P2 report on likely storm rainfall and storm paths, etc. is prepared and released to the city for use in the storms' aftermath by 10:00AM.

The HKA operations center required to support the proposed Phoenix F2-P2 will be located within the city limits and be staffed at contracted levels year-round with emphasis on the wet season(s). HKA resources will provide the appropriate standard weather data for use by HKA F2-P2 meteorologists. The Phoenix operations center would likely be incorporated as an Arizona corporation and computers would be used to prepare all forecasts.

If the F2-P2's focus was enlargened from Phoenix to all of Maricopa County the Phoenix operations center would require additional staffing and an expansion of local data sources. The upgrading of the program would not be difficult and actually offers very attractive returns to members of the Maricopa Association of Governments (MAG). The many benefits of the program could be shared by all MAG members and improve the quality of public services and quality of life in the valley.

4.2 F2-P2 Resources and Investments

The resource and investment presentation in this section considers two alternative configurations to a Phoenix-based flash flood prediction program. The first considers a F2-P2 that only serves the city of Phoenix while the

second alternative considers a MAG supported program which supports all of Maricopa County.

Table 7 summarizes the approximate dollar costs for each alternative assuming a five year commitment to get the F2-P2's started. Considering the cost/benefit analysis the City of Phoenix should anticipate a conservative return in savings of 3-5 times the dollar investment. If a MAG-funded program is considered the potential return to Maricopa County city and county government may approach a return of at least 7-10 times the annual investment each year. These returns are especially significant when considering the shrinking federal dollar availability over the next 5 years. Instead of massive local labor cuts, reduction in services or increased local taxes the potential F2-P2 savings could provide a measure of fiscal stability.

Table 7

Annual Investment in a Five Year Flash Flood Prediction Program for a Phoenix based program serving either Phoenix or Maricopa County.

	Phoenix Only	Maricopa County
Year 1	$150,000	$210,000
Years 2-3	$130,000/year	$180,000/year
Years 4-5	$ 90,000/year	$125,000/year
Total	$590,000	$820,000

Specific cost proposals covering each alternative will be submitted in pre-proposal outline format with this report. More detailed proposals covering each program will be prepared upon request.

5.0 COST/BENEFIT JUSTIFICATION

A favorable cost benefit analysis must be performed in order to justify an operational flashflood program. We believe that the public has developed a predisposition that weather cannot be forecast, and justifiably so based upon their experience. The crime of this predisposition is that the uncertainty of weather forecasting is either assumed, engineered or ignored out of the problem--but the problem does not go away. If you don't address the uncertainty in weather forecasting up front, you'll have to deal with it in unacceptable results. We believe we can take much of the uncertainty out of your weather problems and turn that costly uncertainty into a substantial benefit.

If you wait to measure a flashflood event, it's too late. While measurement has many uses and benefits, with flashfloods the unacceptable result from measuring rather than forecasting comes from insufficient lead time to act. There is certainty in measurement but uncertainty in result. If you minimize the weather uncertainty with a credible forecast, you'll greatly enhance the certainty of a positive result.

In a period of decreasing government and budget cuts, the following

potential benefits from a flashflood program should be considered an investment with a substantial return which would allow allocation of savings from current budgets into other priorities or maintenance of current employment or project levels which would otherwise be cut.

Our initial cost/benefit analysis suggests that the current city response to flashflooding costs Phoenix taxpayers approximately $4.0 million annually. We also believe that improved meteorological input for correct allocation of resources in storm sewer and drainage construction will yield an annual benefit of approximately $3.0 million. While the cost/benefit figures can and should be challenged, the following paragraphs will outline potential benefits attributed to meteorological information in the areas of:

- More effective structural applications such as storm sewers and drainage basins.

- Operational meteorological information as a more attractive alternative to planned structural solutions.

- Not previously realized benefits due to accuracy and timeliness of forecasts.

5.1 MORE EFFECTIVE STRUCTURAL APPLICATIONS

The benefit of quality meteorological information could be derived from improved decisions made from both a planning and operational perspective. Historically, solutions to flood control problems have been almost exclusively structural. Non-structural input in the form of meteorological information can aid in the decisions regarding allocation of resources budgeted for structural solutions.

From a planning perspective a revised design storm criteria needs to be developed so that the budget for flood control and drainage will be allocated to have the highest level of effectiveness. We subjectively believe that improved information on rainfall distribution and frequency will have a positive impact on allocation of resources for flood control and storm drainage of fifteen percent. It is our opinion that the revised storm criteria would allow the re-allocation of funds from areas of the city least likely to experience heavy rains to those areas of the city more susceptible to frequent heavy rains.

A fifteen percent positive impact on an annual budget of approximately $20 million would be $3 million. This impact could be reviewed as increased effectiveness, a savings or monies for additional projects. While not an operational flashflood program benefit, the improved structural solutions will provide some operational structural contribution to the flashflood program.

5.2 OPERATIONAL FLASHFLOOD PROGRAM AS STRUCTURAL ALTERNATIVE

A flashflood program can be justified from the benefits derived not previously enjoyed and possibly as a more desireable alternative to some structural solutions planned for implementation. One consideration for the benefit of a flashflood program as an alternative to a structural solution would be where a particular design for land use is desireable but the structural cost is either marginally justified or prohibitive. It might be prudent to use a flashflood program alternative which could allow the desired land use knowing that in a flooding situation there would be some pre-accepted degree of inconvenience as a tradeoff for land useage and also likely lower taxes to

execute the alternative. An example might be a greenway for recreation or a street in normal conditions blockaded or evacuated and turned into a drainage way during flooding situations.

We would estimate that the flashflood alternative to structural solutions implemented where judged desireable would yield a five percent savings on the total budget for flood control and sewer drainage over the structural solution. A five percent savings on $20 million annually would be $1 million. One percent of the five percent savings could fund the flashflood program with the other four percent for savings, other projects or reduced taxes.

5.3 NOT PREVIOUSLY REALIZED BENEFITS FROM FORECASTS

Benefits to be derived from a flashflood program which have not been previously enjoyed would accrue from the timeliness of forecasts before the fact not reports during or after the fact. There are a number of potential benefits from a flashflood program providing such accuracy and timeliness.

a. INCREASED EFFECTIVENESS PUBLIC SERVICE PERSONNEL

One potential benefit would be in the increased effectiveness of public service personnel from improved direction in a timely manner. Policemen, firemen, emergency preparedness personnel or traffic personnel would be at the right place before the right time. One example would be for the correct blockading of a highway that is going to flood.

One method to quantify the benefit would be to measure the increased effectiveness of public service personnel during stormy periods. An assumption of 200 public service personnel correctly focused in a timely fashion before flooding problems could yield the total difference in effectiveness or non-effectiveness. Assuming that this would occur approximately 32 hours a year, a benefit of approximately $128,000 could be argued. This argument would not be based upon time spent but upon the effectiveness of the time spent.

Overtime is also an important consideration since overtime pay is required instead of comp time. Incorrect determination for the use of overtime when flooding is not a threat would have comparable costs as compared to the 200 public personnel example. It is also as important to know when the danger of flooding is not imminent and manning can be reduced.

b. LIVES NOT LOST

Another method of quantifying the benefits of a flash flood program could be measured in lives saved. While somewhat subjective as to number of lives saved and the value of those lives we would suggest common sense in assigning a dollar value. A government study commissioned by the National Weather Service suggests a life is worth $230,000.

c. PROPERTY DAMAGE AVERTED

Decreased damage to property such as cars, houses, personal belongings, yards, bridges, roads, dams or canals could be considerable. Benefits

could occur as a result of a forecast and the subsequent decision to either blockade streets or areas, dispatch pumpers to areas, release water downstream that would otherwise exaserbate flooding or hold water from causing flooding. While Mother Nature is little modified, she can be listened to and planned for with a credible forecast. The value could easily exceed the expense of a flashflood program. While not documented, it has been suggested that organizations such as Arizona Dept. of Transportation, Maricopa Association of Governments, Salt River Project and Central Arizona Project can suffer damages in the millions of dollars annually, some of which could be averted with a timely, credible forecast.

d. GOLF COURSE WATER SAVINGS

There are a number of potential benefits in the area of water. While again not certain of the correct numbers, if a credible forecast could be made for a day of heavy precipitation, watering could be averted for golf courses and parks. One suggestion was that golf courses pay $1,000 per day for water. With 120 golf courses this would yield $120,000 in one day.

e. WATER MANAGEMENT SAVINGS

Another potential water benefit would be in ordering water to insure no shortages or over-ordering. Phoenix handles approximately 95 billion gallons of water annually which is approximately 291,000 acre-feet. A one percent savings annually in water ordering at $100/acre-foot would yield $291,000. This water dollar savings would result if accurately predicted precipitation water could be used in place of ordered water that would have been discharged downstream due to lack of storage or wet days.

f. WATER TREATMENT SAVINGS

The Environmental Protection Agency requires certain water quality standards. If the capability is available to capture water runoff from thunderstorms then a benefit could occur from a forecast. The first minutes of a thunderstorm wash the majority of contaminants on the ground into storm sewers. If the location and timing could be anticipated a much smaller volume of water could be captured at a significant savings in treatment costs.

g. INCONVENIENCE/PRODUCTIVITY SAVINGS

Another method to measure the benefit of a flashflood program would be a measure of inconvenience or non-productivity of workers. If traffic stoppages can be averted or shortened due to effective actions based upon a credible forecast, that benefit could be quantified. A decision to have employees stay home due to a "flood day" could save employers money. An example would be 5,000 commuters stranded on a highway for two extra hours because detours and pumpers were not established in a timely fashion. 5,000 people for two hours at $20 an hour would be $200,000.

h. LIABILITY/INSURANCE SAVINGS

Decreased insurance premiums and liability losses would occur from improved results and a demonstration to employ the most current technology for solving flooding problems. Insurance is astronomical and lawsuits can range from thousands to millions of dollars.

i. REDUNDANCY SAVINGS

From meetings during the project we have experienced a redundancy in the need for quality weather information with some degrees of duplication in trying to solve the problem by various entities. Entities where a common need could probably be served are Phoenix (specifically the fire department), the Maricopa County Flood Control District and the Salt River Project. It was also suggested that ADOT would have a need for weather information.

j. REDIRECTION BENEFITS

It is probable that the pooling of funds for a common sought solution could justify the flashflood program from current funding levels. We believe very strongly that the usage of rain gages in a measured - computed mode to solve flashflooding problems is doomed to failure because of the flashy nature of flashfloods in the West. That flashiness will not allow sufficient time for response to provide a benefit.

While we strongly endorse raingage networks to provide climatological data bases to be used in planning and storm design, we advise strongly against the use of raingages as a solution to flashflooding. Possibly some of the planned raingage funding could be re-directed into a flashflood program.

k. INTANGIBLE BENEFITS

There are also a number of "intangibles" related to a flashflood program which are:

1. Social - the social benefit would be the public safety provided and the feeling of security that it brings.

2. Public Service - actual perceptions of public service would change from complaints to endorsements.

3. Image - A progressive image in problem solutions would aid in attracting business and tourism.

4. Personal - Personal benefits from a flashflood program would include improved job satisfaction, more self-actualization, more family time and increased job security.

5. Political - Improved public service, increased influence and an enhanced political future.

The potential dollar benefit for each of these features is summarized in Table 8 while Appendix B presents the assumptions and calculations used to derive the benefits.

TABLE 8

PHOENIX BENEFIT RECAP

Section I.D.		Feature	Annual Dollar Benefit (Millions)
5.1		Structural Allocation*	3.000
5.2		Structural Alternative	1.000
5.3	a.	Personnel Effectiveness	0.128
	b.	Lives Saved	0.230
	c.	Property Damage Averted	1.000
	d.	Water-Golf Saved	0.480
	e.	Water Management Savings	0.291
	g.	Productivity Gain	0.800
	h.	Legal/Insur Savings	0.125
Total			7.054

* A Design Storm, not a Flashflood Program Benefit

NOTE: Further details concerning assumptions, formulas and results are presented in Appendix B

6.0 CONCLUSIONS AND RECOMMENDATIONS

A thorough meteorological assessment was completed of the causes and predictability of flash flooding events affecting Phoenix, Arizona. Additionally the characteristics of the rainfall produced by those events and the availability of resources to establish a Phoenix-based flash flood prediction program were evaluated. The results of those studies are listed below:

a. The atmospheric structure which produces Arizona flash flooding events conforms to that found in the other western states.

b. Thunderstorm systems occurring mainly during the nighttime or early morning hours produce most of the heavy rains.

c. A predictability assessment of these thunderstorm systems using the HKA Excessive Convective Rainfall model indicates that all events are predictable with a forecast false alarm rate of less than 20 percent.

d. Reasonably accurate forecasts of total storm rainfall and peak storm intensity are possible before the event begins.

e. Apparent urban effects have altered the distribution and frequency of heavy rain eveents in Phoenix and likely a good deal of Maricopa County.

f. Evidence exists which supports the presence of preferred storm tracks which cross the city and county. These tracks may be caused by topographical or urban influences. The tracks have a profound effect on altering the return frequency of heavy rain events across the city and subsequently design storm criteria.

g. The rain gage network established by the city is a valuable resource for performing rainfall characteristics studies within Phoenix.

h. A Phoenix-based flash flood prediction program (F2-P2) can be economically established and provide timely, accurate forecasts of flash flooding events to response-based city departments before flash flooding begins.

i. A Phoenix F2-P2 can easily be expanded to provide similar flash flood prediction services to all of Maricopa County.

These conclusions and results are very supportive of the following recommendations which are made by the authors to the City of Phoenix for consideration and implementation:

a. A five year Phoenix flash flood prediction program (F2-P2) should be funded to enhance the safety of Phoenix residents and improve city services. Preliminary cost/benefit analyses suggest a potential $4 million savings if the F2-P2 is implemented.

b. The City of Phoenix should consider the advantages of expanding the proposed F2-P2 to include all of Maricopa County through the assistance

of the Maricopa Association of Governments.

c. The existing Phoenix rain gage network should be upgraded to improve system data collection reliability. An automated weather station network should be implemented to support flash flood prediction. Rain/stream gage sites should be added to enhance revision of design storm criteria. Existing rain gage sites should not be moved to preserve their statistical significance for future studies and court case usage.

d. A radar precipitation mapping program should be initiated to identify potential urban effects and topographic influences on the areal and frequency distribution of heavy rainfall as they pertain to revision of existing storm criteria and land use planning.

It should be noted that all the above recommendations can be consolidated into two specific programs: the funded flash flood prediction program and a funded revision of the design storm criteria. Both of these programs will derive immediate benefits from the other's existence but can remain mutually exclusive if necessary.

REFERENCES

Bouvette, T.C., J.L. Lambert and P.B. Bedient, 1982: Revised rainfall frequency analysis for Houston. Journal of the Hydraulics Division, Proceedings of the American Society of Civil Engineers, ASCE, Vol. 108, No. HY4, April 1982.

Changnon, S.A., 1980: Evidence of urban and lake influences on precipation in the Chicago area. Journal of Applied Meteorology, Volume 112, No. 10 p1137-1159.

Corps of Engineers, U.S. Army Engineer District, Los Angeles, 1974: Gila River Basin, New River and Phoenix City Streams, Arizona, Design Memorandum No. 2, Hydrology, Part 1, 51pp.

Hales, J.E., Jr., 1972: A study of radar echo distribution in Arizona during July and August. NOAA Tech. Memo. NWS WR77, July.

1974: Southwestern United States summer monsoon source - Gulf of Mexico or Pacific Ocean? Journal of Applied Meteorology, Volume 13, 331-342.

Henz, J.F., 1976: Meteorological aspects of the Big Thompson Canyon Flood, Chap. II, The Big Thompson Flood of 1976, 1976 Annual Meeting of the Geological Society of American p8-20.

,1977: A broadcast/research meteorologist reflects on the Colorado Big Thompson Flood of 31 July 1976. Presented at the Annual Meeting of American Meteorological Society, Jan. 17-20, 1977, Tucson, Arizona.

,1980: Success and problems encountered in predicting flash flood potential in both urban and foothills locales. Preprints, Second Conference on Flash Floods, March 18-20, 1980, American Meteorological Society, Boston, 155-160.

,1982: Radar precipitation mapping and tracking for the Denver Regional Urban Runoff Program. Final Report to Urban Drainage and Flood Control District, Denver, 48pp.

and R.A. Kelly a, 1985: Thunderstorm rainfall: Storm development, rainfall formation and flash flood prediction. Rainfall-Runoff Modeling: A Symposium Sponsored by the Arizona Floodplain Management Association, Phoenix, 34pp.

b, 1985: The Denver flash flood prediction program - A joint hydrometeorological effort. Paper presented at Joint Session of 14th Conference on Severe Local Storms and Sixth Conference on Hydrometeorology, American Meteorological Society, 8pp.

Kelly, R.A. and J.F. Henz, 1985: Operational prediction of the Denver severe hail/rainstorm of 13 June 1984. Joint session of 14th Conference on Severe Local Storms and Sixth Conference on Hydrometeorology, American Meteorological Society, 9pp.

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. Preprint. 10th Conference on Severe Local Storms, American Meteorological Society, Boston, 364-372.

,L. R. Hoxit and F. Canova, 1980: Meteorological characteristics of heavy precipitation and flash flood events over the western United States. NOAA, Tech. Memo. ERL APCL-23, Boulder, 87pp.

Osborn, H.B. and J.R. Simanton: Use of radar as a supplement to raingage networks. 183-186.

Randerson, R., 1976: Meteorological analysis for the Las Vegas, Nevada, Flood of 3 July 1975. Monthly Weather Review, Volume 104, No. 6, 719-727.

Storm Data, 1978-84: NOAA publication Vol. 9-26. National Climate Data Center, Asheville, N.C.

Szoke, E.J., M.L. Weisman, J.M. Brown, F.X. Caracena, and T.W. Schlatter, 1984: A subsynoptic analysis of the 3 June 1981 Denver tornadoes. Monthly Weather Review, Vol. 112, 790-808.

Appendix A: Data Sources and Case Study Methodology

This appendix describes the data sources used in the attached study and the methodologies used to perform analyses and case studies. In all cases standard techniques were used where applicable.

A.1 Data Sources

The primary data sources used to perform the meteorological analyses were obtained from the National Climate Center (NCC) in Ashville, North Carolina. All sources used were the standard data fields prepared by the National Weather Service's National Meteorological Center (NMC). The data fields are listed below:

a. Standard 850, 700, 500, 300 and 200MB charts for 0000GMT and 1200GMT for the day before through the day after the flash flooding event.

b. Radiosonde data for 0000 and 1200GMT from Tucson and Winslow, Arizona for the day before through the day after the flash flooding event.

c. Three hourly surface analyses for the United States for the event days including Arizona.

d. Hourly surface observations taken by the National Weather Service at Sky Harbor Airport, and by the Air Weather Service at Luke Air Force Base and Williams Air Force Base on the event days.

e. Climatological Data: Arizona as published with temperatures and precipitation records by the NCC for the months of the events.

f. Storm data as published by the National Climate Center with summaries prepared by the NWS of severe weather events that occurred in Arizona for the days of the events.

Additionally, precipitation records were obtained for event days from the City of Phoenix rain gage network through the City Engineer's office. The Arizona State Climatologist's office prepared event day rainfall totals maps, and when available, peak storm intensity data for all event days. This rainfall information along with the NCC-supplied data were used to synthesize event rainfall plots which were used to describe storm rainfall and characteristics.

Thus all the data used in this study was from commonly available data sources. In operational practice all the data used in this study was derived from NMC and would be available along with numerical guidance products not used in this evaluation. On the other hand the information in the Storm Data and Climatological Data publications would not have been available. Hourly surface observations would have been available on normal data lines. Additionally satellite photos would have been available every 30 minutes and radar updates approximately every 5 minutes that were not used in this study.

A.2 Case Study Methodology

The data described in the previous section was integrated into an event day data package. Standard analyses were performed on the upper air charts (850-200MB) and the upper air soundings to identify the meso/synoptic weather features that were present over Arizona in the pre- through and post-storm environment. Two independent analyses were performed by both principal investigators to ensure some degree of impartiality to the analyses.

After these analyses were performed the data was run through the HKA Excessive Convective Rainfall model in a simulated operational environment to obtain forecasts of total storm rainfall, peak storm intensity, storm path and associated weather. The forecasts were derived objectively on the model for each event day until the model indicated that the threat period should be over. The predicted duration of the event was noted and compared to the available verification data. Comparisons were then made of forecast versus observed variables for all the event periods.

At the completion of the model runs and subsequent verification of the results the case study was considered over. Additional verification data was acquired for two case days, June 22, 1972 and July 17/18, 1984 which was used in the final evaluations.

Appendix B: Cost/Benefit Categories, Assumptions, Formulas and Results

The formulas and calculations used to derive appropriately listed benefits from Chapter 5 are presented below. These calculations are based on assumptions made by the authors and can and should be revised to figures judged more appropriate by the user.

5.1 Meteorological information for more effective allocation of resources used in structural solutions (not flashflood program related):

Assumptions:
- $20 Million Annual Budget
- Improved Effectiveness 15%

Formula:

$20 Million x 15% = $3 Million Annually

5.2 Flashflood program as more effective alternative contributing 5% improved effectiveness as compared to structural solution:

Assumptions:
- $20 Million Budget Annually
- 5% Improved Effectiveness

Formulas:

$20 Million x 5% = $1 Million Annually

5.3 Newly realized benefits from a flashflood program:

A. Increased effectiveness public service personnel

Assumptions:
- 200 people
- for 8 hours
- @ $20/hour
- 100% effective versus 0% due to timely forecast providing direction
- occurring 4 days/year

Formula:

200 People x 8 Hours x $20/HR x 4 days/year = $128,000/year

B. Lives not lost

Assumptions:
1 life saved per year
1 life = $230,000

Formula:

1 Life x $230,000/Life = $230,000

C. Property Damage Averted

Assumptions:
0 to $10 Million Damage Annually
Average $5 Million
20% could be averted with forecasts

Formula:

$5 Million Damage Annually x 20% = $1 Million

D. Golfcourse savings from not watering on precipitation days

Assumptions: 120 golf courses
$1000/day/golf course for water
4 days per year

Formula:
120 Courses x $1000/Day x 4 Days/Year = $480,000

E. Savings from water management

Assumptions: 291,000 acre-feet/year
$100/acre-foot
1% savings not ordering on precipitation days

Formula:
291,000 AF x 1% Savings x $100/AF = $291,000

G. Legal judgements/insurance premiums concerning liability

Assumptions: 1 unfavorable lawsuit judgement
1 judgement = $125,000

Formula:
1 Suit x $125,000 Per Suit = $125,000