January 1994

Antecedent Moisture Conditions for Utah Local Storm Probable Maximum Floods

Travis S. Taylor

David S. Bowles

Recommended Citation

Taylor, Travis S. and Bowles, David S., "Antecedent Moisture Conditions for Utah Local Storm Probable Maximum Floods" (1994). *Reports.* Paper 59.
https://digitalcommons.usu.edu/water_rep/59

ANTECEDENT MOISTURE CONDITIONS FOR UTAH LOCAL STORM PROBABLE MAXIMUM FLOODS

by

Travis S. Taylor
and
David S. Bowles

Utah Water Research Laboratory
Utah State University
Logan, UT 84322-8200

1994

TABLE OF CONTENTS

Page

LIST OF TABLES

LIST OF FIGURES

Figure Page

1.0 INTRODUCTION

The critical inflow design flood for most dams in Utah is the probable maximum flood (PMF) resulting from the local storm probable maximum precipitation (PMP) event. Commonly, the Soil Conservation Service (SCS) curve number method is used to determine the PMF from the local storm PMP. An important factor in this determination is the assumption of antecedent moisture conditions (AMC) existing immediately prior to the onset of the PMP event. At one northern Utah dam site the use of AMC III increased the PMF peak flowrate by 50 percent over the peak obtained when AMC II was used (Win 1993).

In this study we explore the occurrence of AMC II (average) and III (saturated) conditions at locations throughout Utah. The occurrence of AMC II or III, which is defined by the magnitude of rainfall over the previous five days, is shown to be independent of the magnitude of precipitation on the sixth day. Also, the probability of occurrence of AMC II and III during the critical months for local storm PMP is shown to be low. While these conclusions do not rule out the possibility of the joint occurrence of a PMP event and AMC III, they do demonstrate that it is an unlikely event. If AMC II is accepted for use in local storm PMF determinations in Utah, a significant reduction in Utah PMF peak flowrates can be expected. In any event, this study should be an important contribution to the evaluation of dam safety in Utah through providing a better basis for the selection of AMC conditions in PMF determinations.

Throughout the course of this research, we have chosen to take the conservative approach to the study. It is the intent of this research to evaluate the use of AMC II or III in semi-arid and arid Utah. Trends were evaluated using upper limits instead of averages and snowmelt was included as a contributor to soil saturation. It is our belief that if one can disprove a theory or practice by being conservative, it is a much stronger case than if a more liberal approach were taken.

1.1 Background

In Utah alone, there are 227 high hazard dams (Borgione 1994). Many of these dams were built in the 1930's and 40's and are in need of reevaluation as far as their structural stability and their ability to withstand floods. The methods of evaluating a possible flood that could occur in the basins above these dams were, in many cases, developed in other parts of the country and are based on assumptions and procedures which have not been fully tested for Utah conditions. The goal of this work was to evaluate some assumptions made in the SCS Curve Number Method which is commonly used to evaluate PMF hydrographs resulting from local summer storms. In particular, the evaluation of the appropriateness of the standard assumption that saturated antecedent moisture conditions (AMC III) be used for the development of the Probable Maximum Flood.

Questions have arisen as to the validity of using AMC III (saturated) for PMF determinations in arid and semi-arid areas such as Utah. The Federal Energy Regulatory Commission has, in at least one case, approved the use of AMC II (average) for PMF evaluation in Utah (Stauffer, 1993). The Utah State Engineer's Office is also open to the use of AMC II, if justified. As part of a project commissioned by the Utah State Engineer's Office, this study investigates the recorded storms and their antecedent moisture conditions, to assess the justification for the use of AMC II or III in Utah PMF determinations.

1.2 Objectives

The focus of the proposed research is to study point precipitation records of summer storms throughout Utah. Specific objectives of this research project are:

1) Assess the statistical significance of the correlation between sixth-day rainfall event magnitudes and the corresponding five-day precipitation totals which are used to define antecedent moisture conditions.
2) Estimate the probability of occurrences of AMC II and III conditions.
3) Evaluate the existence of regional patterns in:
    a) the correlations calculated under Objective 1, if these correlations are significant; and
    b) the probability of occurrence of AMC II and III conditions.

2.0 LITERATURE REVIEW

2.1 Introduction

When a dam is built, it is designed to withstand a particular flood. This inflow design flood (IDF) in Utah is, by default, required to be the probable maximum flood (PMF) for all high and moderate hazard dams (Morgan and Hall 1993), although in some circumstances the State Engineer may approve an IDF as low as the flood based on the 100 year precipitation event or adjust the antecedent soil moisture conditions to less than saturated. The current method for evaluating the probable maximum flood among practicing engineers in Utah is to obtain a probable maximum precipitation storm from the National Weather Service's Hydrometeorological Report (HMR) 49. The storm is positioned over a basin to maximize the resulting PMF. Characteristics such as soil types, area, curve numbers (in the case of local storm floods), and length of channel are calculated for the basin, or for subbasins in the case of a larger basin. The conversion of rainfall to runoff is usually achieved using a hydrologic model such as the U.S. Army Corps of Engineers' HEC 1 model.

2.2 Probable Maximum Precipitation

Probable maximum precipitation (PMP) is defined by Hansen, Schreiner, and Miller (1982) as being "theoretically the greatest depth of precipitation for a given duration that is physically possible over a given size storm area at a particular geographical location at a certain time of the year." PMP should be taken as an estimate since not all of the parameters which contribute to extreme events are quantifiable or even recognized.

This report is used to obtain estimates of either the general-storm PMP or the local-storm PMP. In this study we are concerned only with local storms, occurring in the summer, since according to HMR 49, the critical inflow design event for most dams in Utah are generated by local storm events occurring in the summer months as shown in Figure 2.1. Except for a small portion in the North-West corner of the state where "critical local storm months" are June and July, HMR 49 attributes critical local storms occur to the summer months of July and August. We will refer to the North-West corner of the state as Region A, and the remainder of the sate as Region B.

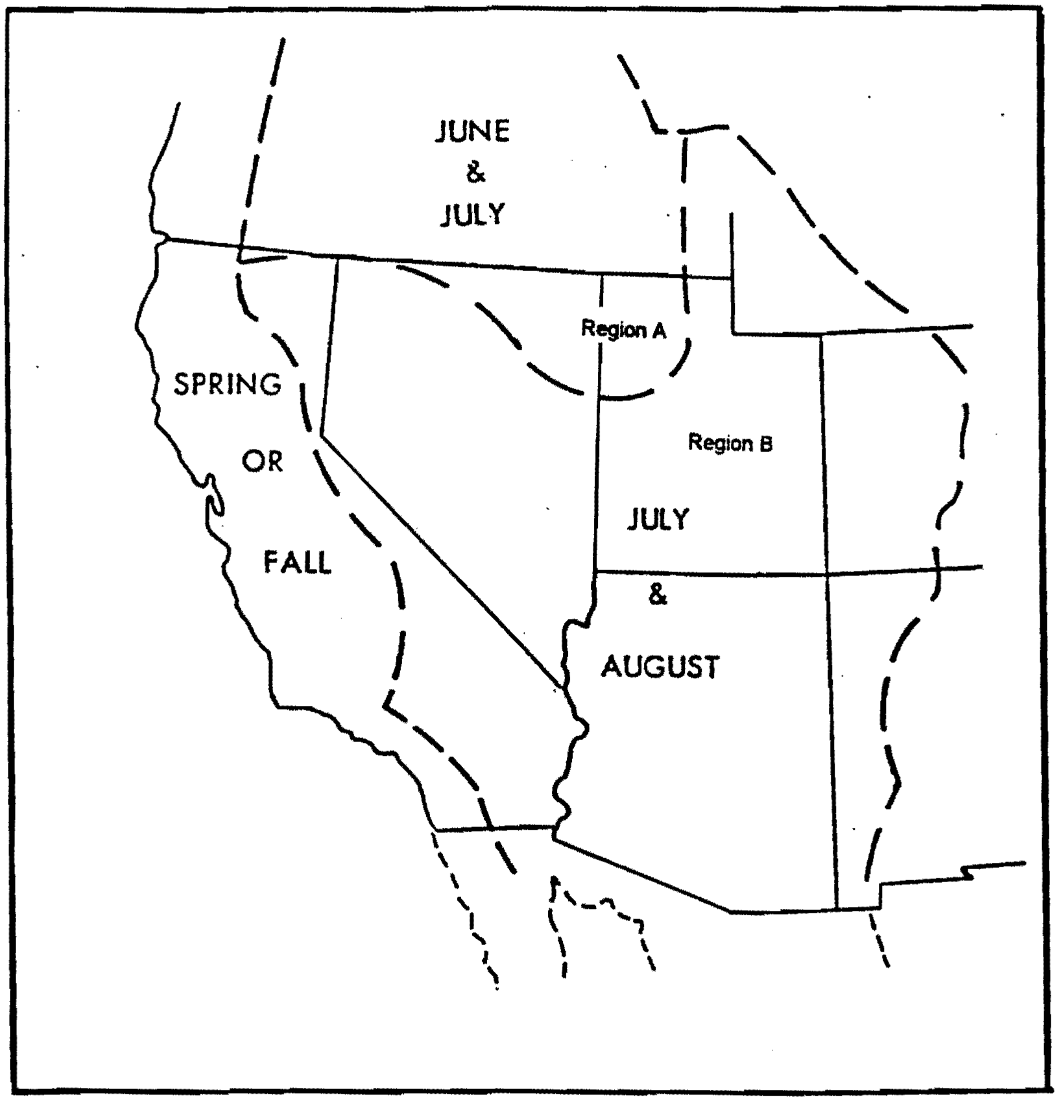


Figure 2.1 Regional Variation of Critical Local Storm Month (After Hansen et al. 1977)

2.3 Curve Numbers

The Soil Conservation Service's curve numbers are dimensionless numbers indicating the runoff potential of a basin. The development of the curve number method was based on 24-hour rainfall-runoff data. On a scale of 0 to 100, a curve number of 100 would represent an impervious surface, while for vegetated surfaces the curve number would be below 100. The curve number is based on the four following catchment properties as described by Ponce (1985):

1) Hydrologic soil group
2) Land use and treatment
3) Ground surface conditions
4) Antecedent moisture conditions

The curve number is used in conjunction with the precipitation to calculate a runoff hydrograph using the following equation (Ponce 1985):

$$Q = \frac{[CN(P+2)-200]^2}{CN[CN(P-8)+800]} \tag{2.1}$$

Where: CN = Curve number

P = Precipitation in inches

Q = Runoff in inches

Typical curve numbers for AMC II are presented in Tables 2.1 to 2.4 for arid and semi-arid rangelands, urban areas, cultivated agricultural lands, and other agricultural lands (SCS 1990).

Table 2.1 Runoff Curve Numbers for Arid and Semi-arid Rangelands (After SCS 1990)

Cover description		Curve numbers for hydrologic soil group—			
Cover type	Hydrologic condition[2]	A[3]	B	C	D
Herbaceous—mixture of grass, weeds, and low-growing brush, with brush the minor element.	Poor		80	87	93
	Fair		71	81	89
	Good		62	74	85
Oak-aspen—mountain brush mixture of oak brush, aspen, mountain mahogany, bitter brush, maple, and other brush.	Poor		66	74	79
	Fair		48	57	63
	Good		30	41	48
Pinyon-juniper—pinyon, juniper, or both; grass understory.	Poor		75	85	89
	Fair		58	73	80
	Good		41	61	71
Sagebrush with grass understory.	Poor		67	80	85
	Fair		51	63	70
	Good		35	47	55
Desert shrub—major plants include saltbush, greasewood, creosotebush, blackbrush, bursage, palo verde, mesquite, and cactus.	Poor	63	77	85	88
	Fair	55	72	81	86
	Good	49	68	79	84

[1] Average runoff condition. For rangelands in humid regions, use table 2-3b.

[2] *Poor:* <30% ground cover (litter, grass, and brush overstory).
Fair: 30% to 70% ground cover.
Good: >70% ground cover.

[3] Curve numbers for group A have been developed only for desert shrub.

Table 2.2 Runoff Curve Numbers for Urban Areas (After SCS 1990)

Cover description		Curve numbers for hydrologic soil group—			
Cover type and hydrologic condition	Average percent impervious area[2]	A	B	C	D
Fully developed urban areas (vegetation established)					
Open space (lawns, parks, golf courses, cemeteries, etc.)[3]:					
Poor condition (grass cover < 50%)		68	79	86	89
Fair condition (grass cover 50% to 75%)		49	69	79	84
Good condition (grass cover > 75%)		39	61	74	80
Impervious areas:					
Paved parking lots, roofs, driveways, etc. (excluding right-of-way)		98	98	98	98
Streets and roads:					
Paved; curbs and storm sewers (excluding right-of-way)		98	98	98	98
Paved; open ditches (including right-of-way)		83	89	92	93
Gravel (including right-of-way)		76	85	89	91
Dirt (including right-of-way)		72	82	87	89
Western desert urban areas:					
Natural desert landscaping (pervious areas only)[4]		63	77	85	88
Artificial desert landscaping (impervious weed barrier, desert shrub with 1- to 2-inch sand or gravel mulch and basin borders)		96	96	96	96
Urban districts:					
Commercial and business	85	89	92	94	95
Industrial	72	81	88	91	93
Residential districts by average lot size:					
1/8 acre or less (town houses)	65	77	85	90	92
1/4 acre	38	61	75	83	87
1/3 acre	30	57	72	81	86
1/2 acre	25	54	70	80	85
1 acre	20	51	68	79	84
2 acres	12	46	65	77	82
Developing urban areas					
Newly graded areas (pervious areas only, no vegetation)[5]		77	86	91	94
Idle lands (CN's are determined using cover types similar to those in table 2-2a).					

[1] Average runoff condition.

[2] The average percent impervious area shown was used to develop the composite CN's. Other assumptions are as follows: impervious areas are directly connected to the drainage system, impervious areas have a CN of 98, and pervious areas are considered equivalent to open space in good hydrologic condition.

[3] CN's shown are equivalent to those of pasture. Composite CN's may be computed for other combinations of open space cover type.

[4] Composite CN's for natural desert landscaping should be computed based on the impervious area (CN = 98) and the pervious area CN. The pervious area CN's are assumed equivalent to desert shrub in poor hydrologic condition.

[5] Composite CN's to use for the design of temporary measures during grading and construction should be computed using the degree of development (impervious area percentage) and the CN's for the newly graded pervious areas.

Table 2.3 Runoff Curve Numbers for Cultivated Agricultural Lands (After SCS 1990)

Cover description			Curve numbers for hydrologic soil group—			
Cover type	Treatment[2]	Hydrologic condition[3]	A	B	C	D
Fallow	Bare soil	—	77	86	91	94
	Crop residue cover (CR)	Poor	76	85	90	93
		Good	74	83	88	90
Row crops	Straight row	Poor	72	81	88	91
		Good	67	78	85	89
	Straight row + CR	Poor	71	80	87	90
		Good	64	75	82	85
	Contoured (C)	Poor	70	79	84	88
		Good	65	75	82	86
	Contoured + CR	Poor	69	78	83	87
		Good	64	74	81	85
	Contoured & terraced (C&T)	Poor	66	74	80	82
		Good	62	71	78	81
	Contoured & terraced + CR	Poor	65	73	79	81
		Good	61	70	77	80
Small grain	Straight row	Poor	65	76	84	88
		Good	63	75	83	87
	Straight row + CR	Poor	64	75	83	86
		Good	60	72	80	84
	Contoured	Poor	63	74	82	85
		Good	61	73	81	84
	Contoured + CR	Poor	62	73	81	84
		Good	60	72	80	83
	Contoured & terraced	Poor	61	72	79	82
		Good	59	70	78	81
	Contoured & terraced + CR	Poor	60	71	78	81
		Good	58	69	77	80
Close-seeded or broadcast legumes or rotation meadow	Straight row	Poor	66	77	85	89
		Good	58	72	81	85
	Contoured	Poor	64	75	83	85
		Good	55	69	78	83
	Contoured & terraced	Poor	63	73	80	83
		Good	51	67	76	80

[1] Average runoff condition.

[2] *Crop residue cover (CR)* applies only if residue is on at least 5% of the surface throughout the year.

[3] Hydrologic condition is based on combination of factors that affect infiltration and runoff, including (a) density and canopy of vegetative areas, (b) amount of year-round cover, (c) amount of grass or close-seeded legumes in rotations, (d) percent of residue cover on the land surface (good ≥ 20%), and (e) degree of surface roughness.
Poor: Factors impair infiltration and tend to increase runoff.
Good: Factors encourage average and better than average infiltration and tend to decrease runoff.

Table 2.4 Runoff Curve Numbers Other Agricultural Lands (After SCS 1990)

Cover description		Curve numbers for hydrologic soil group—			
Cover type	Hydrologic condition	A	B	C	D
Pasture, grassland, or range—continuous forage for grazing.[2]	Poor	68	79	86	89
	Fair	49	69	79	84
	Good	39	61	74	80
Meadow—continuous grass, protected from grazing and generally mowed for hay.	—	30	58	71	78
Brush—brush-weed-grass mixture with brush the major element.[3]	Poor	48	67	77	83
	Fair	35	56	70	77
	Good	30[4]	48	65	73
Woods-grass combination (orchard or tree farm).[5]	Poor	57	73	82	86
	Fair	43	65	76	82
	Good	32	58	72	79
Woods[6]	Poor	45	66	77	83
	Fair	36	60	73	79
	Good	30[4]	55	70	77
Farmsteads—buildings, lanes, driveways, and surrounding lots.	—	59	74	82	86

[1] Average runoff condition.

[2] *Poor:* <50% ground cover or heavily grazed with no mulch.
Fair: 50% to 75% ground cover and not heavily grazed.
Good: >75% ground cover and lightly or only occasionally grazed.

[3] *Poor:* <50% ground cover.
Fair: 50 to 75% ground cover.
Good: >75% ground cover.

[4] Actual curve number is less than 30; use CN = 30 for runoff computations.

[5] CN's shown were computed for areas with 50% woods and 50% grass (pasture) cover. Other combinations of conditions may be computed from the CN's for woods and pasture.

[6] *Poor:* Forest, litter, small trees, and brush have been destroyed by heavy grazing or regular burning.
Fair: Woods are grazed but not burned, and some forest litter covers the soil.
Good: Woods are protected from grazing, and litter and brush adequately cover the soil.

2.4 Hydrologic Soil Grouping

The classification of soils according to their runoff potential is very important to obtaining the correct curve number. This hydrologic soil classification is presented in Table 2.5.

Table 2.5 Hydrologic Soil Grouping (After McCuen 1982)

Soil Group	Runoff Potential	Soil Types
A	Lowest Runoff Potential	Deep sand, deep loess, and aggregated silts
B	Moderately Low	Shallow loess and sandy loam
C	Moderately High	Clay loams, shallow sandy loam, soils low in organic content, and soils usually high in clay
D	Highest Runoff Potential	Soils that swell when wet, heavy plastic soils, and certain saline soils

2.5 Antecedent Moisture Condition

Curve numbers were developed on the basis of average antecedent moisture conditions, that is, AMC II. AMC is defined by the SCS based on the previous five-day total rainfall as shown in Table 2.6.

Table 2.6 Definition of Antecedent Moisture Conditions (After McCuen 1982)

	Total 5-day antecedent rainfall (in)	
AMC	Dormant Season	Growing Season
I	Less than 0.5	Less than 1.4
II	0.5 to 1.1	1.4 to 2.1
III	Over 1.1	Over 2.1

The months in which local storms occur in Utah are June, July, and August (see Figure 2.1) all of which are in the growing season. Typical curve numbers for the AMC II condition were previously shown in Tables 2.1 through 2.4. These curve numbers can be adjusted to AMC I or III using the following equations, respectively (Ponce 1985):

$$CN_I = \frac{CN_{II}}{2.3 - 0.013 * CN_{II}} \tag{2.2}$$

$$CN_{III} = \frac{CN_{II}}{0.43 + 0.0057 * CN_{II}} \tag{2.3}$$

2.6 Probable Maximum Flood

The Probable Maximum Flood (PMF) has been defined by the U.S. Bureau of Reclamation (Cudworth, 1989, P. 25) as "theoretically the maximum runoff condition resulting from the most severe combination of hydrologic and meteorologic conditions that are considered reasonably possible for the drainage basin under study." This study addresses the issue of what is the "most severe combination" of precipitation and antecedent moisture conditions which is "reasonably possible" in Utah for local storm conditions. Specifically, is it reasonable to expect AMC III to occur simultaneously with a PMP event? This question could have a profound effect on PMF peak flowrates and volumes. Figure 2.2 contains a comparison of PMF hydrographs for Porcupine Basin in northern Utah based on both AMC II and III (Bowles et al. 1993). By changing from AMC II to III the PMF peak flowrate increased by about 50 percent from 40,000 cfs. to nearly 60,000 cfs.

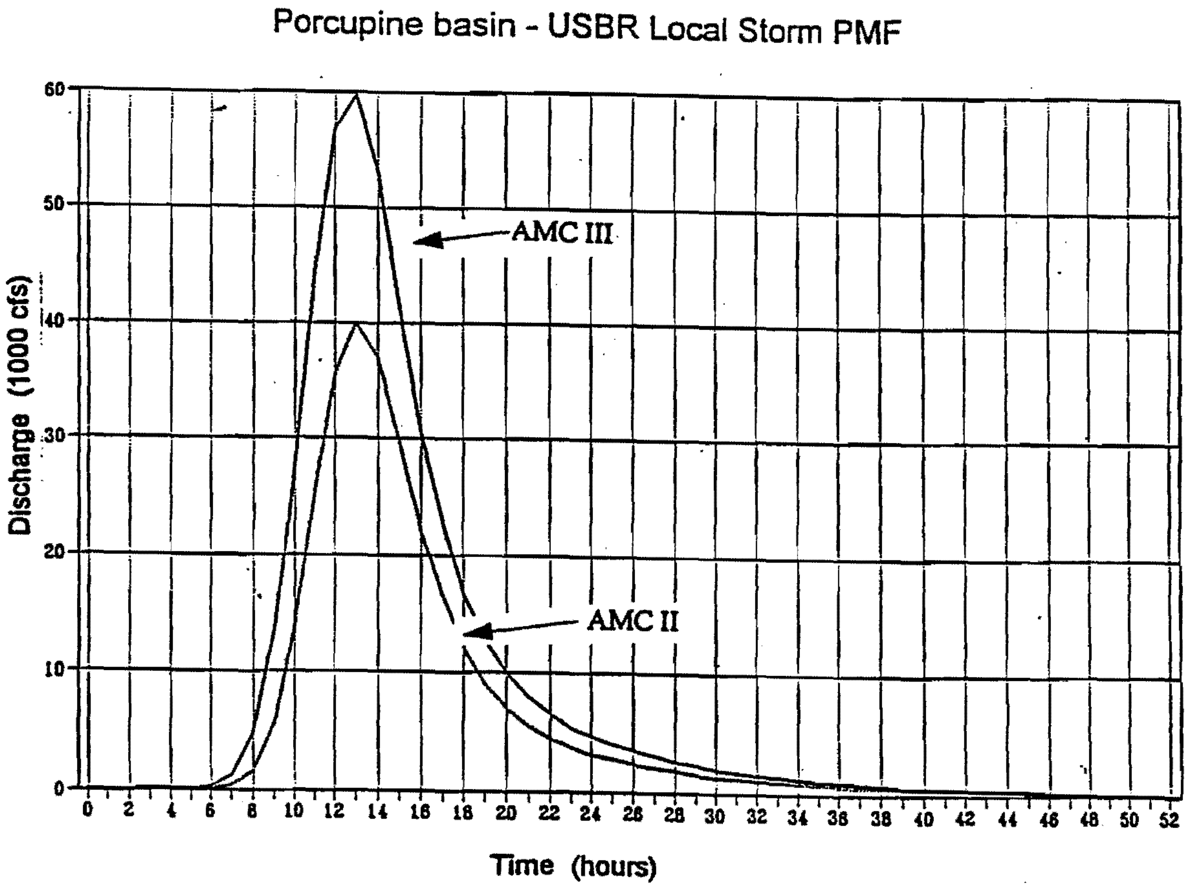


Figure 2.2 Example of the effect of antecedent moisture conditions on the PMF hydrograph (After Bowles et al 1993)

The standard hydrologic model used in practice for calculating the PMF is the U.S. Army Corps of Engineer's HEC 1 model. According to Hoggan (1989), HEC 1 is used to calculate the runoff resulting from a single-storm event over a basin of virtually any complexity.

3.0 RAINFALL DATA SETS AND AMC EVENT IDENTIFICATION

3.1 Data Sets

The following four daily rainfall data sets were available for use in our study: National Climate Data Center (NCDC), Utah Cooperative stations, SNOTEL, and RAWS. The last two data sets were included since they offer more high elevation stations. The distribution of stations according to elevation is shown in Figure 3.1 and their locations are shown in Figure 3.2. Figure 3.3 shows the distribution of record length for these stations. For reasons that will be explained in Section 3.2 we did not use any data from the Utah Cooperative stations, and therefore these stations are not included in Figures 3.1 - 3.3. For each station we examined only data from critical local storm months (see Figure 2.1).

3.2 AMC Event Identification

The occurrence of AMC II or III is defined in Table 2.6 based on the magnitude of five-day rainfall amounts. The antecedent moisture condition (AMC) is an attribute of the sixth day following the five-day period for which the rainfall total is calculated. In our work we restricted our search for antecedent moisture conditions to the critical local storm months and to five-day total rainfall amounts which were greater than or equal to 1.4 inches (corresponding to AMC II or III). Also we considered three types of AMC events, which are defined as follows:

a) Single day AMC: an attribute of a single day defined using Table 2.6 based on total rainfall from the five-day period immediately preceding that day (i.e. the sixth day).

b) Greatest overlapping AMC: the greatest five-day rainfall amount for a series of single day AMC events in which the corresponding five-day periods overlap (see Figure 3.4). In the case of a single day AMC with a non-overlapping five-day period, the single day AMC is the greatest overlapping AMC.

c) Annual maximum AMC: the maximum single day AMC occurring during the critical local storm months.

Several computer programs were used to locate AMC events, according to the definitions given in above. Although they are similar in logic, each data set required a unique adaptation of the base program to deal with the peculiarities of each of those data sets. These modifications are explained in the following subsections for each data set.

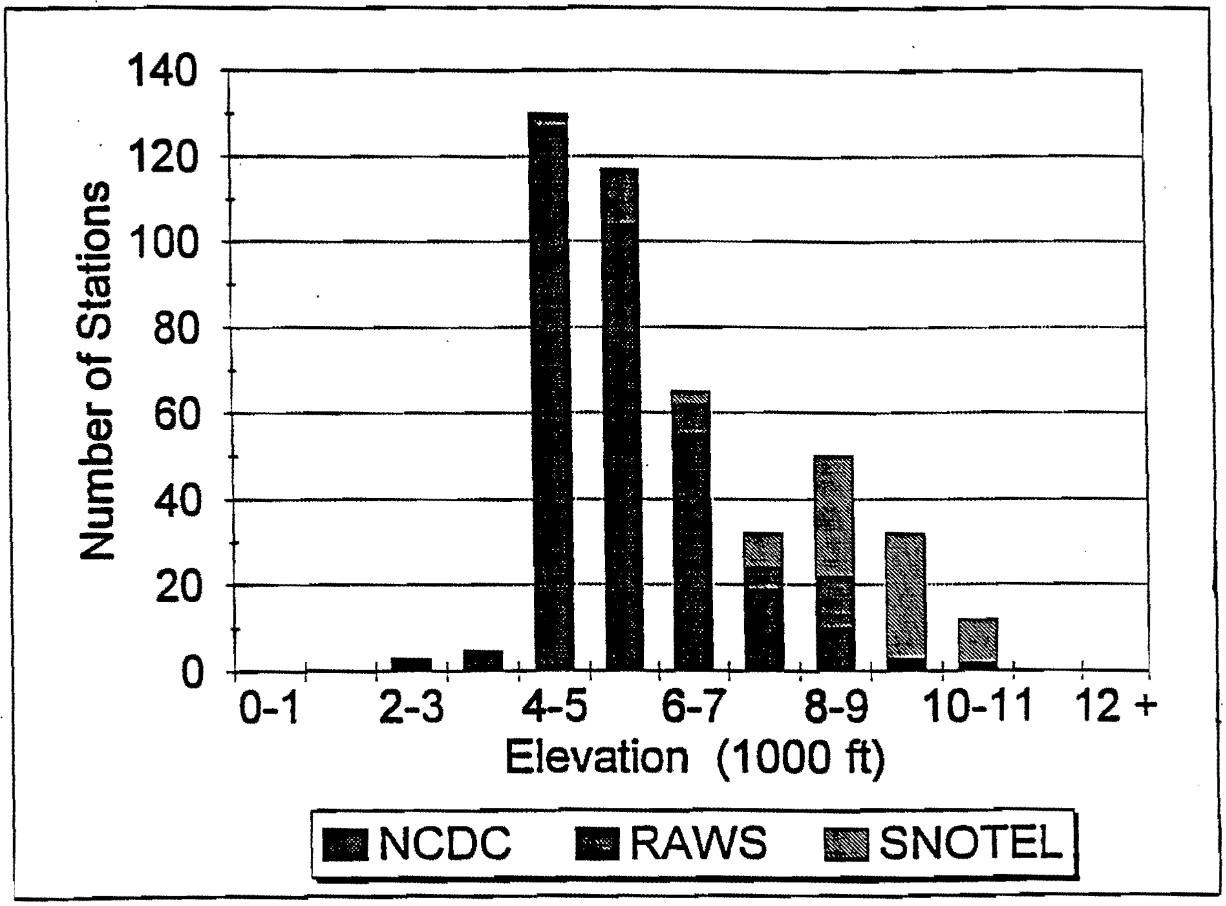


Figure 3.1 Elevation distribution of NCDC, RAWS and SNOTEL rainfall stations

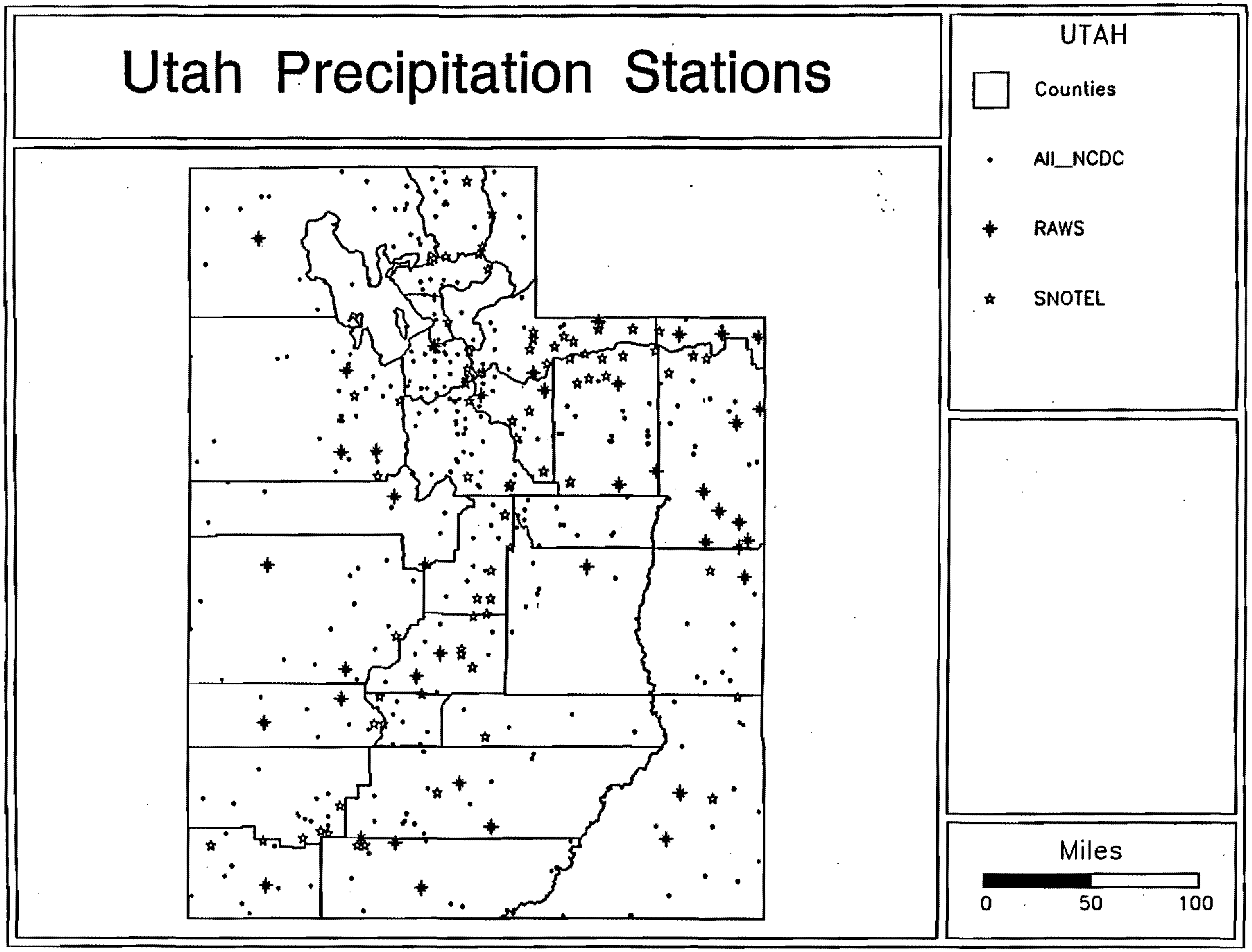


Figure 3.2 Location of Utah Precipitation Stations

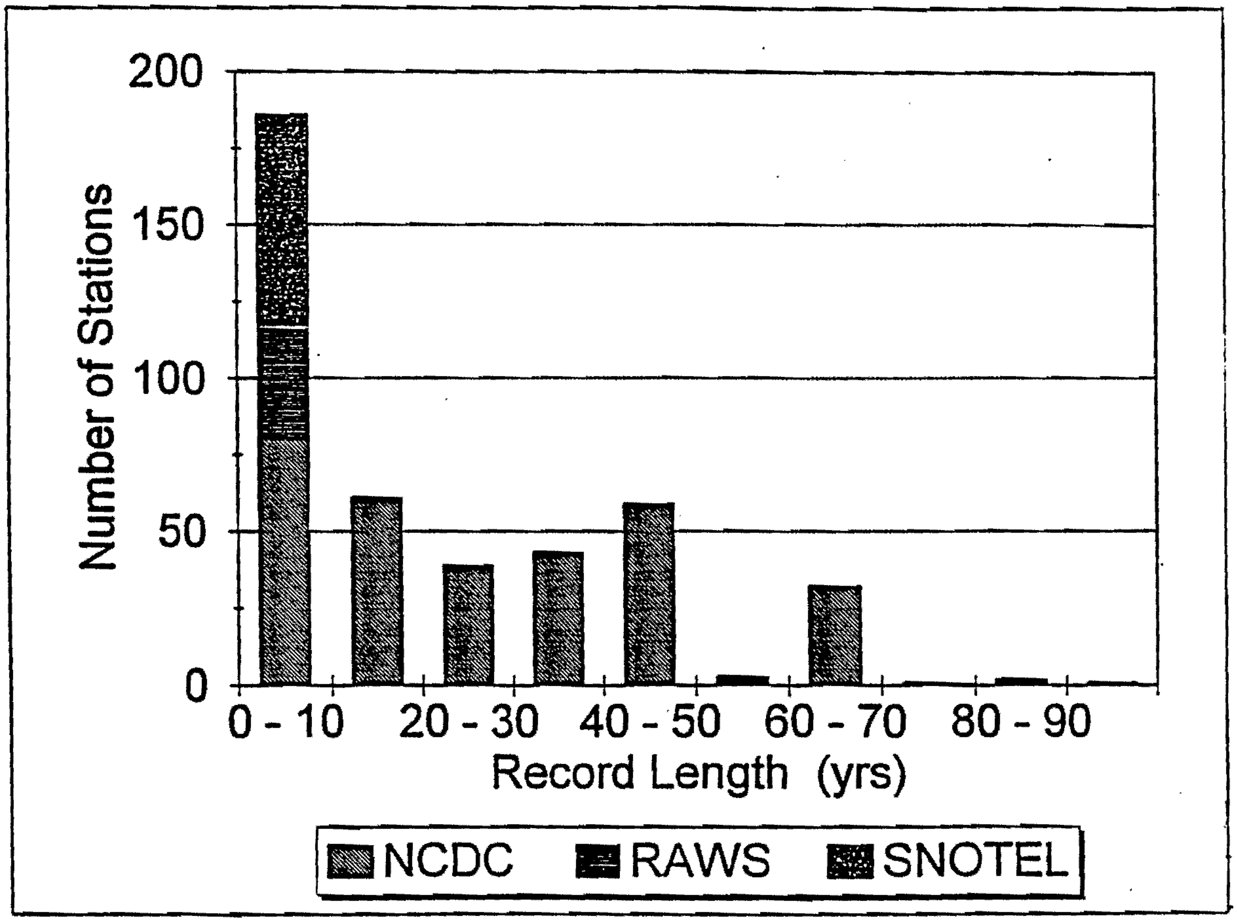


Figure 3.3 Record length distribution of NCDC, RAWS, and SNOTEL rainfall stations

Day	Precipitation (in)	5-day Total
1	0.2	
2	0.3	
3	0.5	
4	0	
5	0.8	
6	0.5	1.8
7	0.4	2.1
8	0	2.2
9	1.5	1.7
10	0.2	**3.2**
11	0.6	2.6
12	0	2.7
13	0.7	2.3
14	0.5	3
15	0.25	2
16	0.3	2.05
17	0.9	1.75
18	0	**2.65**
19	0	1.95
20	0	1.45
21	0.9	1.2
22	1.2	1.8
23	0.5	2.1
24	0	**2.6**
25	0	2.6
26	0	2.6
27	0	1.7
28	0	0.5
29	0	0
30	0	0
31	0	0
32	0	0
33	0	0

Shading represents overlap areas eliminated

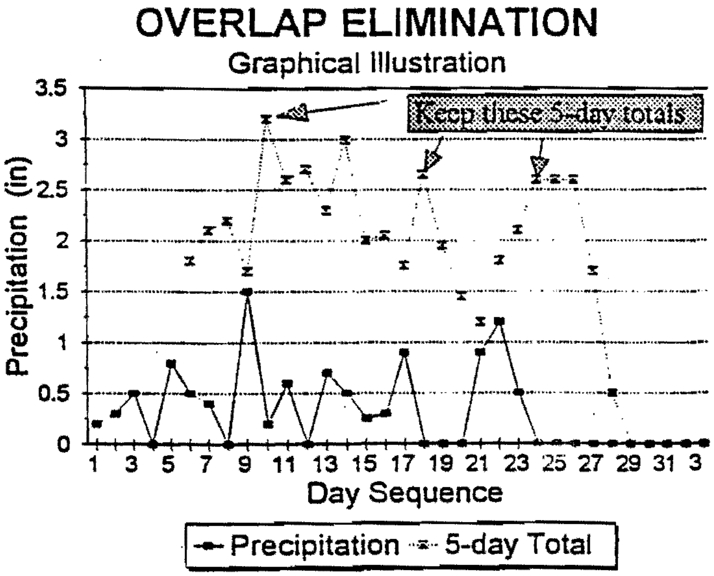


Figure 3.4 Greatest overlapping AMC selection criteria

3.3 National Climate Data Center

The National Climate Data Center (NCDC) daily rainfall data set was obtained through Earthinfo. There are 335 stations in Utah that have been in operation for longer than one month. The period of record for these stations ranges between two and 95 years with the largest concentrations of stations having between 2 and 15 years and between 45 and 50 years (see Figure 3.3). These data are of very high quality and are reported in a format that was very easy to evaluate and manipulate. As a result of screening the NCDC data set for AMC II and III conditions many events were identified throughout the state.

3.4 Utah cooperative stations

Dr. Donald T. Jensen, Director, Utah Climate Center, provided a pre-screened data set of AMC II and III occurrences at Utah Cooperative stations. Inspection of this data set revealed that all but one of the stations, the Yellowstone Ranger Station, were identical to those contained in the NCDC data set. Only one AMC II event was identified at the Yellowstone Ranger Station, but since this station had only a one month period of record we eliminated it from further study.

Matt Linden (1993) of the Utah State Engineer's Office performed an independent search of the Cooperative station records for AMC II and III preceding a minimum daily precipitation event. All but two of the events which he identified during the period of occurrence of local storm PMP events in Utah were also found in our search of the NCDC data set. Both of these events were at one station. It is not clear why this event was not included in Dr. Jensen's data set. However, since the Cooperative data set is not readily accessible and since only one station would be added to our combined data set from all four sources, we chose not to consider it in our analysis.

3.5 SNOTEL

This set of 78 stations provide high elevation precipitation data throughout the mountainous parts of Utah. It is operated by the Soil Conservation Service. The period of record is relatively short (see Figure 3.3), typically beginning in the early 1980's and continuing for almost all stations through 1992. Rainfall events were distinguished from snowfall using a criterion that average daily temperature must be greater than freezing.

The search of this data base was made difficult by many errors in reporting, gaps in the coverage, and temperatures reported in both Centigrade and Fahrenheit. Only unrealistically large values of reported precipitation amounts could be confidently identified as errors. These cases were treated as missing data. These data gaps were taken into account in defining the number of days of record available at a station. Missing temperature entries were stated as "-99.9". In these cases we manually inspected reported temperatures on adjacent days or at adjacent stations and made a determination as to whether precipitation was in the form of rain or snow. In all cases that we examined, during the June-July or July-August periods, this inspection lead to the conclusion that precipitation was rainfall. Missing precipitation entries were stated as "99". Since the SNOTEL precipitation data are presented in cumulative form, any day with a "99" entry was assigned the same cumulative precipitation value as the previous day.

The Portland office of the SCS confirmed that some of the stations were reporting temperatures in Fahrenheit when they should have been consistently reported in Centigrade. Through inspection of the temperature data it was determined whether Fahrenheit or Centigrade temperatures were reported and the data analysis programs were adapted to deal with them accordingly.

Estimated snowmelt contributions were added to rainfall over five-day periods and used to identify AMC conditions at SNOTEL stations. Snowmelt was approximated by using the difference in water equivalents over each five-day period using a June value for snow density of 0.45 (adopted from Win 1993) for the conversion of pillow depth to water equivalent.

The end result of including snowmelt was that at the one station in the North-West region (Region A) of the state, for which critical local storm months are June and July, an AMC III event, which included a snowmelt contribution was identified. Without the snowmelt contribution this event would still have been an AMC III event//would have been only an AMC II//I event. No AMC II or III events, in which there was a snowmelt contribution, were identified in the rest of the state (Region B).

3.6 Remote Automated Weather Stations (RAWS)

The RAWS network was primarily set up to aid in the early detection of forest fires and is operated by the Bureau of Land Management, U.S. Forest Service, Bureau of Indian Affairs, and the National Park Service. There are 41 RAWS stations located in Utah. Working with this data set presented some of the same problems that were encountered with the SNOTEL data set, although we found a lower incidence of data errors. These problems were addressed in a similar manner to that described above for the SNOTEL data set. RAWS precipitation data are reported in a cumulative format and calendar daily totals were calculated for identification of AMC II and III.from the original files and were used for all programs.

4.0 CORRELATION

To assess whether there is any correlation between the magnitude of rainfall and the AMC II or III (i.e. five-day rainfall total greater than or equal to 1.4 inches), we calculated the correlations between non-zero sixth-day rainfall event magnitudes and corresponding greatest overlapping AMC events (see definition in Section 3.2) for each rainfall station. Equations 4.1 and 4.2 were used to evaluate the significance of these correlations for the 102 stations having more than three greatest overlapping AMC events with a non-zero sixth day event. These locations of the 102 evaluated stations are shown in Figure 4.1.

$$t_0 = r\left[(n-2)/(1-r^2)\right]^{.5} \tag{4.1}$$

against a critical value of,

$$t_{1-\alpha/2} \tag{4.2}$$

in which:

t_0 = calculated t-statistic

t = critical t-statistic value

n = number of data points (independent events)

r = correlation coefficient

α = level of significance

The results of this test, as shown in Table 4.1, indicated that only one station (Kamas) has a statistically significant correlation at $\alpha = 0.05$. Figure 4.2 shows a plot of the correlation coefficients calculated for each station, and upper and lower envelope curves of critical correlation coefficients for α of 0.05, plotted as a function of the number of data points (events). Scattergrams for twenty-eight stations with 65 or more years of record are presented in Appendix A. The scattergram for the case of significant correlation at Kamas is also presented as Figure 4.3. Inspection of this figure lead us to conclude that the correlation is spurious since all but one point are clustered together. In any case, with a 5 percent level of significance and a sample size of 102 stations, one would expect that on the average five would be statistically significant, simply by chance. Figure 4.4 shows a typical scattergram for a non-significant correlation at the Hiawatha station.

Based on these results, and the good coverage of the state given by the 102 stations which we considered, we conclude that rainfall magnitude on a day is independent of the occurrence of AMC II or III on that day, for locations throughout the State of Utah during critical local storm months. No attempt was made to explore regional patterns in the correlations since they were not significant throughout the state.

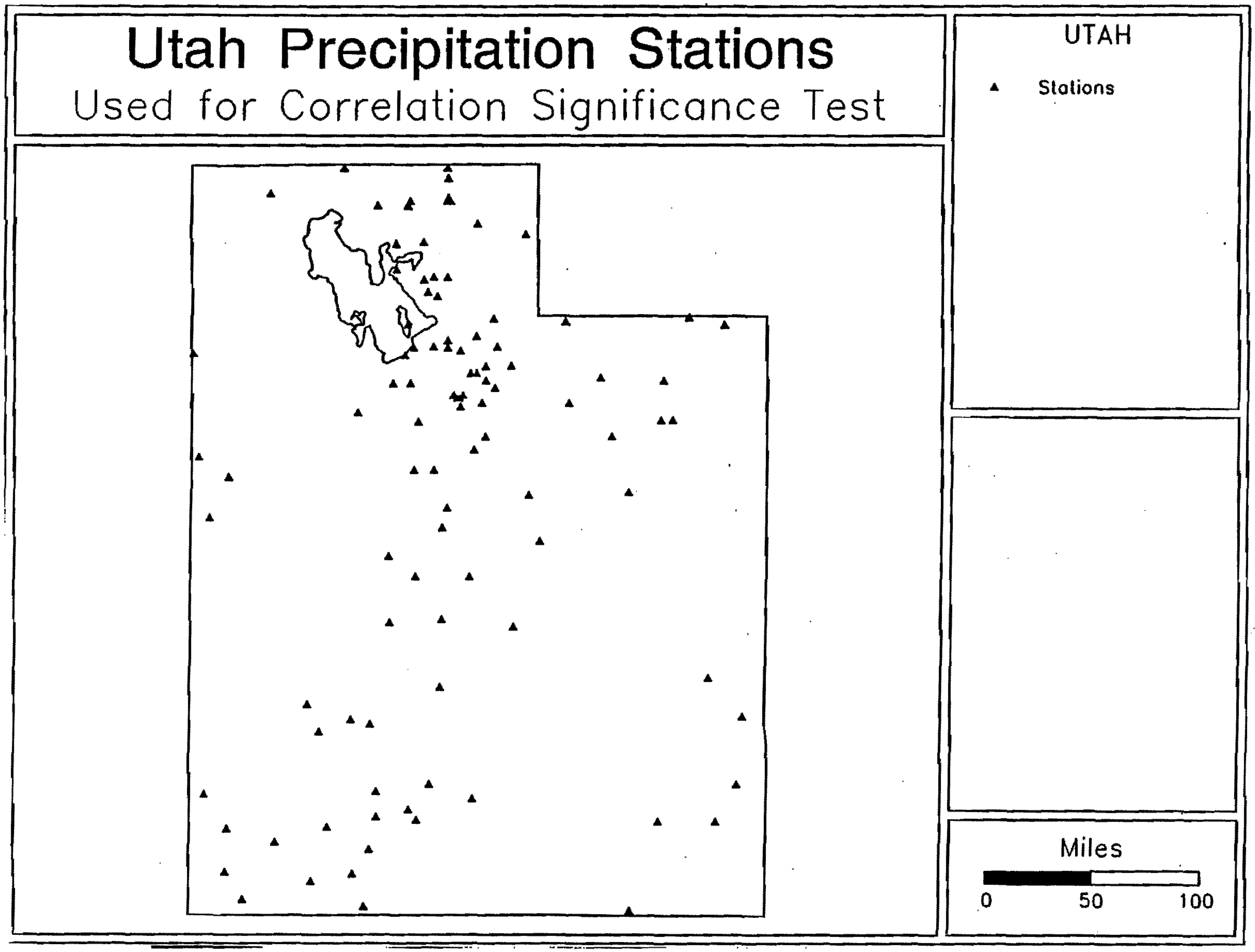


Figure 4.1 Utah rainfall stations used in significance testing of correlation between five-day totals and sixth-day events

Table 4.1 Significance test of five-day totals vs. sixth-day event correlation

Station Name	Record Length	# of data points	n-2	Correlation	Calculated t value	alpha 0.975	
ALPINE	42	7	5	-0.5966	-1.6623	2.57	not signif
ALTA	23	13	11	0.0361	0.1198	2.2	not signif
ALTON	64	12	10	-0.0444	-0.1405	2.23	not signif
ANTELOPE ISLAND	19	6	4	0.0700	0.1403	2.78	not signif
BARTHOLOMEW POWER HOUSE	36	7	5	0.5260	1.3829	2.57	not signif
BEAR RVR BAY	24	4	2	-0.0124	-0.0175	4.3	not signif
BEAR RIVER REFUGE	35	7	5	0.4632	1.1687	2.57	not signif
BEAVER	61	12	10	0.4996	1.8238	2.23	not signif
BEAVER CANYON P H	45	17	15	-0.1096	-0.4271	2.13	not signif
BINGHAM CANYON	26	10	8	0.5265	1.7516	2.31	not signif
BLANDING	85	13	11	-0.1498	-0.5025	2.2	not signif
BLOWHARD MTN RADAR	29	16	14	-0.2854	-1.1142	2.14	not signif
BRIGHAM CITY	25	11	9	0.1761	0.5367	2.26	not signif
BRYCE CANYON FAA AP	33	5	3	0.0747	0.1297	3.18	not signif
CALLAO	44	5	3	-0.1060	-0.1846	3.18	not signif
DEER CREEK DAM	45	5	3	0.0973	0.1693	3.18	not signif
DUCHESNE	80	4	2	-0.0476	-0.0674	4.3	not signif
EAST CANYON	19	4	2	0.1893	0.2726	4.3	not signif
ECHO DAM	45	7	5	-0.1834	-0.4172	2.57	not signif
ELBERTA	64	5	3	-0.0792	-0.1376	3.18	not signif
ELKHORN GUARD STN	36	4	2	0.0316	0.0447	4.3	not signif
EMERY	48	4	2	0.6116	1.0932	4.3	not signif
ENTERPRISE	39	4	2	-0.8909	-2.7739	4.3	not signif
ESCALANTE	85	14	12	-0.1770	-0.6230	2.18	not signif
EUREKA	35	13	11	0.3370	1.1871	2.2	not signif
FAIRFIELD	40	6	4	-0.1378	-0.2783	2.78	not signif
FILLMORE	65	9	7	0.1546	0.4140	2.36	not signif
FLAMING GORGE	35	7	5	0.3502	0.8360	2.57	not signif
FORT DUCHESNE	64	4	2	-0.4408	-0.6945	4.3	not signif
GARLAND 1 NE	32	9	7	0.3198	0.8930	2.36	not signif
GARFIELD	42	11	9	0.1993	0.6101	2.26	not signif
GUNLOCK POWER HOUSE	45	5	3	-0.0861	-0.1497	3.18	not signif
HANNA	38	8	6	-0.1484	-0.3676	2.45	not signif
HARDWARE RANCH	34	8	6	0.6562	2.1301	2.45	not signif
HATCH	45	9	7	0.0033	0.0087	2.36	not signif
HEBER	65	10	8	-0.0523	-0.1481	2.31	not signif
HIAWATHA	70	27	25	-0.0645	-0.3232	2.06	not signif
HIGH LINE CITY CREEK	8	4	2	0.7938	1.8458	4.3	not signif
IBAPAH	44	9	7	-0.0252	-0.0667	2.36	not signif
JOHNSON PASS	20	6	4	-0.3021	-0.6338	2.78	not signif
KAMAS	42	7	5	0.7661	2.6653	2.57	signif
KANAB	45	5	3	0.6220	1.3759	3.18	not signif
KOOSHAREM	44	4	2	-0.1710	-0.2454	4.3	not signif
LA SAL	23	5	3	0.7117	1.7548	3.18	not signif
LEVAN	65	8	6	-0.0032	-0.0078	2.45	not signif
LEWISTON	47	14	12	-0.0094	-0.0326	2.18	not signif
LOGAN UTAH ST U	65	14	12	0.0833	0.2896	2.18	not signif
LOGAN USU EXP STN	28	8	6	0.0374	0.0917	2.45	not signif
LOGAN RADIO KVNU	36	7	5	-0.2848	-0.6643	2.57	not signif
LOWER AMERICAN FORK PH	29	8	6	-0.5278	-1.5221	2.45	not signif
MANTI	65	6	4	0.6989	1.9544	2.78	not signif

Table 4.1 (Continued) Significance test of five-day totals vs. sixth-day event correlation

Station Name	Record Length	# of data points	n-2	Correlation	Calculated t value	alpha 0.975	
MANILA	38	6	4	0.7283	2.1256	2.78	not signif
MILFORD WSMO	64	5	3	0.3758	0.7024	3.18	not signif
MINERSVILLE	45	4	2	0.7885	1.8131	4.3	not signif
MOAB 4 NW	63	5	3	0.1190	0.2076	3.18	not signif
MODENA	45	8	6	-0.0892	-0.2194	2.45	not signif
MONUMENT VLY MISSION	28	4	2	-0.0576	-0.0816	4.3	not signif
MONTICELLO	44	15	13	0.3762	1.4640	2.16	not signif
MOON LAKE	20	7	5	0.1334	0.3010	2.57	not signif
MOUNTAIN DELL DAM	43	13	11	-0.2061	-0.6986	2.2	not signif
NATURAL BRIDGES N M	28	10	8	-0.0429	-0.1215	2.31	not signif
NEPHI	51	6	4	0.5232	1.2279	2.78	not signif
NEW HARMONY	45	9	7	-0.0620	-0.1644	2.36	not signif
NUTTERS RANCH	23	5	3	-0.0738	-0.1282	3.18	not signif
OAK CITY	65	5	3	0.5178	1.0483	3.18	not signif
OGDEN SUGAR FACTORY	65	17	15	0.1410	0.5516	2.13	not signif
OGDEN PIONEER P H	45	18	16	-0.0054	-0.0216	2.12	not signif
ORDERVILLE	65	7	5	-0.4404	-1.0969	2.57	not signif
PANGUITCH	44	9	7	-0.0205	-0.0542	2.36	not signif
PARK CITY RADIO	13	5	3	-0.6234	-1.3809	3.18	not signif
PARTOUN	41	7	5	0.1134	0.2552	2.57	not signif
PARK VALLEY	40	6	4	-0.4063	-0.8893	2.78	not signif
PINE VIEW DAM	45	17	15	-0.0289	-0.1120	2.13	not signif
PLEASANT GROVE	45	4	2	0.1450	0.2073	4.3	not signif
RICHMOND	65	16	14	0.1118	0.4210	2.14	not signif
RIVERDALE	62	22	20	0.1999	0.9124	2.09	not signif
ROOSEVELT	45	4	2	-0.3190	-0.4760	4.3	not signif
SALTAIR SALT PLANT	36	5	3	0.3206	0.5862	3.18	not signif
SALT LAKE CITY WSO CI	45	6	4	-0.0339	-0.0678	2.78	not signif
SALINA	62	7	5	-0.1007	-0.2263	2.57	not signif
SCIPIO	63	8	6	0.0213	0.0522	2.45	not signif
SCOFIELD DAM	43	8	6	0.2585	0.6555	2.45	not signif
SILVER LAKE BRIGHTON	45	20	18	0.0086	0.0365	2.1	not signif
SNAKE CREEK P H	65	7	5	-0.5100	-1.3258	2.57	not signif
SNOWVILLE	40	11	9	0.2081	0.6383	2.26	not signif
SPANISH FORK P H	65	4	2	0.2948	0.4363	4.3	not signif
ST GEORGE	64	5	3	-0.2865	-0.5179	3.18	not signif
THIOKOL PLANT 78	31	9	7	-0.4432	-1.3081	2.36	not signif
TIMPANOGOS CAVE	45	21	19	-0.0351	-0.1531	2.09	not signif
TOOELE	45	5	3	0.6887	1.6452	3.18	not signif
TREMONTON	13	5	3	-0.2862	-0.5174	3.18	not signif
TROPIC	43	11	9	0.2067	0.6338	2.26	not signif
UINTALANDS	11	4	2	-0.6537	-1.2216	4.3	not signif
UNIVERSITY OF UTAH	37	7	5	-0.1308	-0.2950	2.57	not signif
UPPER AM FORK P H	28	12	10	0.1760	0.5654	2.23	not signif
WANSHIP DAM	38	7	5	-0.1283	-0.2893	2.57	not signif
WEBER BASIN PUMPG PLT 3	31	17	15	0.2650	1.0644	2.13	not signif
WENDOVER AUTOB	58	4	2	-0.3503	-0.5289	4.3	not signif
WIDTSOE 3 NNE	15	4	2	0.7468	1.5881	4.3	not signif
WOODRUFF	45	4	2	-0.8967	-2.8649	4.3	not signif
ZION NATL PARK	65	12	10	-0.2297	-0.7463	2.23	not signif

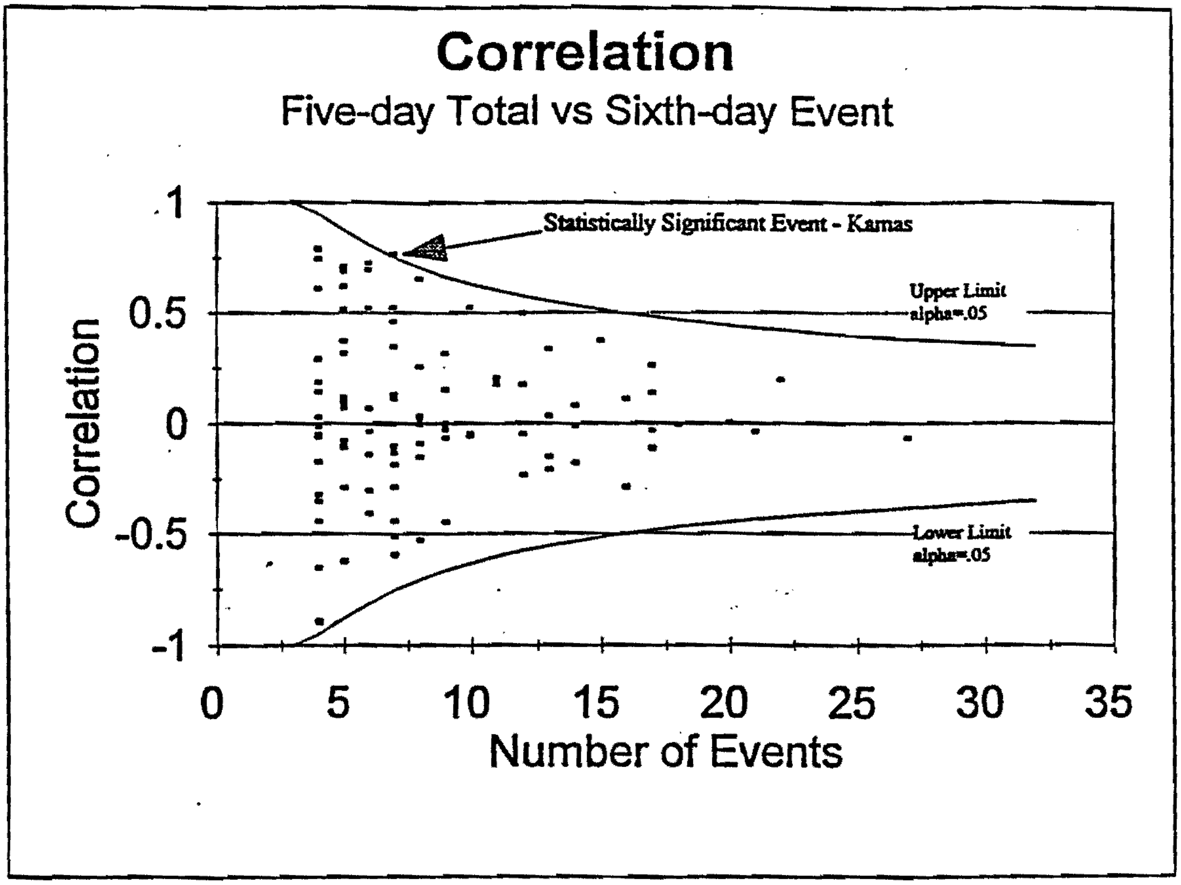


Figure 4.2 Correlation vs. number of events with envelope curves

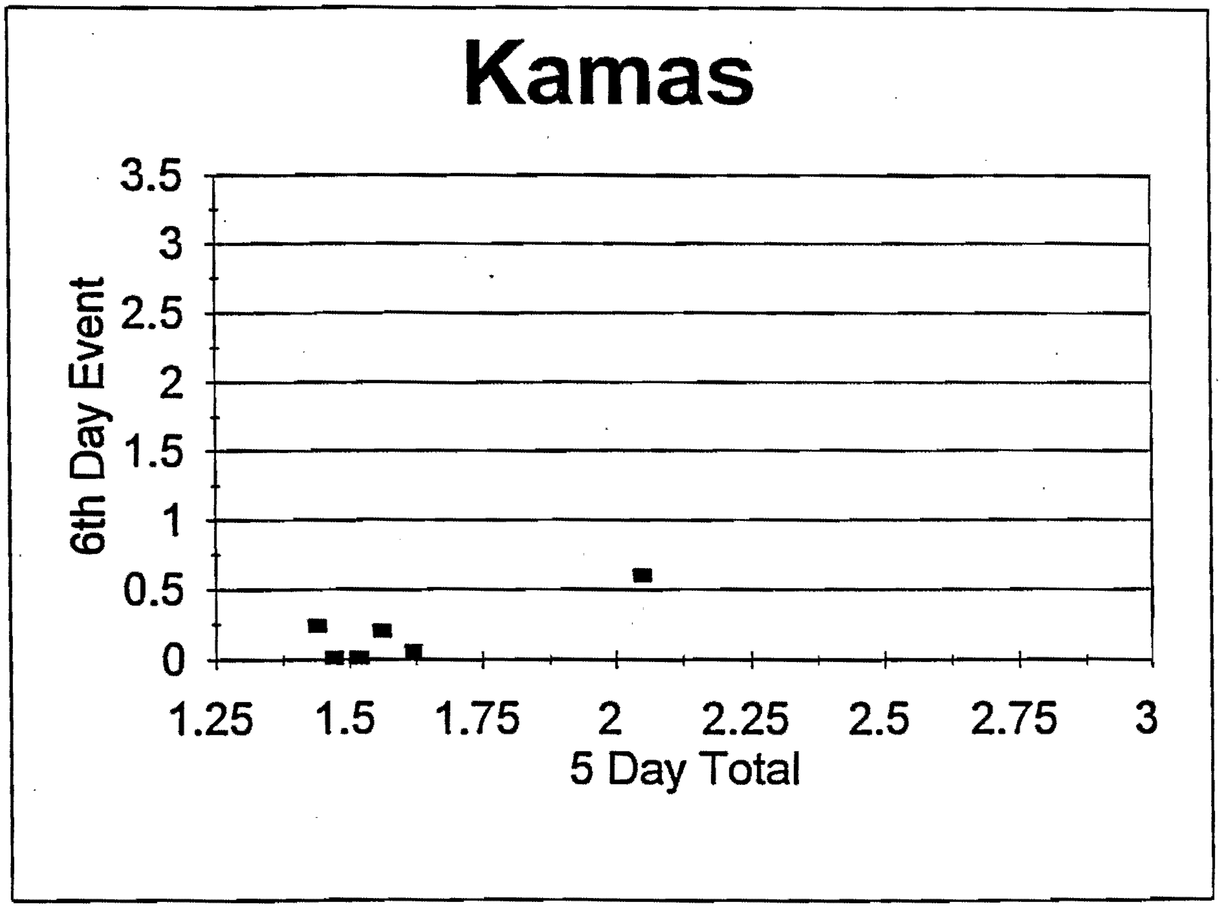


Figure 4.3 Scattergram example of spurious correlation

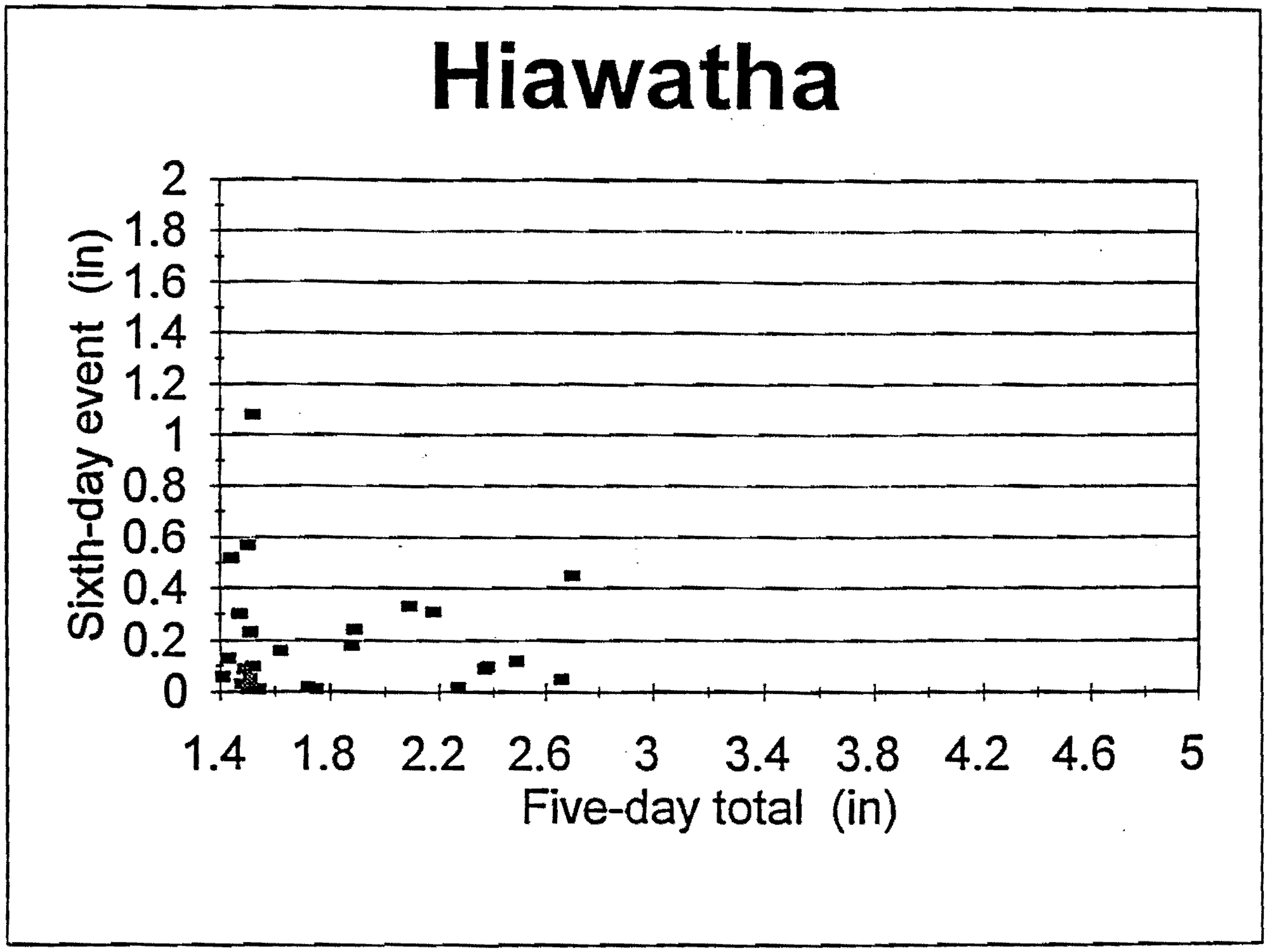


Figure 4.4 Typical scattergram of five-day totals versus sixth-day event

5.0 PROBABILITIES

The objectives of this study include estimating the probability of occurrences of AMC II and III conditions. These probabilities were evaluated using two strategies. Annual maximum AMCs were used to estimate annual exceedence probabilities and the probability of the number of days of AMC II or III were estimated using single day AMC II and III events.

As stated in Section 1.0, we made every effort to remain conservative in our analyses. The graphs included in this section were interpreted by relying on the upper limits of any trends. The availability of data for the extremes such as the very long record lengths was taken into consideration by relying more heavily on the grouping of stations having around 65 years when evaluating these graphs.

5.1 Annual Exceedence Probabilities for Annual Maximum AMC

The annual maximum AMC values (five-day total rainfalls) for each year were ranked separately for all rainfall stations. Each value was assigned a Weibull plotting position (annual exceedence probability) defined by (Haan 1977):

$$\frac{m}{n+1} \tag{5.1}$$

in which:

m = ranked position of the annual maximum AMC value

n = total number of years of record

Annual exceedence probabilities (AEP) for annual maximum AMC values of 1.4 and 2.1 inches, the AMC II and III thresholds, respectively, were estimated by interpolation of Weibull plotting positions. These AEPs are plotted for each station against station record length in Figures 5.1 and 5.2 for the annual maximum AMC II (1.4 inches) and in Figures 5.3 and 5.4 for the annual maximum AMC III (2.1 inches) thresholds for the two CLSM regions of the state. Since these AEPs can only be interpolated for AEPs between 1/n+1 and n/n+1 [e.g. for an n = 9-year record the range of interpolation is 0.1 (10%) to 0.9 (90%)] as displayed on Figures 5.1 - 5.4. These plots show greater variability in AEP estimates for shorter record lengths. This trend was expected due to the well recognized tendency for sampling error to decrease as sample size (record length) increases. Thus as the record length increases, the trend is for the AEP for the annual maximum AMC II threshold (ie. AMC II or III) to decrease to an upper limit of about 40% (Figures 5.1 and 5.2) and for AMC III to decrease to about 15% (Figures 5.3 and 5.4). Thus AMC II has approximately a 25% (ie. 40-15%) probability of occurring at least once per year while AMC III has 15% or lower probability of occurring at least once per year.

5.2 Probability of Number of Days of AMC II or III

The total number of single day AMC II or III events in the CLSM for each year were calculated for each station. These totals were converted to (average per year) percent days which are single day AMC II or III events in the CLSM and are plotted against record length in Figures 5.5 through 5.8 for AMC II and III in the two CLSM regions. Again these plots show greater variability for shorter record lengths. As record length increases, the trend is for the percent days with AMC II (Figures 5.5 and 5.6) to decrease to an upper limit of less than 2 percent, or approximately one day per (CLSM) year on the average. For AMC III (Figures 5.7 and 5.8) this upper limit is even lower at less than 1 percent, or approximately one day every three (CLSM) years on the average.

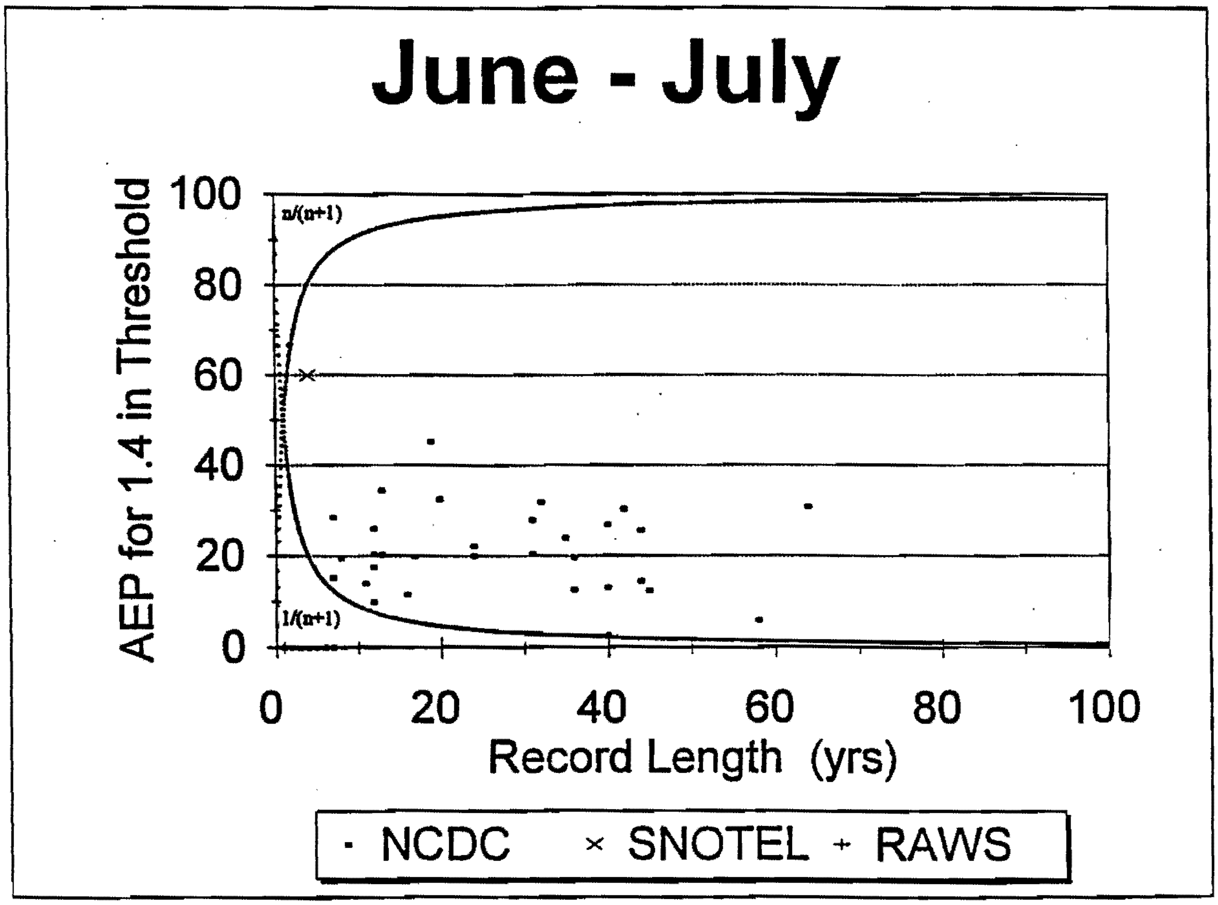


Figure 5.1 Annual Exceedence Probabilities for each station against station record length for the annual maximum AMC II or III in region A

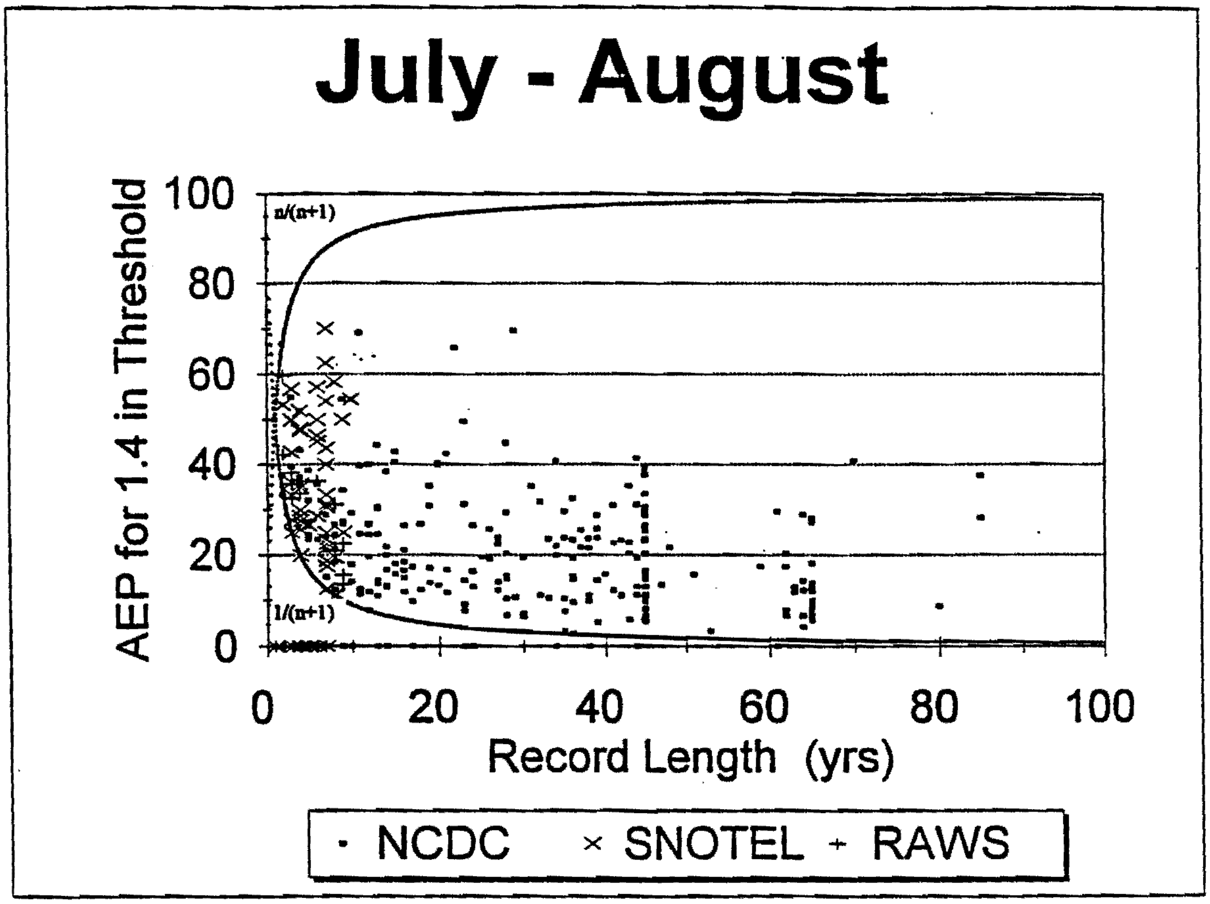


Figure 5.2 Annual Exceedence Probabilities for each station against station record length for the annual maximum AMC II or III in region B

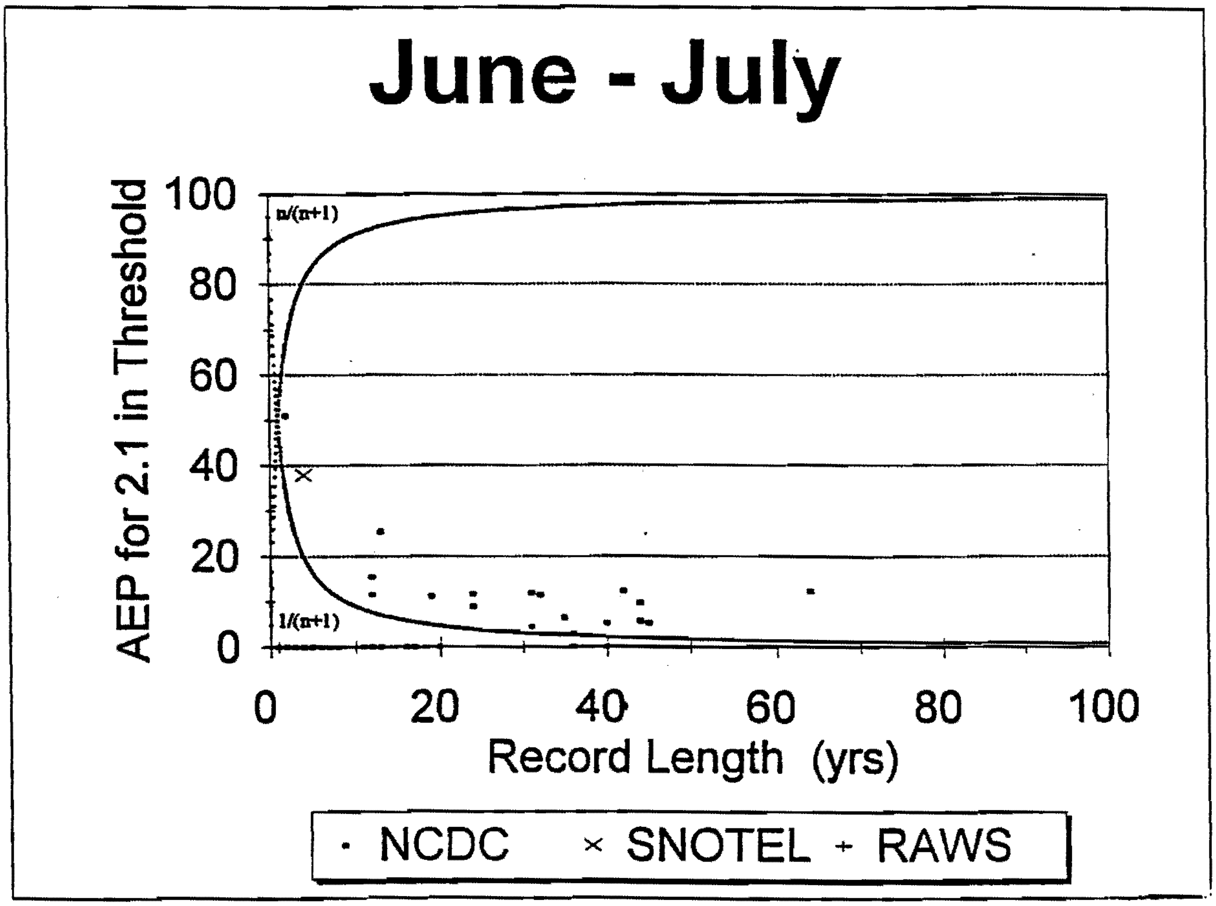


Figure 5.3 Annual Exceedence Probabilities for each station against station record length for the annual maximum AMC III in region A

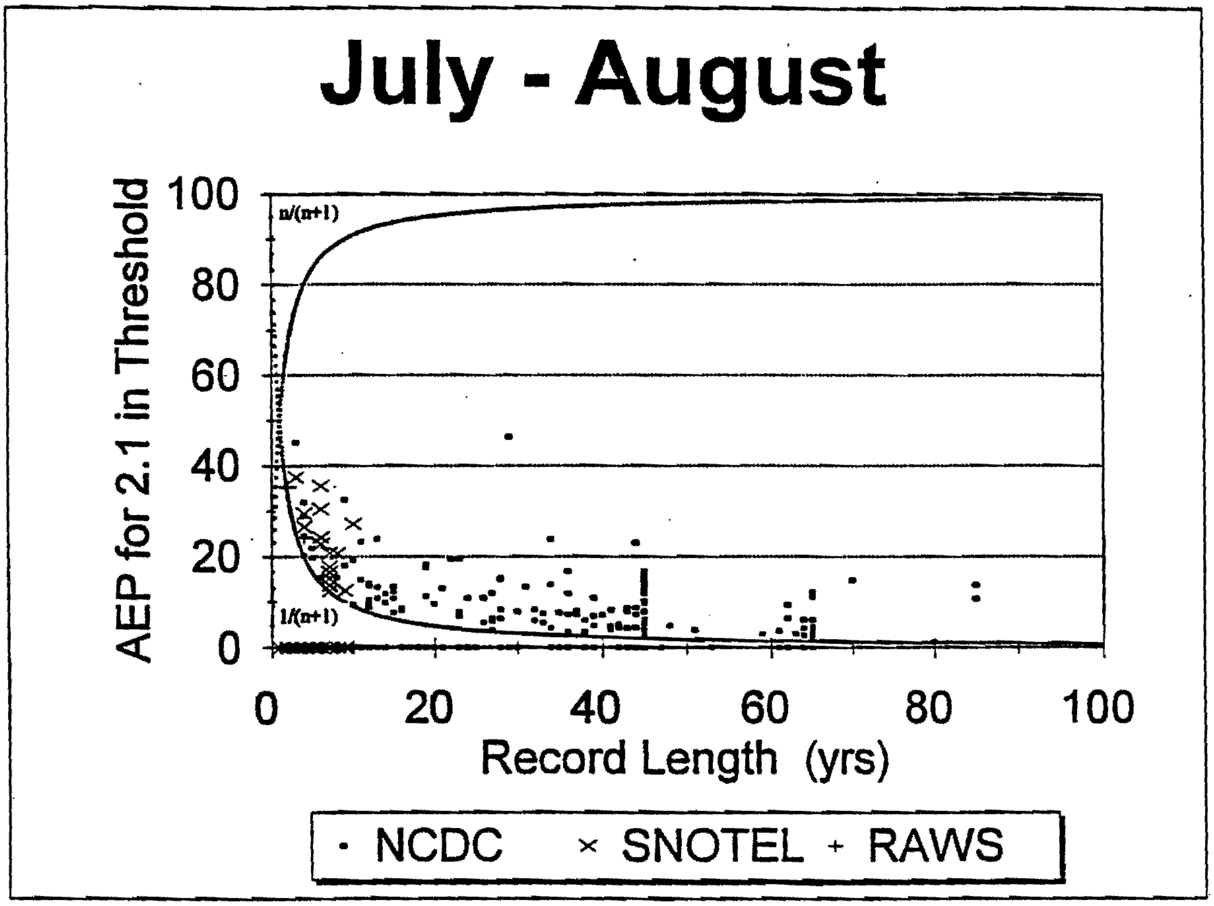


Figure 5.4 Annual Exceedence Probabilities for each station against station record length for the annual maximum AMC III in region B

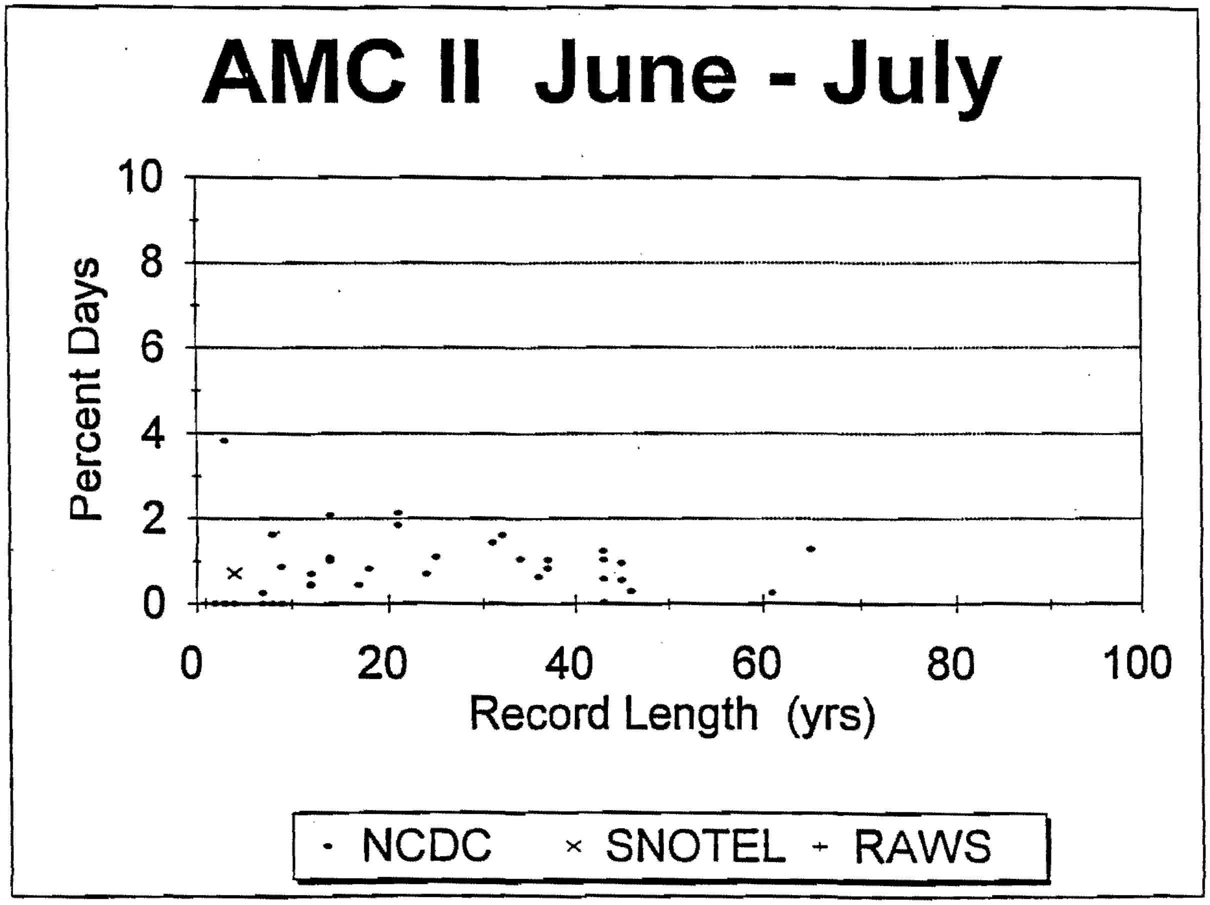


Figure 5.5 Percentage of days (average per year) experiencing AMC II for region A

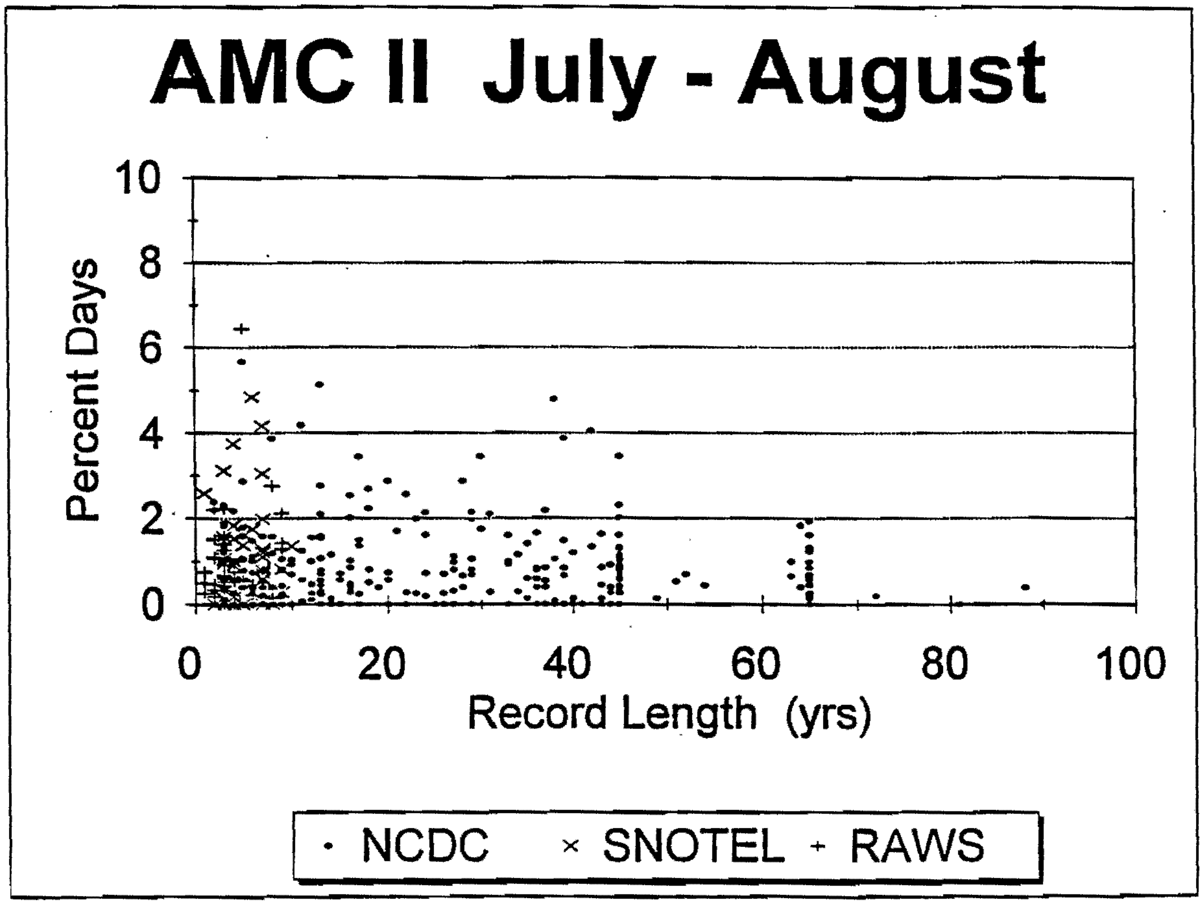


Figure 5.6 Percentage of days (average per year) experiencing AMC II for region B

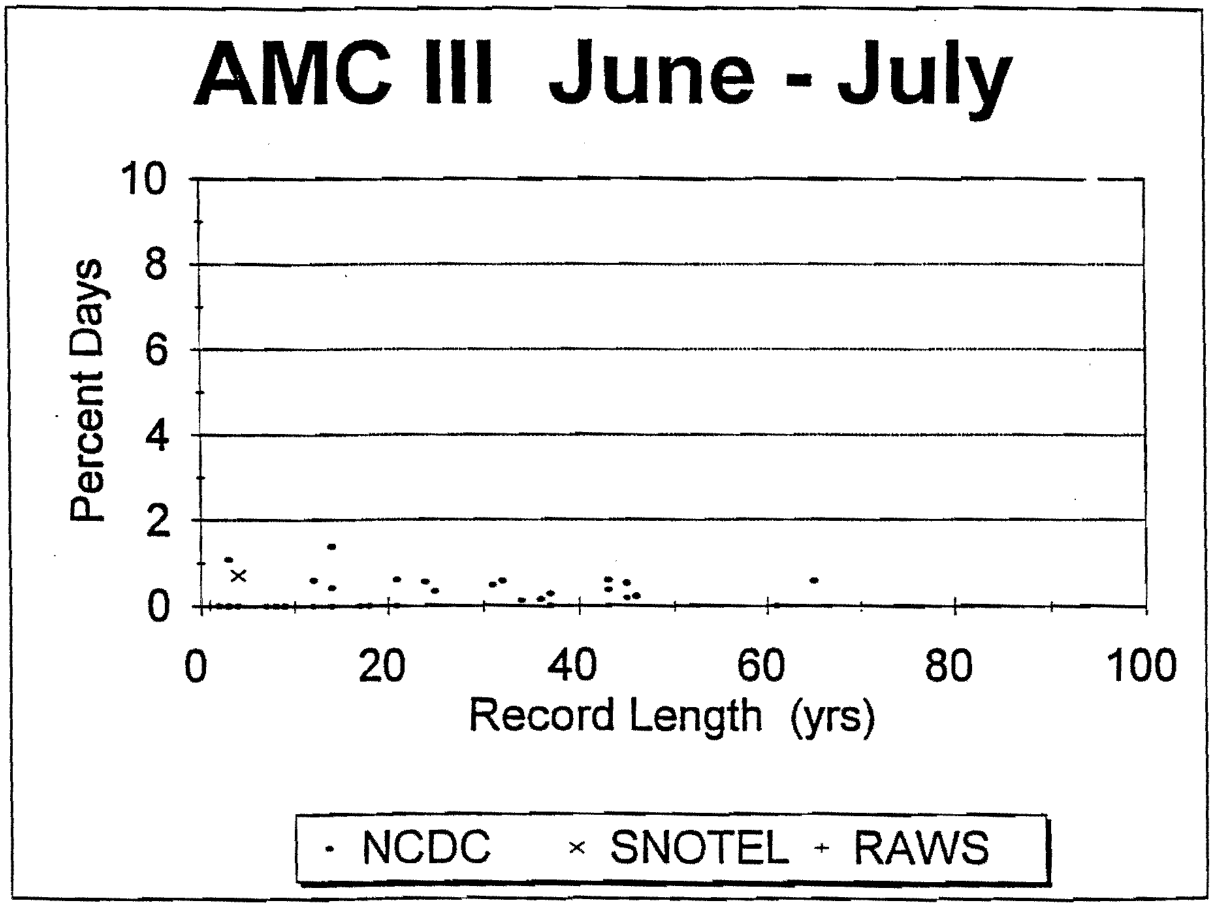


Figure 5.7 Percentage of days (average per year) experiencing AMC III for region A

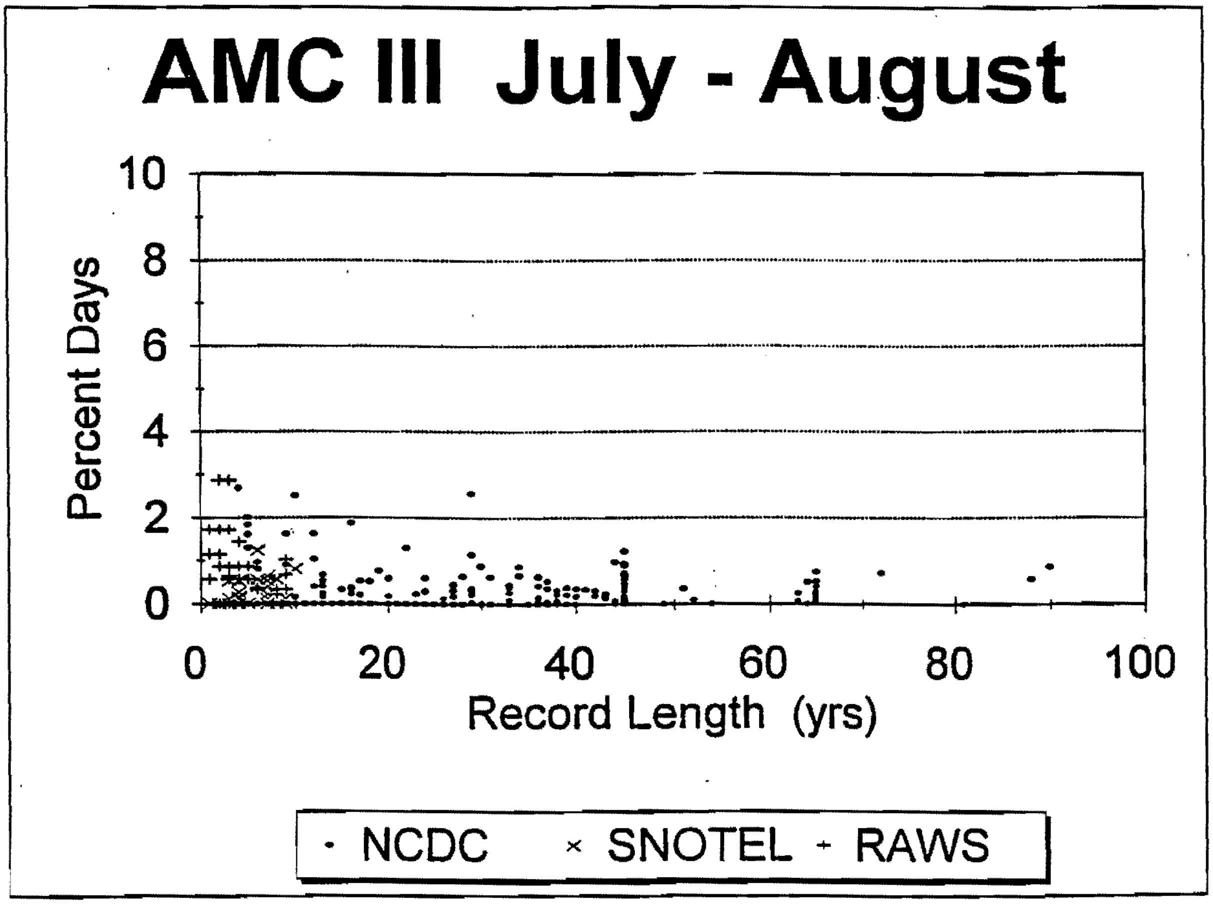


Figure 5.8 Percentage of days (average per year) experiencing AMC III for region B

We also calculated and plotted the AEP for the percent days which are single day AMC II or III events in the CLSM for each year were calculated for each station. These plots are presented for 2, 3, 4, 5, 10, and 25 percent AEPs in Figures 5.9 and 5.10 for AMC II and Figures 5.11 and 5.12 for AMC III for each CLSM region. The upper limit of percent days which are single day AMC II or III events were estimated from these plots and are presented in Table 5.1 and Figure 5.13. The number of AEP points available for evaluation decreases as data set extremes are approached (50% and 2% AEP). These results demonstrate that even at low return periods the number of AMC III days which occur in a (CLSM) year is relatively small. Although slightly larger than for AMC III, the number of days AMC II days which occur in a (CLSM) year is also quite small.

5.3 Summary of Probability Results

The occurrence of the PMP and AMC were demonstrated to be independent in Section 4.0. It follows that the probability of the joint occurrence of the PMP and AMC III would be obtained simply by taking the product of three factors: i) the annual probability of occurrence of the PMP, ii) the AEP for the annual maximum AMC event, and iii) the (average annual) percent days which are single day AMC III events. The effect would be to reduce the probability of occurrence of the PMP or PMF by an amount equal to the product of factors ii and iii. These factors are on the order of which is of the order of fifteen percent (see section 5.1) and one percent (see section 5.2), respectively. Therefore, the total probability reduction is .0015 (ie. 0.15x0.01).

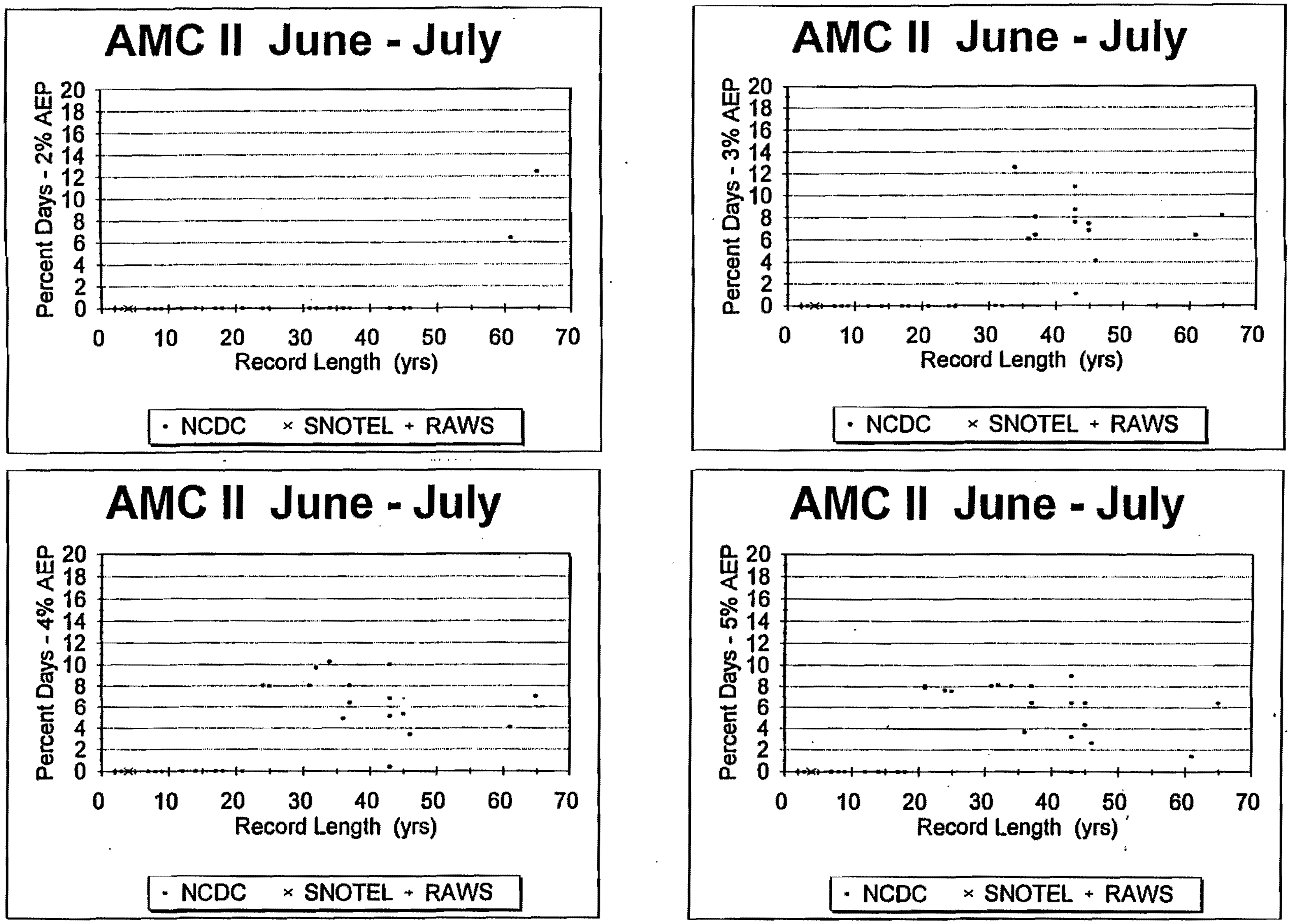


Figure 5.9 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC II in region A

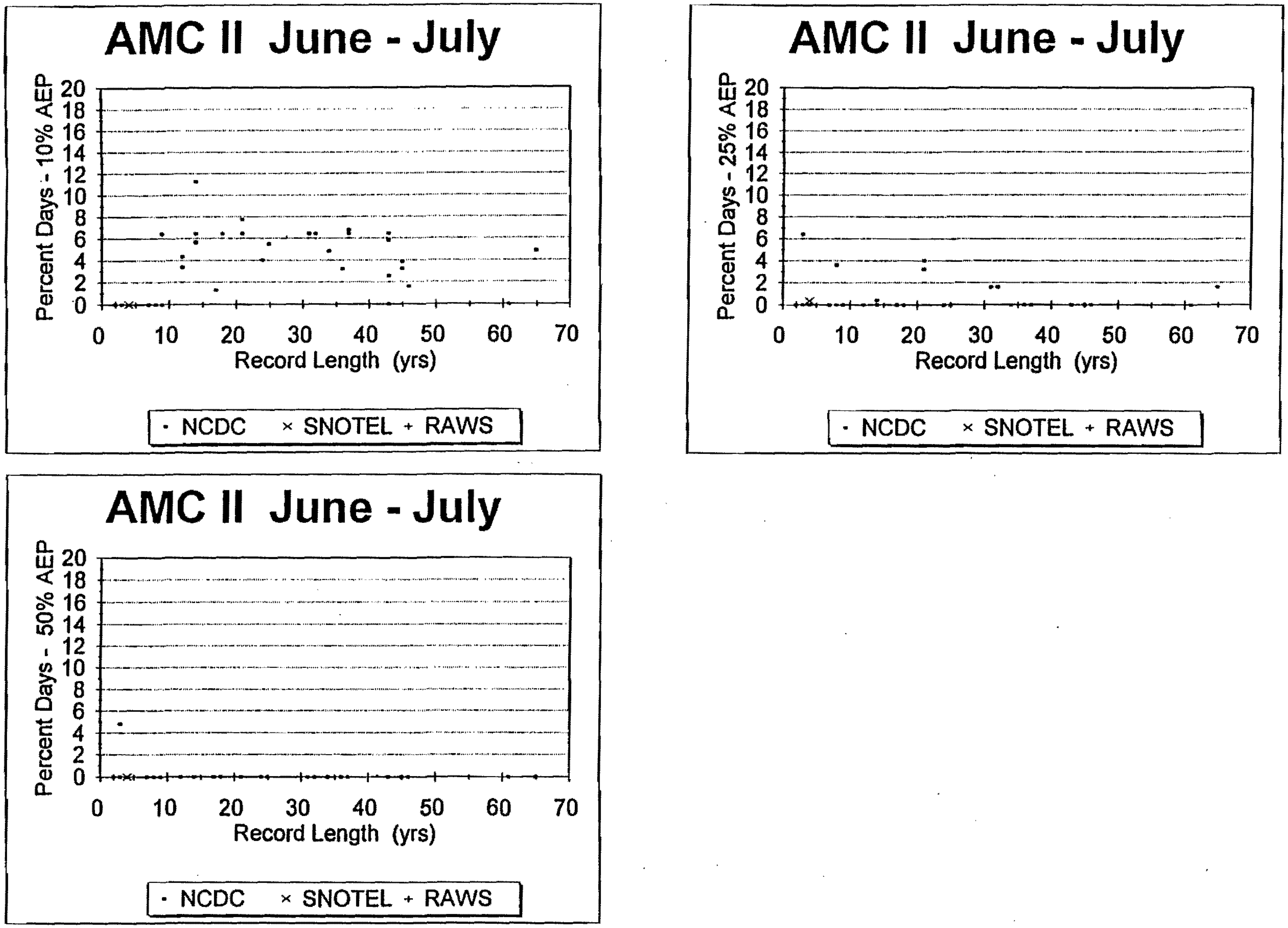


Figure 5.9 (Continued) 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC II in region A

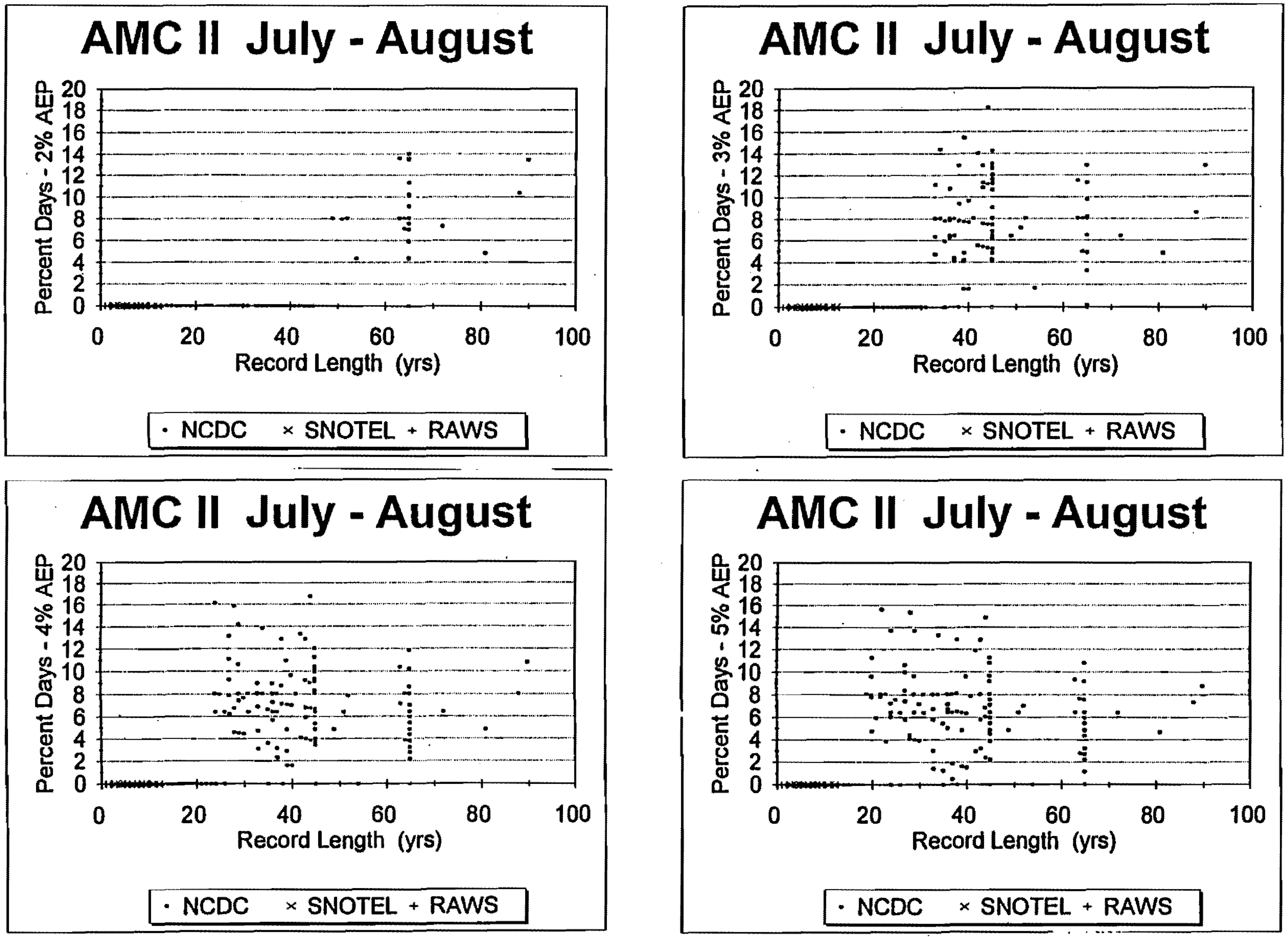


Figure 5.10 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC II in region B

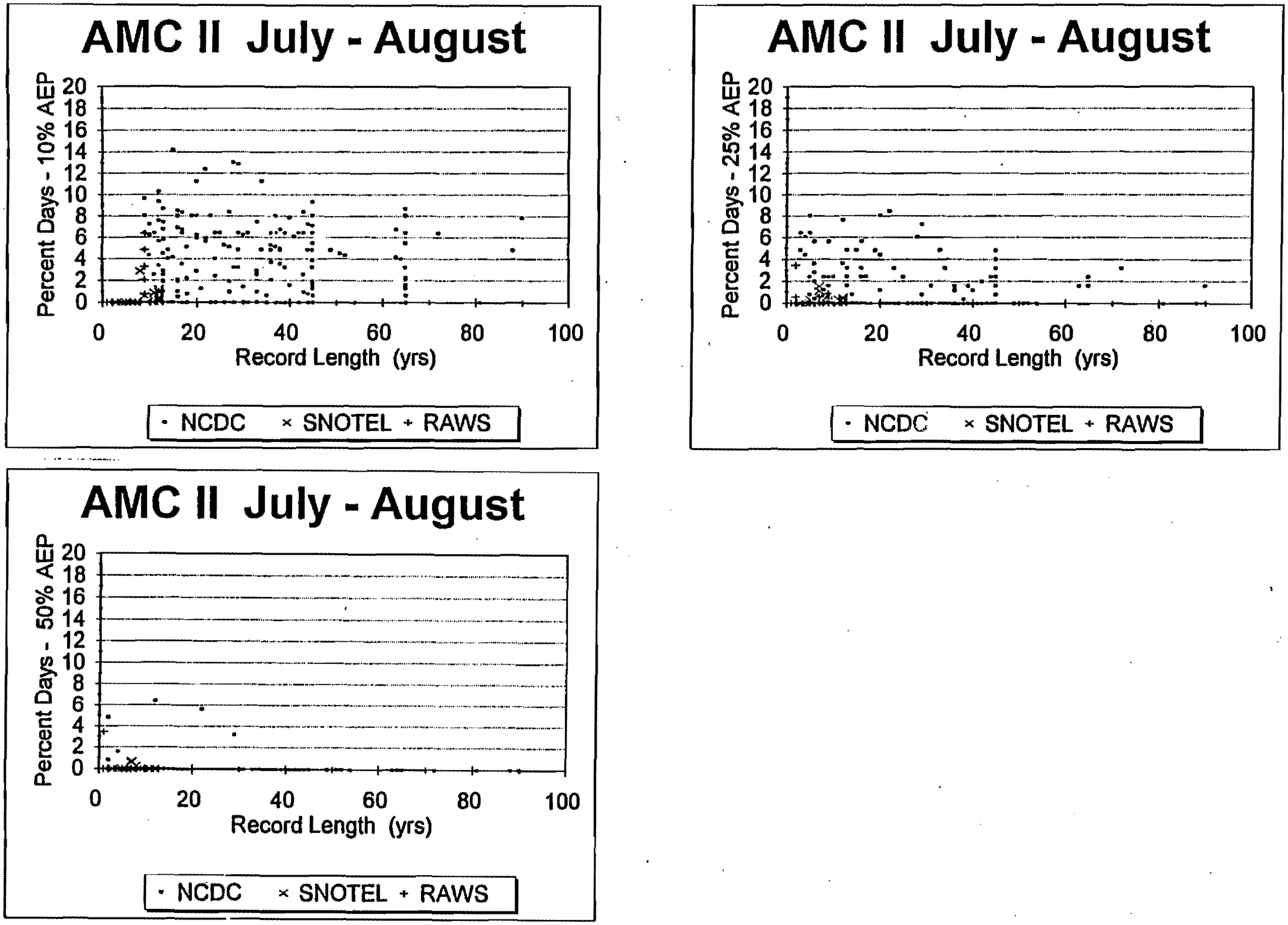


Figure 5.10 (Continued) 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC II in region B

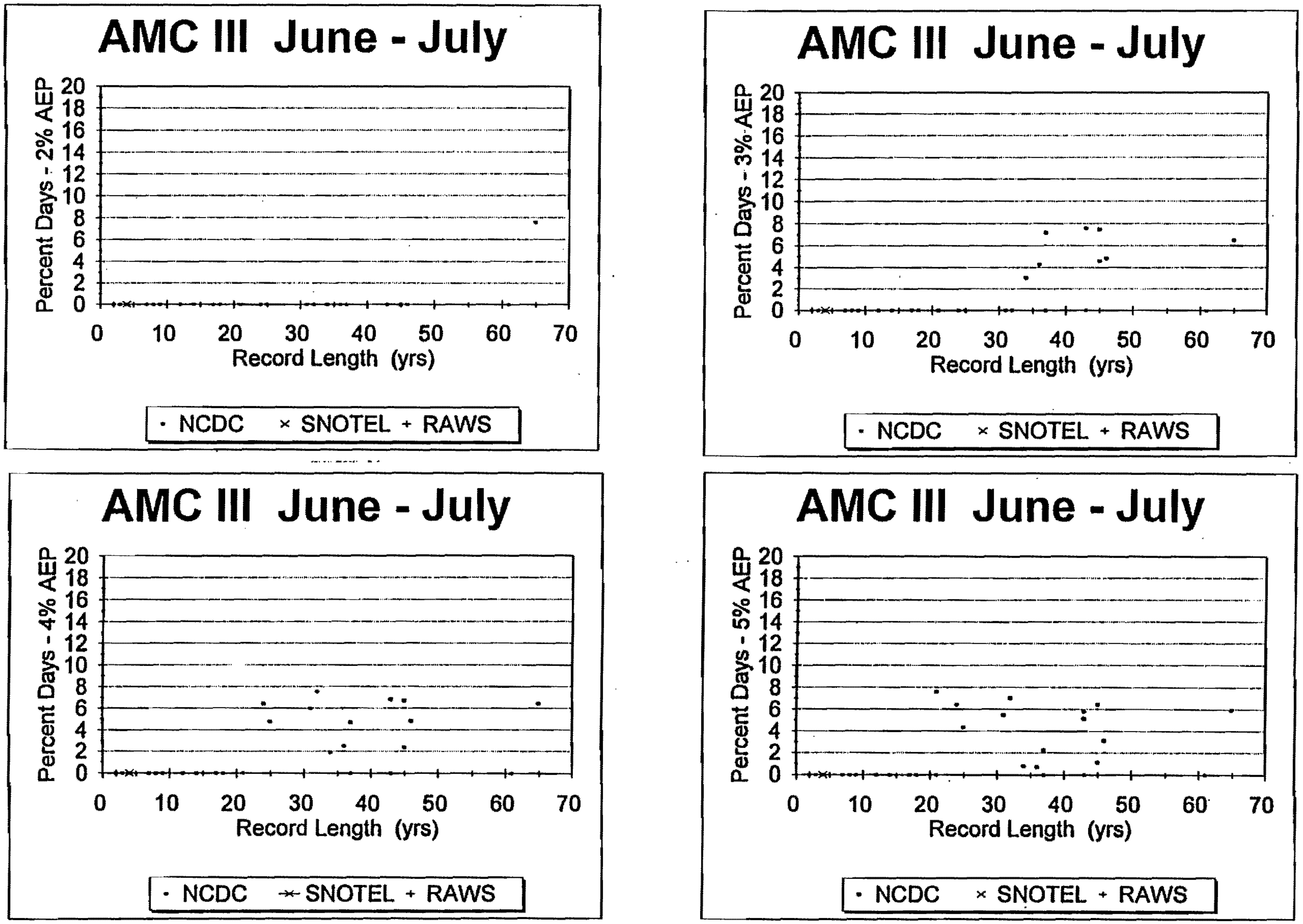


Figure 5.11 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC III in region A

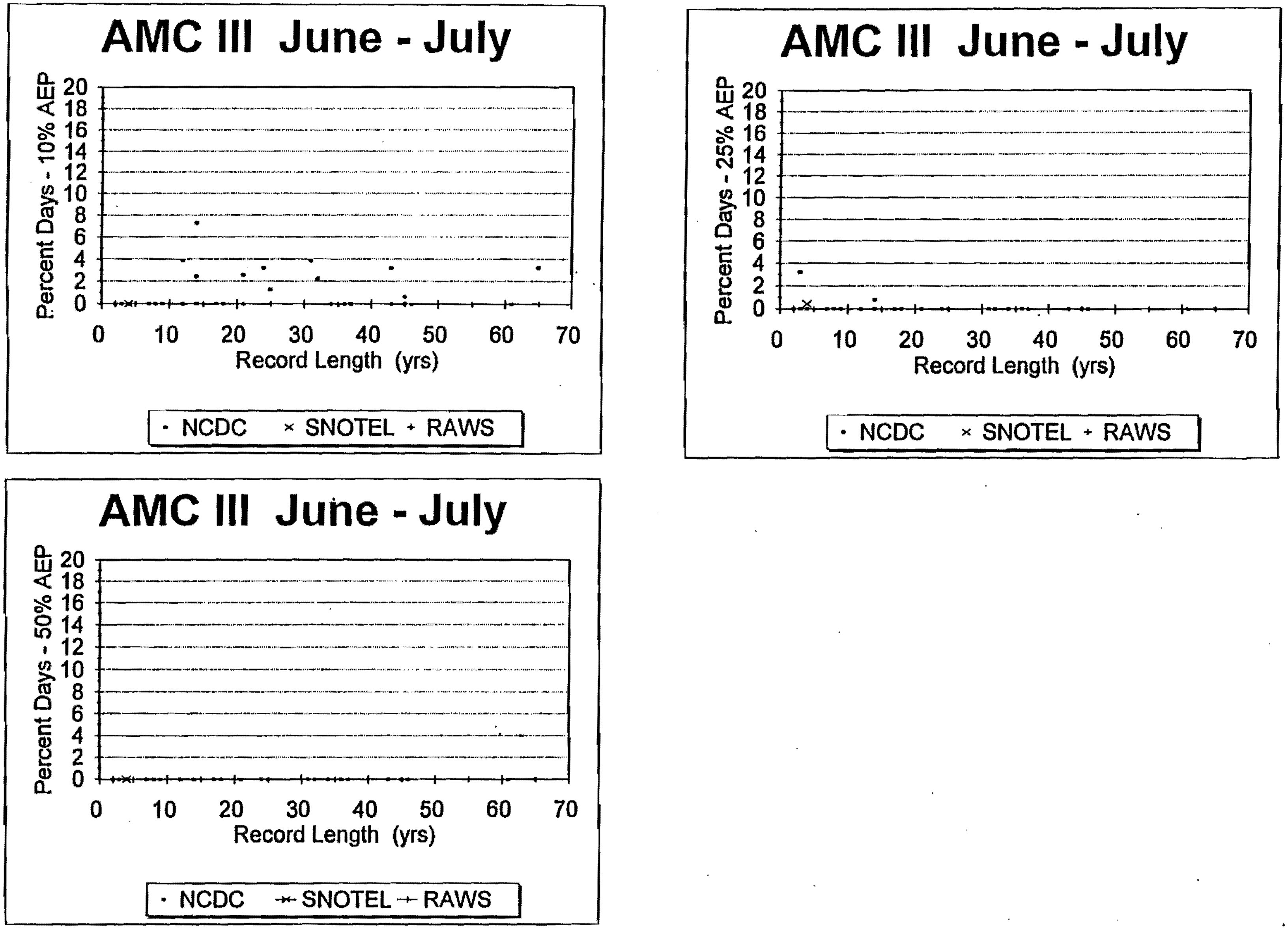
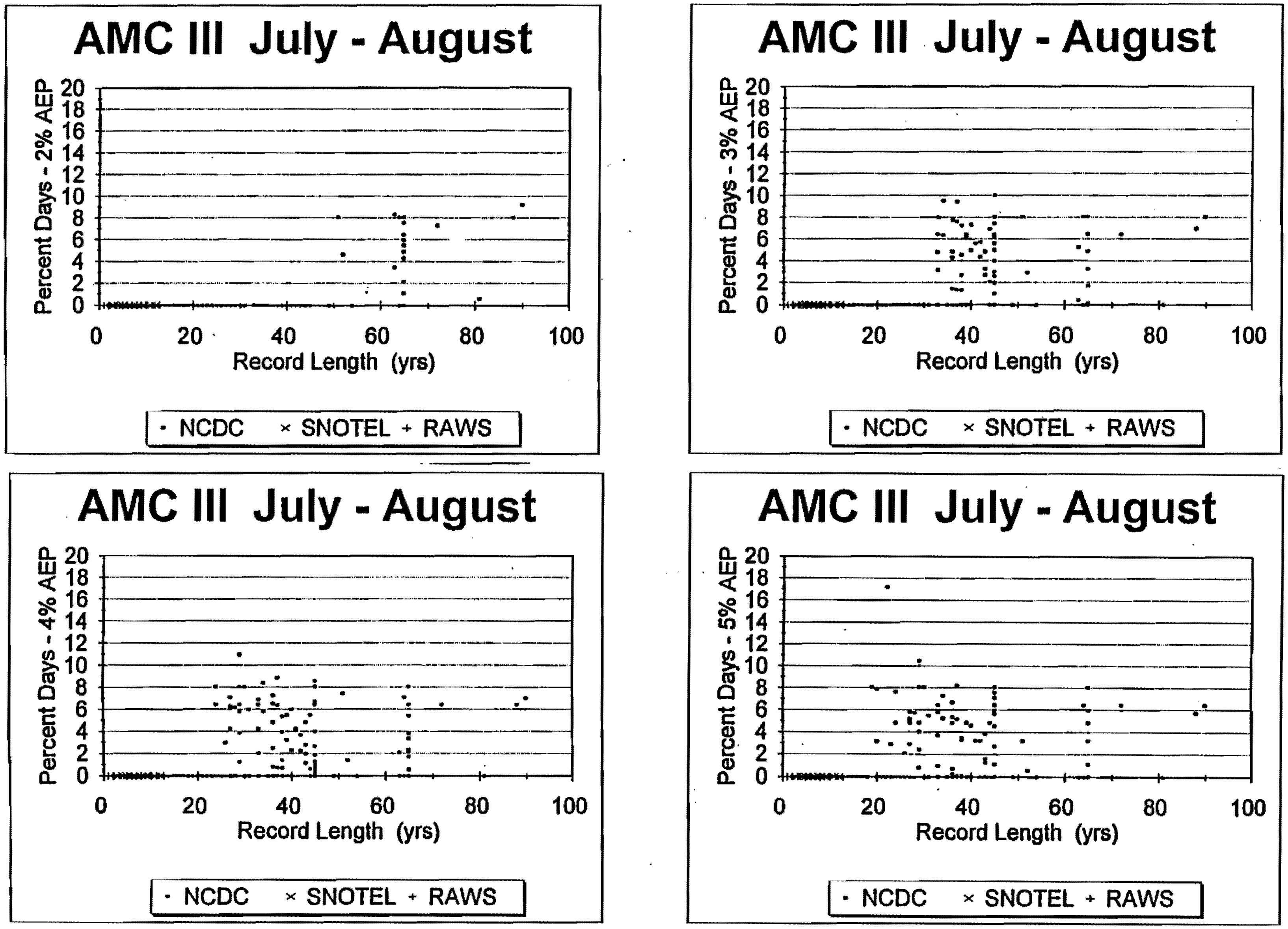


Figure 5.11 (Continued) 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC III in region A



AMC III July - August

AMC III July - August

AMC III July - August

AMC III July - August

Figure 5.12 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC III in region B

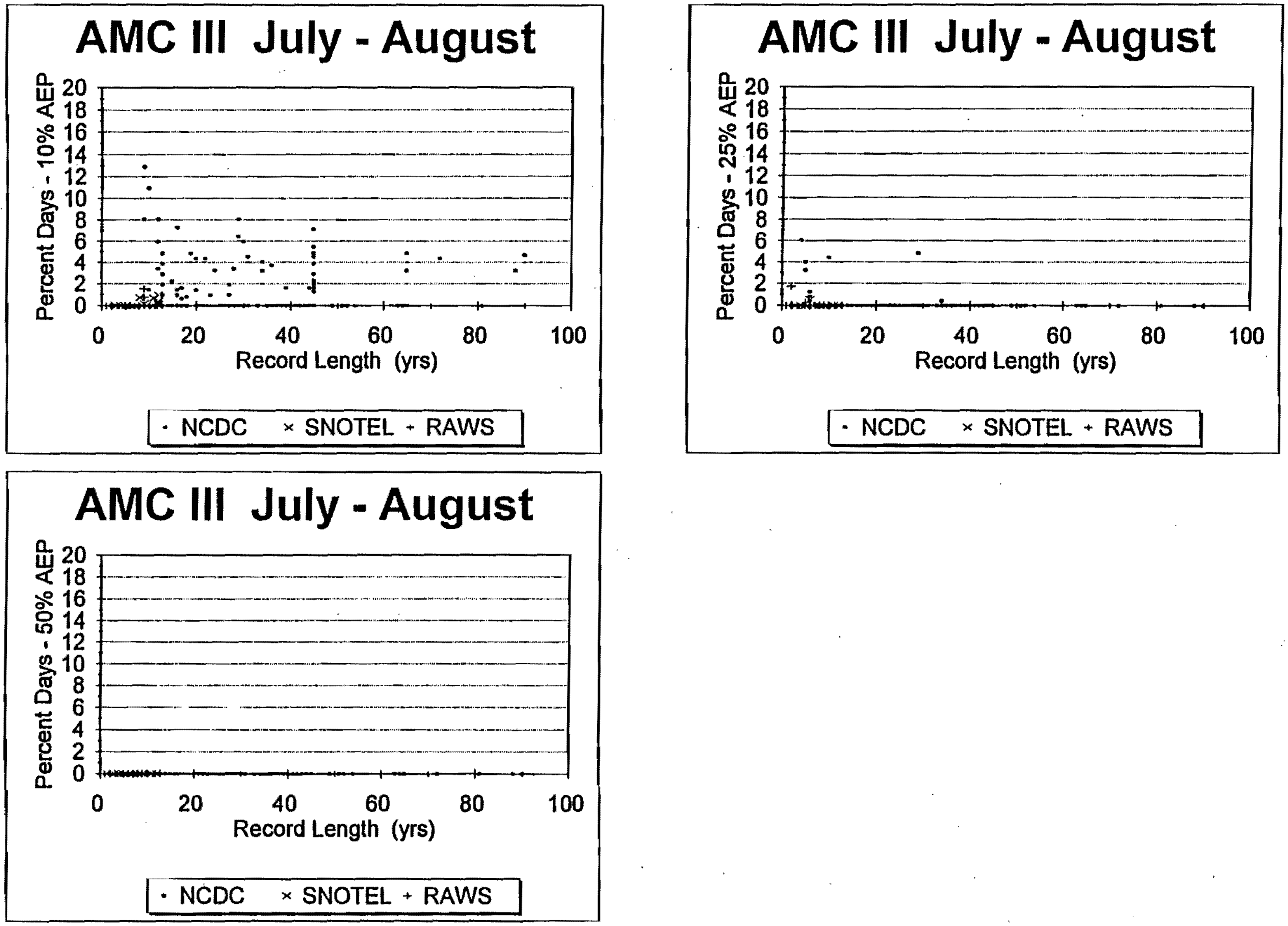


Figure 5.12 (Continued) 2, 3, 4, 5, 10, and 25 percent annual exceedence probabilities for the percentage of CLSM days experiencing AMC III in region B

Table 5.1 Upper limit of percent days which are single day AMC II or III events

AEP (%)	AMC II		AMC III	
	Region A (Figure 5.9)	Region B (Figure 5.10)	Region A (Figure 5.11)	Region B (Figure 5.12)
2	7.9	8.7	5.2	6.2
3	6.7	8.1	4.9	5.6
4	6.1	6.8	4.3	5.0
5	4.9	6.2	3.7	5.0
10	3.7	5.0	2.4	3.1
25	1.2	2.5	1.8	2.5

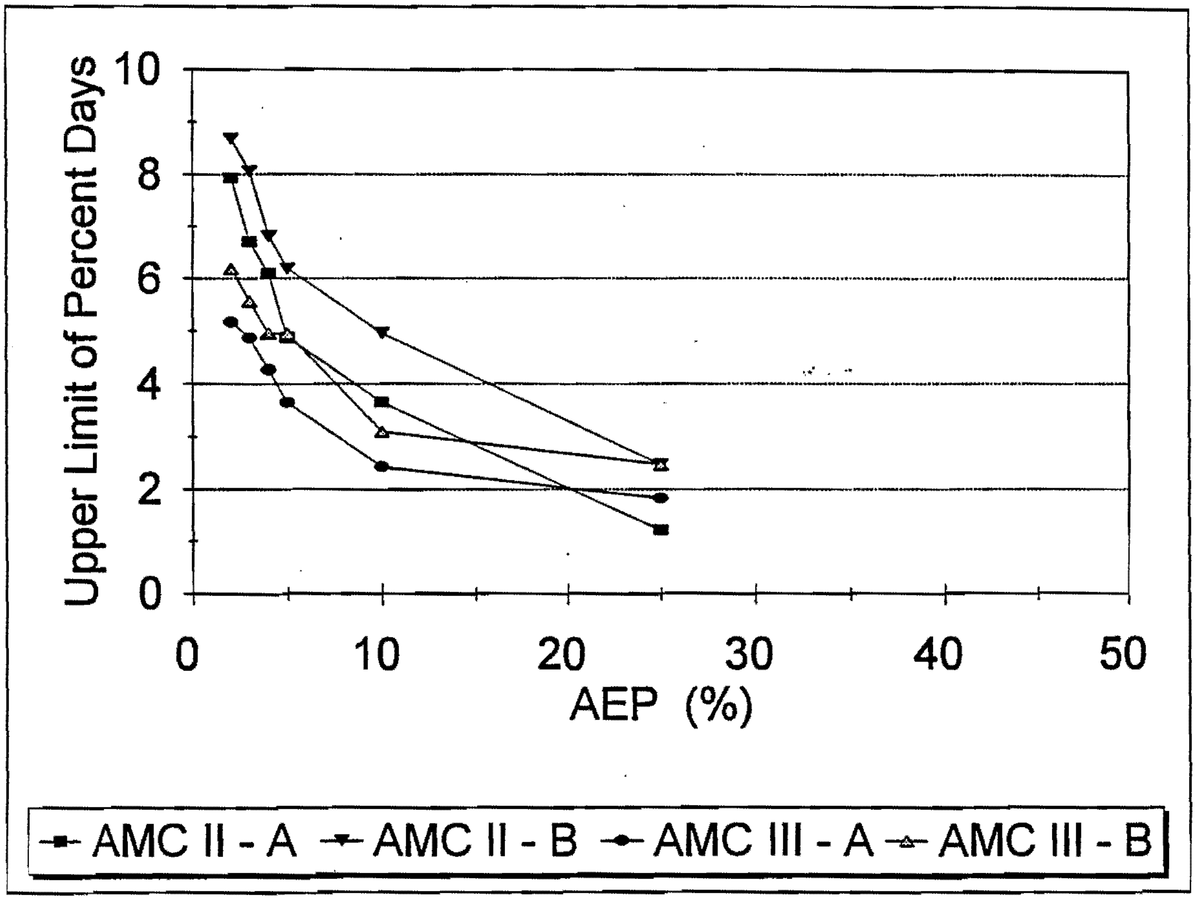


Figure 5.13 Upper limit of percent days which are single day AMC II or III events

5.4 Regionalization

Since the probabilities of occurrence of AMC II and III throughout the State were found to be quite low (see Sections 5.1 and 5.2) there is not a strong need to identify a regional pattern for these probabilities. Also there is the problem that probabilities estimated from records of different lengths have varying degrees of sampling error as was demonstrated in the plots against record length. This has the effect of confounding the search for regional patterns since the "signal" is somewhat buried in the "noise". However, two approaches were explored for identifying spatial trends in the probabilities. The first was to plot occurrence probabilities against station elevations. These plots showed no trends with elevation.

The second approach to regionalization was to plot the 25, 10, 5, and 2% AEPs for the percent CLSM days experiencing AMC II and III using gray-scale images and vector plots. These plots are included in Appendix B. They were visually inspected for patterns which showed consistency between AEP levels and AMC II and III were inspected for any identifiable patterns or relationship to topography. Although some trends may be discernable, no useful patterns seemed to emerge from this exercise.

6.0 SUMMARY, CONCLUSIONS, AND RECOMMENDATIONS

The occurrence of AMC II or III, which is defined by the magnitude of rainfall over the previous five days, is shown to be independent of the rainfall magnitude on the sixth day for locations throughout the State of Utah during critical local storm months (CLSM). Thus there is no tendency for high rainfall magnitudes to be associated with a high AMC. The AEP of

AMC III during the critical local storm months is shown to be very low and of the order of one to two percent per year. Actually, we have shown that even the probability of occurrence of AMC II during these months is quite low. While these conclusions do not rule out the possibility of the joint occurrence of a PMP event and AMC III, they do demonstrate that it is a very unlikely event. Furthermore, recent work by the National Weather Service in the mid-west has indicated that "There is no evidence that large storms with substantial precipitation tend to be associated with large antecedent precipitation amounts" (Chin and Vogel 1994).

Underlying the PMF definition quoted in Section 2.6 is the concept of the "most severe combination of hydrologic and meteorologic conditions that are considered reasonably possible for the drainage basin under study." Unfortunately, there appears to be no objective definition of what can be considered "reasonably possible" when selecting the combination of hydrologic and meteorologic factors to be used in a PMF determination. There are of course working definitions, such as the widespread use of AMC III, but the purpose of this study is to assess the empirical basis for the use of AMC III in the semi-arid state of Utah. Based on our findings, the assumption of AMC III in conjunction with the occurrence of the PMP is a compounding of unlikely events (see section 5.3), and may not be "reasonably possible."

Some alternative ways in which Utah PMF determination practice could be changed in response to our study include:

1) Adopt AMC II as the standard for all Utah dams;
2) Adopt AMC II as the standard for all but very high hazard dams, for which AMC III would be used;
3) Define curve numbers on a continuous scale which interpolates between AMC II and

III curve numbers based on the degree of (high) hazard rating for a dam; or

4) Continue using AMC III as the standard for all Utah dams.

Alternatives 2 and 3 would require a means of defining degrees of high hazard dams, rather than the single category of high hazard dams which is currently defined in Utah dam safety regulations. An example of subdividing the high hazard category is the approach presented in Table 6.1 from the State of Washington Dam Safety Guidelines (Schaefer 1992).

Table 6.1 State of Washington dam hazard classifications (After Schaefer 1992)

DOWNSTREAM HAZARD POTENTIAL	DOWNSTREAM HAZARD CLASSIFICATION	POPULATION AT RISK	ECONOMIC LOSS GENERIC DESCRIPTIONS	ENVIRONMENTAL DAMAGES	TYPICAL DESIGN STEP
LOW	3	0	Minimal. No inhabited structures. Limited agriculture development.	No deleterious materials in reservoir	1 - 2
SIGNIFICANT	2	1 to 6	Appreciable. 1 or 2 inhabited structures. Notable agriculture.or work sites. Secondary highway and/or rail lines.	Limited water quality degradation from reservoir contents and only short term consequences	3 - 4
HIGH	1C	7 to 30	Major. 3 to 10 inhabited structures. Low density suburban area with some industry and work sites. Primary highways and rail lines.	Severe water quality degradation potential from reservoir contents and long term effects on aquatic and human life	3 - 6
HIGH	1B	31-300	Extreme. 11 to 100 inhabited structures. Medium density suburban or urban area with associated industry, property and transportation features.		4 - 8
HIGH	1A	More than 300	Extreme. More than 100 inhabited structures. Highly developed, densely populated suburban or urban area with associated industry, property, transportation and community life line features.		8

A possible effect of adopting either alternatives 1, 2, or 3 is that for some dams, the local storm PMF might replace the general storm PMF as the most critical inflow design flood event. It is also possible that such a shift would require that a greater emphasis be given to the role of snowmelt, at least in some areas of the state.

The low probability of occurrence of AMC II or III implies that the most likely antecedent moisture condition at the time of the PMP is AMC I. However, we do not propose the use of AMC I for PMF determinations in Utah. We instead recommend that alternatives 1, 2, or 3 be carefully considered for adoption by the Utah State Engineer for PMF determinations.

Additional research in this field could include a basin-scale physically-based study of the infiltration and runoff under local storm rainfall. Such work could be used to evaluate the reasonableness of the five-day cumulative precipitation basis for the definition of AMC in the SCS curve number method when applied under Utah conditions. Further analyses of the type described in this paper also could be conducted in states adjacent to Utah to verify our findings.

REFERENCES

Ashcroft, G.L., Jensen, D.T., and Brown, J.L. (1992). Utah Climate. Utah Climate Center, Utah State University, Logan, Utah.

Borgione, J. (1994). Personal Communication.

Bowles, D. S., Jensen, D. T., Win, K. M., and Kuchment, L. (1992). A Preliminary Assessment of Probable Maximum Precipitation Estimation Procedures and the Basis for Loss Rates: Bear River Basin, Utah. Utah Water Research Laboratory, Logan, Utah.

Chin, E. H. and Vogel, J. H. (1994). Relationship Between Storm and Antecedent Precipitation over Kansas, Oklahoma, and Eastern Colorado. Water Management Information Division, Office of Hydrology, Silver Spring, Maryland.

Chow, V. T., Maidment, D. R., and Mays, L. W. (1988). Applied Hydrology. McGraw-Hill Publishing Company, New York, New York.

Haan, C. T. (1977). Statistical Methods in Hydrology. The Iowa State University Press, Ames, Iowa.

Hansen, E. M., Schwarz, F. K., and Riedel, J. T. (1977). Probable Maximum Precipitation Estimates, Colorado River and Great Basin Drainages, Hydrometeorological Report No. 49. USDC, NOAA, National Weather Service, Hydrometeorological Branch, Silver Spring, MD. Stock No. 003-017-00408-2. U.S. Government Printing Office, Washington, D.C.

Hoggan, D. H. (1989). Computer-Assisted Floodplain Hydrology and Hydraulics. McGraw-Hill Publishing Company, New York, New York.

Linden, M. (1993). Personal Communication.

Linsley, R. K., Franzini, J. B., Freyberg, D. L., and Tchobanoglous, G. (1992). Water-Resources Engineering. McGraw-Hill Publishing Company, New York, New York.

Linsley, R. K., Kohler, M. A., and Paulhus, J. L. H. (1982). Hydrology for Engineers. McGraw-Hill Publishing Company, New York, New York.

McCuen, R. C. (1983). Hydraulic Analysis and Design. Prentice Hall, Englewood Cliffs, New Jersey.

McCuen, R. C. (1982). A Guide to Hydraulic Analysis Using SCS Methods. Prentice Hall, Englewood Cliffs, New Jersey.

Morgan, R. L. and Hall, R. B. (1993). State of Utah Statutes and Administrative Rules for Dam Safety. Utah Department of Natural Resources, Salt Lake City, Utah.

National Research Council. (1985). Safety of Dams - Flood and Earthquake Criteria. National Academy Press, Washington, D.C.

Ponce, V. M. (1985). Engineering Hydrology - Principles and Practices. Prentice Hall, Englewood Cliffs, New Jersey.

Schaefer, M. G. (1992). State of Washington Dam Safety Guidelines - Technical Note 2: Selection of Design Performance Goals for Critical Project Elements. Ecology Technical Publication # 92-55F, State of Washington, Department of Ecology, Olympia, Washington.

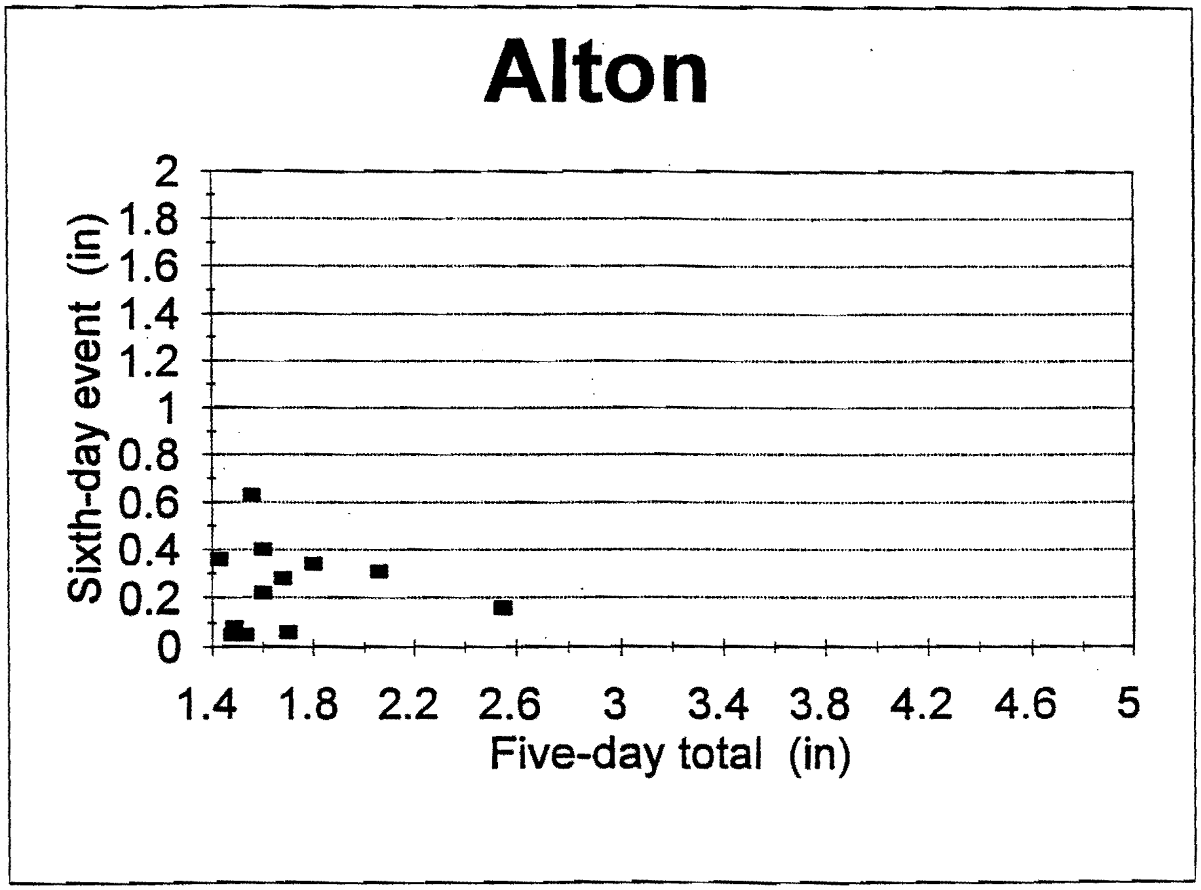
Stauffer, N. (1993). Personal Communication.

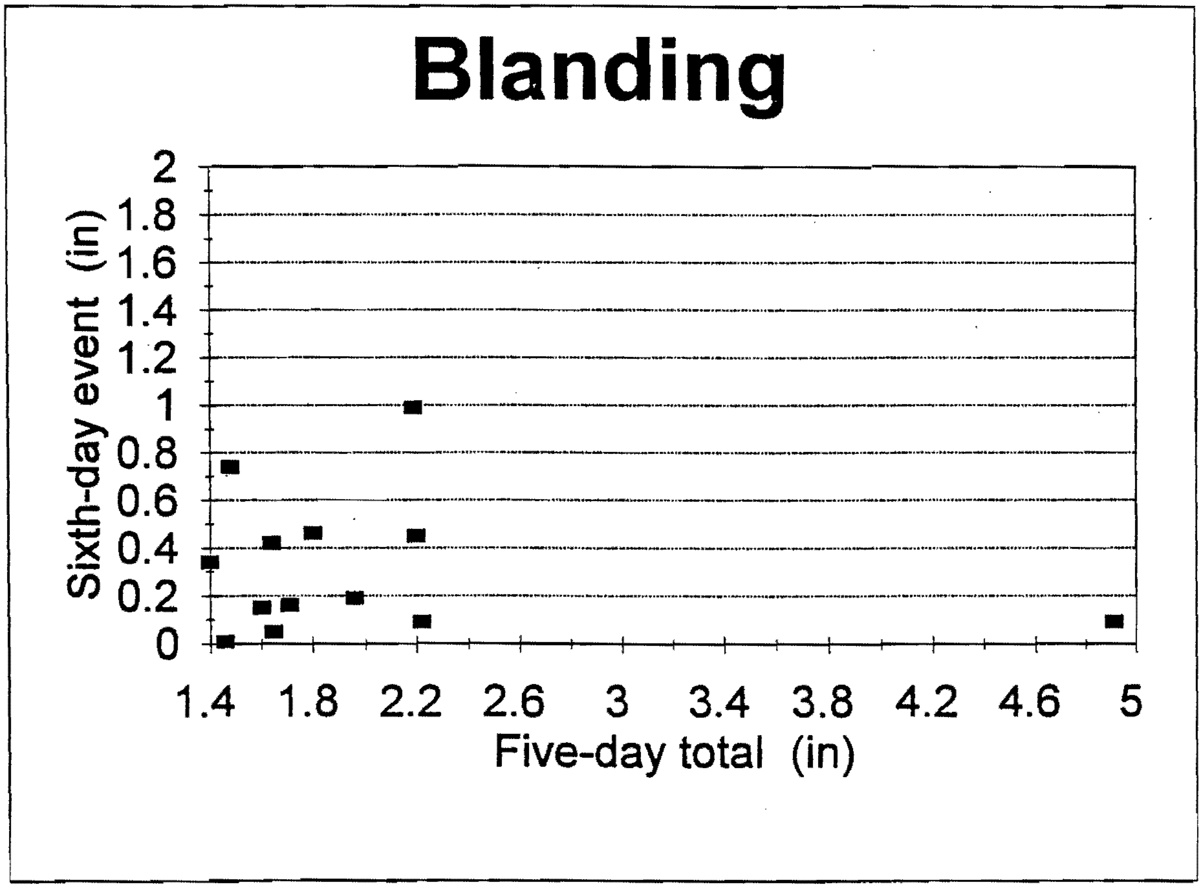
United States Department of Agriculture, Soil Conservation Service. (1990). Engineering Field Manual. United States Department of Agriculture, Washington, D.C.

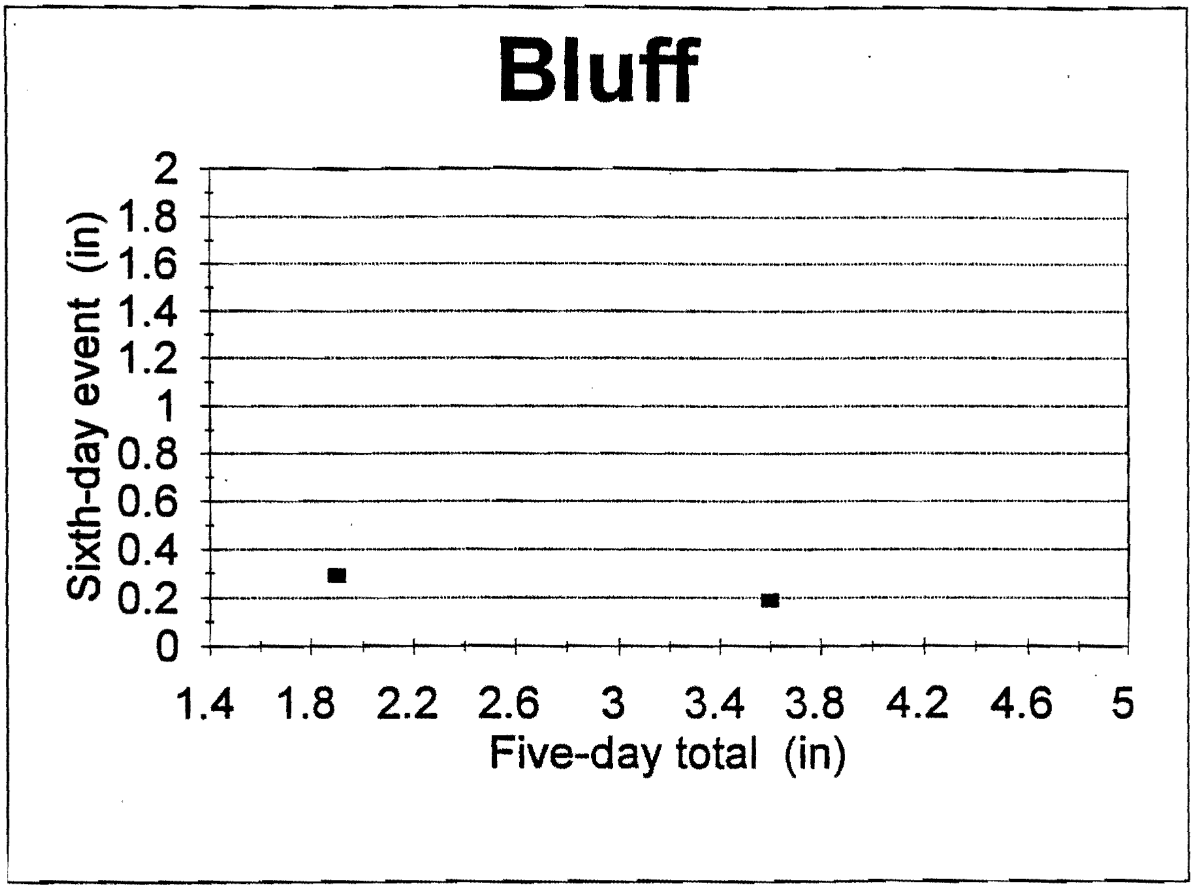
Vardeman, S. B. (1994). Statistics for Engineering Problem Solving. PWS Publishing Company, Boston, Mass.

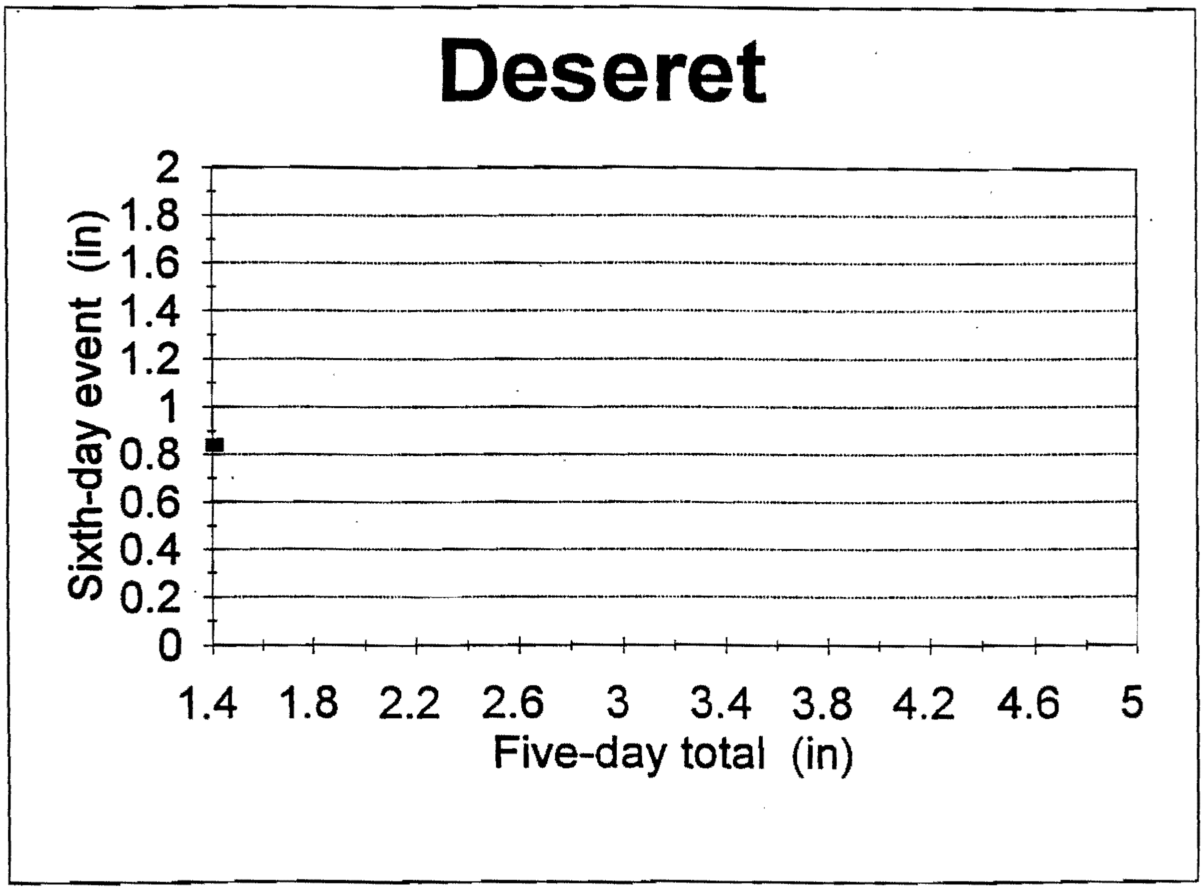
APPENDIX A

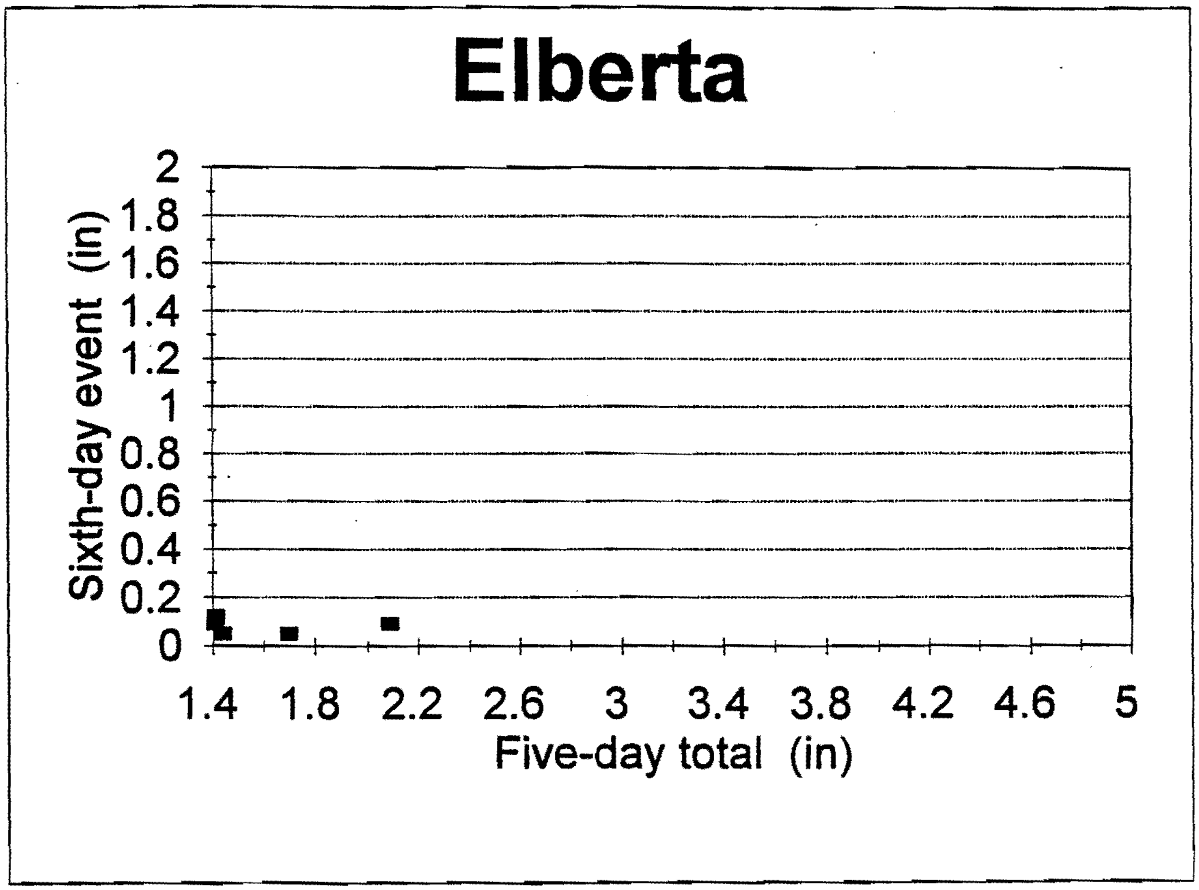
SCATTERGRAMS OF FIVE-DAY TOTALS VS SIXTH-DAY EVENTS FOR 28 SELECTED STATIONS

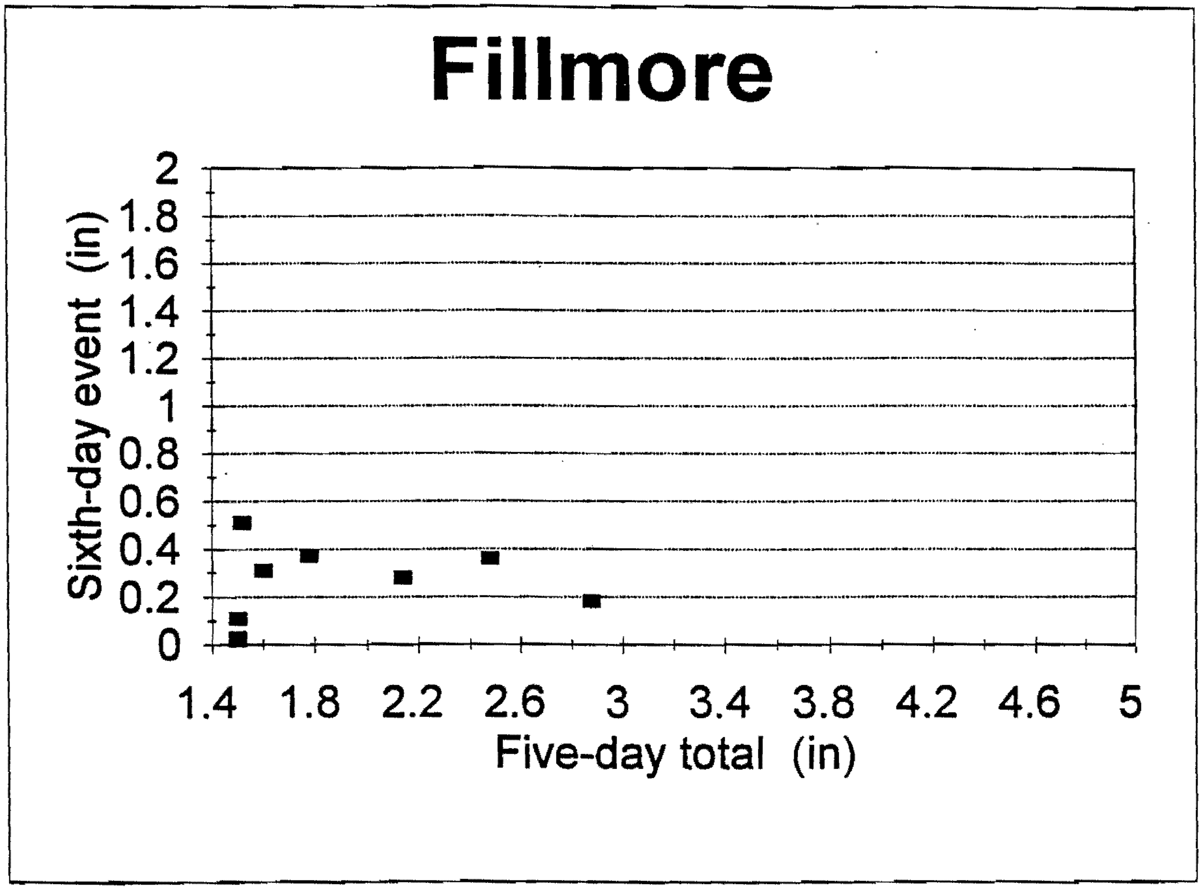

Alton
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Sixth-day event (in)
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

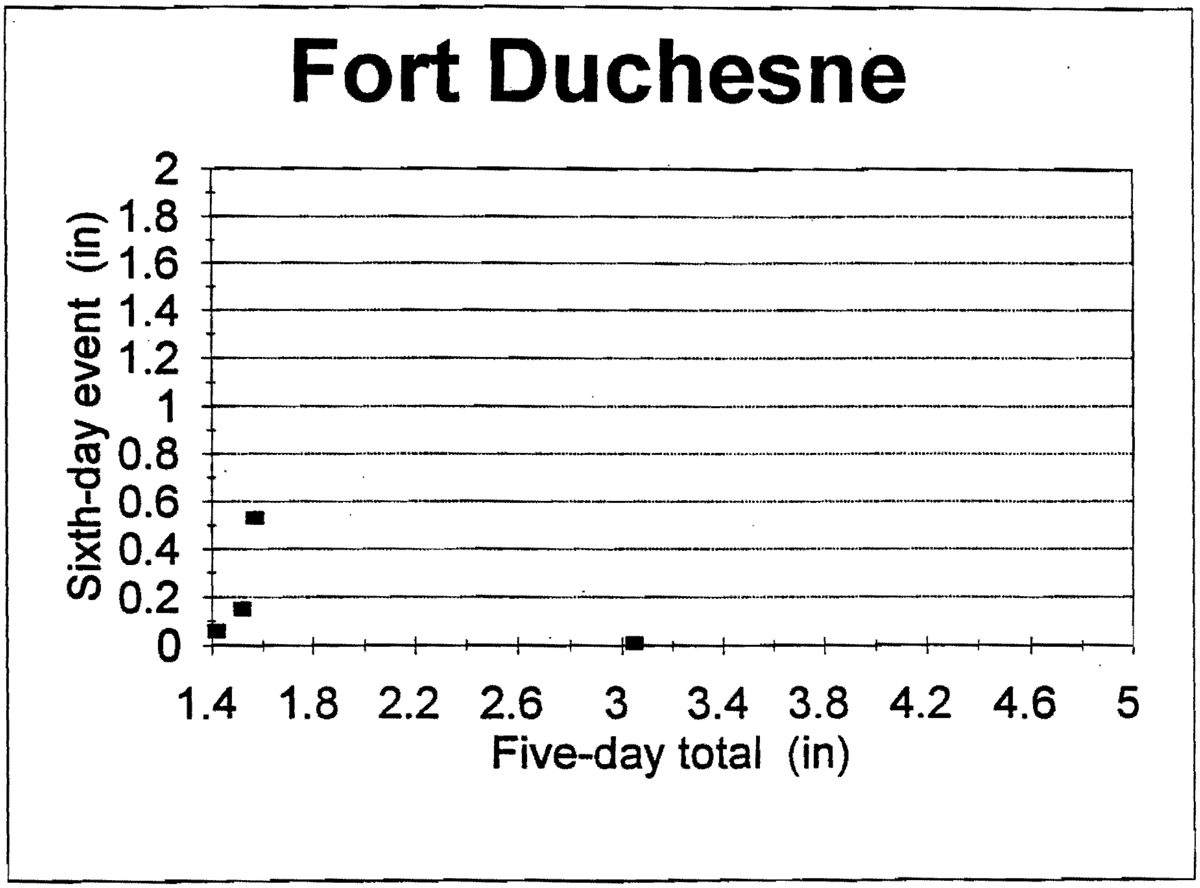

Blanding
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

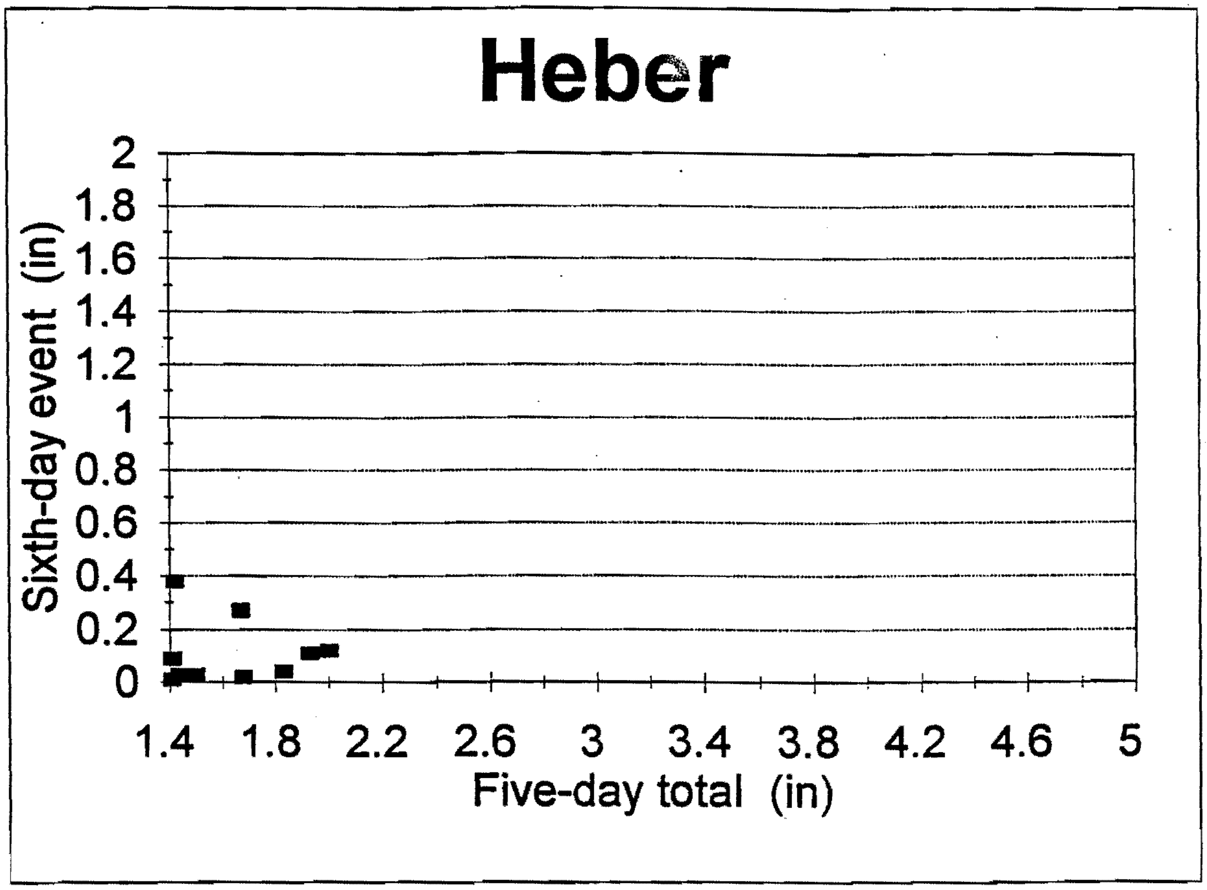

Bluff
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


Deseret
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

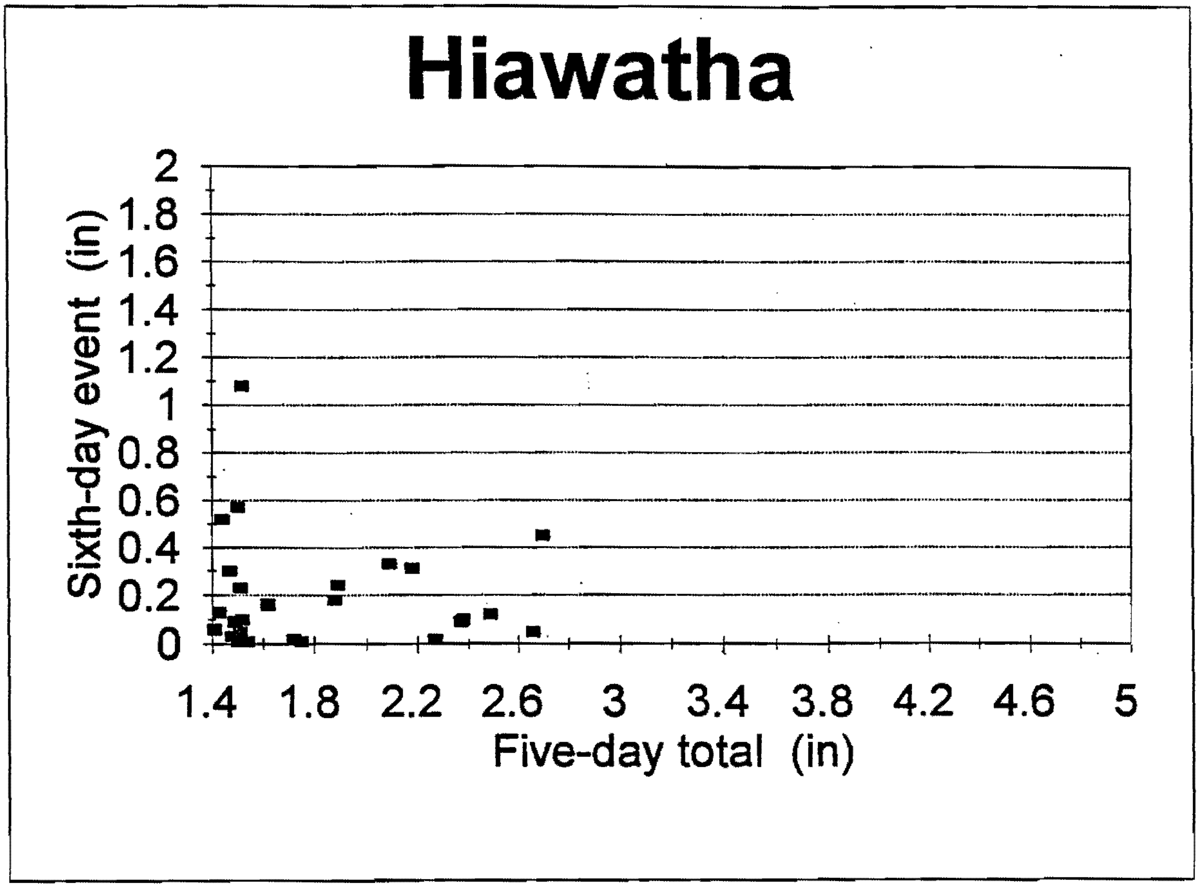

Elberta
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

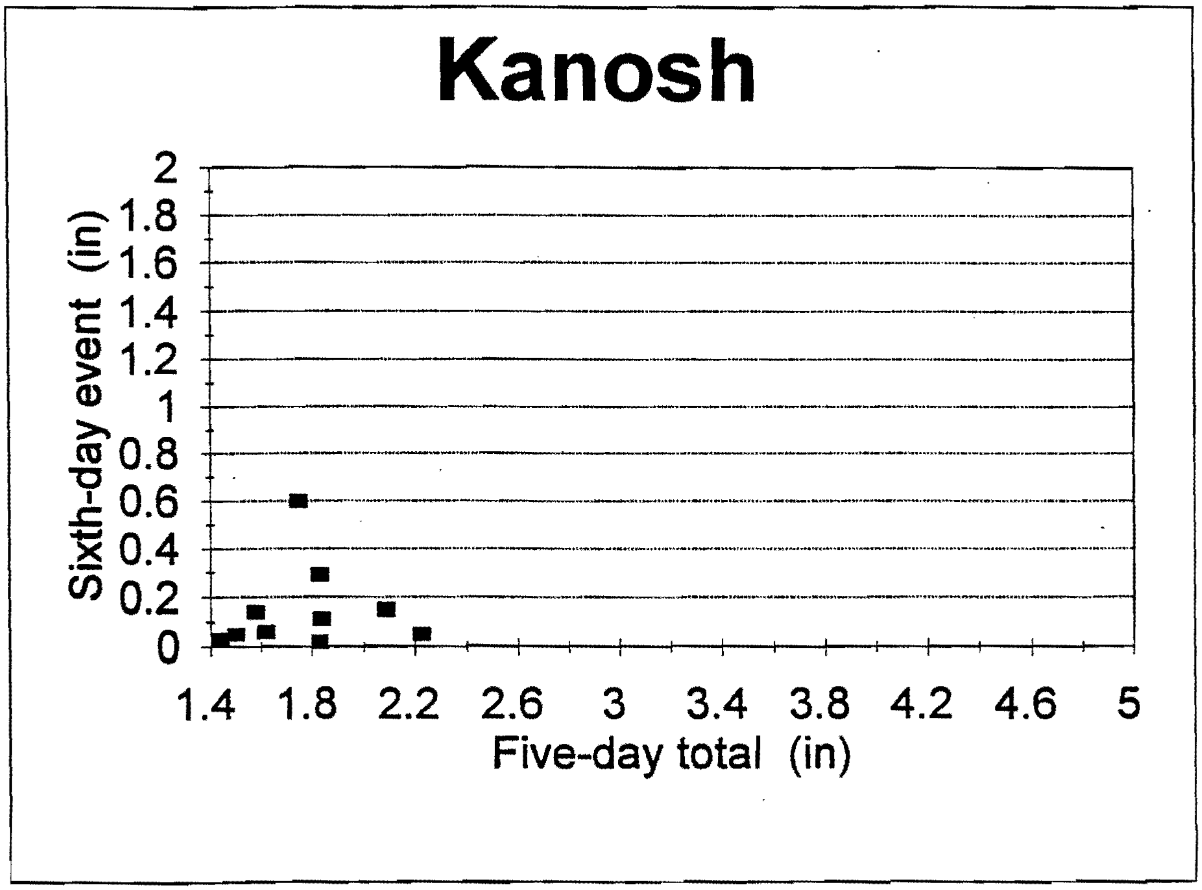

Fillmore
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

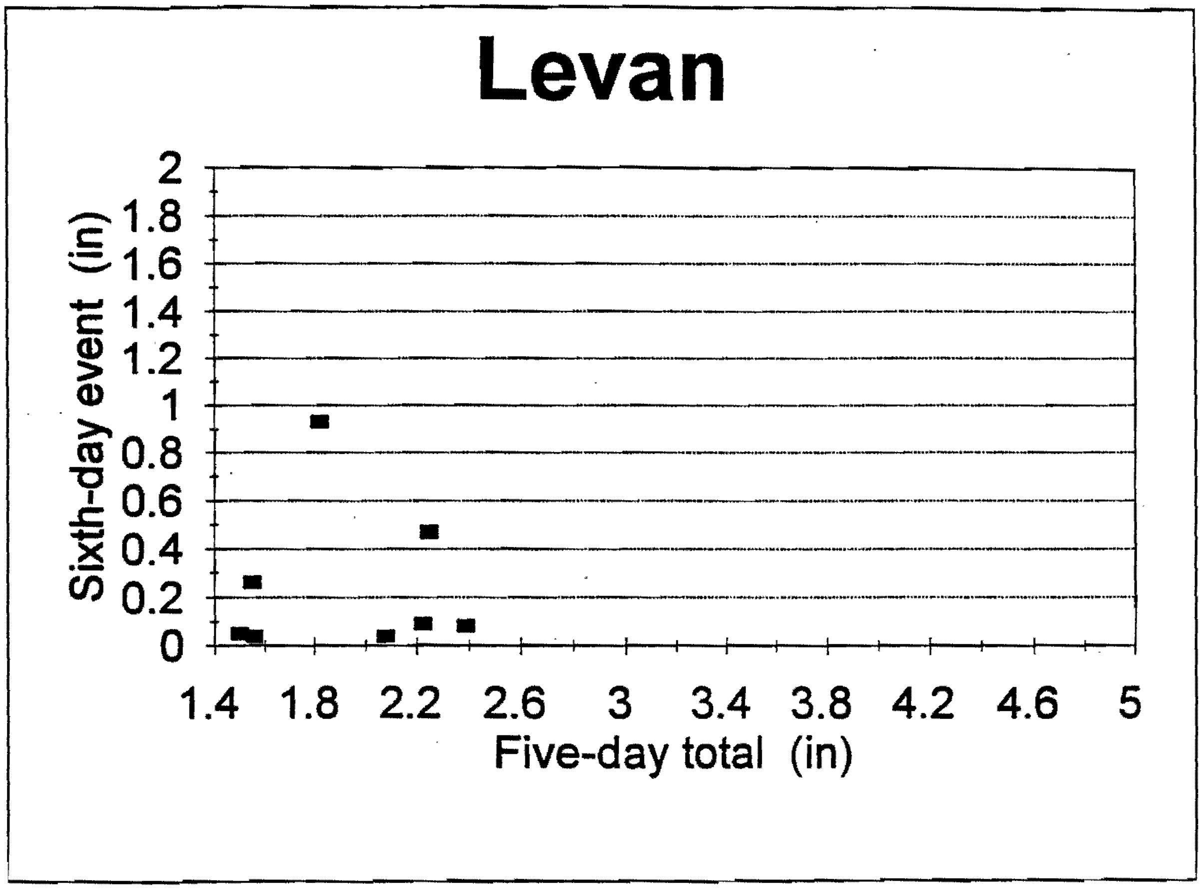

Fort Duchesne
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

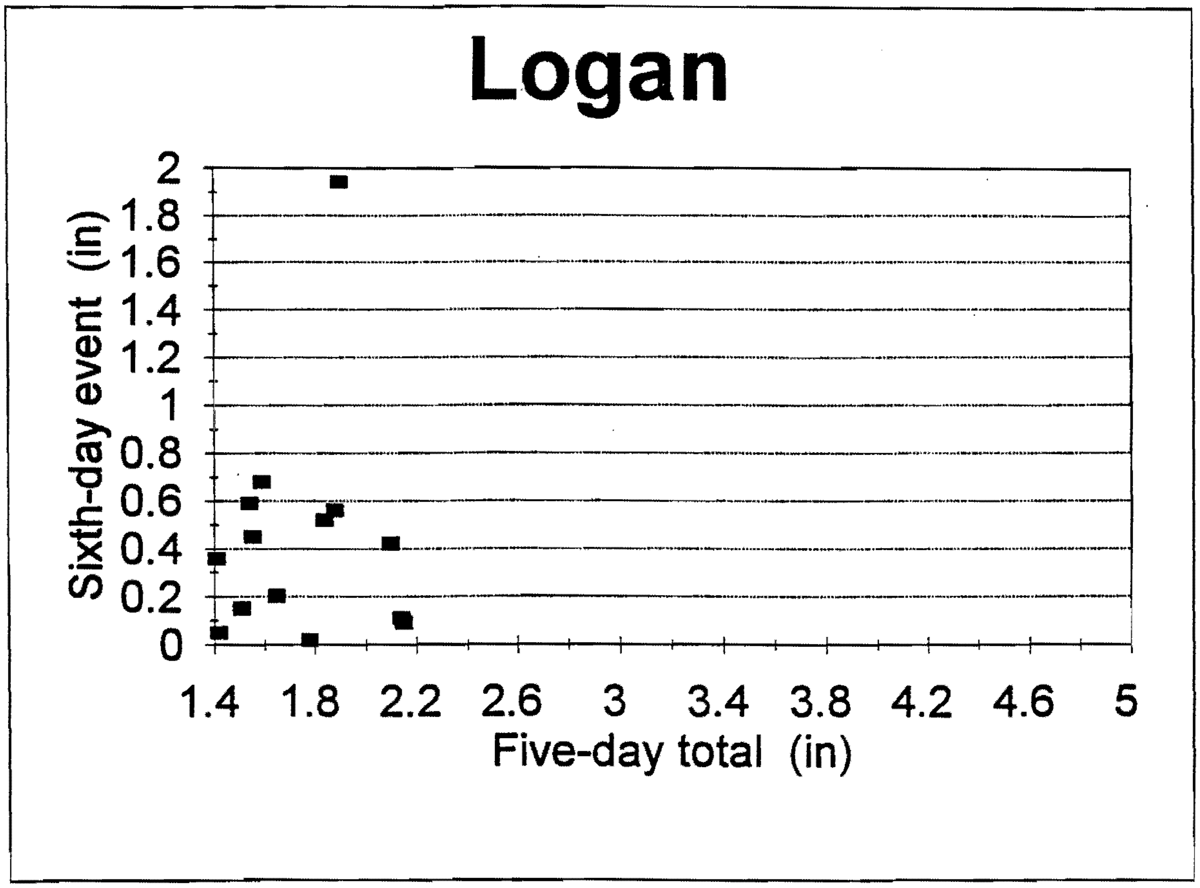


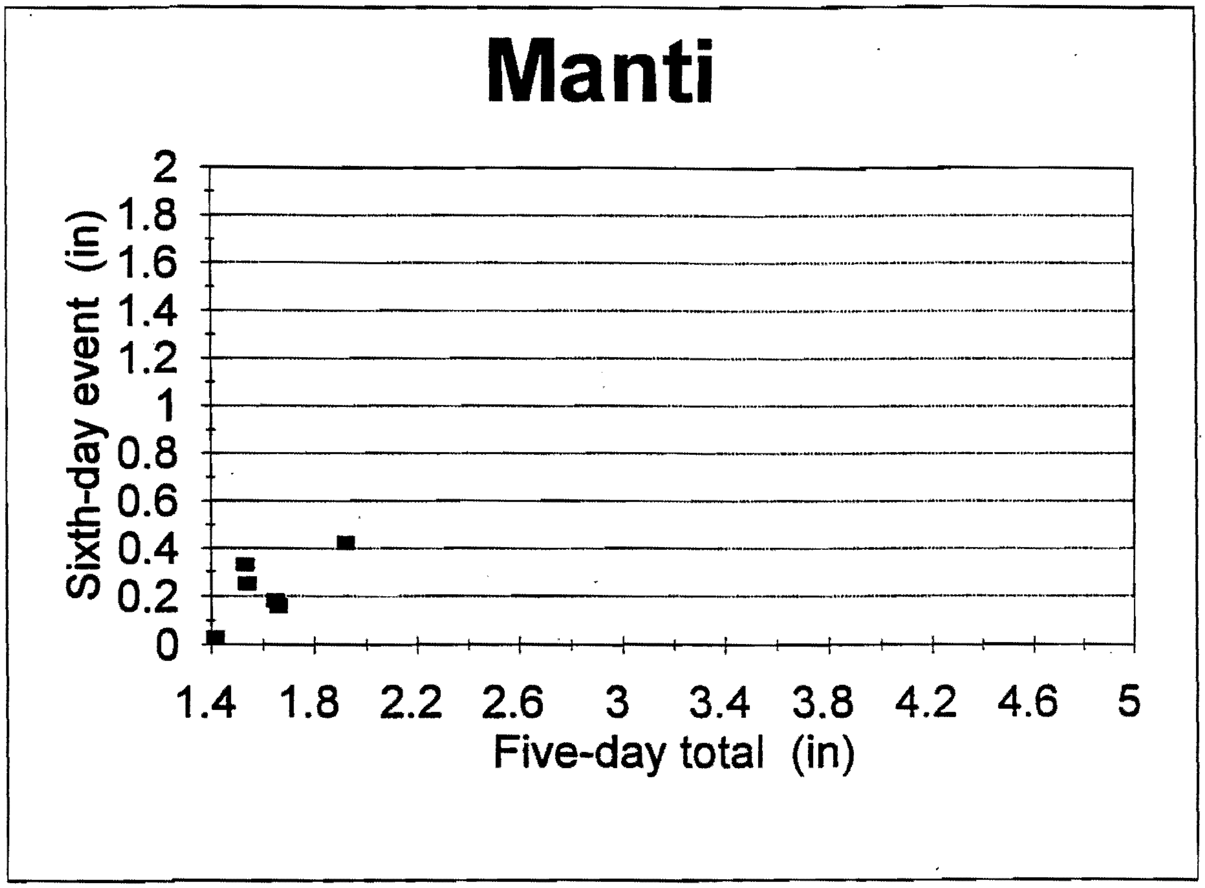
Heber
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

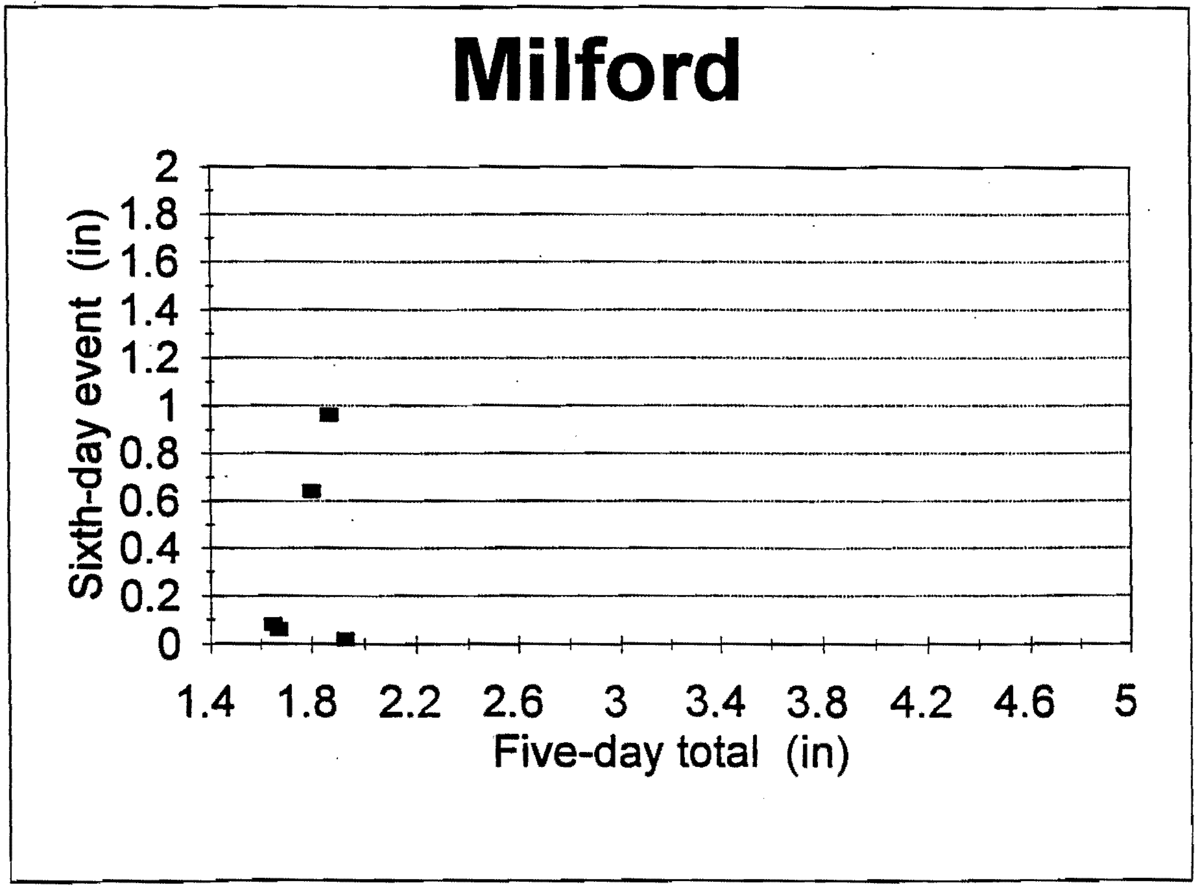

Hiawatha
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

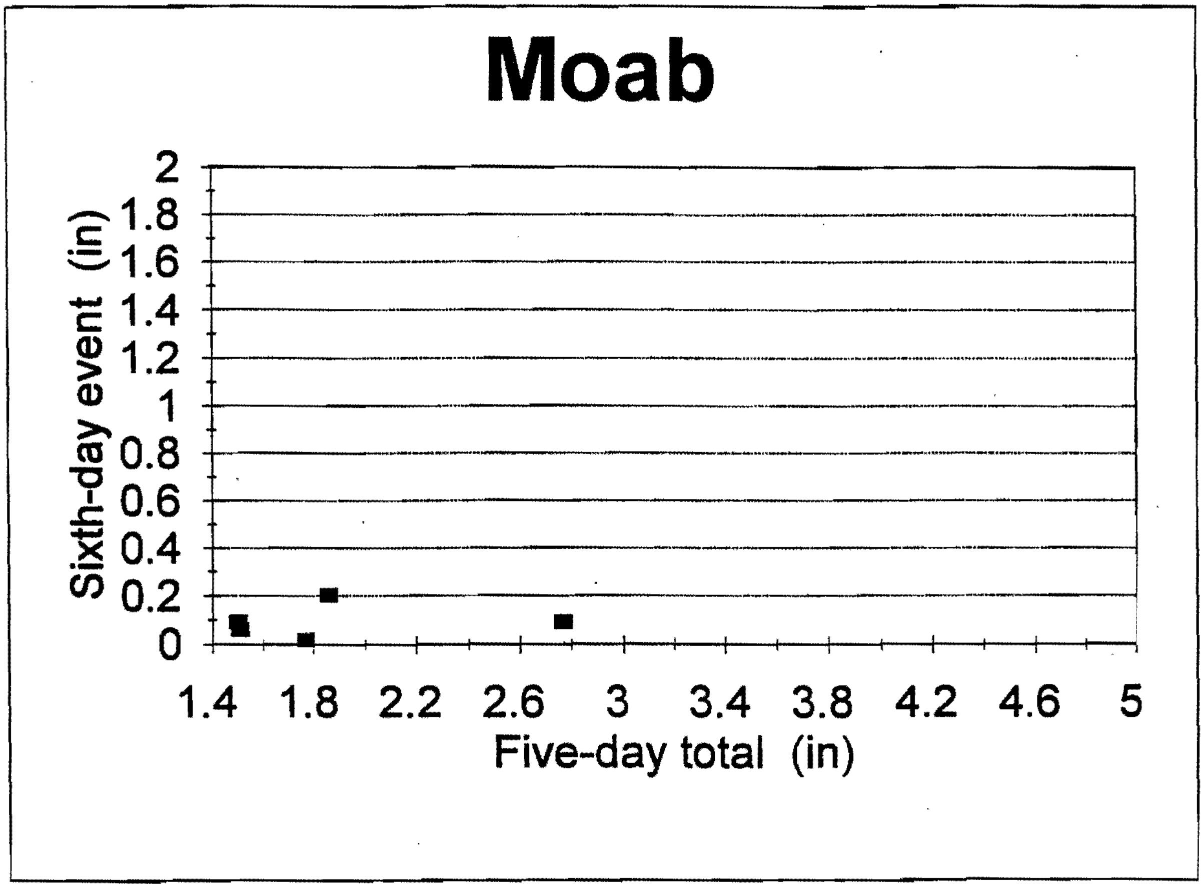

Kanosh
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

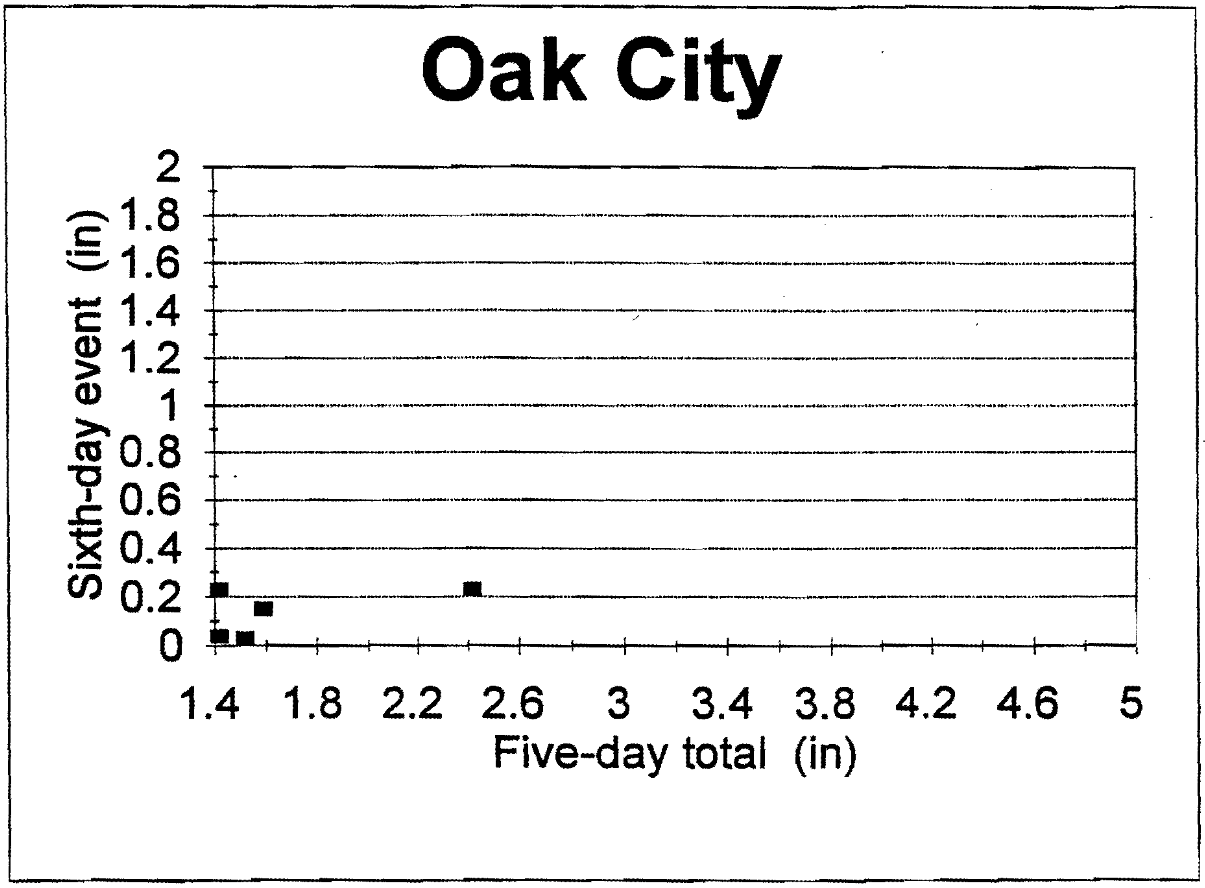

Levan
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

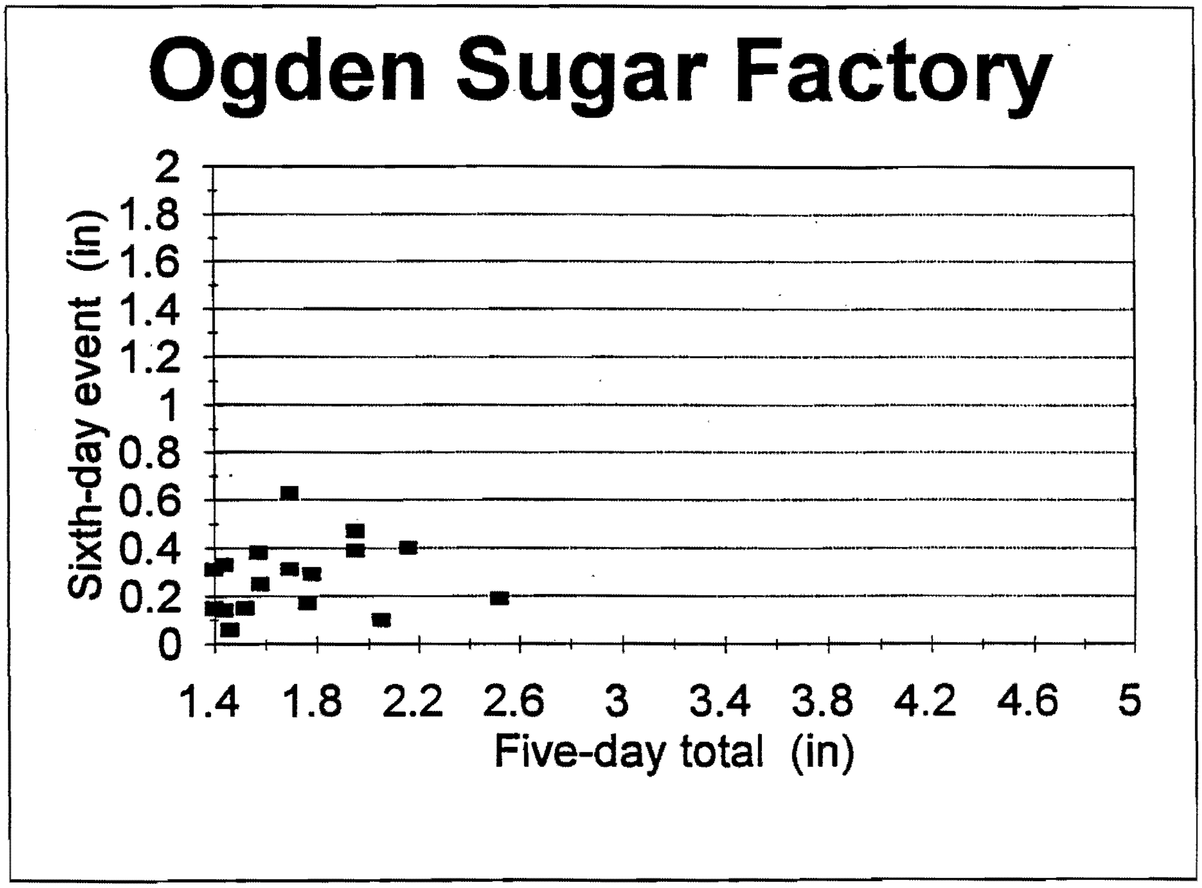

Logan
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

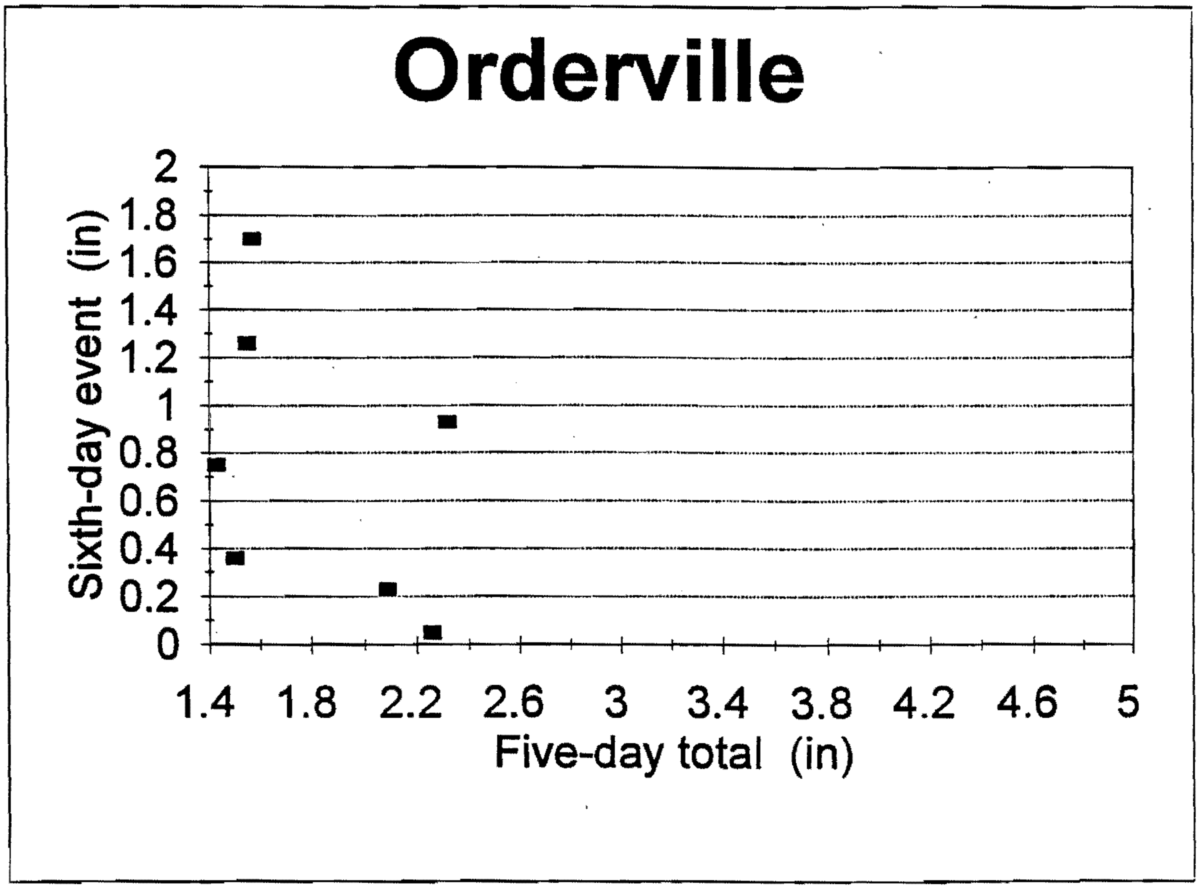

Manti
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

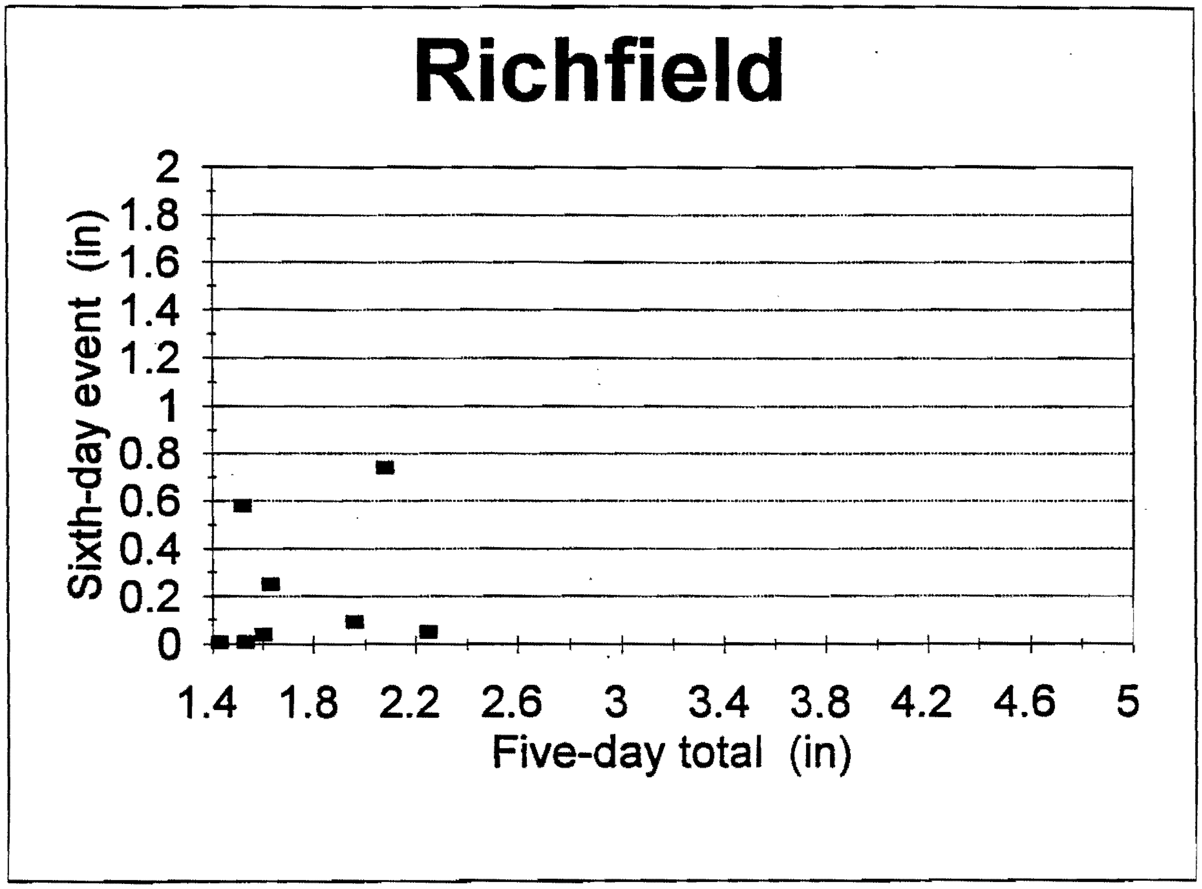

Milford
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


Moab
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


Oak City
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

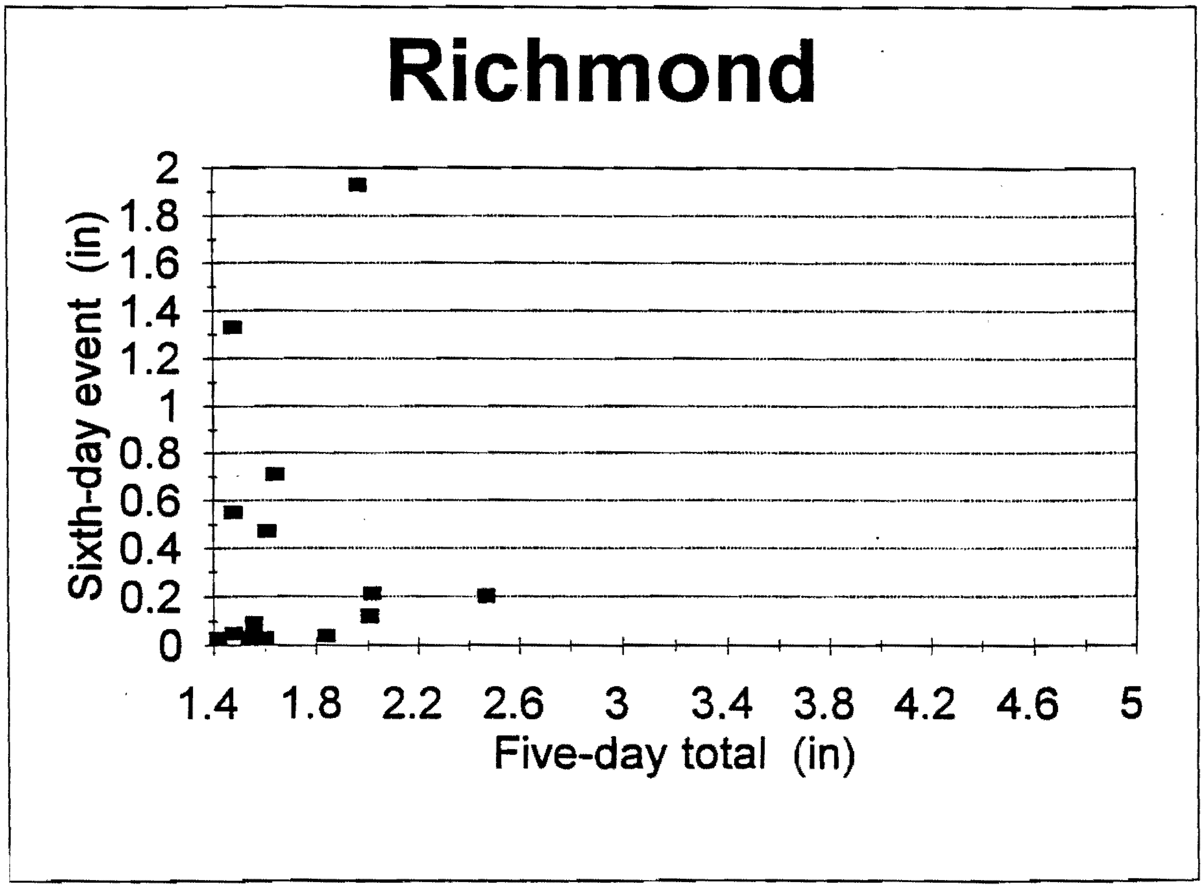

Ogden Sugar Factory
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

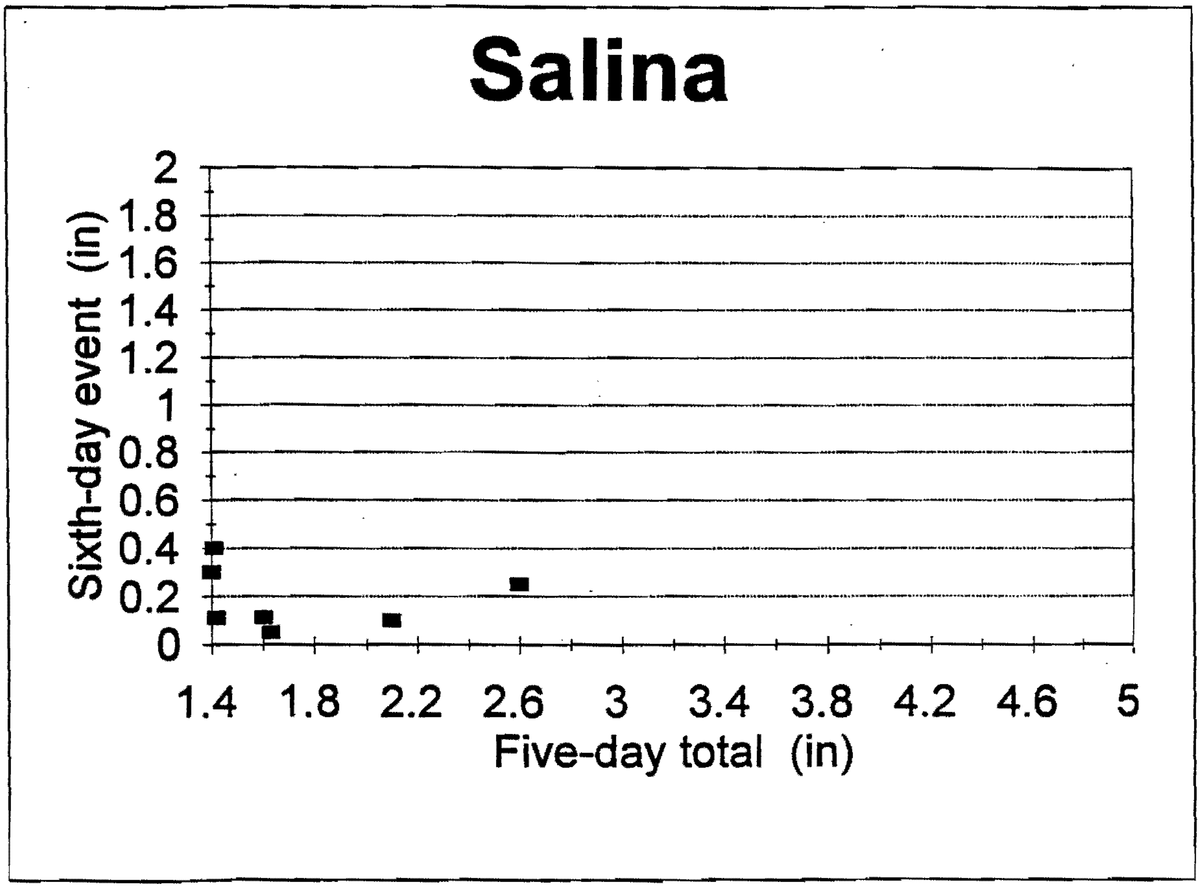

Orderville
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

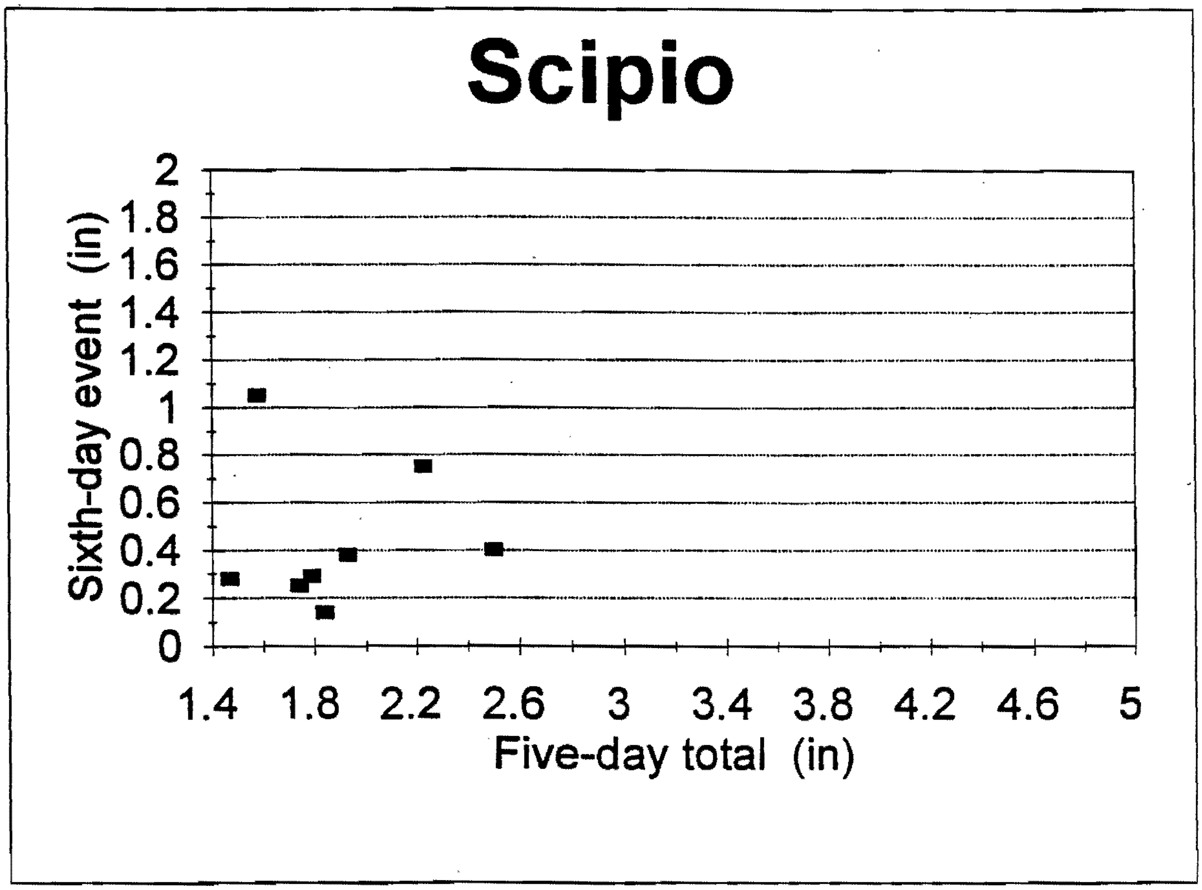


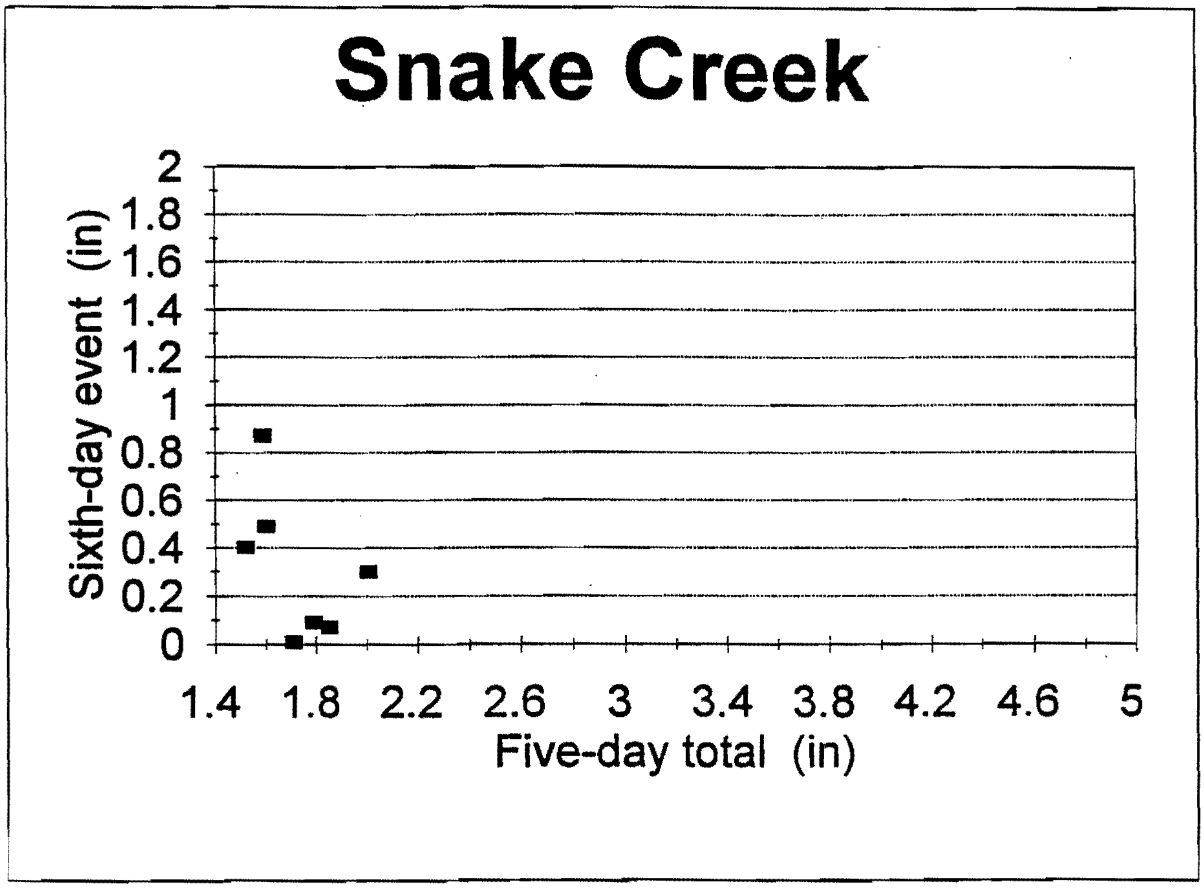
Richfield

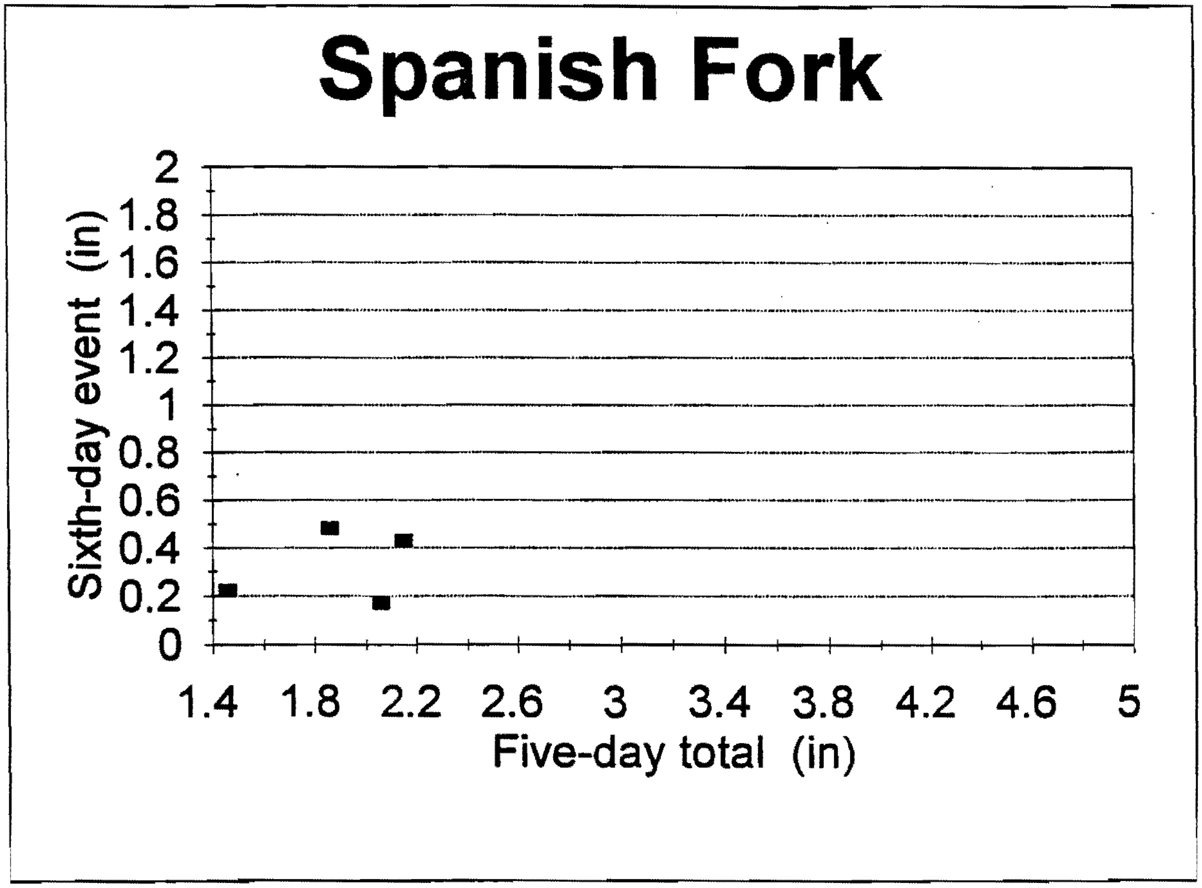
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
Sixth-day event (in)
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

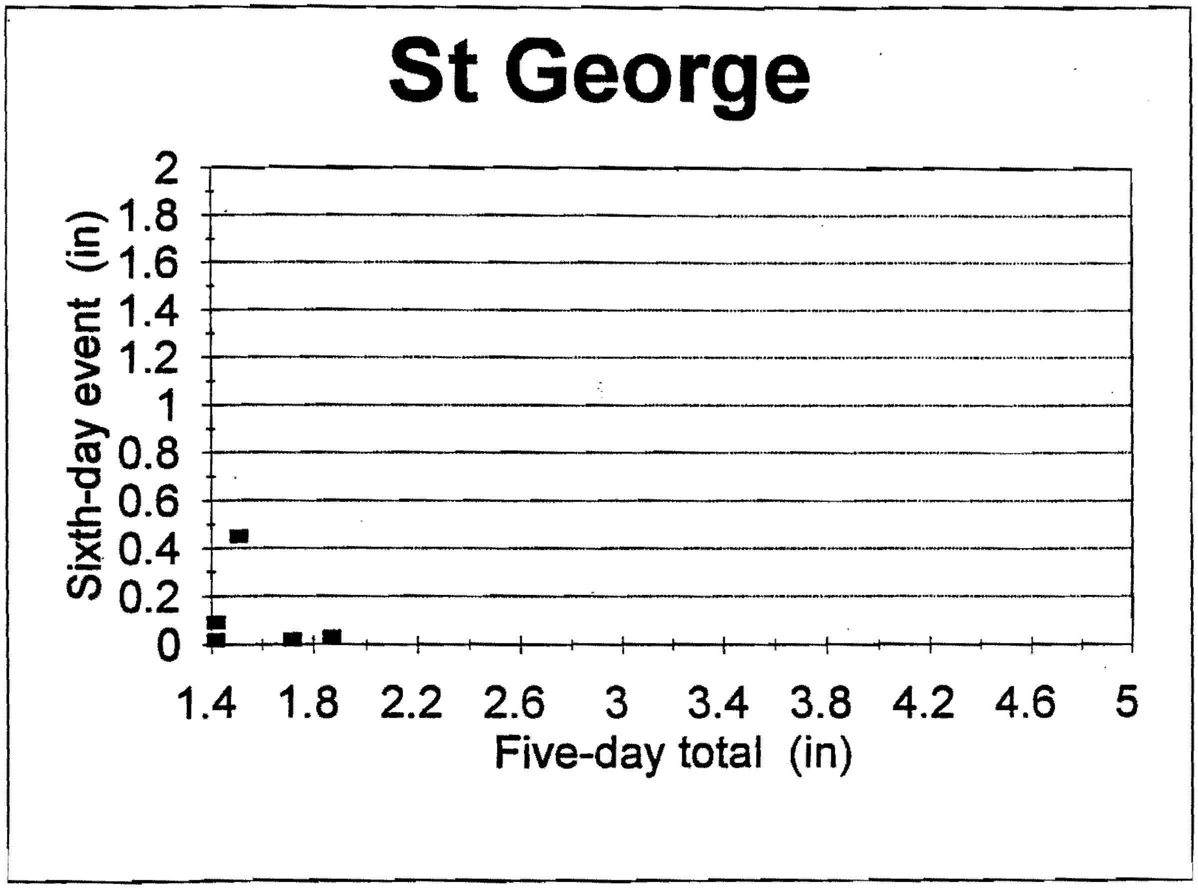

Richmond
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

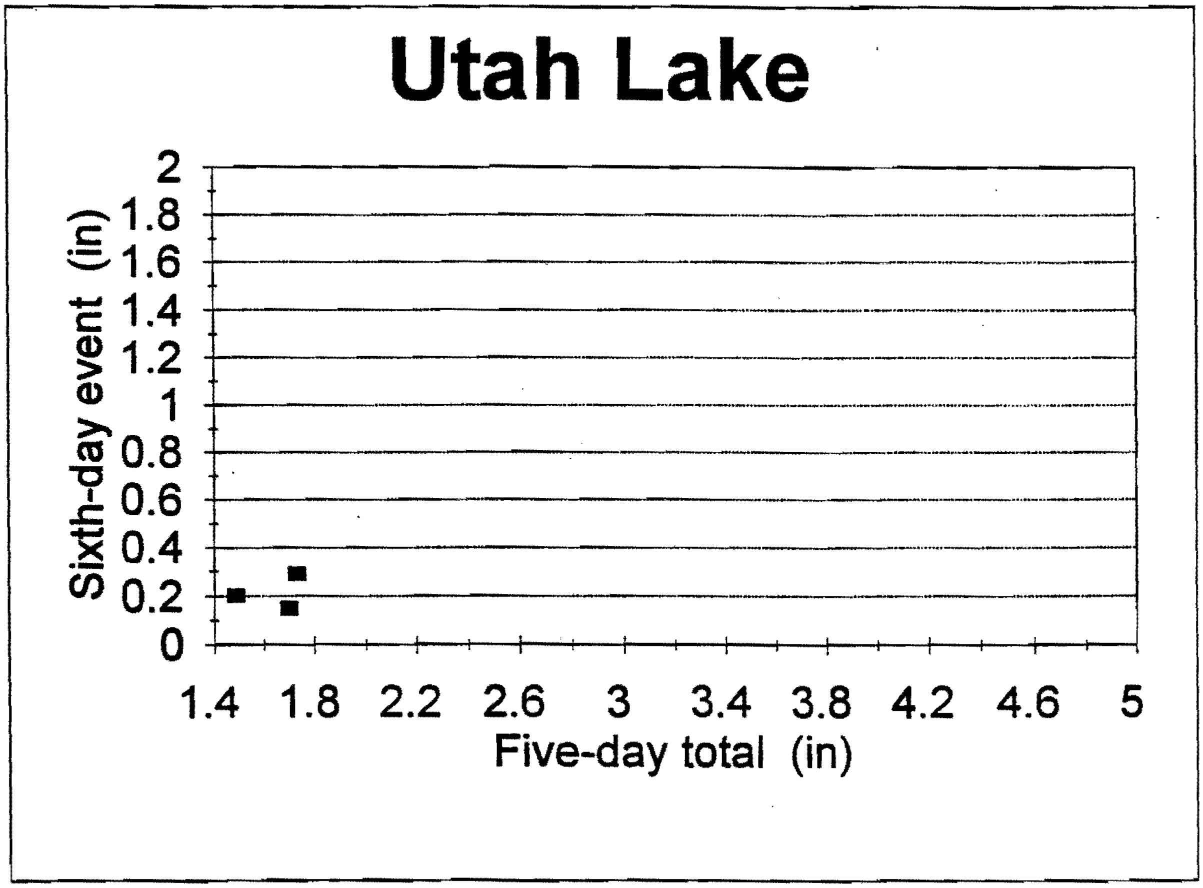

Salina
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

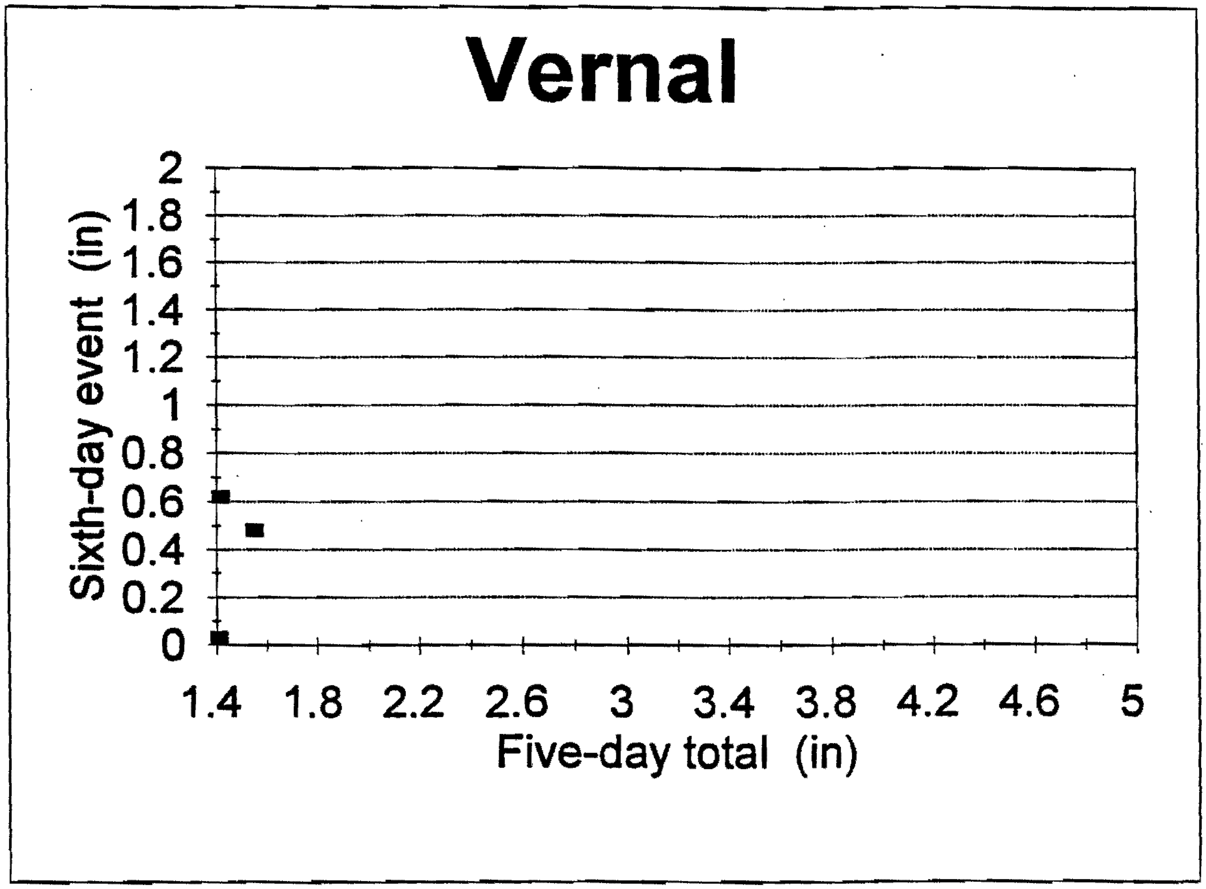

Scipio
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

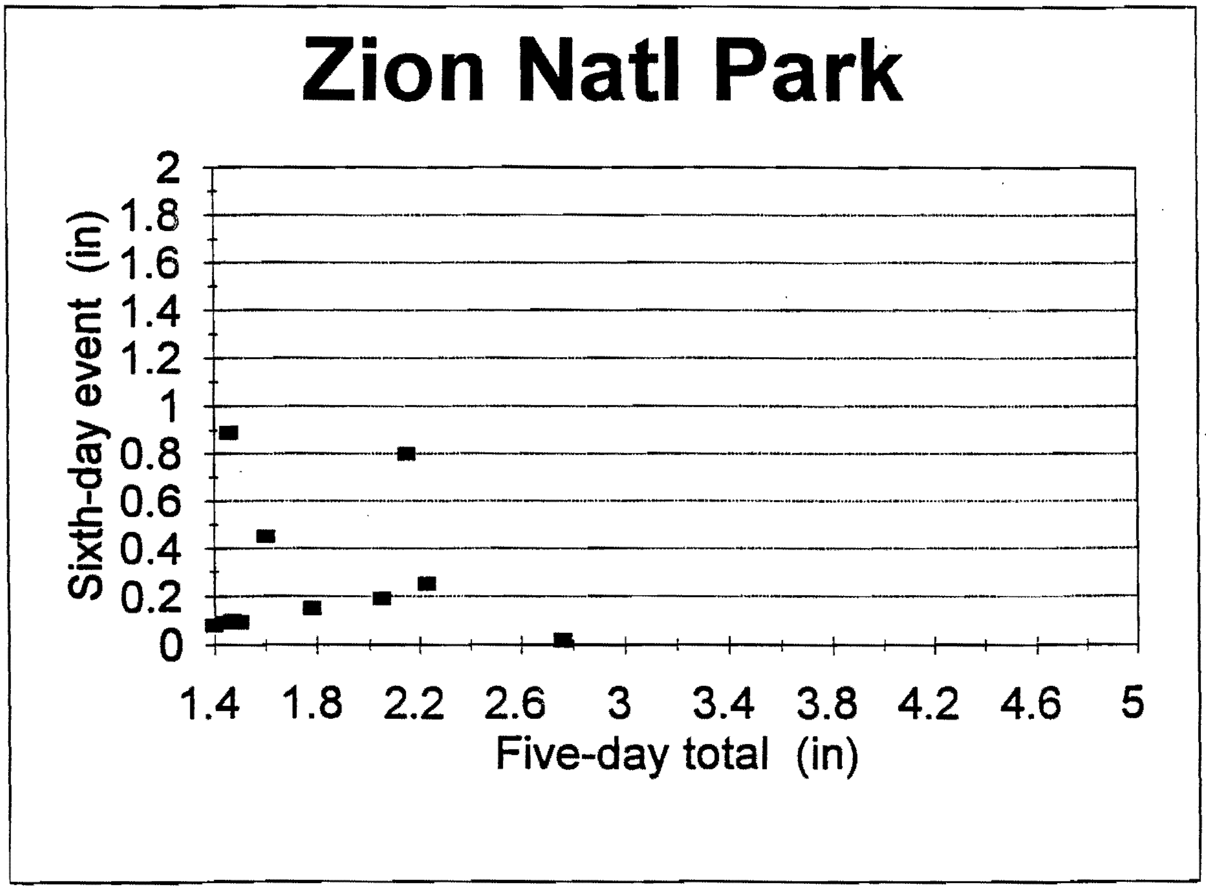

Snake Creek
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


Spanish Fork
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


St George
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


Utah Lake
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

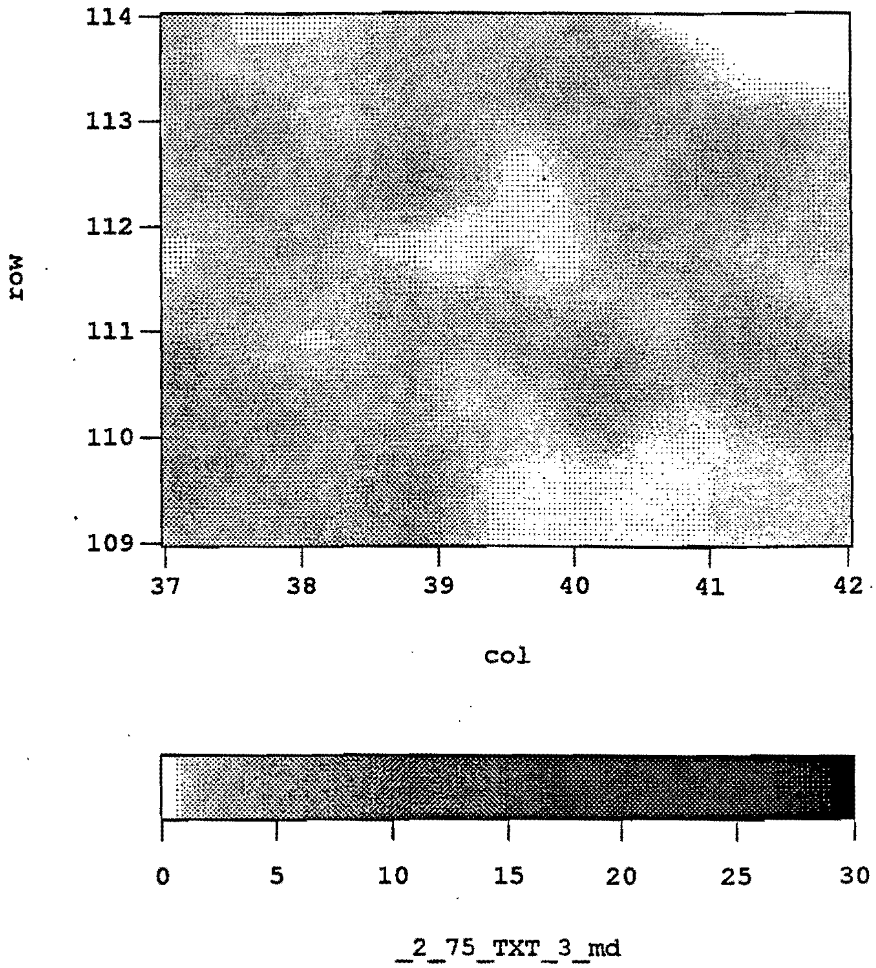

Vernal
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)


Zion Natl Park
Sixth-day event (in)
2
1.8
1.6
1.4
1.2
1
0.8
0.6
0.4
0.2
0
1.4
1.8
2.2
2.6
3
3.4
3.8
4.2
4.6
5
Five-day total (in)

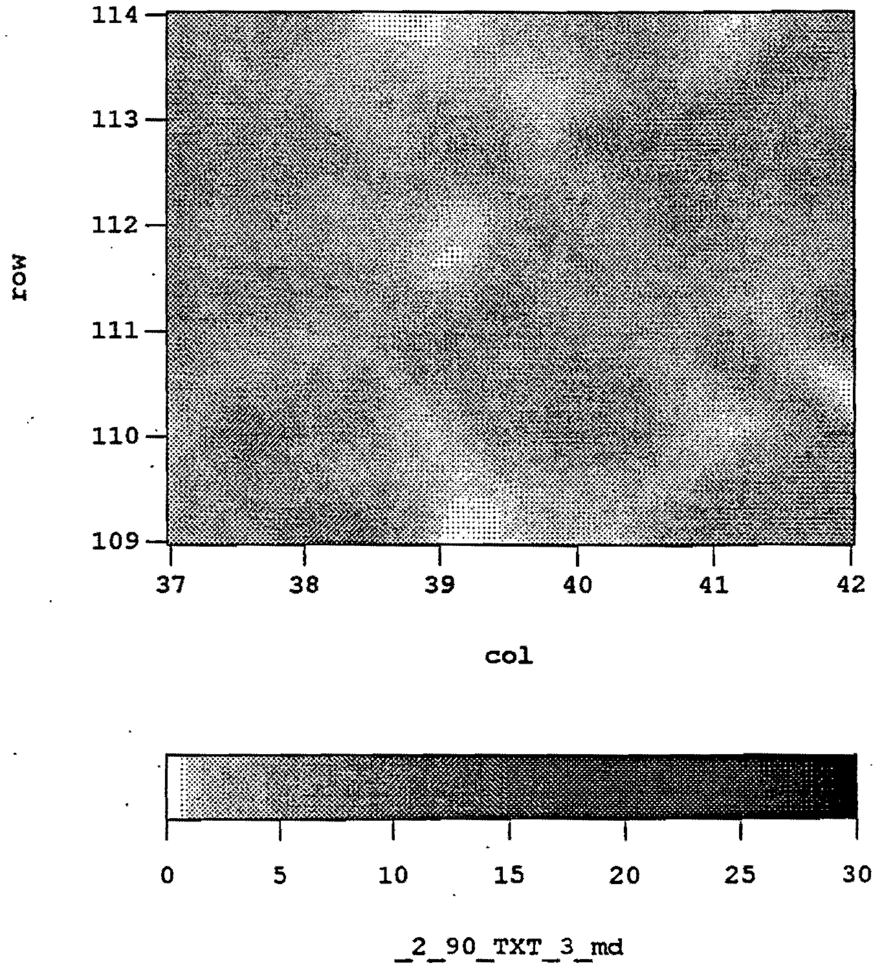
APPENDIX B

GRAY-SCALE AND VECTOR IMAGES OF 25, 10, 5, AND 2% AEPs FOR THE PERCENT DAYS EXPERIENCING AMC II AND III

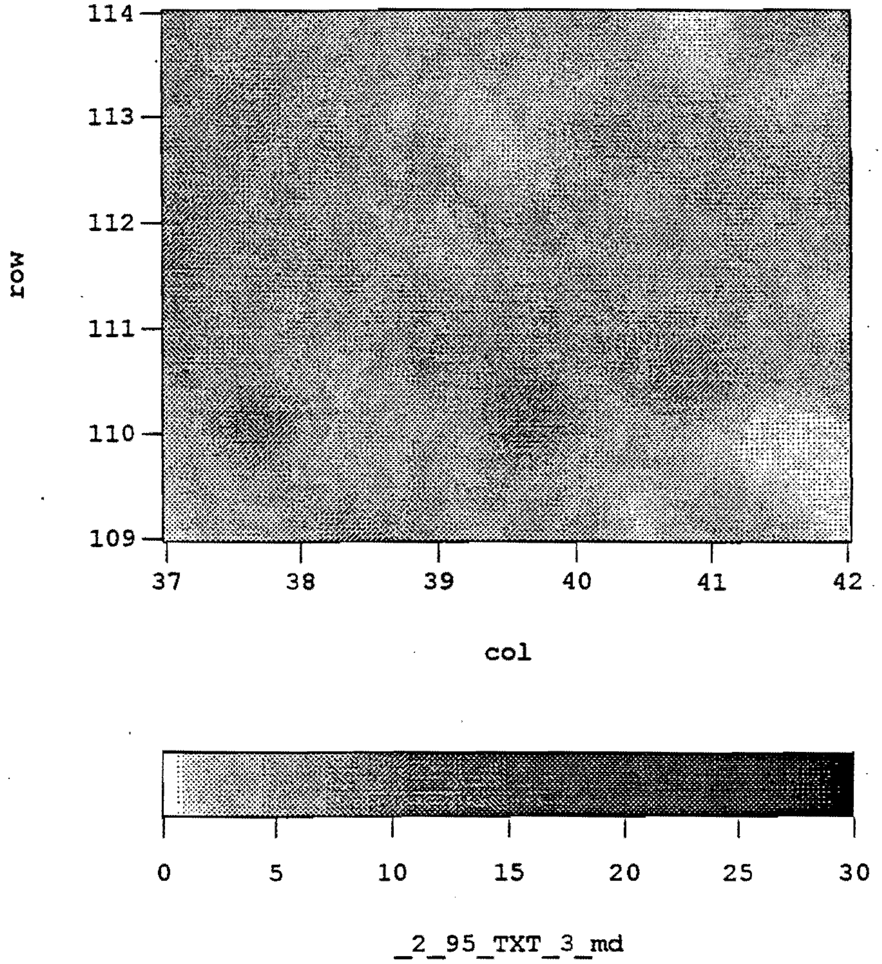
_2_75_TXT_3_md


25% EP Percent Days AMC 2

10% EP Percent Days AMC 2

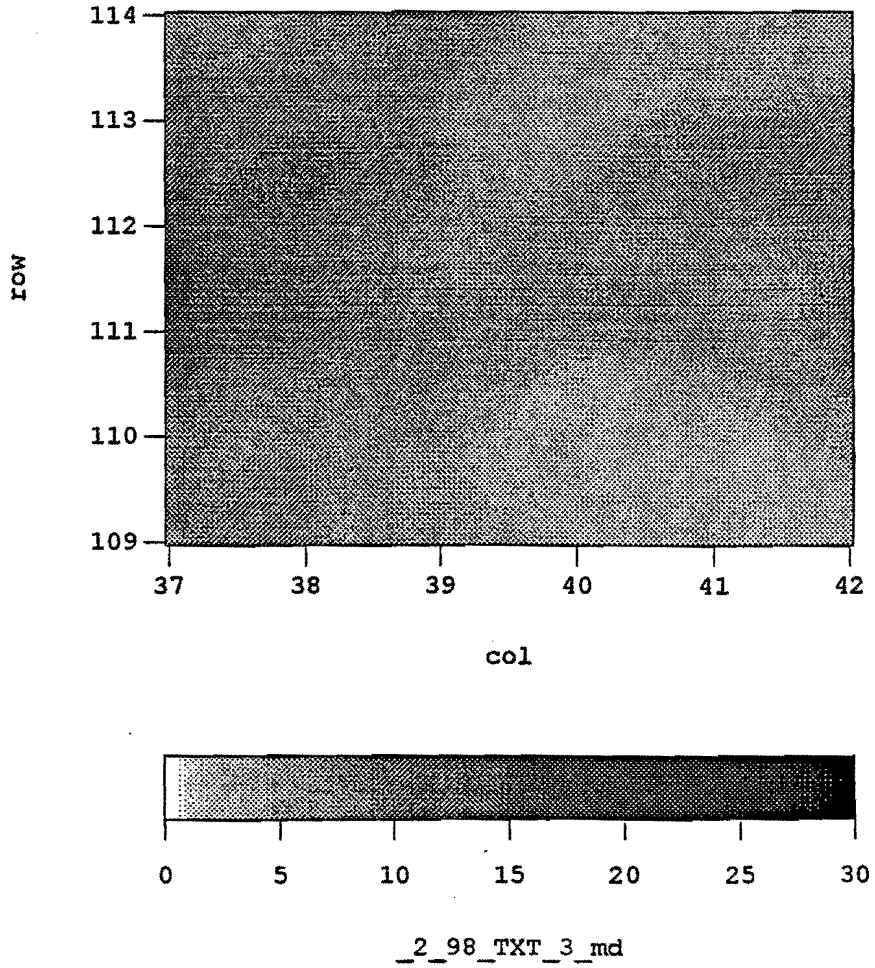


5% EP Percent Days AMC 2

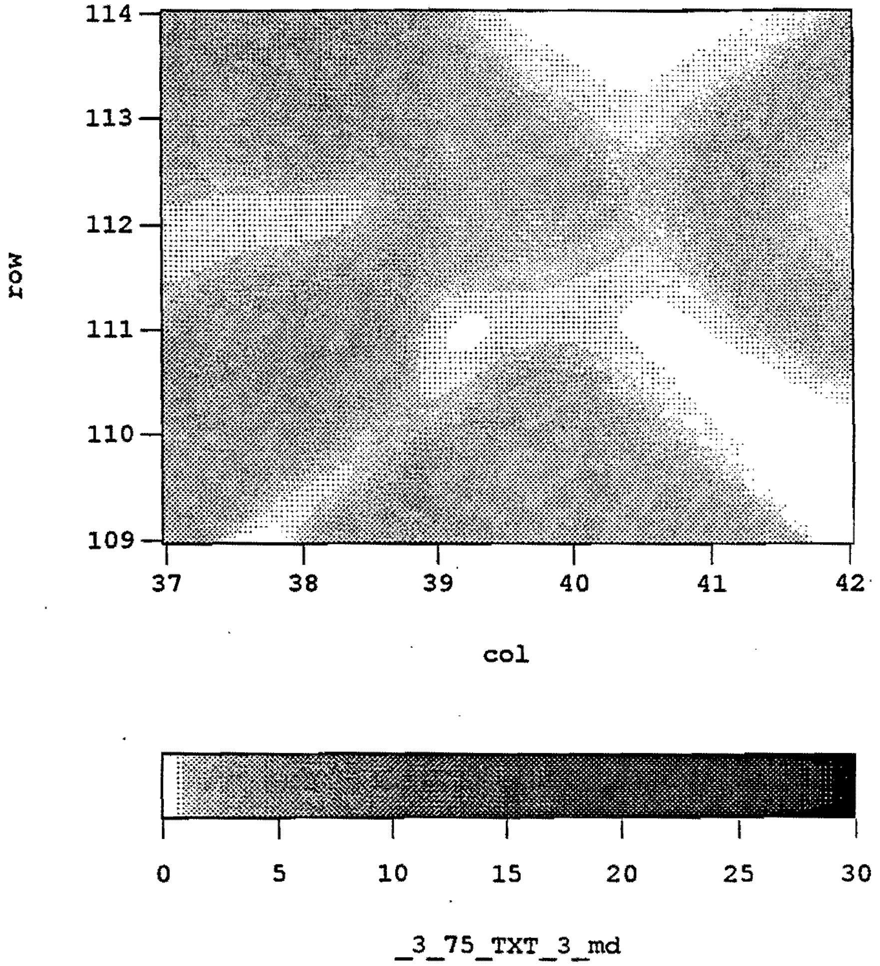


_2_98_TXT_3_md

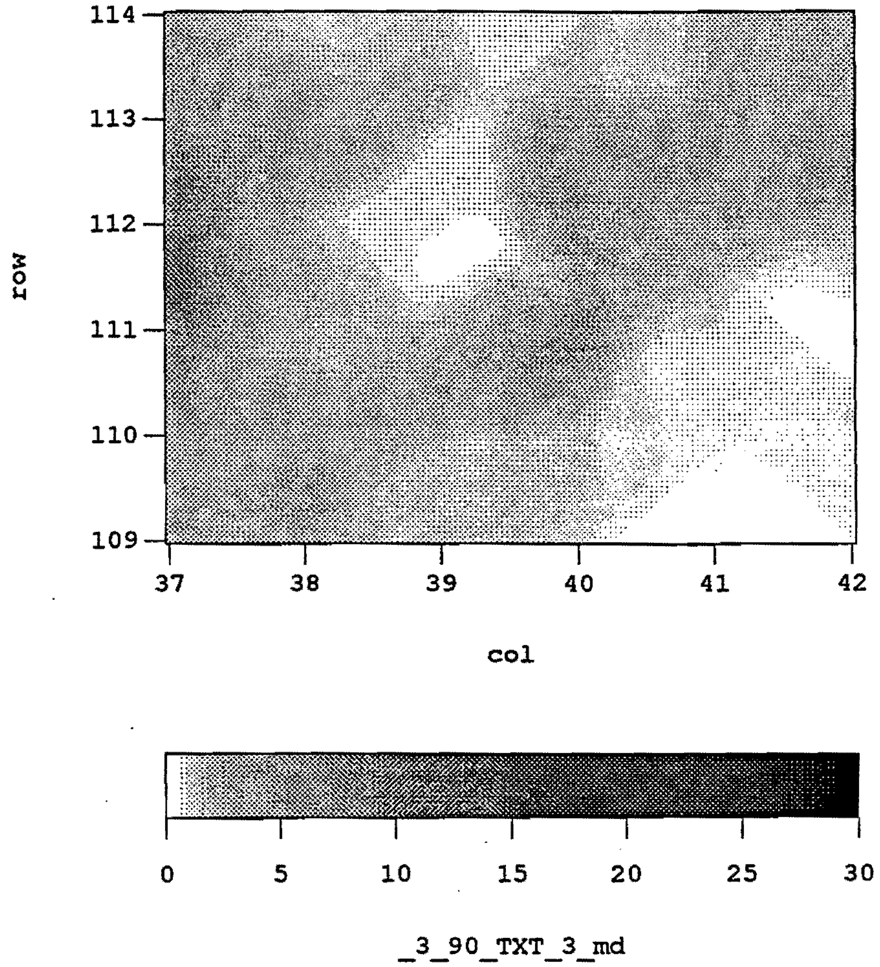
2% EP Percent Days AMC 2



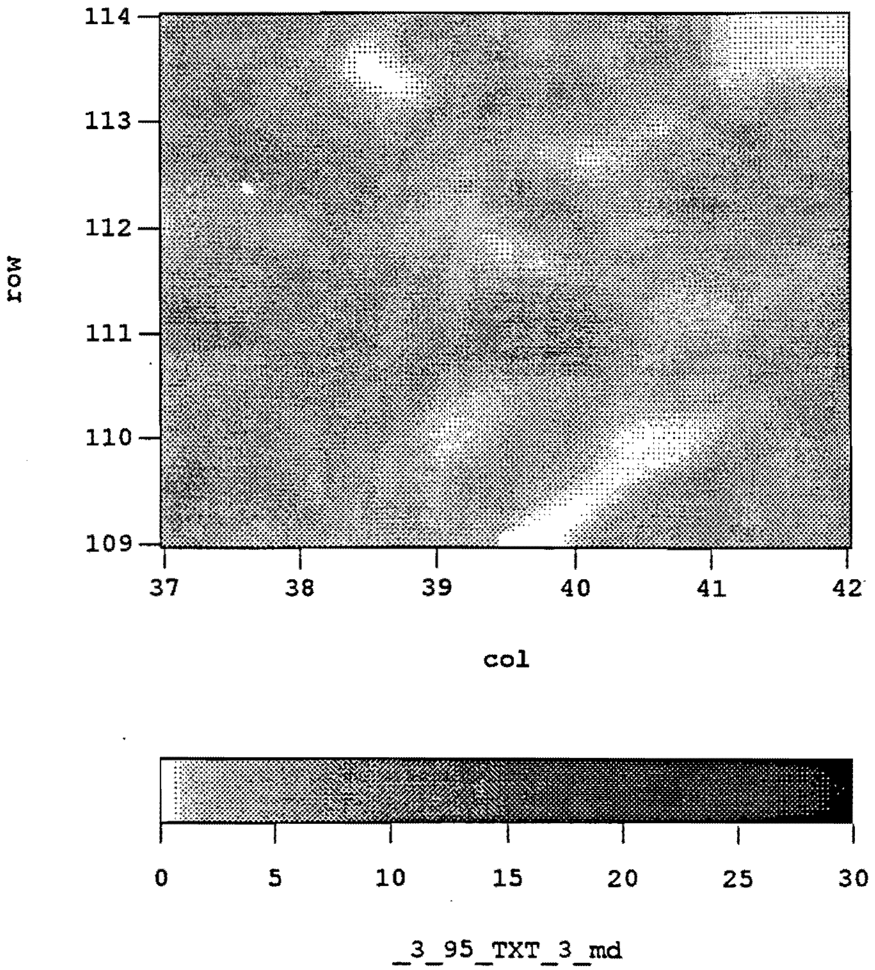
25% EP Percent Days AMC 3



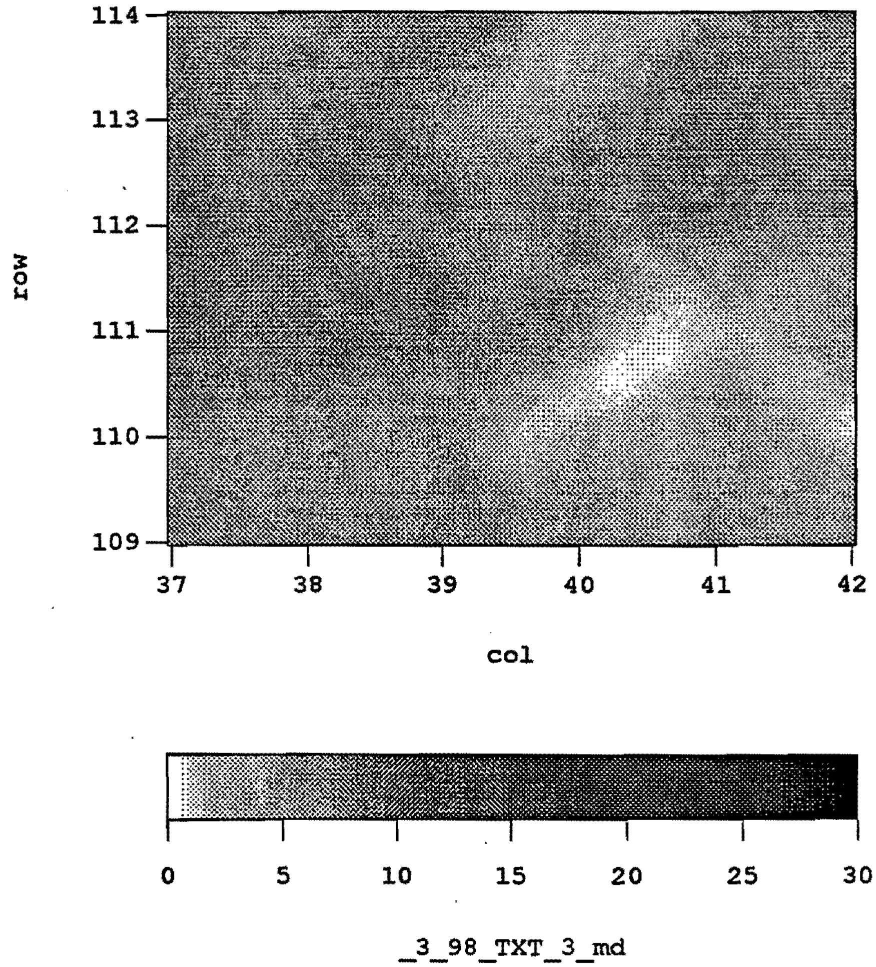
10% EP Percent Days AMC 3



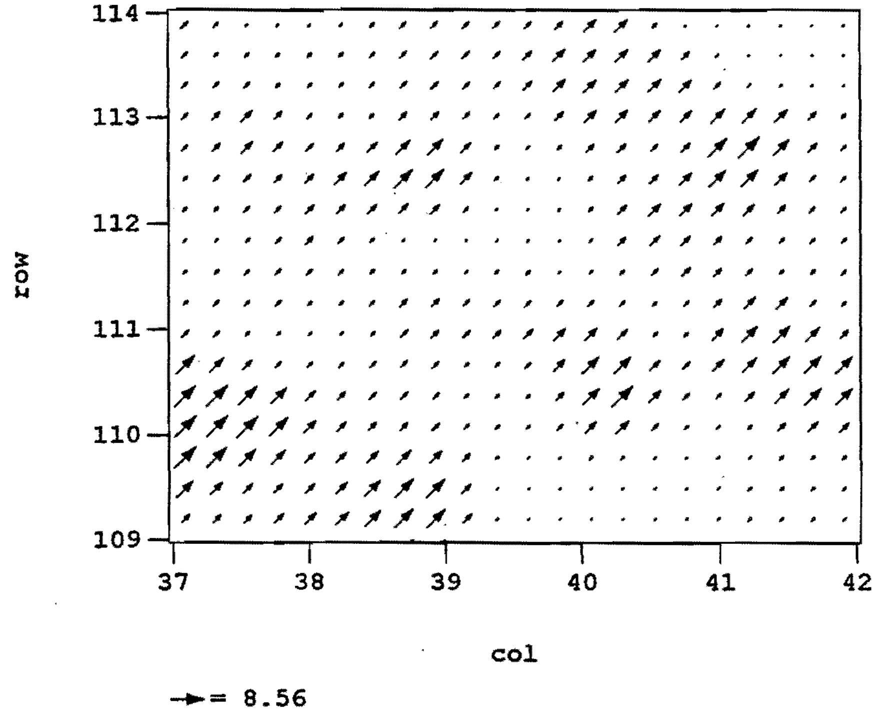
5% EP Percent Days AMC 3



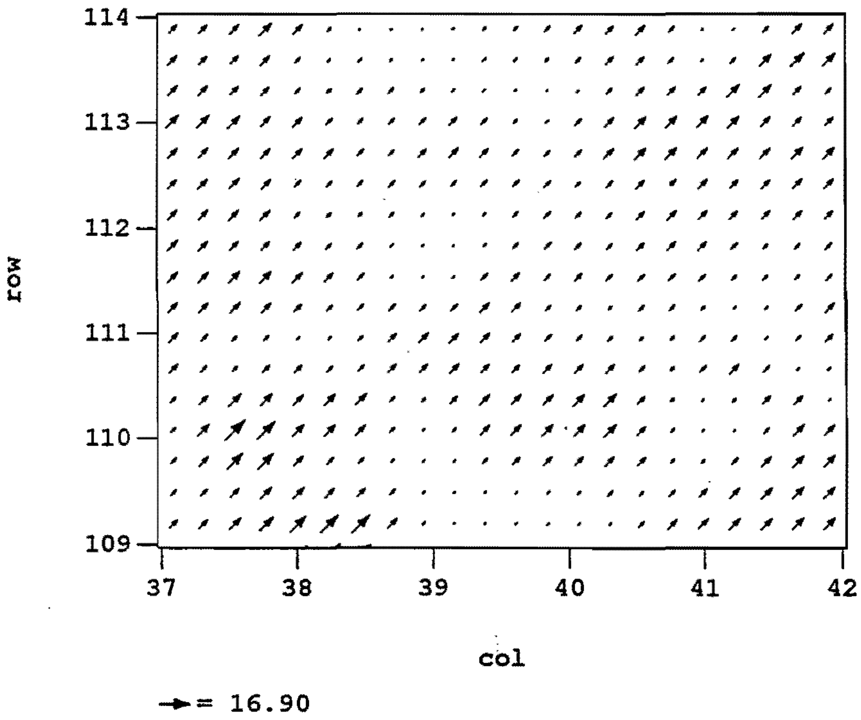
2% EP Percent Days AMC 3



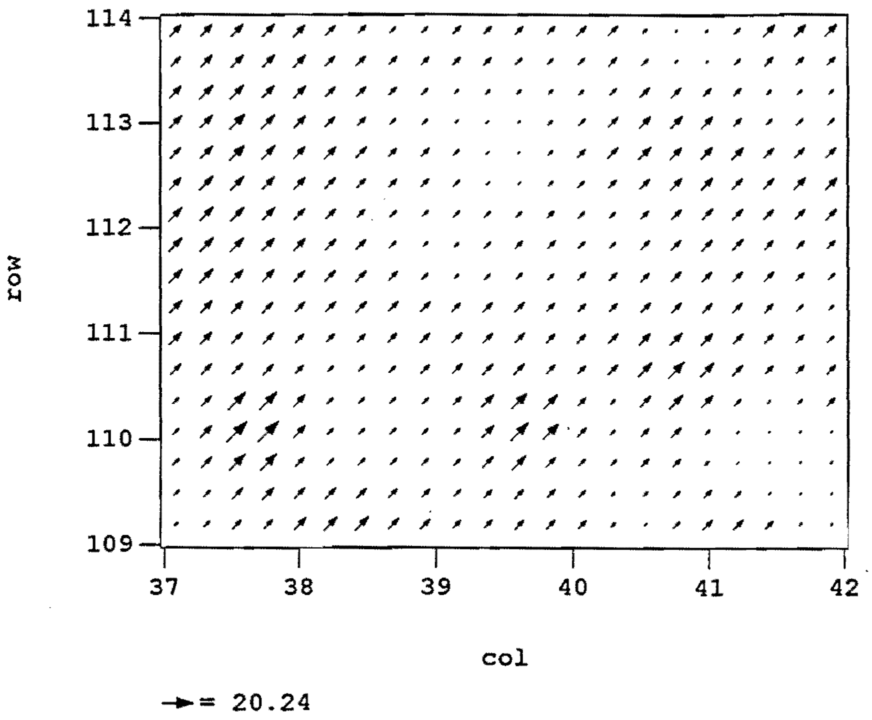
AMC 2 25% EP



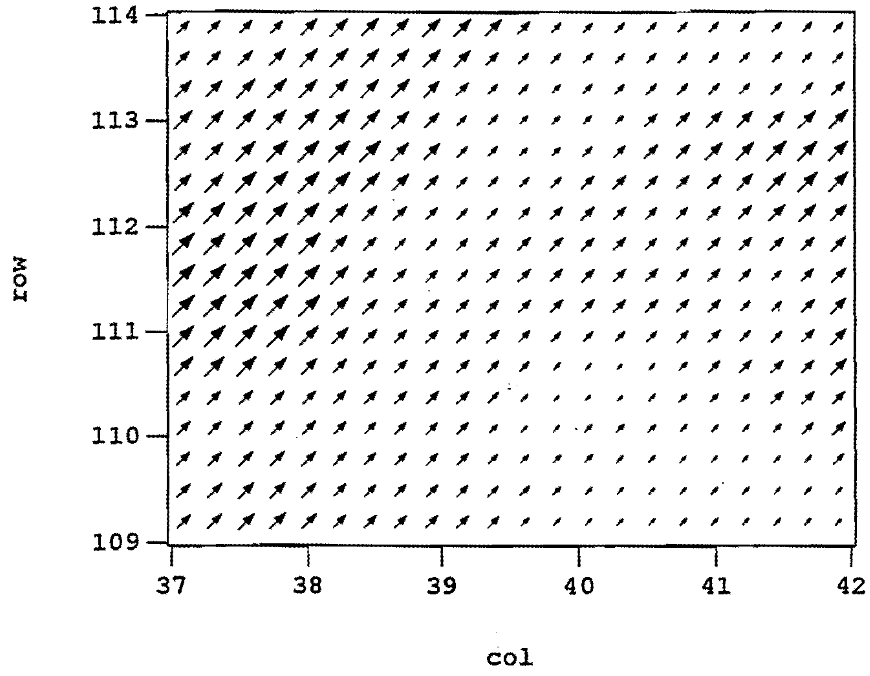
AMC 2   10% EP



AMC 2   5% EP

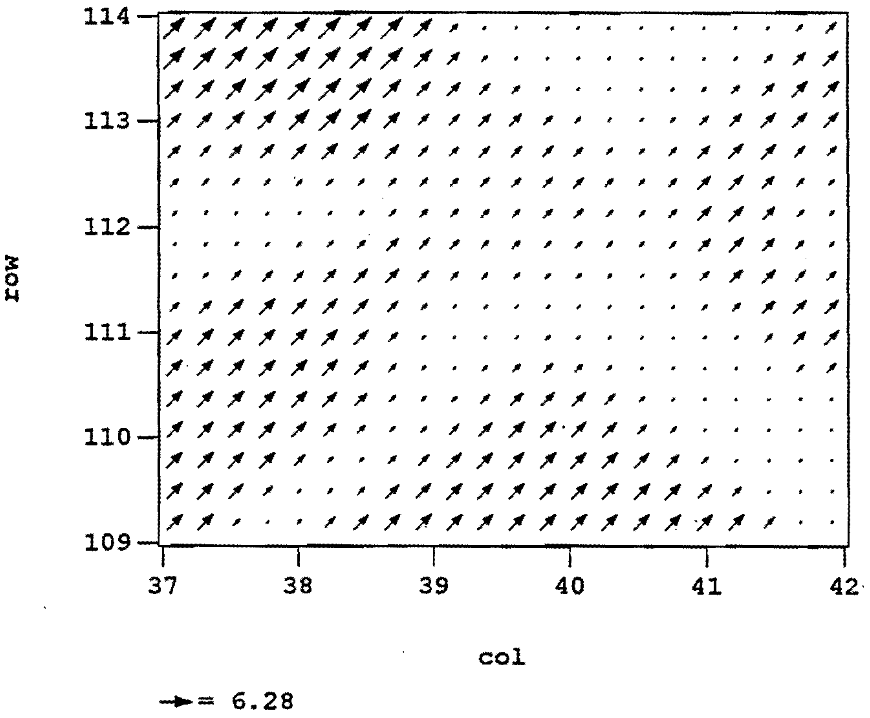


AMC 2   2% EP

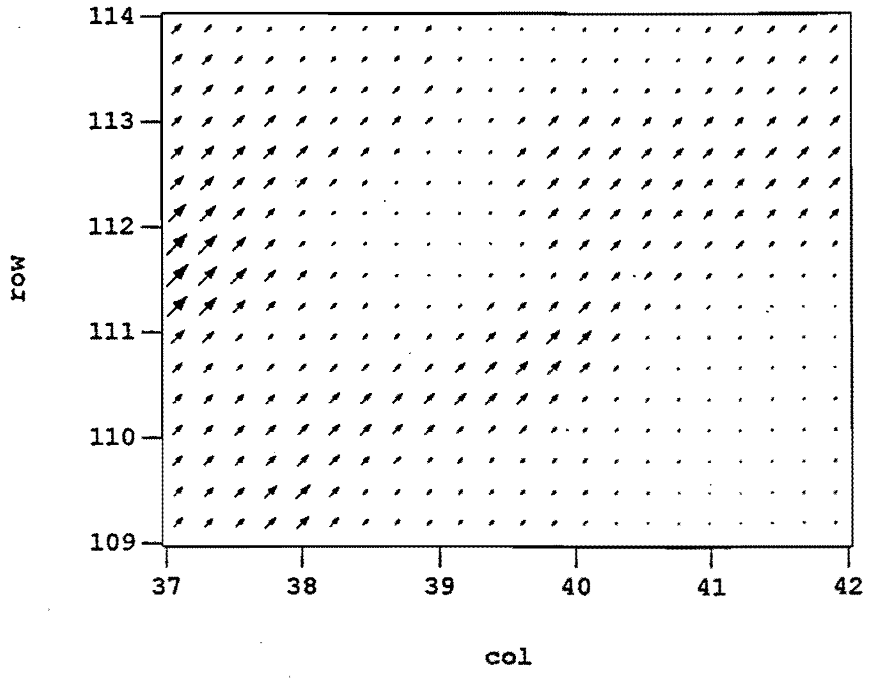


→ = 19.43

AMC 3 25% EP



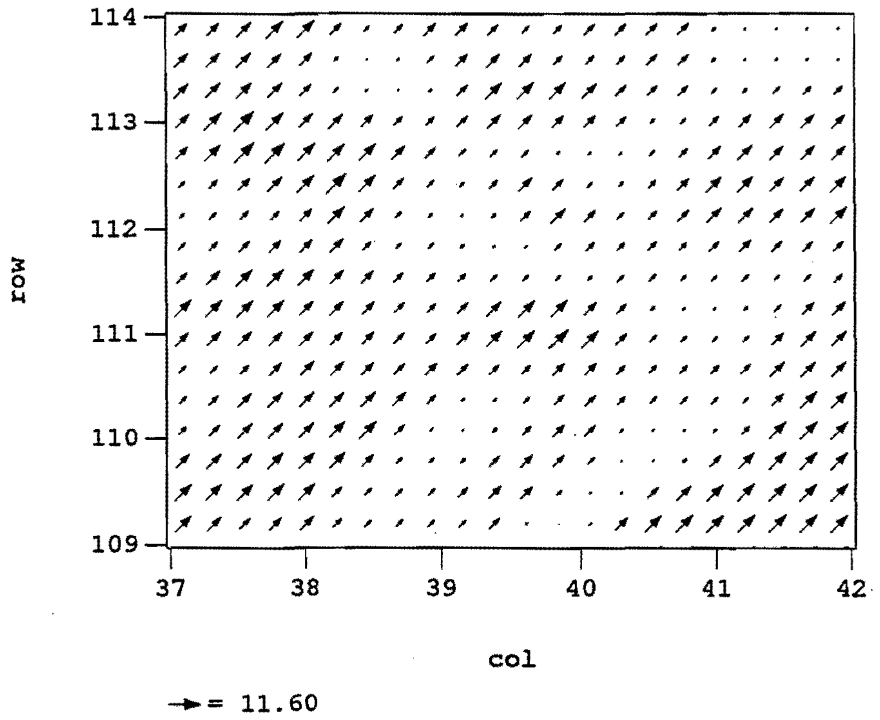
AMC 3 10% EP



→ = 11.30

_3_95_TXT_3_md

AMC 3 5% EP



AMC 3 2% EP