Final Report 1998-09U

MINNESOTA DEPARTMENT OF TRANSPORTATION

Research

Intensity of Extreme Rainfall Over Minnesota

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16. Abstract (Limit: 200 words)

This study looks at precipitation design values, among the most important and widely used pieces of climatological information. Researchers explored the question of whether a high-density network can result in more realistic time series of annual 24-hour extreme precipitation amounts. They also looked at the possible impact of the variability and fluctuations of climate, since standard sources assume a static climate.

Study areas included Minneapolis and St. Paul, and an area west of Duluth, Minnesota, near Hibbing. The following highlights study conclusions:

• The spatial variability of the design values estimated for 20 km by 20 km is far too great to make that approach practical.

• Based on the experience with the Hibbing study area, it is likely that the density of observations over large parts of the state would be too small to allow using 10 km by 10 km or 20 km by 20 km areas.

• If the purpose of the design values is to provide guidance on extreme precipitation likely to be experienced a point, the current standard sources underestimate the values about one inch for a 24-hour duration and 100-year return period.

• If the purpose of the design values is to provide guidance on extreme precipitation likely to be experienced at some point over an area, the current standard sources greatly underestimate the values.

• There are no long-term trends in the magnitude of extreme precipitation events.

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Intensity of Extreme Rainfall Events over Minnesota

Final Report

Prepared by

Richard H. Skaggs

Department of Geography
University of Minnesota
Minneapolis, MN 55455

November 1998

Prepared for the

Minnesota Department of Transportation
Office of Research Administration
200 Ford Building Mail Stop 330
117 University Avenue
St. Paul, MN 55155

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Chapter 1
Introduction

Precipitation design values are among the most important and widely used pieces of climatological information. They are essential in nearly all water drainage, water storage, and road construction projects in Minnesota as well as the other states. The required information is usually obtained from standard published sources. These standard sources for extreme precipitation design values are Hershfield (2) and Huff and Angel (3).

There are two interrelated problems with using the standard sources. First, the published sources are based on widely spaced data that may not adequately represent that actual intensity of precipitation observed. Precipitation is known to exhibit substantial variability in space and in time. A unique high spatial density precipitation measurement network has existed in Minnesota since about 1970. The purpose of this pilot study is to determine whether the high density network can result in more realistic time series of annual 24-hour extreme precipitation amounts. From these time series estimates of rainfall intensities from 5 minutes to 24 hours and for return periods of two years to one hundred years will be calculated. The Rainfall Frequency Atlas of the Midwest used the graphical method for estimating precipitation intensity for various durations and return periods. This method relies on long data series and means that the number of data points is generally small. The alternative is to use extreme value frequency distributions and calculate the intensities for the needed recurrence intervals (1). These methods allow use of shorter observation periods such as is the case with the Minnesota dense network data.

The second problem is that the standard sources effectively assume a static climate and do not consider the possible impact of the variability and fluctuations of climate. It is clear from long records that temperature and precipitation have varied significantly over the past 150 years. For example, precipitation was lower than today in the middle of the last century. It rose to a peak higher than today by the end of the last century but then decreased abruptly to lower values for much of the period from 1910 to 1965. Since then precipitation has increased and reached values similar to those late in the 1800s. A crucial question is whether extreme observation day precipitation values show any similar variations. This is especially important because both of the standard sources are based largely on observations during the relatively drier period earlier in this century.

This study addresses both of these problems for two pilot study areas. One study area is the metropolitan region of Minneapolis and St. Paul. The second area is west of Duluth, Minnesota near Hibbing. On the basis of this pilot study a decision as to whether to extend the analysis to the full state of Minnesota will be made.

Chapter 2

Study Areas and Data

This project is a pilot on the basis of which a decision about whether to study the whole state will be made. Two study areas were selected for the pilot. One is located in the metropolitan area where the density of observations is largest and is about 120 kilometers east/west by 80 kilometers north/south. The second is in the Hibbing area and is a square approximately 120 kilometers on a side. Both study areas are shown on the attached figures. Each study area is made up of 10 km by 10 km squares. For each of these squares, a time series of annual maximum daily precipitation will be developed. The full time series will be 1958 through 1997. However, the density of observations increases substantially in 1970 and some of the analyses will use this shorter (1970-1997) time series.

The standard precipitation intensity-duration-return period sources use relatively sparse observation networks. Figure 1 shows the location the National Weather Service stations in Minnesota in 1997. The stations shown approximate the stations used for Technical Paper No. 40 (2). Figure 2 shows the limited number of stations used by Huff and Angel (3). Both of the standard sources rely on long record stations at a relatively small number of points. This study takes a different approach by attempting to use a much larger number of stations that generally do not have long records and are not stable in location.

Figure 3 gives the location of observation sites in June 1997, for the Minnesota high density precipitation network. The much larger number of stations over the state and in the two study areas is obvious. This high density network is made up of a number of individual networks (see Table 1). While these networks provide a very dense network of observations, most of the observations are made by volunteers who sometimes miss observations and report accumulated precipitation amounts rather than values for a single day that is what this study requires. There is, therefore, need for good quality control.

The observations in this high density network are available electronically in the Office of the State Climatologist. In cooperation with the State Climatology Office, and Jim Zandlo in

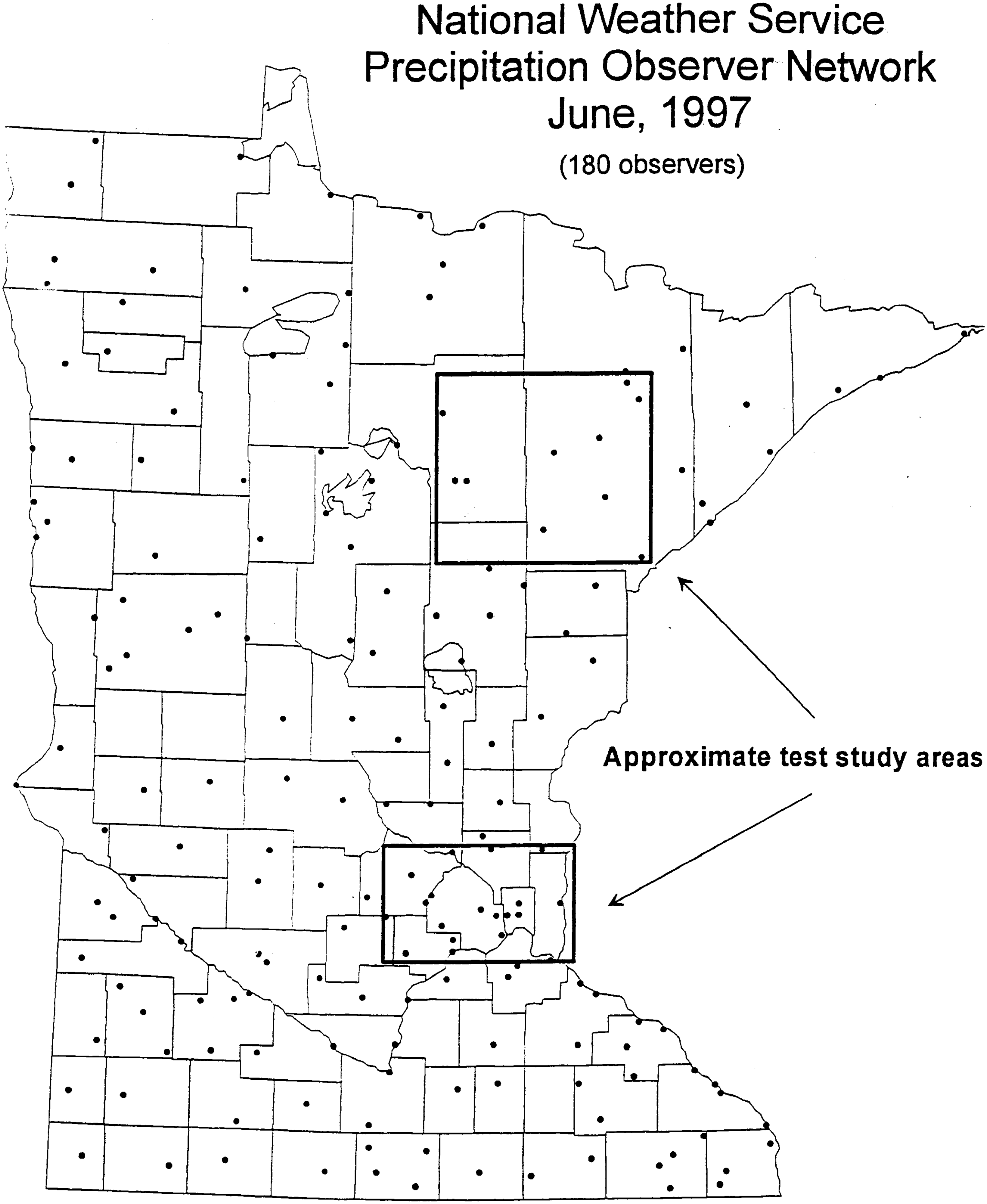

National Weather Service
Precipitation Observer Network
June, 1997
(180 observers)
Approximate test study areas

Figure 1

Huff and Angel Station Locations

(25 observers)

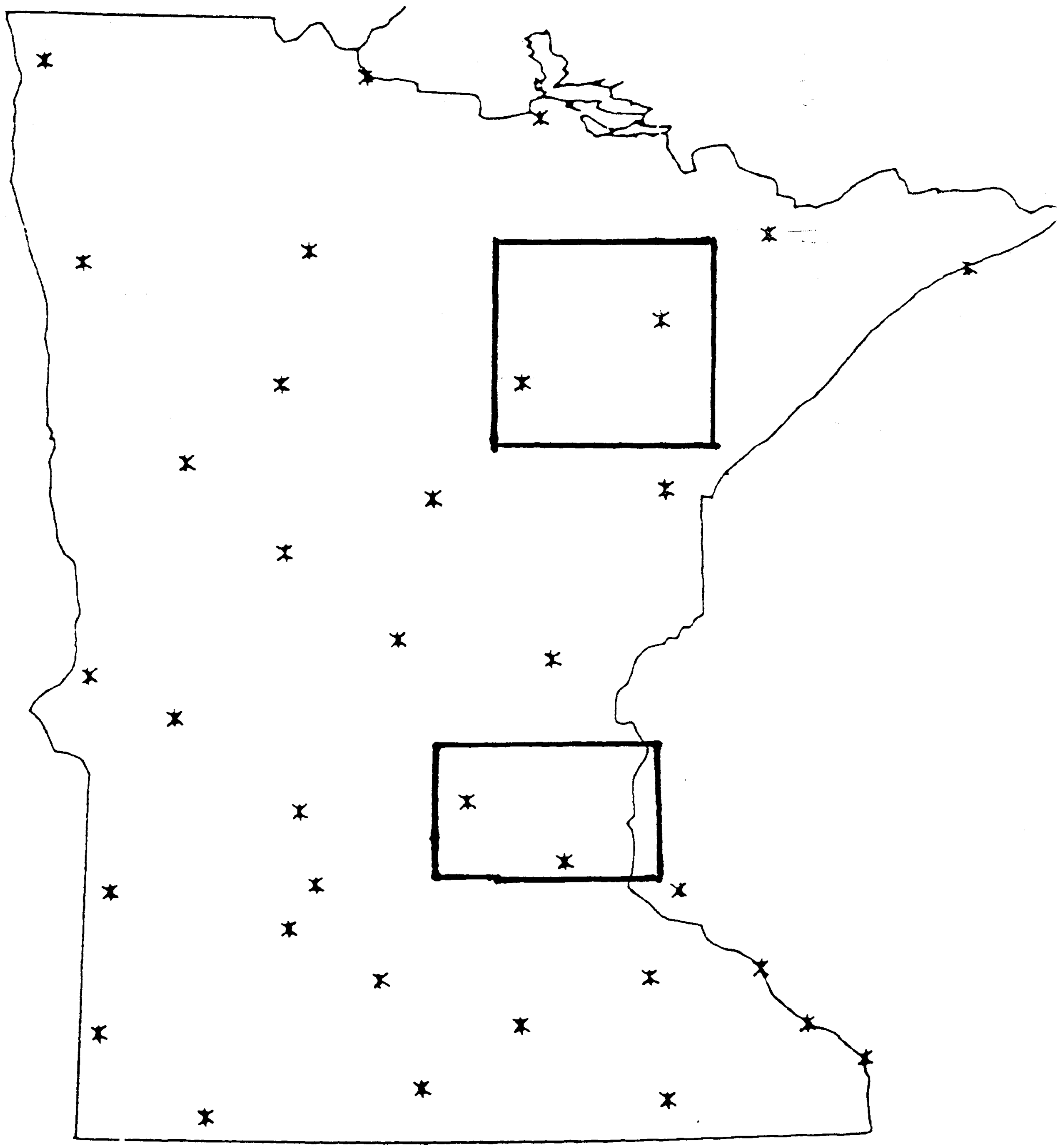


Figure 2

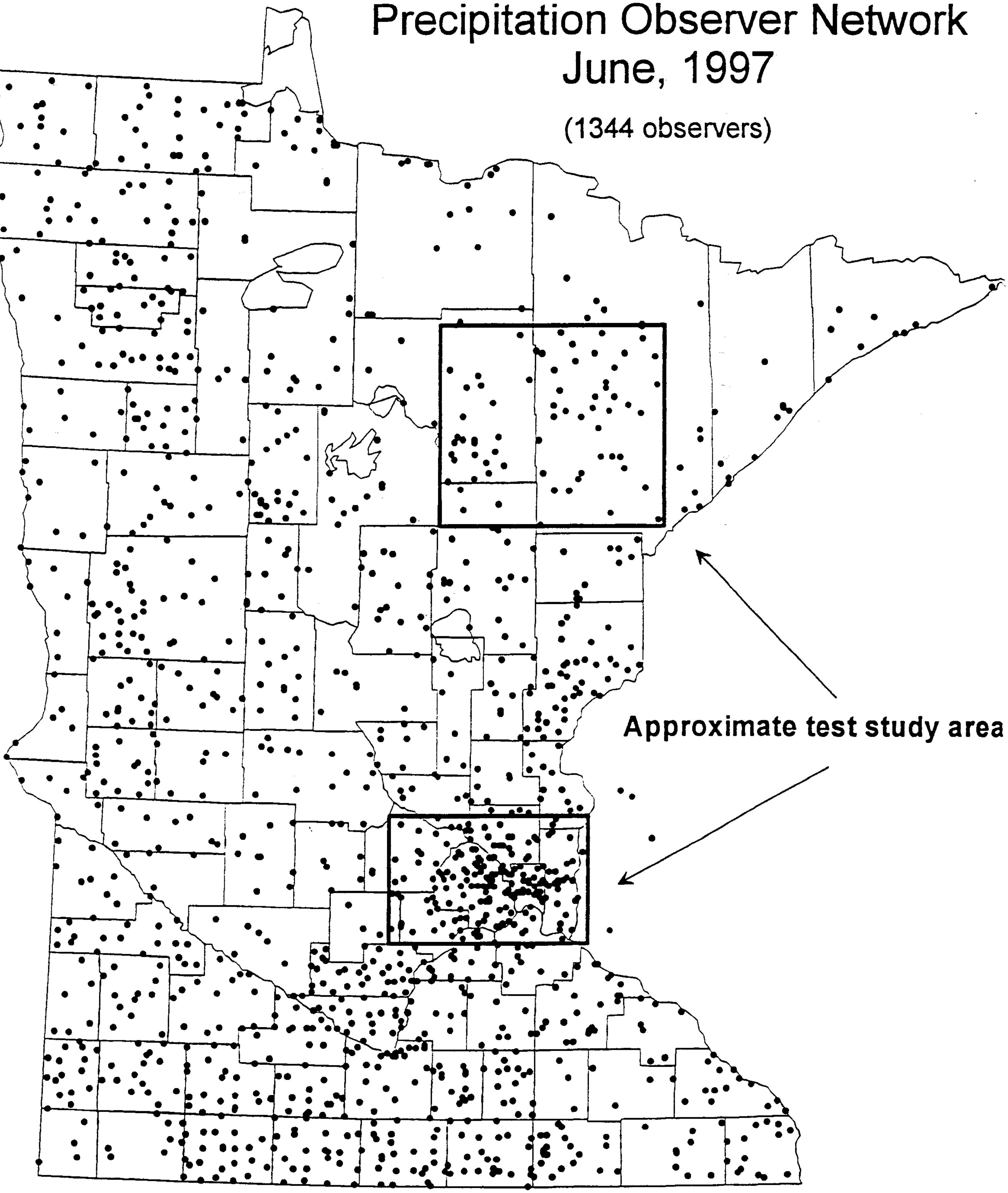

Precipitation Observer Network
June, 1997
(1344 observers)
Approximate test study area

Figure 3

particular, a program was developed which accessed these observations for the two study areas, and automatically selected the maximum observation for each 10 km by 10k m cell.

Table 1: Minnesota High Density Precipitation Network

Network	Number of Stations	Quality	Coverage
National Weather Service	About 150	Good	Observations 12 months per year
Department of Natural Resources	About 80	Good	Observations 12 months per year
Metropolitan Mosquito District	About 60	Good early but declining	Observations 9 months per year
State Climatologist Backyard Volunteers	About 300	Good	About 50% 12 months per year and 50% 9 months per year
Future Farmers of America	Declining from 1000 in 1970s to 10 or so	Poor	Variable
KSTP Network	About 30	Good	Discontinued but 12 and 9 month observations from 1980 to early 1990s
Soil and Water Conservation Districts	700 to 1000	Good	Variable with most in summer
Miscellaneous, e.g., WCCO network.	Variable	Variable	Variable

These selections were then quality-checked. The program highlighted observations that, for example, did not record precipitation the day before or which were unique dates for the maximum value. The task is to decide whether a particular value is valid or must be discarded in favor of the next largest value, which, of course, also might be found invalid. A human operator checks the suspect observations for each year, using other tools built into the program. A grid showing the selected study area, dates of maxima, precipitation recorded at surrounding stations, observer network (DNR, NWS, and so forth) and maximum precipitation values for the selected year help the operator make a decision. The most common data error is a value that has accumulated over several days. Other errors include values that are apparently incorrect readings or incorrect data entries based on comparison to precipitation patterns on the date of observation. The erroneous values are removed from consideration; some stations were removed from consideration in a particular year if observations were made for only a few weeks during the year.

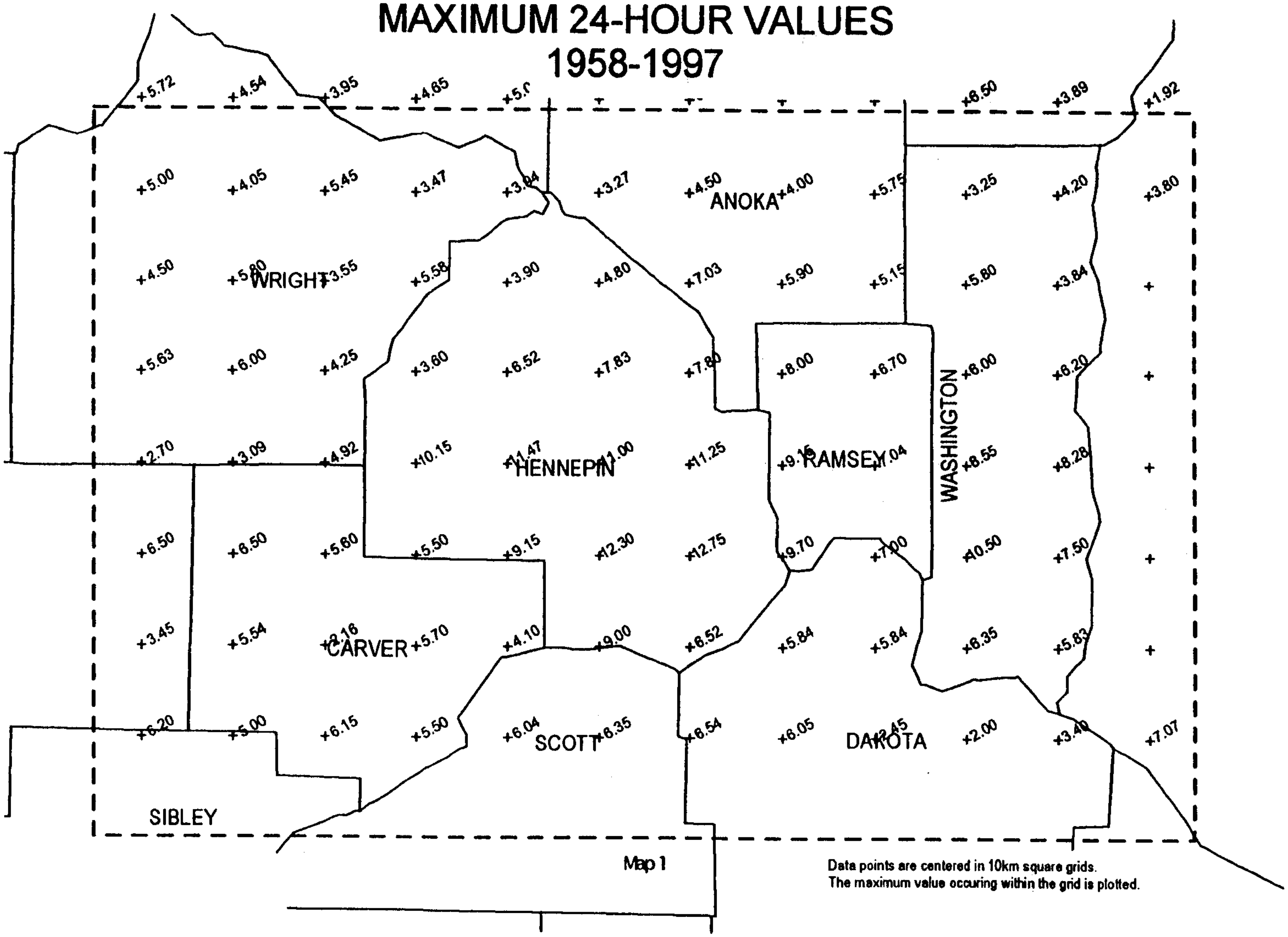
The resulting annual, observation-day, maximum precipitation values are placed in an Excel workbook (one workbook for each study area). Each workbook has separate spreadsheets for each year. Each workbook has an additional sheet that contains the study area size, UTM coordinates for the lower left and upper corners of the study area, and the years studied. The data included in the spreadsheet for each year are detailed (see Table 2). In the table the location of the data on the sheet is specified by the column/row range for each data type

Table 2: Data Collected from the High Density Precipitation Data Base

Data Description	**Metro.**	**Hibbing**
Annual maximum observation day precipitation in hundredths of inches	A2:L9	A2:L13
Date of annual maximum observation day precipitation	A11:L18	A15:L26
Number of stations in cell	A20:L27	A28:L39
Location (PLSS) and name of station recording the maximum	A29:L36	A41:L52
X UTM coordinate of station recording the maximum	N29:Y36	N41:Y52
Y UTM coordinate of station recording the maximum	AA29:AL 36	AA41:AL 52
Number of estimated values	A38:L45	A54:L65
Number of days with zero precipitation prior to maximum	N38:Y45	N54:Y52
Decision made if datum quality was checked by operator	A47:L54	A67:L78
Initials of editor	N47:Y54	N67:Y78
List of events discarded with reasons	A55	A80

The data in the spreadsheets can be mapped in a variety of ways. For purposes of this report I include four maps, two for each study area. The maps were constructed the Golden Graphics Surfer™ program. Maps 1 and 2 show the maximum observed observation precipitation for each 10 km by 10 km square that had any observations for the Twin Cities and Hibbing study areas respectively. It is clearly seen that the observed maxima are large and quite variable spatially. This illustrates the point that precipitation is extremely variable in space and that a single point is likely to be missed by many large precipitation events. Kriging was used to grid the data. Maps 3 and 4 display the mean annual maximum precipitation for the two study area. Again the spatial variability is clearly shown. The spatial pattern in the metropolitan area is strongly influenced by a single large event in the 1987 in southern Hennepin County.

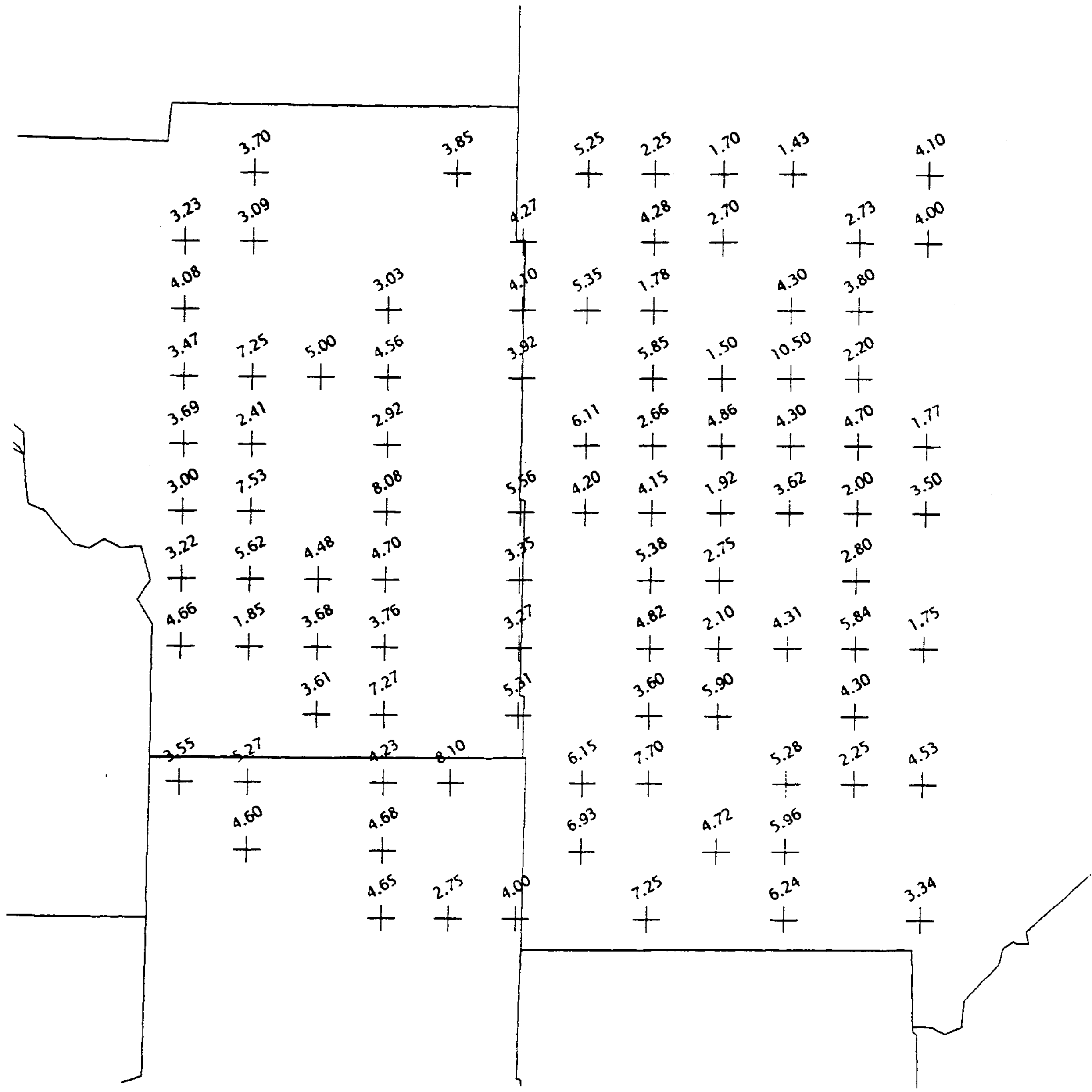
MNDOT PRECIPITATION STUDY
METRO TEST AREA
MAXIMUM 24-HOUR VALUES
1958-1997



Map 1

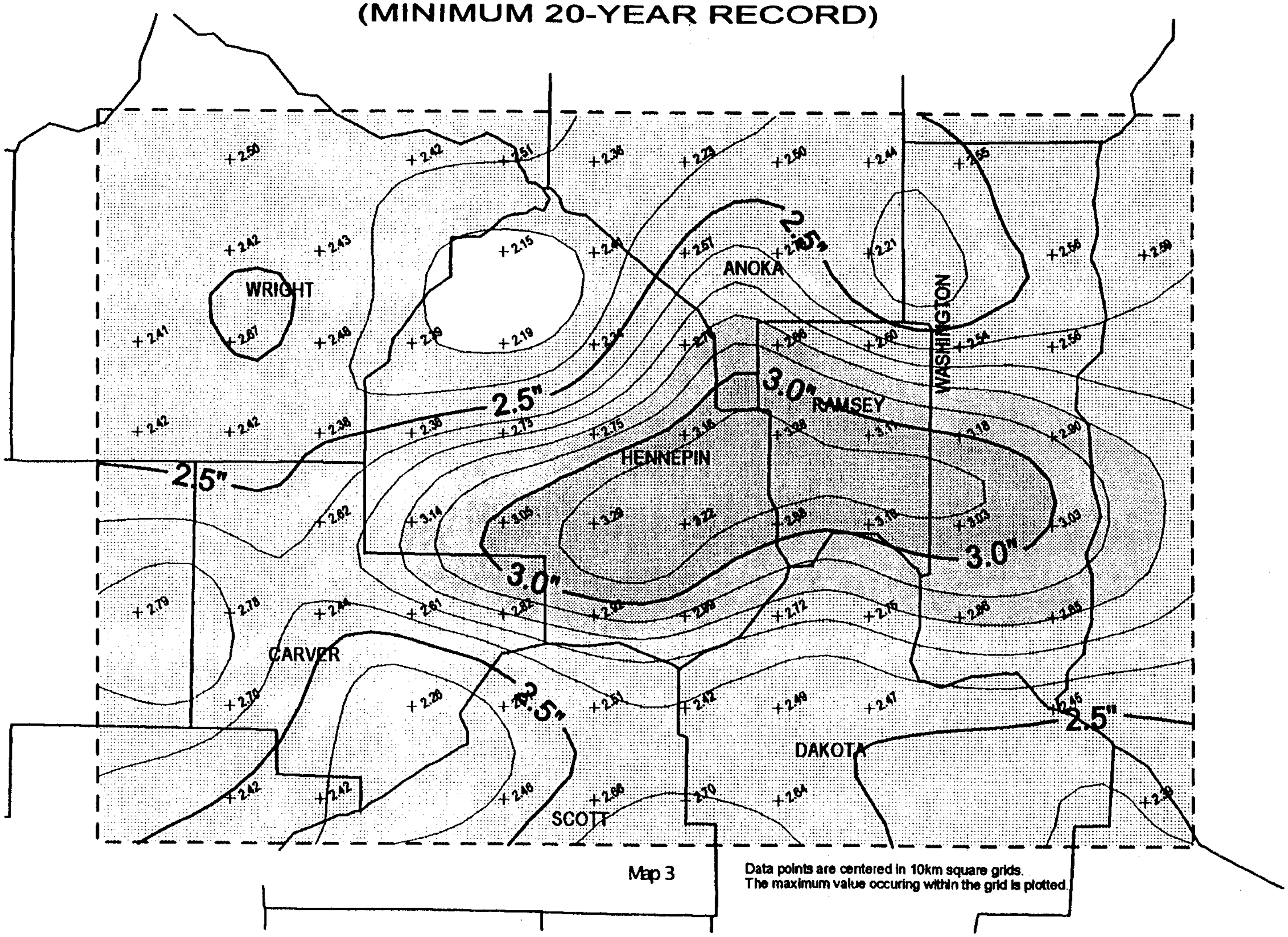
Data points are centered in 10km square grids.
The maximum value occuring within the grid is plotted.

Hibbing Test Area
Maximum 24-Hour Values
1958-1997



Map 2

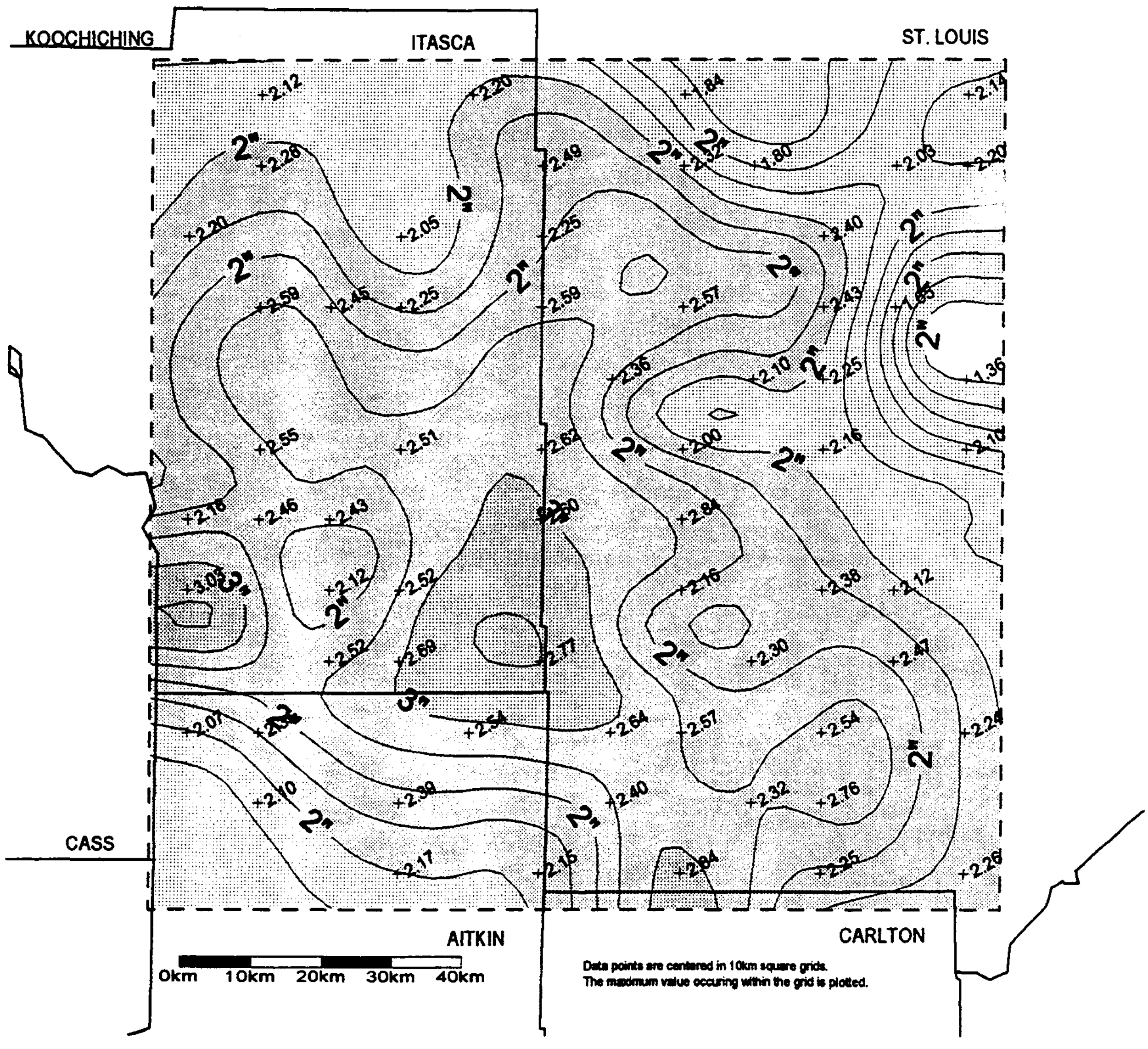
MN DOT PRECIPITATION STUDY
METRO TEST AREA
AVERAGE MAXIMUM 24-HOUR VALUES
(MINIMUM 20-YEAR RECORD)



Map 3

Data points are centered in 10km square grids.
The maximum value occuring within the grid is plotted.

MN DOT PRECIPITATION STUDY
HIBBING STUDY AREA
AVERAGE MAXIMUM 24-HOUR VALUES



Map 4

Chapter 3

Statistical Analysis and Comparison with Standard Sources

The time series of annual maximum observation day precipitation are for 10 km by 10 km squares. The observation day precipitation values are transformed to maximum 24 hour values by multiplying the observation day values by 1.13, the standard inflation factor. For durations shorter than 24 hours, deflation factors cited in F. Huff and J. Angel (3, Table 3, page 6) were used because we have no direct observations for shorter durations in the high density network.

There are two basic methods of estimating the design values. The first is to fit empirical curves to observed data. This is the method used by Huff and Angel in their Rainfall Frequency Atlas of the Midwest. The second approach, which is employed in this study, is to use extreme value statistical distributions with the parameters estimated from the observed data. I follow closely the theory and practice in Faragó and Katz (1). Faragó and Katz give a generalized form for the three usual types of asymptotic distributions for extremes:

$$G(y;k) = \exp[-(1-ky)^{(1/k)}]. \qquad \text{Eq. (1)}$$

In this expression k is the shape parameter and $y = (x - u)/b$ where u and b the location and scale parameters respectively and y is called the reduced or standardized variate. The expression above is the Gumbel distribution for $k = 0$, the Weibull distribution for $k > 0$, and the Fréchet distribution for $k < 0$. The design values can be calculated using the inverse expression:

$$y_p = [1-(-\ln p)^k]/k. \qquad \text{Eq. (2)}$$

In this expression, y_p is called the reduced design value; p is the probability of occurrence and is related to the return period, T, by $T = 1/(1-p)$. The magnitude of the design value (x_p) then can be calculated using:

$$x_p = by_p + u. \qquad \text{Eq. (3)}$$

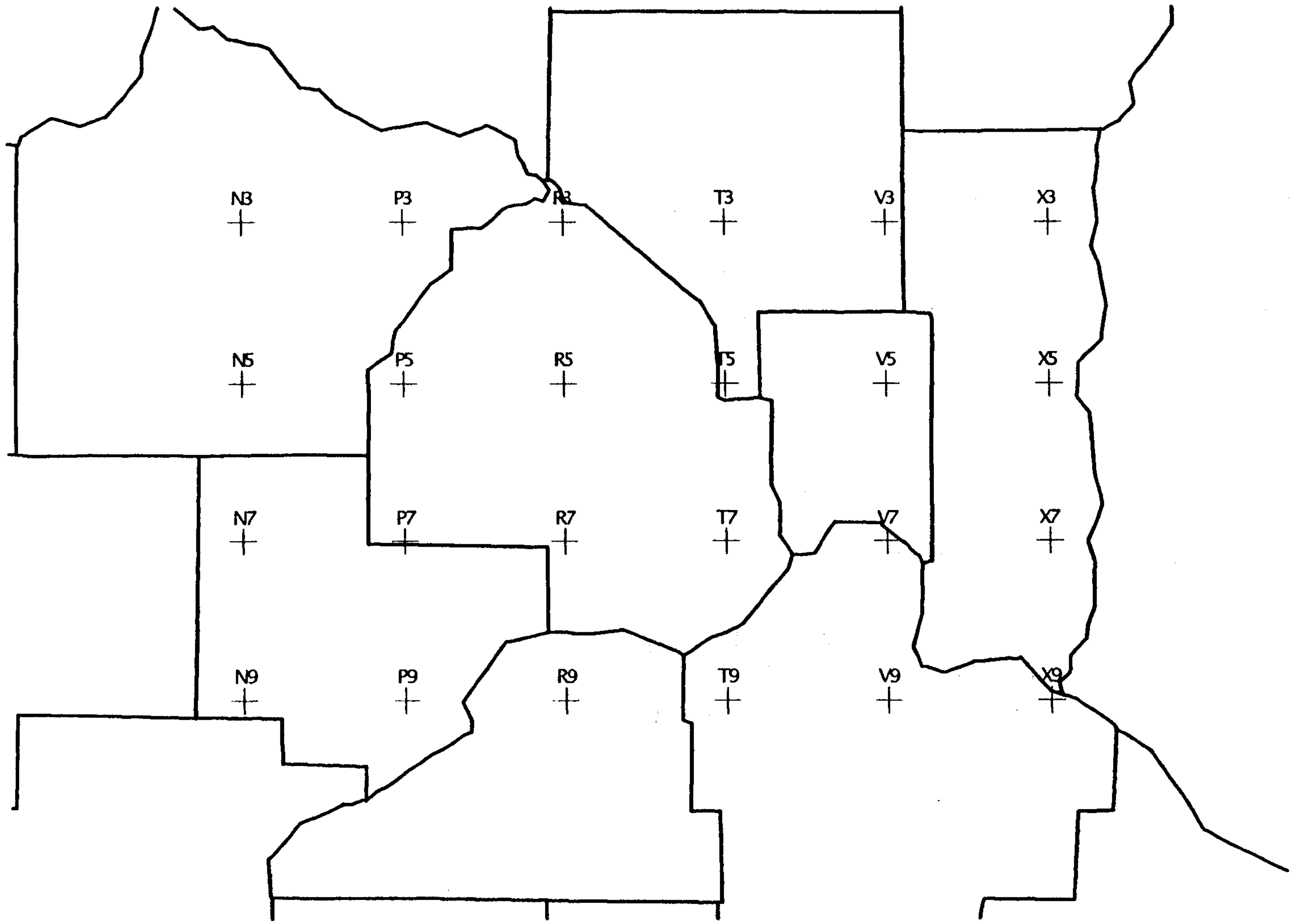
Thus, the three parameters (k, u, and b) must be estimated from the observed time series of annual 24-hour maximum precipitation values. There are several methods of making the estimates. In this study I use the maximum likelihood estimators and a computer program written by Faragó. Thirty years of record is taken as the minimum needed to estimate the parameters of the generalized extreme value distribution.

Of the 96 10 km by 10 km cells that constitute the metropolitan study area, only 30 had 30 or more years of record. Therefore, the 10 km by 10 km cells were combined into 20 km by 20 km cells and the maximum observational day precipitation over that area was extracted. Of the 24 cells 20 km on a side, 19 had 30 or more years of record. The time series of maximum observation day precipitation were converted to 24 hour maximum precipitation series and the generalized extreme value distribution parameters (k, u, and b) estimated. From the distribution parameters, the design values were calculated using equations 2 and 3. Attached are tables with the results and a map of the spatial pattern of the 24 hour, 100 year return period design values (Map 6). The location and index map (Map 5) shows the centers of the 20 km by 20 km cells. The five locations (N3, N7, P7, X3, and X7) without 30 years of record are excluded in constructing the contour map and the tables (see attached Tables 3A though 3F). There is substantial spatial variation in the estimates with a range from 5.11 inches to 12.15 inches for the 24 hour, 100 return period design value. The same spatial pattern and differences will be mirrored at the other durations and return periods. It is clear that the strong gradient across the area makes use of these design values very problematic. A single set of design values generally applicable to the total area is needed.

The large spatial differences across the metropolitan area are the result of one rainfall event in 1987 in which over 12 inches of rain occurred on one observation day in the southern metropolitan area. One interpretation of this event is that it has a return interval of several hundred to several thousand years. Another interpretation is that rainfall events of this magnitude have a much shorter return period and that our observation density is simply too low to "see" these events. Another way of putting the issues is to ask whether the design values are for a point in the area or for some point over the area. I approximate the implications of these two interpretations by different treatments of the high density precipitation times series.

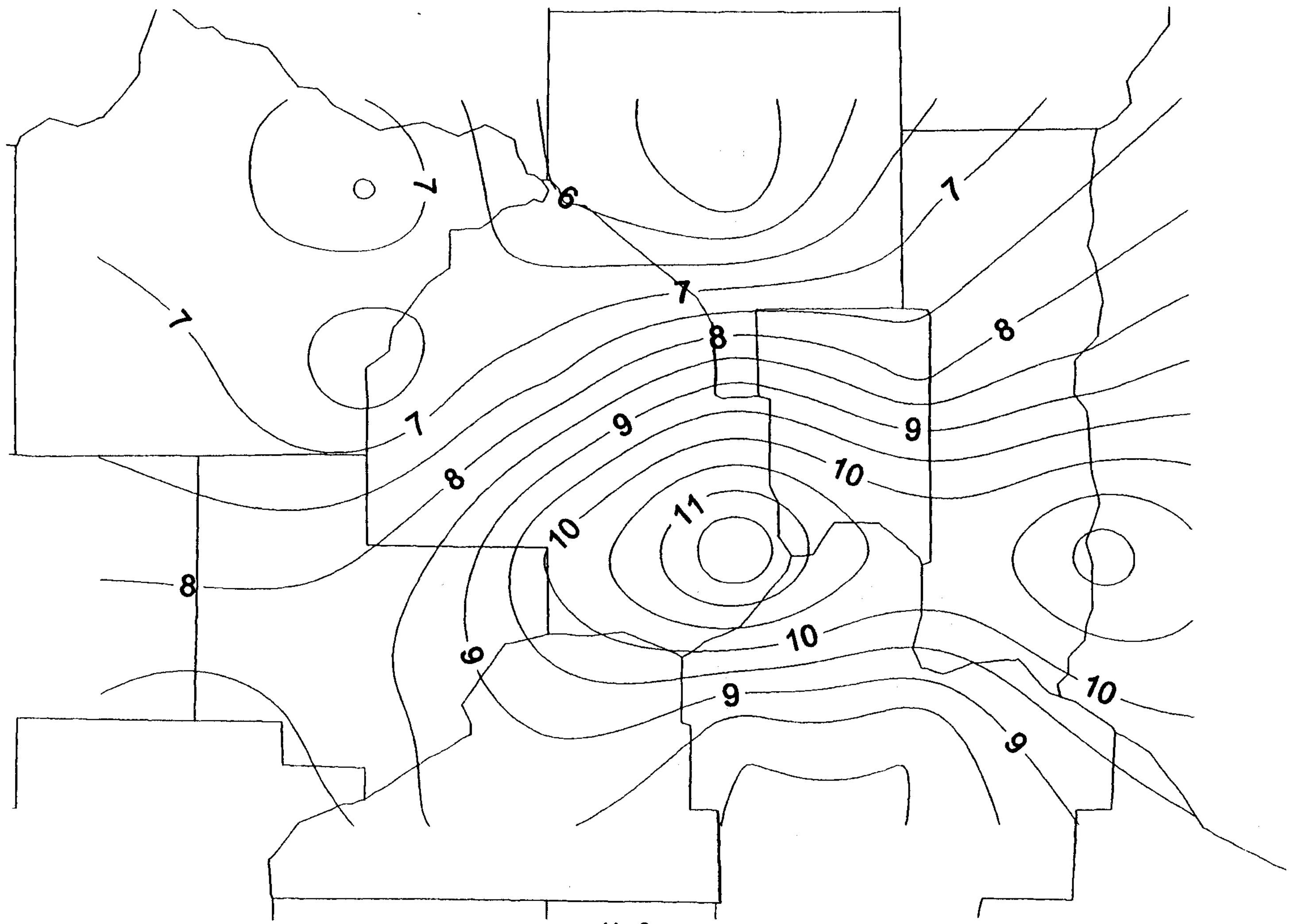
The interpretation of design values as applicable to a point in the area can be approximated by substituting space for time to create a long, hypothetical record. I combine all of the annual maximum observation day precipitation values over the study area for the 40 years of record into a single series. For the metropolitan study area, a 2,525 year synthetic record results. This record was processed in the same manner as the area data (see attached Table 8). The 24 hour, 100 year return period value is 7.47 inches. This value is larger than the standard sources. It is

Location and Index Map for 20 KM by 20 KM Grid



Map 5

24-Hour Duration, 100 Year Return Period



Map 6

Table 3A: Estimates for 20 KM by 20 KM Cells

Return Period T	Prob-ability p	Reduced Variate y 24 hr	Duration 24 hr	Duration 18 hr	Duration 12 hr	Duration 6 hr	Duration 3 hr	Duration 2 hr	Duration 1 hr	Duration 30 min	Duration 15 min	Duration 10 min	Duration 5 min

N3

Record length less than 30 years.

N5													
2	0.500	0.369	2.95	2.77	2.56	2.21	1.89	1.71	1.38	1.09	0.80	0.62	0.35
3	0.667	0.915	3.44	3.24	3.00	2.58	2.20	2.00	1.62	1.27	0.93	0.72	0.41
4	0.750	1.269	3.77	3.54	3.28	2.82	2.41	2.18	1.77	1.39	1.02	0.79	0.45
5	0.800	1.534	4.01	3.77	3.49	3.00	2.56	2.32	1.88	1.48	1.08	0.84	0.48
10	0.900	2.328	4.73	4.44	4.11	3.55	3.03	2.74	2.22	1.75	1.28	0.99	0.57
25	0.960	3.357	5.66	5.32	4.93	4.25	3.63	3.29	2.66	2.10	1.53	1.19	0.68
50	0.980	4.139	6.38	5.99	5.55	4.78	4.08	3.70	3.00	2.36	1.72	1.34	0.77
100	0.990	4.933	7.10	6.67	6.18	5.32	4.54	4.12	3.34	2.63	1.92	1.49	0.85

N7

Record length less than 30 years.

N9													
2	0.500	0.374	3.10	2.91	2.69	2.32	1.98	1.80	1.45	1.15	0.84	0.65	0.37
3	0.667	0.949	3.69	3.47	3.21	2.77	2.36	2.14	1.73	1.36	1.00	0.77	0.44
4	0.750	1.335	4.09	3.84	3.55	3.06	2.61	2.37	1.92	1.51	1.10	0.86	0.49
5	0.800	1.631	4.39	4.13	3.82	3.29	2.81	2.55	2.06	1.62	1.19	0.92	0.53
10	0.900	2.553	5.34	5.02	4.65	4.00	3.42	3.10	2.51	1.98	1.44	1.12	0.64
25	0.960	3.833	6.66	6.26	5.79	4.99	4.26	3.86	3.13	2.46	1.80	1.40	0.80
50	0.980	4.873	7.73	7.27	6.72	5.80	4.95	4.48	3.63	2.86	2.09	1.62	0.93
100	0.990	5.988	8.88	8.34	7.72	6.66	5.68	5.15	4.17	3.28	2.40	1.86	1.07

Table 3B: Estimates for 20 KM by 20 KM Cells

Return Period T	Prob-ability p	Reduced Variate y 24 hr	Duration 24 hr	Duration 18 hr	Duration 12 hr	Duration 6 hr	Duration 3 hr	Duration 2 hr	Duration 1 hr	Duration 30 min	Duration 15 min	Duration 10 min	Duration 5 min
P3													
2	0.500	0.374	2.82	2.65	2.45	2.11	1.80	1.63	1.32	1.04	0.76	0.59	0.34
3	0.667	0.949	3.31	3.11	2.88	2.48	2.12	1.92	1.55	1.22	0.89	0.69	0.40
4	0.750	1.335	3.64	3.42	3.16	2.73	2.33	2.11	1.71	1.34	0.98	0.76	0.44
5	0.800	1.631	3.89	3.65	3.38	2.91	2.49	2.25	1.83	1.44	1.05	0.82	0.47
10	0.900	2.553	4.67	4.39	4.06	3.50	2.99	2.71	2.20	1.73	1.26	0.98	0.56
25	0.960	3.833	5.76	5.41	5.01	4.32	3.69	3.34	2.71	2.13	1.55	1.21	0.69
50	0.980	4.873	6.64	6.24	5.78	4.98	4.25	3.85	3.12	2.46	1.79	1.39	0.80
100	0.990	5.988	7.59	7.13	6.60	5.69	4.86	4.40	3.57	2.81	2.05	1.59	0.91
P5													
2	0.500	0.369	3.09	2.90	2.68	2.31	1.97	1.79	1.45	1.14	0.83	0.65	0.37
3	0.667	0.915	3.44	3.23	2.99	2.58	2.20	1.99	1.61	1.27	0.93	0.72	0.41
4	0.750	1.269	3.66	3.44	3.19	2.75	2.34	2.12	1.72	1.36	0.99	0.77	0.44
5	0.800	1.534	3.83	3.60	3.33	2.87	2.45	2.22	1.80	1.42	1.03	0.80	0.46
10	0.900	2.328	4.34	4.08	3.78	3.25	2.78	2.52	2.04	1.61	1.17	0.91	0.52
25	0.960	3.357	5.00	4.70	4.35	3.75	3.20	2.90	2.35	1.85	1.35	1.05	0.60
50	0.980	4.139	5.50	5.17	4.78	4.12	3.52	3.19	2.58	2.03	1.48	1.15	0.66
100	0.990	4.933	6.01	5.65	5.23	4.51	3.84	3.48	2.82	2.22	1.62	1.26	0.72

P7

Record less than 30 years

P9													
2	0.500	0.381	2.65	2.49	2.31	1.99	1.70	1.54	1.25	0.98	0.72	0.56	0.32
3	0.667	0.994	3.13	2.94	2.72	2.34	2.00	1.81	1.47	1.16	0.84	0.66	0.38
4	0.750	1.424	3.46	3.25	3.01	2.59	2.21	2.00	1.62	1.28	0.93	0.73	0.41
5	0.800	1.763	3.72	3.49	3.23	2.79	2.38	2.16	1.75	1.38	1.00	0.78	0.45
10	0.900	2.877	4.58	4.30	3.98	3.43	2.93	2.65	2.15	1.69	1.24	0.96	0.55
25	0.960	4.560	5.87	5.52	5.11	4.40	3.76	3.41	2.76	2.17	1.59	1.23	0.70
50	0.980	6.044	7.01	6.59	6.10	5.26	4.49	4.07	3.30	2.60	1.89	1.47	0.84
100	0.990	7.750	8.33	7.83	7.24	6.25	5.33	4.83	3.91	3.08	2.25	1.75	1.00

Table 3C: Estimates for 20 KM by 20 KM Cells

Return Period	Prob-ability	Reduced Variate	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration
T	p	y 24 hr	24 hr	18 hr	12 hr	6 hr	3 hr	2 hr	1 hr	30 min	15 min	10 min	5 min
R3													
2	0.500	0.364	3.01	2.83	2.62	2.26	1.93	1.75	1.42	1.12	0.81	0.63	0.36
3	0.667	0.887	3.42	3.22	2.98	2.57	2.19	1.98	1.61	1.27	0.92	0.72	0.41
4	0.750	1.215	3.68	3.46	3.20	2.76	2.35	2.13	1.73	1.36	0.99	0.77	0.44
5	0.800	1.456	3.87	3.63	3.36	2.90	2.47	2.24	1.82	1.43	1.04	0.81	0.46
10	0.900	2.152	4.41	4.14	3.84	3.31	2.82	2.56	2.07	1.63	1.19	0.93	0.53
25	0.960	3.002	5.07	4.77	4.41	3.80	3.25	2.94	2.38	1.88	1.37	1.07	0.61
50	0.980	3.613	5.55	5.22	4.83	4.16	3.55	3.22	2.61	2.05	1.50	1.17	0.67
100	0.990	4.202	6.01	5.65	5.23	4.51	3.84	3.48	2.82	2.22	1.62	1.26	0.72
R5													
2	0.500	0.378	3.14	2.95	2.73	2.36	2.01	1.82	1.48	1.16	0.85	0.66	0.38
3	0.667	0.976	3.52	3.31	3.07	2.64	2.26	2.04	1.66	1.30	0.95	0.74	0.42
4	0.750	1.388	3.79	3.56	3.30	2.84	2.42	2.20	1.78	1.40	1.02	0.80	0.45
5	0.800	1.709	3.99	3.75	3.47	3.00	2.56	2.32	1.88	1.48	1.08	0.84	0.48
10	0.900	2.741	4.65	4.38	4.05	3.49	2.98	2.70	2.19	1.72	1.26	0.98	0.56
25	0.960	4.250	5.62	5.28	4.89	4.21	3.60	3.26	2.64	2.08	1.52	1.18	0.67
50	0.980	5.537	6.44	6.06	5.61	4.83	4.12	3.74	3.03	2.38	1.74	1.35	0.77
100	0.990	6.976	7.36	6.92	6.41	5.52	4.71	4.27	3.46	2.72	1.99	1.55	0.88
R7													
2	0.500	0.380	3.12	2.94	2.72	2.34	2.00	1.81	1.47	1.16	0.84	0.66	0.37
3	0.667	0.985	3.73	3.51	3.25	2.80	2.39	2.17	1.76	1.38	1.01	0.78	0.45
4	0.750	1.406	4.16	3.91	3.62	3.12	2.66	2.41	1.96	1.54	1.12	0.87	0.50
5	0.800	1.736	4.49	4.22	3.91	3.37	2.88	2.61	2.11	1.66	1.21	0.94	0.54
10	0.900	2.808	5.58	5.24	4.85	4.18	3.57	3.23	2.62	2.06	1.51	1.17	0.67
25	0.960	4.401	7.19	6.75	6.25	5.39	4.60	4.17	3.38	2.66	1.94	1.51	0.86
50	0.980	5.783	8.58	8.07	7.47	6.44	5.49	4.98	4.03	3.17	2.32	1.80	1.03
100	0.990	7.350	10.16	9.55	8.84	7.62	6.50	5.89	4.78	3.76	2.74	2.13	1.22
R9													
2	0.500	0.377	3.17	2.98	2.76	2.38	2.03	1.84	1.49	1.17	0.86	0.67	0.38
3	0.667	0.971	3.71	3.49	3.23	2.79	2.38	2.15	1.75	1.37	1.00	0.78	0.45
4	0.750	1.379	4.08	3.84	3.55	3.06	2.61	2.37	1.92	1.51	1.10	0.86	0.49
5	0.800	1.695	4.37	4.11	3.80	3.28	2.80	2.54	2.06	1.62	1.18	0.92	0.52
10	0.900	2.709	5.30	4.98	4.61	3.97	3.39	3.07	2.49	1.96	1.43	1.11	0.64
25	0.960	4.176	6.63	6.23	5.77	4.97	4.24	3.85	3.12	2.45	1.79	1.39	0.80
50	0.980	5.418	7.76	7.30	6.75	5.82	4.97	4.50	3.65	2.87	2.10	1.63	0.93
100	0.990	6.798	9.02	8.47	7.84	6.76	5.77	5.23	4.24	3.34	2.43	1.89	1.08

Table 3D: Estimates for 20 KM by 20 KM Cells

Return Period T	Prob-ability p	Reduced Variate y 24 hr	Duration 24 hr	Duration 18 hr	Duration 12 hr	Duration 6 hr	Duration 3 hr	Duration 2 hr	Duration 1 hr	Duration 30 min	Duration 15 min	Duration 10 min	Duration 5 min
T3													
2	0.500	0.346	3.26	3.07	2.84	2.45	2.09	1.89	1.53	1.21	0.88	0.68	0.39
3	0.667	0.784	3.66	3.44	3.18	2.74	2.34	2.12	1.72	1.35	0.99	0.77	0.44
4	0.750	1.027	3.87	3.64	3.37	2.91	2.48	2.25	1.82	1.43	1.05	0.81	0.46
5	0.800	1.191	4.02	3.78	3.50	3.02	2.57	2.33	1.89	1.49	1.09	0.84	0.48
10	0.900	1.604	4.39	4.13	3.82	3.30	2.81	2.55	2.07	1.63	1.19	0.92	0.53
25	0.960	2.002	4.75	4.47	4.13	3.56	3.04	2.76	2.23	1.76	1.28	1.00	0.57
50	0.980	2.228	4.96	4.66	4.31	3.72	3.17	2.87	2.33	1.83	1.34	1.04	0.59
100	0.990	2.408	5.12	4.81	4.45	3.84	3.27	2.97	2.41	1.89	1.38	1.07	0.61
T5													
2	0.500	0.365	3.72	3.50	3.24	2.79	2.38	2.16	1.75	1.38	1.00	0.78	0.45
3	0.667	0.895	4.39	4.12	3.82	3.29	2.81	2.54	2.06	1.62	1.18	0.92	0.53
4	0.750	1.231	4.81	4.52	4.19	3.61	3.08	2.79	2.26	1.78	1.30	1.01	0.58
5	0.800	1.478	5.12	4.81	4.46	3.84	3.28	2.97	2.41	1.90	1.38	1.08	0.61
10	0.900	2.200	6.03	5.67	5.25	4.52	3.86	3.50	2.84	2.23	1.63	1.27	0.72
25	0.960	3.098	7.16	6.73	6.23	5.37	4.58	4.16	3.37	2.65	1.93	1.50	0.86
50	0.980	3.754	7.99	7.51	6.95	5.99	5.11	4.63	3.76	2.96	2.16	1.68	0.96
100	0.990	4.395	8.80	8.27	7.65	6.60	5.63	5.10	4.13	3.26	2.38	1.85	1.06
T7													
2	0.500	0.387	3.39	3.18	2.95	2.54	2.17	1.96	1.59	1.25	0.91	0.71	0.41
3	0.667	1.037	3.98	3.74	3.47	2.99	2.55	2.31	1.87	1.47	1.08	0.84	0.48
4	0.750	1.511	4.42	4.15	3.85	3.31	2.83	2.56	2.08	1.64	1.19	0.93	0.53
5	0.800	1.894	4.77	4.49	4.15	3.58	3.05	2.77	2.24	1.77	1.29	1.00	0.57
10	0.900	3.214	5.99	5.63	5.21	4.49	3.83	3.47	2.81	2.22	1.62	1.26	0.72
25	0.960	5.368	7.97	7.49	6.93	5.98	5.10	4.62	3.75	2.95	2.15	1.67	0.96
50	0.980	7.413	9.85	9.26	8.57	7.39	6.30	5.71	4.63	3.64	2.66	2.07	1.18
100	0.990	9.917	12.15	11.42	10.57	9.12	7.78	7.05	5.71	4.50	3.28	2.55	1.46
T9													
2	0.500	0.373	3.10	2.91	2.70	2.32	1.98	1.80	1.46	1.15	0.84	0.65	0.37
3	0.667	0.945	3.62	3.40	3.15	2.71	2.32	2.10	1.70	1.34	0.98	0.76	0.43
4	0.750	1.327	3.97	3.73	3.45	2.98	2.54	2.30	1.86	1.47	1.07	0.83	0.48
5	0.800	1.618	4.23	3.98	3.68	3.17	2.71	2.45	1.99	1.57	1.14	0.89	0.51
10	0.900	2.524	5.06	4.75	4.40	3.79	3.24	2.93	2.38	1.87	1.37	1.06	0.61
25	0.960	3.769	6.19	5.82	5.39	4.64	3.96	3.59	2.91	2.29	1.67	1.30	0.74
50	0.980	4.773	7.10	6.68	6.18	5.33	4.55	4.12	3.34	2.63	1.92	1.49	0.85
100	0.990	5.841	8.08	7.59	7.03	6.06	5.17	4.68	3.80	2.99	2.18	1.70	0.97

Table 3E: Estimates for 20 KM by 20 KM Cells

Return Period T	Prob-ability p	Reduced Variate y 24 hr	Duration 24 hr	Duration 18 hr	Duration 12 hr	Duration 6 hr	Duration 3 hr	Duration 2 hr	Duration 1 hr	Duration 30 min	Duration 15 min	Duration 10 min	Duration 5 min
V3													
2	0.500	0.371	2.96	2.78	2.58	2.22	1.90	1.72	1.39	1.10	0.80	0.62	0.36
3	0.667	0.928	3.40	3.20	2.96	2.55	2.18	1.97	1.60	1.26	0.92	0.71	0.41
4	0.750	1.294	3.69	3.47	3.21	2.77	2.36	2.14	1.74	1.37	1.00	0.78	0.44
5	0.800	1.570	3.91	3.68	3.40	2.93	2.50	2.27	1.84	1.45	1.06	0.82	0.47
10	0.900	2.409	4.57	4.30	3.98	3.43	2.93	2.65	2.15	1.69	1.23	0.96	0.55
25	0.960	3.526	5.46	5.13	4.75	4.09	3.49	3.16	2.56	2.02	1.47	1.15	0.65
50	0.980	4.397	6.14	5.77	5.34	4.61	3.93	3.56	2.89	2.27	1.66	1.29	0.74
100	0.990	5.298	6.86	6.44	5.96	5.14	4.39	3.98	3.22	2.54	1.85	1.44	0.82
V5													
2	0.500	0.362	3.68	3.46	3.20	2.76	2.35	2.13	1.73	1.36	0.99	0.77	0.44
3	0.667	0.875	4.27	4.01	3.71	3.20	2.73	2.47	2.01	1.58	1.15	0.90	0.51
4	0.750	1.193	4.63	4.35	4.03	3.47	2.96	2.69	2.18	1.71	1.25	0.97	0.56
5	0.800	1.424	4.90	4.60	4.26	3.67	3.13	2.84	2.30	1.81	1.32	1.03	0.59
10	0.900	2.082	5.65	5.32	4.92	4.24	3.62	3.28	2.66	2.09	1.53	1.19	0.68
25	0.960	2.866	6.56	6.16	5.70	4.92	4.20	3.80	3.08	2.43	1.77	1.38	0.79
50	0.980	3.414	7.19	6.76	6.25	5.39	4.60	4.17	3.38	2.66	1.94	1.51	0.86
100	0.990	3.933	7.78	7.32	6.77	5.84	4.98	4.51	3.66	2.88	2.10	1.63	0.93
V7													
2	0.500	0.378	3.31	3.11	2.88	2.48	2.12	1.92	1.55	1.22	0.89	0.69	0.40
3	0.667	0.976	3.95	3.72	3.44	2.97	2.53	2.29	1.86	1.46	1.07	0.83	0.47
4	0.750	1.388	4.40	4.13	3.83	3.30	2.82	2.55	2.07	1.63	1.19	0.92	0.53
5	0.800	1.709	4.75	4.46	4.13	3.56	3.04	2.75	2.23	1.76	1.28	1.00	0.57
10	0.900	2.741	5.86	5.51	5.10	4.40	3.75	3.40	2.75	2.17	1.58	1.23	0.70
25	0.960	4.250	7.49	7.04	6.52	5.62	4.79	4.34	3.52	2.77	2.02	1.57	0.90
50	0.980	5.537	8.88	8.35	7.73	6.66	5.68	5.15	4.17	3.29	2.40	1.86	1.07
100	0.990	6.976	10.43	9.81	9.08	7.83	6.68	6.05	4.90	3.86	2.82	2.19	1.25
V9													
2	0.500	0.380	2.51	2.36	2.19	1.88	1.61	1.46	1.18	0.93	0.68	0.53	0.30
3	0.667	0.989	2.98	2.80	2.59	2.24	1.91	1.73	1.40	1.10	0.81	0.63	0.36
4	0.750	1.415	3.31	3.11	2.88	2.48	2.12	1.92	1.56	1.22	0.89	0.69	0.40
5	0.800	1.749	3.57	3.35	3.10	2.68	2.28	2.07	1.68	1.32	0.96	0.75	0.43
10	0.900	2.842	4.41	4.14	3.84	3.31	2.82	2.56	2.07	1.63	1.19	0.93	0.53
25	0.960	4.480	5.67	5.33	4.93	4.25	3.63	3.29	2.66	2.10	1.53	1.19	0.68
50	0.980	5.912	6.77	6.37	5.89	5.08	4.33	3.93	3.18	2.51	1.83	1.42	0.81
100	0.990	7.547	8.03	7.55	6.99	6.02	5.14	4.66	3.77	2.97	2.17	1.69	0.96

Table 3F: Estimates for 20 KM by 20 KM Cells

Return Period T	Prob-ability p	Reduced Variate y 24 hr	Duration 24 hr	Duration 18 hr	Duration 12 hr	Duration 6 hr	Duration 3 hr	Duration 2 hr	Duration 1 hr	Duration 30 min	Duration 15 min	Duration 10 min	Duration 5 min

X3

Record length less than 30 years.

X5													
2	0.500	0.380	2.95	2.78	2.57	2.22	1.89	1.71	1.39	1.09	0.80	0.62	0.35
3	0.667	0.989	3.44	3.23	2.99	2.58	2.20	2.00	1.62	1.27	0.93	0.72	0.41
4	0.750	1.415	3.78	3.55	3.29	2.84	2.42	2.19	1.78	1.40	1.02	0.79	0.45
5	0.800	1.749	4.05	3.81	3.52	3.04	2.59	2.35	1.90	1.50	1.09	0.85	0.49
10	0.900	2.842	4.92	4.63	4.28	3.69	3.15	2.86	2.31	1.82	1.33	1.03	0.59
25	0.960	4.480	6.23	5.86	5.42	4.68	3.99	3.62	2.93	2.31	1.68	1.31	0.75
50	0.980	5.912	7.38	6.94	6.42	5.53	4.72	4.28	3.47	2.73	1.99	1.55	0.89
100	0.990	7.547	8.69	8.17	7.56	6.52	5.56	5.04	4.08	3.21	2.35	1.82	1.04

X7

Record length less than 30 years.

X9													
2	0.500	0.398	2.74	2.58	2.38	2.06	1.75	1.59	1.29	1.01	0.74	0.58	0.33
3	0.667	1.108	3.15	2.96	2.74	2.36	2.02	1.83	1.48	1.17	0.85	0.66	0.38
4	0.750	1.659	3.47	3.26	3.02	2.60	2.22	2.01	1.63	1.28	0.94	0.73	0.42
5	0.800	2.124	3.74	3.52	3.26	2.81	2.39	2.17	1.76	1.38	1.01	0.79	0.45
10	0.900	3.845	4.74	4.46	4.12	3.55	3.03	2.75	2.23	1.75	1.28	1.00	0.57
25	0.960	7.012	6.58	6.18	5.72	4.93	4.21	3.81	3.09	2.43	1.78	1.38	0.79
50	0.980	10.380	8.53	8.02	7.42	6.40	5.46	4.95	4.01	3.16	2.30	1.79	1.02
100	0.990	14.930	11.17	10.50	9.72	8.38	7.15	6.48	5.25	4.13	3.02	2.35	1.34

Table 4--Metro. Area: Maximum over Area

Return Period	Prob-ability	Reduced Variate	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration
T	p	y 24 hr	24 hr	18 hr	12 hr	6 hr	3 hr	2 hr	1 hr	30 min	15 min	10 min	5 min
2	0.500	0.368	5.27	4.95	4.58	3.95	3.37	3.05	2.48	1.95	1.42	1.11	0.63
3	0.667	0.911	6.10	5.74	5.31	4.58	3.91	3.54	2.87	2.26	1.65	1.28	0.73
4	0.750	1.262	6.64	6.24	5.78	4.98	4.25	3.85	3.12	2.46	1.79	1.39	0.80
5	0.800	1.523	7.04	6.62	6.13	5.28	4.51	4.09	3.31	2.61	1.90	1.48	0.85
10	0.900	2.302	8.24	7.75	7.17	6.18	5.28	4.78	3.88	3.05	2.23	1.73	0.99
25	0.960	3.303	9.79	9.20	8.51	7.34	6.26	5.68	4.60	3.62	2.64	2.06	1.17
50	0.980	4.058	10.95	10.29	9.53	8.21	7.01	6.35	5.15	4.05	2.96	2.30	1.31
100	0.990	4.818	12.12	11.39	10.54	9.09	7.76	7.03	5.70	4.48	3.27	2.55	1.45

Table 5--Minneapolis Airport: 1891 - 1997

Return Period	Prob-ability	Reduced Variate	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration
T	p	y 24 hr	24 hr	18 hr	12 hr	6 hr	3 hr	2 hr	1 hr	30 min	15 min	10 min	5 min
2	0.500	0.382	2.32	2.18	2.02	1.74	1.49	1.35	1.09	0.86	0.63	0.49	0.28
3	0.667	0.999	2.73	2.57	2.37	2.05	1.75	1.58	1.28	1.01	0.74	0.57	0.33
4	0.750	1.433	3.02	2.84	2.62	2.26	1.93	1.75	1.42	1.12	0.81	0.63	0.36
5	0.800	1.777	3.24	3.05	2.82	2.43	2.08	1.88	1.52	1.20	0.88	0.68	0.39
10	0.900	2.912	3.99	3.75	3.47	2.99	2.55	2.32	1.88	1.48	1.08	0.84	0.48
25	0.960	4.642	5.13	4.83	4.47	3.85	3.29	2.98	2.41	1.90	1.39	1.08	0.62
50	0.980	6.179	6.15	5.78	5.35	4.61	3.93	3.57	2.89	2.27	1.66	1.29	0.74
100	0.990	7.960	7.32	6.88	6.37	5.49	4.69	4.25	3.44	2.71	1.98	1.54	0.88

substantially smaller than the largest design values calculated for the 20 km by 20 km areas and in the lower half of all of the estimates for the 20 km by 20km areas.

Another way to approximate the design values applicable to a point is to use the so-called Minneapolis precipitation record that consists of observations downtown on top of a building from 1891 through 1936 and at the airport after 1937. These data were processed in the same manner and the results are in Table 5. The design values are very similar to those for the long synthetic record in Table 8.

An approximation of the design values for some point over the area is obtained by constructing a 40 year time series consisting of the maximum precipitation each year over the study area. This time series was processed as the others and the results are in Table 4. The design values are very large in comparison with the standard sources and the estimates for a point. Indeed the 24 hour, 100 year return period event for a point (about 7 inches) is expected to occur **at some point** in the area once every 5 years on the average.

The question is not which is the best estimate. They are qualitatively different estimates. Which should be used is a public policy issue. If the design values for a point are used, it will be necessary to spend money on repairs at some point in the area relatively frequently. If the design values for some point are used, it will be necessary to spend money in the initial design and construction.

In the Hibbing study area only 7 of the 144 10 km by 10 km cells had more than 30 years of data. Combining these cells into 20 km by 20 km does not increase the frequency of cells with 30 years or more of data sufficiently to allow calculation of the spatial pattern. Therefore, the estimates for the Hibbing study area are limited to the design values for a point in the study area and for some point in the study area. The estimates are given in Tables 6 and 7 respectively.

The similarity between the design values for Hibbing and the comparable ones for the metropolitan area is most striking. The design values for a point in the Hibbing area are consistently a half inch, plus or minus, smaller than those for the metropolitan area. The Hibbing design values for some area are an inch or so smaller for return periods up to 10 years and then

Table 6--Hibbing: All Data

Return Period	Prob-ability	Reduced Variate	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration
T	p	y 24 hr	24 hr	18 hr	12 hr	6 hr	3 hr	2 hr	1 hr	30 min	15 min	10 min	5 min
2	0.500	0.380	2.35	2.21	2.05	1.77	1.51	1.37	1.11	0.87	0.64	0.49	0.28
3	0.667	0.989	2.76	2.60	2.40	2.07	1.77	1.60	1.30	1.02	0.75	0.58	0.33
4	0.750	1.415	3.05	2.87	2.65	2.29	1.95	1.77	1.43	1.13	0.82	0.64	0.37
5	0.800	1.749	3.27	3.08	2.85	2.45	2.09	1.90	1.54	1.21	0.88	0.69	0.39
10	0.900	2.842	4.00	3.76	3.48	3.00	2.56	2.32	1.88	1.48	1.08	0.84	0.48
25	0.960	4.480	5.10	4.80	4.44	3.83	3.26	2.96	2.40	1.89	1.38	1.07	0.61
50	0.980	5.912	6.06	5.70	5.27	4.55	3.88	3.52	2.85	2.24	1.64	1.27	0.73
100	0.990	7.547	7.16	6.73	6.23	5.37	4.58	4.15	3.36	2.65	1.93	1.50	0.86

Table 7--Hibbing: Maximum over Area

Return Period	Prob-ability	Reduced Variate	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration	Duration
T	p	y 24 hr	24 hr	18 hr	12 hr	6 hr	3 hr	2 hr	1 hr	30 min	15 min	10 min	5 min
2	0.500	0.380	4.33	4.07	3.77	3.25	2.77	2.51	2.04	1.60	1.17	0.91	0.52
3	0.667	0.989	5.04	4.74	4.38	3.78	3.22	2.92	2.37	1.86	1.36	1.06	0.60
4	0.750	1.415	5.53	5.20	4.81	4.15	3.54	3.21	2.60	2.05	1.49	1.16	0.66
5	0.800	1.749	5.92	5.56	5.15	4.44	3.79	3.43	2.78	2.19	1.60	1.24	0.71
10	0.900	2.842	7.19	6.76	6.25	5.39	4.60	4.17	3.38	2.66	1.94	1.51	0.86
25	0.960	4.480	9.09	8.54	7.91	6.81	5.82	5.27	4.27	3.36	2.45	1.91	1.09
50	0.980	5.912	10.75	10.10	9.35	8.06	6.88	6.23	5.05	3.98	2.90	2.26	1.29
100	0.990	7.547	12.64	11.89	11.00	9.48	8.09	7.33	5.94	4.68	3.41	2.66	1.52

gradually approach those for the metropolitan area at longer return periods. Indeed a return period of 100 years, the estimate for Hibbing is larger.

The precipitation design values from TP-40 were obtained by interpolation of the maps presented therein. The interpolated values are not exact but rather are representative for each of the two study areas. The values from the Huff and Angel study are the Minnesota sectional values found in Table 6 (pages 130 - 132). Sections (actually climatological divisions) six and three were used for the Metropolitan Study Area and the Hibbing Study Area respectively. The design values from this study area the high and low estimates for each of the two study areas.

The comparisons are given in four tables--two for each of study area (Tables 8-11). For each study area the high and low estimates from this study are compared with the design values from TP-40 and Huff and Angel. A few observations about the comparisons can be made.

- The design values in TP-40 are generally larger than the design values in Angel and Huff.
- Both the high and low design values in this study are larger than both the TP-40 and Huff and Angel estimates.
- Both the high and low estimates in this study (and especially the low estimates) are closer to the TP-40 and Huff and Angel estimates of shorter return periods. The differences increase as the return period increases. This is apparently the result of having negative values for k in the generalized design value equations, i.e., a Fréchet distribution. The Fréchet distribution is concave upwards with return period.
- The high estimate design values from this study are on the order of twice the design value contained in TP-40 and Huff and Angel.
- The low estimate design values from this study are quite similar to the design values in TP-40 and Huff and Angel at low return periods. They are one to two inches larger than the standard sources at longer return periods.

A final comparison can be made between the low estimate of design values and design values for the MSP precipitation record (see Table 5: Minneapolis Airport: 1891-1997). The two estimates are remarkably similar.

Table 8:Metropolitan Area: Comparison of TP40, Huff & Angel, and Skaggs--Low Estimate

Duration\ Return Period	1 Year	2 Years	3 Years	5 Years	10 Years	25 Years	50 Years	100 Years
5 Minutes								
TP 40								
Huff & Angel	0.27	0.32		0.39	0.44	0.52	0.59	0.66
Skaggs		0.32	0.38	0.45	0.54	0.67	0.78	0.90
10 Minutes								
TP 40								
Huff & Angel	0.47	0.56		0.68	0.77	0.91	1.02	1.15
Skaggs		0.56	0.66	0.78	0.94	1.17	1.36	1.57
15 Minutes								
TP 40								
Huff & Angel	0.60	0.72		0.87	1.00	1.17	1.32	1.47
Skaggs		0.72	0.85	1.00	1.21	1.51	1.75	2.02
30 Minutes								
TP 40	0.70	1.10		1.45	1.65	1.90	2.10	2.40
Huff & Angel	0.82	0.98		1.20	1.37	1.61	1.81	2.02
Skaggs		0.99	1.16	1.37	1.66	2.07	2.40	2.76
1 Hour								
TP 40	1.15	1.40		1.80	2.10	2.40	2.70	3.00
Huff & Angel	1.04	1.25		1.52	1.73	2.04	2.29	2.57
Skaggs		1.26	1.48	1.63	2.11	2.62	3.05	3.51
2 Hours								
TP 40	1.40	1.65		2.20	2.50	2.75	3.20	3.50
Huff & Angel	1.29	1.54		1.87	2.14	2.52	2.83	3.17
Skaggs		1.55	1.82	2.01	2.60	3.24	3.76	4.33
3 Hours								
TP 40	1.50	1.75		2.25	2.65	3.00	3.40	3.70
Huff & Angel	1.42	1.70		2.07	2.36	2.78	3.12	3.49
Skaggs		1.71	2.01	2.22	2.87	3.57	4.15	4.78
6 Hours								
TP 40	1.75	2.20		2.60	3.20	3.50	4.00	4.50
Huff & Angel	1.66	1.99		2.42	2.77	3.26	3.66	4.10
Skaggs		2.01	2.36	2.78	3.37	4.19	4.87	5.60
12 Hours								
TP 40	2.00	2.50		3.20	3.60	4.25	4.60	5.25
Huff & Angel	1.93	2.31		2.81	3.21	3.78	4.25	4.75
Skaggs		2.33	2.74	3.23	3.90	4.86	5.64	6.50
18 Hours								
TP 40								
Huff & Angel	2.09	2.49		3.04	3.47	4.09	4.59	5.13
Skaggs		2.51	2.96	3.49	4.22	5.25	6.10	7.02
24 Hours								
TP 40	2.35	2.75		3.55	4.20	4.70	5.40	6.10
Huff & Angel	2.22	2.65		3.23	3.69	4.35	4.88	5.46
Skaggs		2.67	3.15	3.71	4.49	5.58	6.49	7.47

Table 9: Metropolitan Area: Comparison of TP40, Huff & Angel, and Skaggs--High Estimate

Duration\ Return Period	1 Year	2 Years	3 Years	5 Years	10 Years	25 Years	50 Years	100 Years
5 Minutes								
TP 40								
Huff & Angel	0.27	0.32		0.39	0.44	0.52	0.59	0.66
Skaggs		0.63	0.73	0.85	0.99	1.17	1.31	1.45
10 Minutes								
TP 40								
Huff & Angel	0.47	0.56		0.68	0.77	0.91	1.02	1.15
Skaggs		1.11	1.28	1.48	1.73	2.06	2.30	2.55
15 Minutes								
TP 40								
Huff & Angel	0.60	0.72		0.87	1.00	1.17	1.32	1.47
Skaggs		1.42	1.65	1.90	2.23	2.64	2.96	3.27
30 Minutes								
TP 40	0.70	1.10		1.45	1.65	1.90	2.10	2.40
Huff & Angel	0.82	0.98		1.20	1.37	1.61	1.81	2.02
Skaggs		1.95	2.26	3.05	3.62	3.62	4.05	4.48
1 Hour								
TP 40	1.15	1.40		1.80	2.10	2.40	2.70	3.00
Huff & Angel	1.04	1.25		1.52	1.73	2.04	2.29	2.57
Skaggs		2.48	2.87	3.31	3.88	4.60	5.15	5.70
2 Hours								
TP 40	1.40	1.65		2.20	2.50	2.75	3.20	3.50
Huff & Angel	1.29	1.54		1.87	2.14	2.52	2.83	3.17
Skaggs		3.05	3.54	4.09	4.78	5.68	6.35	7.03
3 Hours								
TP 40	1.50	1.75		2.25	2.65	3.00	3.40	3.70
Huff & Angel	1.42	1.70		2.07	2.36	2.78	3.12	3.49
Skaggs		3.37	3.91	4.51	5.28	6.26	7.01	7.76
6 Hours								
TP 40	1.75	2.20		2.60	3.20	3.50	4.00	4.50
Huff & Angel	1.66	1.99		2.42	2.77	3.26	3.66	4.10
Skaggs		3.95	4.58	5.28	6.18	7.34	8.21	9.09
12 Hours								
TP 40	2.00	2.50		3.20	3.60	4.25	4.60	5.25
Huff & Angel	1.93	2.31		2.81	3.21	3.78	4.25	4.75
Skaggs		4.58	5.31	6.13	7.17	8.51	9.53	10.54
18 Hours								
TP 40								
Huff & Angel	2.09	2.49		3.04	3.47	4.09	4.59	5.13
Skaggs		4.95	5.74	6.62	7.75	9.20	10.29	11.39
24 Hours								
TP 40	2.35	2.75		3.55	4.20	4.70	5.40	6.10
Huff & Angel	2.22	2.65		3.23	3.69	4.35	4.88	5.46
Skaggs		5.27	6.10	7.04	8.24	9.79	10.95	12.12

Table 10: Hibbing Area: Comparison of TP40, Huff & Angel, and Skaggs--High Estimate

Duration\ Return Period	1 Year	2 Years	3 Years	5 Years	10 Years	25 Years	50 Years	100 Years
5 Minutes								
TP 40								
Huff & Angel	0.23	0.28		0.35	0.40	0.49	0.56	0.62
Skaggs		0.52	0.60	0.71	0.86	1.09	1.29	1.52
10 Minutes								
TP 40								
Huff & Angel	0.40	0.49		0.60	0.71	0.86	0.97	1.09
Skaggs		0.91	1.06	1.24	1.51	1.91	2.26	2.66
15 Minutes								
TP 40								
Huff & Angel	0.52	0.62		0.78	0.91	1.10	1.25	1.40
Skaggs		1.17	1.36	1.60	1.94	2.45	2.90	3.41
30 Minutes								
TP 40	0.80	1.00		1.25	1.45	1.65	1.85	2.10
Huff & Angel	0.71	0.85		1.07	1.24	1.51	1.72	1.92
Skaggs		1.60	1.86	2.19	2.66	3.36	3.98	4.68
1 Hour								
TP 40	0.90	1.20		1.55	1.80	2.10	2.30	2.55
Huff & Angel	0.90	1.09		1.35	1.58	1.92	2.18	2.44
Skaggs		2.04	2.37	2.78	3.38	4.27	5.05	5.94
2 Hours								
TP 40	0.90	1.20		1.55	1.80	2.10	2.30	2.55
Huff & Angel	1.11	1.34		1.67	1.95	2.37	2.69	3.02
Skaggs		2.51	2.92	3.43	4.17	5.27	6.23	7.33
3 Hours								
TP 40	1.30	1.65		2.00	2.25	2.70	3.00	3.25
Huff & Angel	1..22	1.48		1.84	2.15	2.61	2.97	3.33
Skaggs		2.77	3.22	3.79	4.60	5.82	6.88	8.09
6 Hours								
TP 40	1.55	1.75		2.40	2.75	3.15	3.40	3.85
Huff & Angel	1.43	1.73		2.16	2.52	3.06	3.48	3.90
Skaggs		3.25	3.78	4.44	5.39	6.81	8.06	9.48
12 Hours								
TP 40	1.75	2.25		2.75	3.25	3.75	4.10	4.50
Huff & Angel	1.66	2.01		2.51	2.92	3.55	4.04	4.52
Skaggs		3.77	4.38	5.15	6.25	7.91	9.35	11.00
18 Hours								
TP 40								
Huff & Angel	1.80	2.17		2.71	3.16	3.84	4.36	4.89
Skaggs		4.07	4.74	5.56	6.76	8.54	10.10	11.89
24 Hours								
TP 40	2.20	2.50		3.25	3.75	4.30	4.75	5.35
Huff & Angel	1.91	2.31		2.88	3.36	4.08	4.64	5.20
Skaggs		4.33	5.04	5.92	7.19	9.09	10.75	12.64

Table 11: Hibbing Area: Comparison of TP40, Huff & Angel, and Skaggs--Low Estimate

Duration\ Return Period	1 Year	2 Years	3 Years	5 Years	10 Years	25 Years	50 Years	100 Years
5 Minutes								
TP 40								
Huff & Angel	0.23	0.28		0.35	0.40	0.49	0.56	0.62
Skaggs		0.28	0.33	0.39	0.48	0.61	0.73	0.86
10 Minutes								
TP 40								
Huff & Angel	0.40	0.49		0.60	0.71	0.86	0.97	1.09
Skaggs		0.49	0.58	0.69	0.84	1.07	1.27	1.50
15 Minutes								
TP 40								
Huff & Angel	0.52	0.62		0.78	0.91	1.10	1.25	1.40
Skaggs		0.64	0.75	0.88	1.08	1.38	1.64	1.93
30 Minutes								
TP 40	0.80	1.00		1.25	1.45	1.65	1.85	2.10
Huff & Angel	0.71	0.85		1.07	1.24	1.51	1.72	1.92
Skaggs		0.87	1.02	1.21	1.48	1.89	2.24	2.65
1 Hour								
TP 40	0.90	1.20		1.55	1.80	2.10	2.30	2.55
Huff & Angel	0.90	1.09		1.35	1.58	1.92	2.18	2.44
Skaggs		1.11	1.30	1.54	1.88	2.40	2.85	3.36
2 Hours								
TP 40	0.90	1.20		1.55	1.80	2.10	2.30	2.55
Huff & Angel	1.11	1.34		1.67	1.95	2.37	2.69	3.02
Skaggs		1.37	1.60	1.90	2.32	2.96	3.52	4.15
3 Hours								
TP 40	1.30	1.65		2.00	2.25	2.70	3.00	3.25
Huff & Angel	1..22	1.48		1.84	2.15	2.61	2.97	3.33
Skaggs		1.51	1.77	2.09	2.56	3.26	3.88	4.58
6 Hours								
TP 40	1.55	1.75		2.40	2.75	3.15	3.40	3.85
Huff & Angel	1.43	1.73		2.16	2.52	3.06	3.48	3.90
Skaggs		1.77	2.07	2.45	3.00	3.83	4.55	5.37
12 Hours								
TP 40	1.75	2.25		2.75	3.25	3.75	4.10	4.50
Huff & Angel	1.66	2.01		2.51	2.92	3.55	4.04	4.52
Skaggs		2.05	2.40	2.85	3.48	4.44	5.27	6.23
18 Hours								
TP 40								
Huff & Angel	1.80	2.17		2.71	3.16	3.84	4.36	4.89
Skaggs		2.21	2.60	3.08	3.76	4.80	5.70	6.73
24 Hours								
TP 40	2.20	2.50		3.25	3.75	4.30	4.75	5.35
Huff & Angel	1.91	2.31		2.88	3.36	4.08	4.64	5.20
Skaggs		2.35	2.76	3.27	4.00	5.10	6.06	7.16

The analysis of changes in the magnitude of the maximum annual 24 hour precipitation event was investigated using simple linear regression. Two time series were analyzed: the Minneapolis record from 1891 through 1997 and the maximum over the Twin Cities study area from 1970 through 1997. The Minneapolis record shows a slight negative slope or decrease between 1891 and 1997 while the time series of the maximum over the Twin Cities shows a slight increase. Neither slope is, however, significantly different from zero. There is some indication that the maximum annual 24 hour precipitation event decreased in size in the middle part of the Minneapolis record (1920 through 1960) and then increased again at the end of the record. The evidence, however, is not very conclusive.

Chapter 4

Conclusions

The conclusions of this pilot study are of two types. One type is substantive conclusions about the design values calculated in this study and their relationship to the design values in the standard sources. The other type is a conclusion about whether this pilot study should be replicated for the remainder of Minnesota.

The substantive conclusions may be summarized as follow.

1. The spatial variability of the design values estimated for 20 km by 20 km is far too great to make that approach practical.
2. Based on the experience with the Hibbing study area, it is likely that the density of observations over large part of the state would be too small to allow using 20-km by 20-km areas.
3. If the purpose of the design values is to provide guidance on extreme precipitation likely to be experienced at a point, the current standard sources underestimate the 24 hour, 100 year return period value by about one inch. At shorter durations and return periods the values computed here correspond well with those in the standard sources.
4. If the purpose of the design values is to provide guidance on extreme precipitation likely to be experience at some point over an area, the design values computed in this study are much larger.
5. There are no long-term trends in the magnitude of extreme precipitation events.

Based on these five substantive conclusions, the conclusion concerning whether the methods and data of this study should be extended to the rest of the state is that they should not. There are other potentially more valuable approaches that should be considered. One approach is producing grids of daily precipitation over the State from the end of the last century to the present time. These gridded values would allow a Geographic Information System analysis of design values. A second approach is the archiving and analysis of precipitation rate data from the NEXRAD system. This data source needs substantially more study in terms of the durations that can be abstracted from the data and the reliability of the intensities measured.

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