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Stream Flow Response to Climate in Minnesota

by

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Abstract

The variability of stream flows in Minnesota, and the relationship between stream flows and climate are the focus of this report. We analyze historical flow records of Minnesota streams to determine how much frequency and magnitude of flows have been affected by climate and land use changes. Flow duration analysis, high and low flow ranking, and flood frequency analysis were applied to recorded mean daily stream flows, 7-day average low flows, and annual peak flows. Data from 36 gauging stations located in five river basins of Minnesota (Minnesota River, Rainy River, Red River of the North, Lake Superior, and Upper Mississippi River Basins) covering the 1946-2005 period were used.

To detect any changes that have occurred over time, data from the 1986-2005 and the 1946-1965 periods of record were analyzed separately. Flow duration curves were prepared for all gauging stations, and low flows (Q90, Q95), medium flows (Q50), and high flows (Q5, Q10) in the two time periods were examined. Multiple stream gauging stations in the same river basin generally showed consistent changes in stream flows, although deviations from a typical river basin pattern were noted at a few gauging stations.

The Minnesota River Basin has experienced the largest stream flow changes compared to the other four basins. High, medium, and low flows have increased significantly from the 1946-1965 to the 1986-2005 period in the Minnesota River basin. The increases in medium to low flows were larger than the increases in high flows. Considerable changes in flows were also observed in the Upper Mississippi River Basin and the Red River of the North Basin. Streams in the Rainy River Basin and tributaries to Lake Superior showed little or no change in stream flow between the 1946-1965 and 1986-2005 periods. The changes observed in these river basins were also variable. In two tributaries to Lake Superior, average flows seem to have increased on the order of 10%, 7-day low flows seem to have decreased, and annual peak flows seem to be unchanged.

The occurrence (temporal distribution) of extreme flows (annual peak flows and annual 7-day (average) low flows) over the period of record (1946-2005) was examined using a sorting/ranking method. The occurrence of extreme flows was not distributed uniformly over the period from 1946 to 2005. Most of the lowest 7-day (average) low flows did not occur in the recent 1986-2005 period, except in the Lake Superior basin. Based on event occurrence, both

annual peak flows and 7-day average low flows were higher in 1986-2005 than in 1946-1965 in the Minnesota River Basin, Red River of the North Basin, and Upper Mississippi River Basin.

Separate flood frequency analyses were conducted on the stream flow data from the 36 stream gauging stations for the 1946-1965 and the 1986-2005 periods to identify changes in the 1-, 2-, 5-, 10- and 25-yr floods. The results were most consistent for the Red River of the North Basin. In this basin, magnitudes of the 2- to 25-yr floods increased at all six stream gauging stations (average increases were from about 30 to 60%) and the magnitude of the 1-yr flood decreased (average of 20%). Results obtained for the Minnesota River, Rainy River, Lake Superior, and Upper Mississippi River Basins were not conclusive because the changes observed at individual stations in each river basin were not consistent; both increases and decreases were observed. Average changes in the 1- to 25-yr floods were between 21 and 320% in the Minnesota River Basin, -7% and -20% in the Rainy River Basin, -11% and 26% in the Lake Superior Basin, and -8 and 23% in the Upper Mississippi River Basin.

A low flow frequency analysis was conducted on the stream flow data for 1946-1965 and 1986-2005 to identify changes in the 2-, 5-, 10- and 20-yr seven-day annual (average) low flows. The largest changes in low flows were identified for stream gauging stations in the Minnesota River Basin. In this river basin flows with 2-, 5-, 10- and 20-yr return periods increased from the 1946-1965 to the 1986-2005 period. Similar changes were also evident in the Red River of the North and Upper Mississippi River Basins. Frequent low flows, e.g., 7-day average low flows with a 2-yr return period (7Q2) increased more than low flows of rarer occurrence, e.g., 7Q10 or 7Q20.

There are many potential causes for changes in stream flows. Precipitation is one. The river basins which showed the largest increases in stream flows (Minnesota River Basin and Red River of the North Basins) drain regions (climate divisions) where significant increases in precipitation have been observed. River basins which showed little or no change in stream flow (Rainy River and Lake Superior Basin) drain climate divisions where changes in precipitation were not significant. Agricultural drainage, changes in crop patterns, and urbanization are other potential causes for stream flow changes that need to be considered in separate studies.

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1. INTRODUCTION

The State of Minnesota is proud of its more than 10,000 lakes. However, the State's streams and rivers are equally important as wildlife habitat, for recreation, as a source of water supply, and as recipients of waste water. On rare occasions the streams and rivers of Minnesota have become devastating torrents. An enlightening description of Minnesota's streams and rivers was given by Waters (1977). Now the threat of climate change raises legitimate questions about the future of Minnesota's streams and rivers

Stream flow changes with climate and is therefore an indicator of climatic change. In this study we will analyze historical flow records of streams in Minnesota to determine how frequency and magnitude of flows have changed, i.e., been affected by climate and climatic changes in the past. It is important to identify the response of stream flows to climate because changes in stream flow, particularly in flood/drought patterns, have important ecological impacts and socio-economic implications. Flood characteristics affect the design of structures such as dams, bridges, culverts, and water intakes. Flood insurance programs depend on flow frequency, and so do the ecological characteristic of streams. Low flows and droughts affect stream and river water quality, as well as municipal or agricultural water uses, and the health of stream biota (Gordon et al., 2004) to mention but a few concerns.

This study is a continuation of a previous study by Novotny and Stefan (2006; 2007) on Minnesota stream flows. Novotny and Stefan (2006; 2007) analyzed the trends in seven stream-flow statistics (e.g., mean annual flows, peak and low flows, and number of days with high and low flows) in the 20th century. In this study, we analyze mean daily stream flow, 7-day low flow, and annual peak flow for the 1946-2005 period to identify changes in frequencies and magnitudes of stream flows in Minnesota. Since climate is progressively changing in Minnesota (Seeley, 2003), our analysis will focus on a comparison of stream flows in the 1986-2005 period and the 1946-1965 period. We will use flow duration analysis, peak flow ranking, low flow ranking, flood frequency analysis, and low flow frequency analysis.

2. BACKGROUND

2.1 Previous Studies of Stream Flows and Climate Change

Previous studies of stream flows in various parts of the world have shown that stream flow patterns have been changing due to climatic changes (IPCC, 2001). Lettenmaier et al.

(1994) examined trends in annual and monthly stream flows across the conterminous United States (U.S.) and found positive trends, i.e., increasing stream flows, particularly in the north-central states. Lins and Slack (1999) calculated the trends in selected quantiles of stream discharge at 395 stream gauging sites distributed over the conterminous U.S. and found mostly positive or upward trends in the annual minimum to median flow range. Trends in annual maximum stream flows were not as apparent. Douglas et al. (2000) examined the trends in floods and low flows and found upward trends in low flows particularly in the Midwest region. A trend in floods was not evident. Milly et al. (2002) found that the frequency of great floods (floods that came from basins larger than 200,000 km^2 and had return periods greater than 100 years) increased worldwide in the 20th century. McCabe and Wolock (2002) examined the trends in minimum, median, and maximum daily stream flow at 400 stream sites in the conterminous U.S. and found a step increase in minimum and median flows around 1970s. The timing of the increase in flow coincided with an increase in precipitation. Kundzewicz et al. (2005) analyzed the trends in annual maximum flows at 195 stream flow stations worldwide with at least 40 years of records. Their analysis showed that only 27 stations had a significant increasing trend and 31 had a significant decreasing trend. Among the 70 U.S. stations included in the study, 14 showed significant increases and 12 showed significant decreases. Svensson et al. (2005) used daily stream flow records of 68-year average length (range of 44-100 years) from 21 stream gauging stations worldwide (including 4 U.S. stations) to analyze the trends in floods and low flows. They found that a majority of the stations had decreasing trends in floods and increasing trends in low flows. The only station from the midwestern U.S. was a station in North Dakota where strong increasing trends in both floods and low flows were observed.

Several other studies focused on the stream flow changes in the midwestern U.S. including Minnesota. Knox (1993) analyzed the relationships between floods and climatic changes in the Upper Mississippi River watersheds using 7,000-year geological records of overbank floods. His analysis concluded that abrupt changes in flood magnitudes and frequencies occurred with moderate changes in mean annual temperature (1 - 2 ^{o}C) and mean annual precipitation (less than 10% to 20%). Knox (1993) concluded that climatic changes projected by global circulation models are much larger than historical changes and can cause significant changes in flood magnitudes and frequencies in many regions. Changnon and Kunkel (1995) found upward trends in flood flows that occur in the warm-season (May-November) or in the cold-season (December-April) in Minnesota. The former are caused by heavy rainfall events, while the latter are snowmelt floods. Heavy-precipitation amounts in Minnesota (e.g., from 7-day precipitation events at the 1-yr recurrence level) increased from 1921 to 1985 according to Changnon and Kunkel (1995). Schiller and Libra (2003) found increased base flow in Iowa over the second half of the 20th century, and Gebert and Krug (1996) analyzed stream flow trends in Wisconsin's driftless area. An analysis of historical stream flow records from 36 USGS stream gauging stations in Minnesota (Novotny and Stefan, 2007) showed significant trends in seven stream-flow statistics including mean annual flows, peak and low flows, and number of days with high and low flows. A strong correlation between mean annual stream flow and total annual precipitation was also documented.

It has been projected that climate change will increase the likelihood of floods and droughts over many regions due to increases in intensity and variability of precipitation (Kundzewicz et al., 2007). For Minnesota, the trends found by Novotny and Stefan (2007) support this general finding for rainfall-induced floods. There seems to be no trend towards a lowering of low flows in Minnesota in either summer or winter, indicating that sufficient ground-water sources exist to overcome any seasonal shortages of rainfall. The annual precipitation in Minnesota has a rising trend. Considering the historical changes and projections of further changes in intensity and variability of precipitation in Minnesota, potential variations in stream flow patterns deserve further analysis.

2.2. Historical Floods and Droughts in Minnesota

Major floods in Minnesota river basins have been caused by either snowmelt, sometimes accompanied by heavy rainfall, or by summer thunderstorms of high intensity (Carlson, 1991). The five most damaging floods prior to 1991 occurred in 1950, 1965, 1969, 1978, and 1979 (Carlson, 1991). A major and damaging flood occurred in Minnesota in the summer of 1993 due to extreme wet conditions (MN-DNR-Division of Waters, 1995). Recently, a devastating flood occurred in southeastern Minnesota due to heavy rainfall on 18-20 August 2007. Flash floods in Minnesota (http://www.climate.umn.edu/doc/flashflood.htm) have been analyzed by the Minnesota Department of Natural Resources (MNDNR) - Division of Waters, the State Climatology Office, and the University of Minnesota's Department of Soil, Water and Climate using rainfalls records (rather than stream flow records).

In this study 114 flash floods between 1970 and 2006 have been identified. A flash flood was defined as “the occurrence of 6 inches or more rainfall within a 24 hour period” at a given range gage. In addition it would be desirable to determine flashfloods from stream flow records. In fact, the National Weather Service (NWS, 2005) defines a flash flood as “the flood which is caused by heavy or excessive rainfall in a short period of time, generally less than 6 hours”. However, identification of historical flash floods in stream flow records requires analysis of historical data collected at least on an hourly timescale. Such records are rarely available.

Major droughts were experienced in Minnesota in the periods 1911-1914, 1921-1942, 1954-1961, and 1976-1977 (Carlson, 1991). The recurrence interval of these droughts was 30 years, 60 to 70 years, 50 years, and 10 to 30 years, respectively (Carlson, 1991). The most recent drought was experienced during the 1987-1988 period. Although dry conditions started in October 1987, the observed drop in stream flow was not strong until April 1988 due to adequate groundwater and lake water supply in the winter. In July 1988, stream flow throughout Minnesota was deficient or within the range of low flows that occur 25% of the time for the month (MN-DNR-Division of Waters, 1989).

2.3. Characteristics of River Basins in Minnesota

Minnesota is divided into eight major river basins (Figure 2.1). These basins were separately analyzed in the previous study by Novotny and Stefan (2007).

The Minnesota River Basin covers about 16,770 square miles, and is located in southern Minnesota (http://mrbdc.mnsu.edu/mnbasin/fact_sheets/fastfacts.html), except for small portions that extend into South Dakota and Iowa (Figure 2.1). 92% of the basin area is used for agriculture. The basin includes an extensive network of agricultural drainage tiles and man made ditches.

The Red River of the North Basin comprises 37,100 square miles of land in Minnesota, South Dakota and North Dakota. 17,730 square miles of it is in Minnesota. The majority of the land in the Minnesota portion of the Red River of the North Basin is used for agriculture (66%), some is covered by forests (12%), and some is urban residential land (8%) (Paakh et al., 2006).

The Rainy River Basin covers a total area of 27,114 square miles, of which 11,244 square miles are located in northern Minnesota. The majority of the Rainy River Basin is covered by forests, lakes, and wetlands (MPCA, 2001).

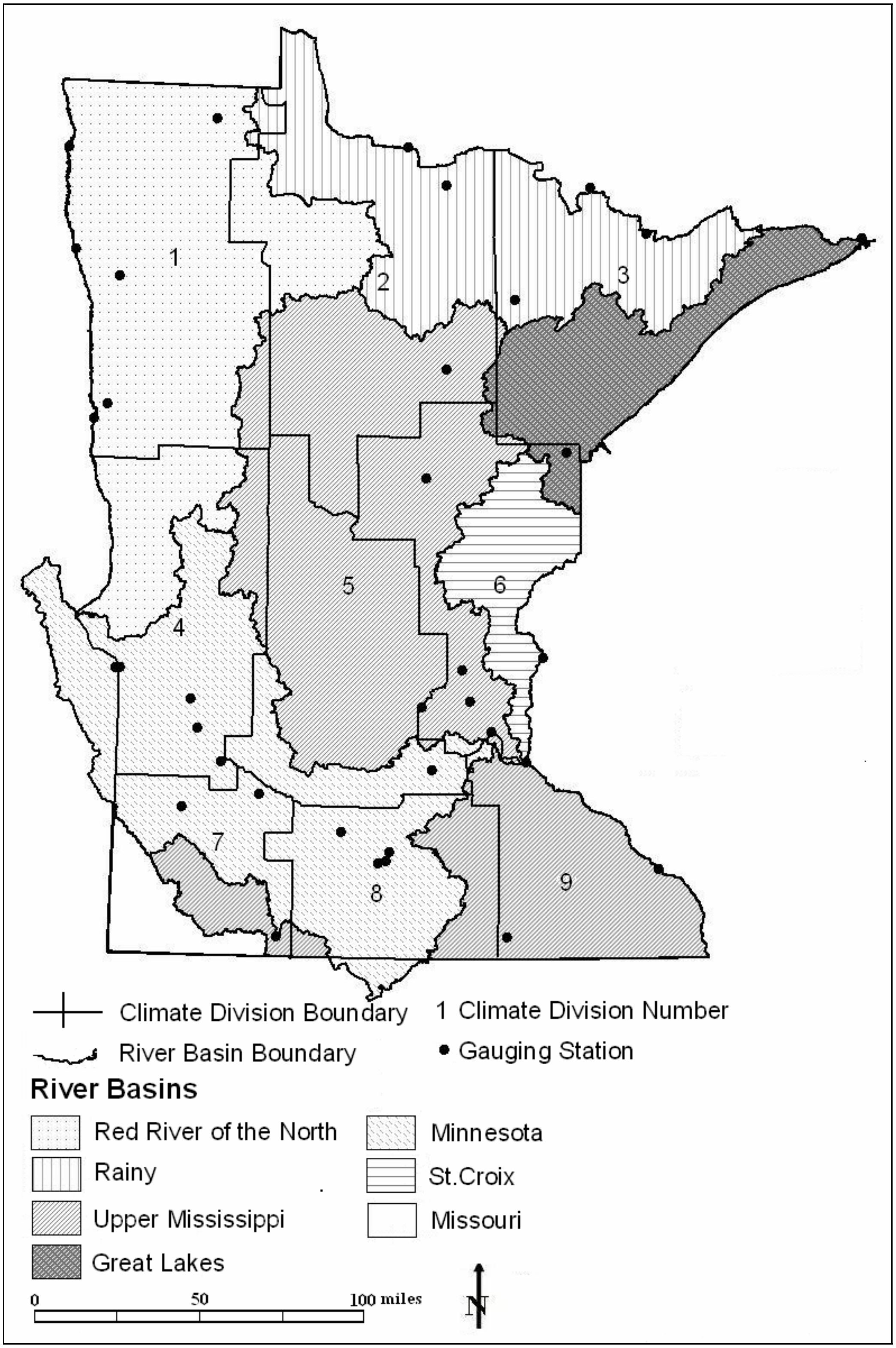

Figure 2.1. River basins (shaded) and climate divisions (numbered) of Minnesota. Stream gauging stations included in this study are shown as black dots.

The Lake Superior Watershed Basin in Minnesota is 6,200 square miles in size, and is covered mainly by forests with little agriculture and several urban areas.

The Upper Mississippi River Basin covers 30,800 square miles entirely within the state of Minnesota. Land cover in this part of the Upper Mississippi River Basin ranges from conifer and hardwood forests to agriculture where corn, soybean, and forage crops are cultivated (MPCA, 2000). In St. Paul the Minnesota River discharges into the Mississippi River and puts its imprint on Mississippi River flows. Downstream from St. Paul the St. Croix River, which drains portions of eastern Minnesota and western Wisconsin, enters the Mississippi River at Prescott, WI. Downstream from Prescott additional portions of western Wisconsin and southeastern Minnesota become part of the Mississippi River drainage (Figure 2.1). The Twin Cities metropolitan area is in the Mississippi River drainage.

A small piece of southwestern Minnesota (Figure 2.1) drains into the Missouri River, and another into the Upper Mississippi River through Iowa; both are not included in the study.

3. METHODS OF ANALYSIS

3.1. Stream Flow Data Used

Thirty-six gauging stations in the five major basins of Minnesota, previously analyzed by Novotny and Stefan (2007), were used in the analysis (Figure 2.1). These stations were selected based on the length and continuity of data and included the stations which were not affected by man-made structures. Twelve of the stations were in the Minnesota River Basin, 5 in the Rainy River Basin, 6 in the Red River of the North Basin, 11 in the Upper Mississippi River Basin, and 2 on tributary streams to Lake Superior. The locations of the stream flow gauging stations are shown in Figure 2.1. The list of gauging stations and where their drainage area is located (climate division) can be found in Table 3.1. Nine climate divisions of Minnesota and 2 climate divisions of North Dakota (no. 3 and 4) and a climate division of Wisconsin (no. 1) are included. The climate divisions of Minnesota are identified in Figure 2.1 by numbers 1 to 9. Stream flow data analyzed in this study include (1) daily average flows, (2) annual 7-day average low flows, and (3) annual peak flows. Records were available for at least 50 years (1946-2005) for most of the 36 stream gauging stations.

Table 3.1. Stream gauging stations included in this study

USGS Gauging Station No.	Stream/River Name	Record Length Used	Climate Division
Minnesota River Basin			
05291000	Whetstone River Big Stone City, SD	1993-2005	SD 3,4
05292000	Minnesota River at Ortonville, MN	1929-2005	4, SD 3
05304500	Chippewa River Near Milan, MN	1938-2005	4,5
05311000	Minnesota River at Montevideo, MN	1939-2005	4, SD 3
05313500	Yellow Medicine River Granite Falls, MN	1940-2005	4,7
05315000	Redwood River Near Marshall, MN	1941-2005	7
05316500	Redwood River Near Redwood Falls, MN	1936-2005	7
05317000	Cottonwood River Near New Ulm, MN	1939-2005	7,8
05320000	Blue Earth River Near Rapidan, MN	1950-2005	8
05320500	Le Sueur River Near Rapidan, MN	1950-2005	8
05325000	Minnesota River at Mankato, MN	1930-2005	4,5,7,8
05330000	Minnesota River Near Jordan, MN	1935-2005	4,5,7,8
Red River of the North Basin			
05054000	Red River of the North at Fargo, ND	1902-2005	1
05062000	Buffalo River Near Dilworth, MN	1932-2005	1
05079000	Red Lake River at Crookston, MN	1902-2005	1
05082500	Red River of the North Grand Forks, ND	1904-2005	1
05092000	Red River of the North at Drayton, ND	1942-2005	1
05104500	Roseau River Near Milung, MN	1947-2005	
Rainy River Basin			
05127500	Basswood River Near Winton, MN	1939-2005	3
05128000	Namakan River at outlet of Lac La Croix	1923-2005	3
05130500	Sturgeon River Near Chisholm, MN	1943-2005	3
05131500	Little Fork River at Littlefork, MN	1929-2005	2
05133500	Rainy River at Manitou Rapids, MN	1929-2005	2

USGS Gauging Station No.	Stream/River Name	Record Length Used	Climate Division
Tributaries to Lake Superior			
04010500	Pigeon River at Middle Falls	1924-2005	3
04024000	St. Louis River at Scanlon, MN	1908-2005	3
Upper Mississippi River Basin			
05211000	Mississippi River at Grand Rapids, MN	1912-2005	2
05227500	Mississippi River at Aitkin, MN	1946-2005	2,6
05280000	Crow River at Rockford, MN	1935-2005	5
05286000	Rum River Near St. Francis, MN	1934-2005	6
05288500	Mississippi River Near Anoka, MN	1932-2005	2,5,6
05331000	Mississippi River at St. Paul, MN	1907-2005	2,4,5,6,7,8
05340500	St. Croix River at St. Croix Falls, WI	1910-2005	6, WI1
05344500	Mississippi River at Prescott, WI	1929-2005	2,4,5,6,7,8
05378500	Mississippi River at Winona, MN	1929-2005	2,4,5,6,7,8,9
05457000	Cedar River Near Austin, MN	1945-2005	9
05476000	Des Moines River at Jackson, MN	1936-2005	7

3.2. Selection of Time Periods for Analysis

The analysis of historical stream flow records described in this report focused on two twenty-year time periods, 1946-1965 and 1986-2005, for each station. These time periods were selected for comparison to determine if stream flow conditions had changed over time. A trend analysis over the total record lengths was previously conducted by Novotny and Stefan (2006; 2007). 1946 was selected as the starting year because continuous data for 33 of the 36 stream gauging stations were available after 1946. By selecting 1946, we did not include the very dry 1920-1940 period in our analysis (Figure 3.1).

Annual average precipitation and annual average temperatures over the 1895-2007 period are shown in Figure 3.1(http://www.wrcc.dri.edu/spi/divplot1map.html). The values plotted are statewide averages. Both climate parameters showed an upward linear trend over this period of record. The rates of increase were 0.028 in/yr (0.71 mm/yr) and 0.014 ^{o}F/yr (0.008 ^{o}C /yr), respectively. The average annual precipitation was 26.1 in (662 mm) for the 1946-2005 period, compared to 28.0 in (710 mm) for the 1986-2005 period. The annual average temperature for the 1946-1965 and 1986-2005 periods were 40.64 ^{o}F (4.82 ^{o}C) and 41.94 ^{o}F (5.52 ^{o}C), respectively. In other words, the 1986-2005 period was slightly warmer and wetter than the 1946-2005 period.

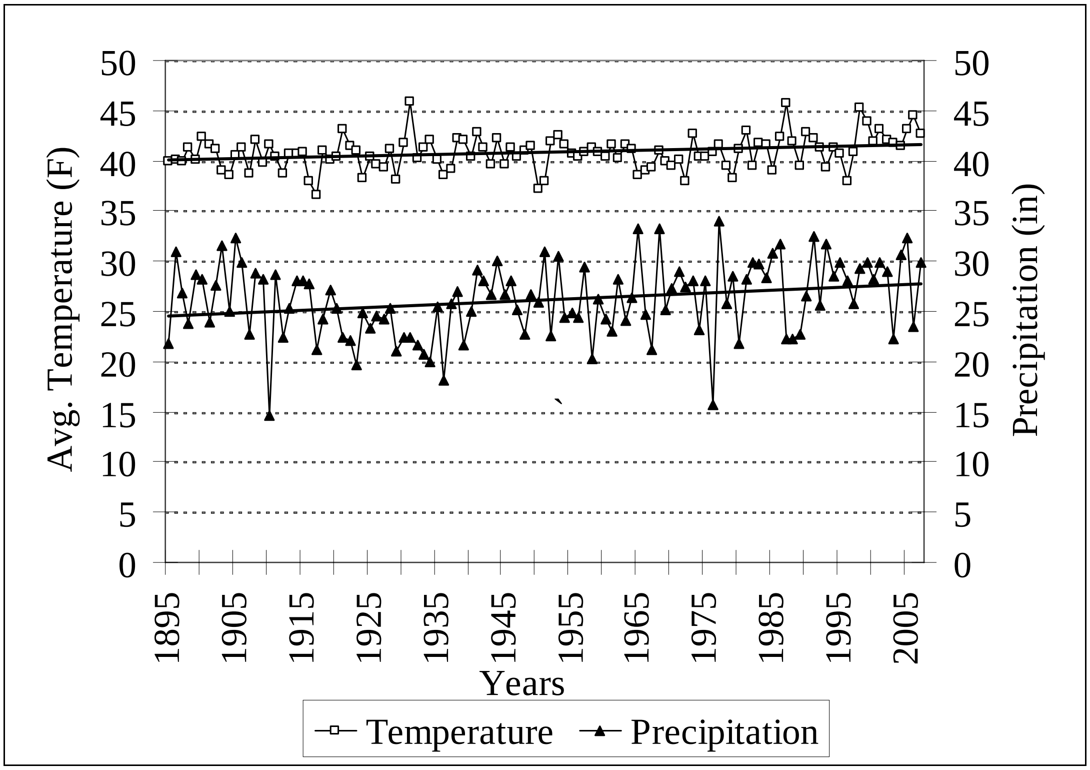

Figure 3.1. Annual average temperature and annual precipitation in Minnesota for the 1895-2007 period.

3.3. Determination of Flow-Duration Curves (FDCs)

In a flow-duration curve (FDC), stream discharge is plotted as a function of exceedence probability (percent of the time a certain magnitude of discharge is exceeded). A FDC provides a graphical representation of cumulative frequency of discharge (Chow, 1964; Mosley and McKerchar, 1992). Flow-duration curves (FDCs) were prepared for the daily average stream flow data.

Stream flow distributions depend strongly on precipitation and basin (watershed) characteristics. An FDC can therefore be used to detect changes in precipitation or land use in a river basin. FDCs have been used in a wide range of applications including stream water quality management, hydropower feasibility studies, and in-stream low flow requirement determination (Smakhtin, 2001; Vogel and Fennessey, 1995). Lane et al. (2005) evaluated the response of FDCs to land-use changes (i.e., deforestation). FDCs have also been used to evaluate the effects of different climate scenarios on stream flow (e.g., Gosain et al., 2006; Wilby et al., 1994).

To prepare FDCs, we first sorted the flow data from the highest to the lowest and determined the order (m) of each flow. Probability of exceedence (P) was found using Equation 1, where N is the total number of data points. FDCs were prepared by plotting the probability of exceedence on the horizontal axis and stream flow on a logarithmic scale on the vertical axis.

$$P = \frac{m}{N+1} \times 100 \tag{1}$$

FDCs provide a visual and quantitative representation of stream flows. Index values can be extracted from FDCs to evaluate the similarities or differences in the shape of the FDC curves for two time periods. For example, the discharge (Q50) at which flows are exceeded 50% of the time denotes the median flow. According to Pyrce (2004), the Q95 and Q90 flows are most often used as low flow indices. Smakhtin (2001) gave the “design” low flow in the Q70 to Q99 range. Another low flow index is the ratio (Q20/Q90). This index is called “flow-duration ratio” and represents the slope of the straight line portion of a FDC (Arihood and Glatfelter, 1991). This slope integrates several factors affecting low flow characteristics such as geology, climate, land use, and soils (Arihood and Glatfelter, 1991). A low (Q20/Q90) value is an indicator of high base flows that cause stream discharge to become stable. A high (Q20/Q90) value indicates a “flashy stream”, i.e. where flows are more variable. The base flow contribution to streams can be evaluated by the ratio (Q90/Q50) (Gordon et al., 2004). The opposite ratio is an indicator of variability of low flows (Smakhtin, 2001). Q5 and Q10 can be used as high flow indices (Pyrce, 2004).

In this study we used Q95 and Q90 to evaluate changes in low flow characteristics and Q5 and Q10 for high flow characteristics of streams. We also calculated the ratios Q90/Q50, Q50/Q90, Q20/Q90, and Q10/Q50 to evaluate the changes in contributions from base flow and variability of low flows.

3.4. Analysis of Extreme Flow Occurrences in Time

The temporal distribution of extreme events (annual peak flows and annual 7-day average low flows) over the period of record was examined using a sorting/ranking method explained by Johnson and Stefan (2006). In this approach, peak flows are sorted from the highest to the lowest, and low flows from the lowest to the highest. The years when the highest 3-, 5-, and 10-year events occurred are marked against time. It becomes thus apparent if extreme flow events are distributed uniformly over the period of record, of if they occurred more frequently in an earlier or a later period of the record. This procedure worked well, but did not for the 7-day (average) low flow because in several tributaries theses flows were zero. Therefore low-flows were ranked also from the highest to the lowest – just as peak flows and plotted on a time line without loss of information. The plot still showed if there was a shift in time in the low flow distributions – not the lowest low flows, but the highest.

To determine if a shift had occurred we determined the number of extreme events expected in a period, e.g., 1986-2005. If the events were distributed uniformly over the entire period of record (1946-2005), for example, 1 out of 3 highest or 3 of the 9 highest events that occurred in the 1946-2005 period would be expected in the 1986-2005 period. We compared the expected number with the actual number of events observed. By this method, we were able to examine if the extreme events were distributed uniformly or aggregated within a specific time period.

3.5. Flood Frequency Analysis (FFA)

A flood frequency analysis (FFA) was conducted for the 36 gauging stations by using the data from 1946-1965 and 1986-2005. The purpose was to identify changes in the magnitude of floods. Annual peak flow data were used in the analysis.

In FFA, a flood frequency curve is developed by fitting historical flood data to a statistical distribution function. Flood values corresponding to different return periods can then be estimated by using the fitted distribution function. Floods can be fitted to Log normal distributions, Pearson type 3 distributions, Log- Pearson type 3 distributions, and extreme value distributions (Stedinger et al., 1992). We followed the guidelines in Bulletin 17B by the U.S. Geological Survey (Interagency Advisory Committee On Water Data, 1982) and used the Log-Pearson Type 3 distribution. According to this method, a log-transformation is applied to a minimum of 10 years of annual flood data to determine the appropriate frequency distribution. The Log-Pearson Type 3 distribution is given in its general form by Equation 2.

$$\log Q = \mu_{\log Q} + K\sigma_{\log Q} \tag{2}$$

In Equation 2, Q = peak annual stream discharge (cfs), and μ and σ are mean and standard deviation of log transformed annual flood flow (cfs) data. K is a frequency factor, which is a function of the selected return period skew coefficient of the frequency distribution; K can be found in a table given in Bulletin 17B.

Statistical parameters (i.e., mean, standard deviation, and skew coefficient (C_s)) can be obtained from the stream flow data using Equations 3 to 5. n is the number of years of data included in the analysis.

$$\mu_{\log Q} = \frac{\sum Q}{n} \tag{3}$$

$$\sigma_{\log Q} = \sqrt{\frac{\sum(\log Q - \mu_{\log Q})^2}{n-1}} \tag{4}$$

$$C_s = \frac{n\sum(\log Q - \mu_{\log Q})^3}{(n-1)(n-2)(\sigma \log Q)^3} \tag{5}$$

When a small number of data is used, the error in the estimation of the skew coefficient increases. To solve this problem, Bulletin 17B recommends the use of a weighted skew coefficient (C_w) that is obtained by weighting the skew coefficient obtained from the station record (C_s) with a generalized skew coefficient (C_g) obtained by using information from nearby sites (Equation 6). In this study, we used the generalized skew coefficients estimated by the U.S. Geological Survey for Minnesota (Lorenz, 1997).

$$C_w = WC_s + (1-W)C_g \tag{6}$$

In Equation 6, W is a weighting factor obtained using equation 7, where V_s denotes the variance of C_s and V_g denotes to variance of C_g..

$$W = \frac{V_s}{V_s + V_g} \tag{7}$$

V_s can be calculated by equation 8.

$$V_s = 10^{[A-B[\log(n/10)]]} \tag{8}$$

where $\quad A = -0.33 + 0.08|C_s| \quad if \quad |Cs| \le 0.90$

$$A = -0.52 + 0.30|C_s| \qquad if \qquad |Cs| > 0.90$$

$$B = 0.94 - 0.26|C_s| \qquad if \qquad |Cs| \leq 1.50$$

$$B = 0.55 \qquad\qquad if \qquad |Cs| > 1.50$$

3.6. Low Flow Frequency Analysis

A low flow frequency analysis was conducted using the data from the 1946-1965 and 1986-2005 periods to determine the changes in 7-day low flow values. One of the most widely used low flow indices in the U.S. is 7-day 10-year low flow or 7Q10. It refers to the lowest average flow that occurs for a 7-day period with 10 year recurrence interval. In this study we calculated the changes not only in 7Q10 but also 7-day low flows with 2, 5, and 20 year recurrence intervals.

7Q2, 7Q5, 7Q10, and 7Q20 values were determined using a computer program, DFLOW 3.1b, which was developed and is distributed by the U.S. Environmental Protection Agency (available at http://www.epa.gov/waterscience/models/dflow/) to estimate flows for low flow water quality analysis. This computer program uses the principles explained in the USGS Surface Water Branch Technical Memorandum NO. 79.06, "PROGRAMS AND PLANS - Low-Flow Programs (available at http://water.usgs.gov/admin/memo/SW/sw79.06.html), which recommends fitting low flow data to a Log-Pearson Type III distribution. The data used by the program are mean daily flows. However, these data are converted to annual 7-day average low flow values by the program before fitting.

4. RESULTS - FLOW DURATION CURVES (FDCs)

4.1. FDCs for the Minnesota River Basin

The flow duration curves (FDCs) for daily data from 12 stream gauging stations in the Minnesota River Basin showed a substantial shift to higher stream flows from 1946 -1965 to 1986-2005. (Figure 4.1a and b). All 12 stations consistently had higher flows in the range of Q5 to Q90 in the 1986 -2005 period (Q5 are high flows that are exceeded 5% of the time, Q90 are low flows exceeded 90% of the time). Q95 showed an increase at 11 of the 12 stations between the two periods. Median flow (Q50) during the 1986 -2005 period increased on average by 203% (range from 68% to 300%) relative to the median flow during the 1946 -1965 period (Figure 4.2

and Table 4.1). In other words, the average median flow in the Minnesota River Basin in the 1986 -2005 period was about three times (303%) of the average median flow in the 1946 -1965 period. The largest increases in flows were recorded in the Redwood River and the Chippewa River, both tributaries of the Minnesota River (Figure 4.1a).

To increase the resolution for the extreme high flows, e.g., flows that occur during 10 days in 20 years (probability of occurrence = 0.00137), log-log plots of the FDCs were generated (Appendix A. Figures A.1a and b). To increase the resolution for extreme low flows, exceedence probabilities (p) have to be converted to non-exceedence probabilities (1 – p). The resulting plots are given in Appendix B as Figures B.1a and b.

The slopes of the straight-line portions of the FDCs for the 12 gauging stations did not show any consistent change. The Q20/Q90 ratios changed on average by only -3% from the 1946-1965 period to the 1986-2005 period, but the changes for individual gauging stations ranged from -72% to 48% (Table 4.1). This indicates that the relationship between base flow and high (quick) flow at most stations was not consistent from 1946 to 2005, although the average change for all 12 stations was nearly zero. Similarly, the base flow ratio to mean stream flow as measured by the (Q90/Q50) ratio varied from -48% to 182% between the earlier and the latter time periods, but the average for all 12 stations was 0% (Table 4.1).

Q95 and Q90 are low flow indices. Q95 increased in the more recent 20-year period for all stations with one exception (Minnesota River at Montevideo). On average Q95 increased to 148% (range from -16% to 390%) (Table 4.2). Similarly, Q90 showed an average increase to 187% (range from 34% to 418%) at the 12 gauging stations. Overall, the low flows became higher and more variable (Table 4.1).

Q5 and Q10 are indicators of high flows including floods. Both Q5 and Q10 were higher in the latter period. The average rise in Q5 was 79% (range of 62 to 97%) and the average rise in Q10 was 100% (in the range of 58 to 142%) (Table 4.1). Change in flow (%) in Table 4.1 is the difference in flow between the 1986 -2005 period and the 1946-1965 period divided by the flow in the 1946 -1965 period. These numbers show that the changes in high flows in the Minnesota River Basin were not as large as the changes in low flows.

In summary, the FDC indices for the Minnesota River Basin suggest that in the 60-year period from 1946 - 2005 low flows have, on average, increased about 150%, median flows have increased, on average, about 200%, and high flows have increased on average, about 100%. Deviations from these averages are, however, very large for individual stream gauging sites. Specifically, high flows have increased in the upper reaches of the Minnesota River (Figure 4.1a), but have decreased in the lower reaches (Figure 4.1b).

Table 4.1. Change in FDC index values in the Minnesota River Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change(%)	Maximum Change(%)
Q5	79	10	62	97
Q10	100	28	58	142
Q50	203	75	68	300
Q90	187	143	34	418
Q95	148	153	-16	390
Q20/Q90	-3	39	-72	48
Q90/Q50	0	65	-48	182
Q50/Q90	27	52	-65	92

Note: Change in flow (%) is the difference in flow between the 1986-2005 period and the 1946-1965 period divided by the flow in the 1946-1965 period.

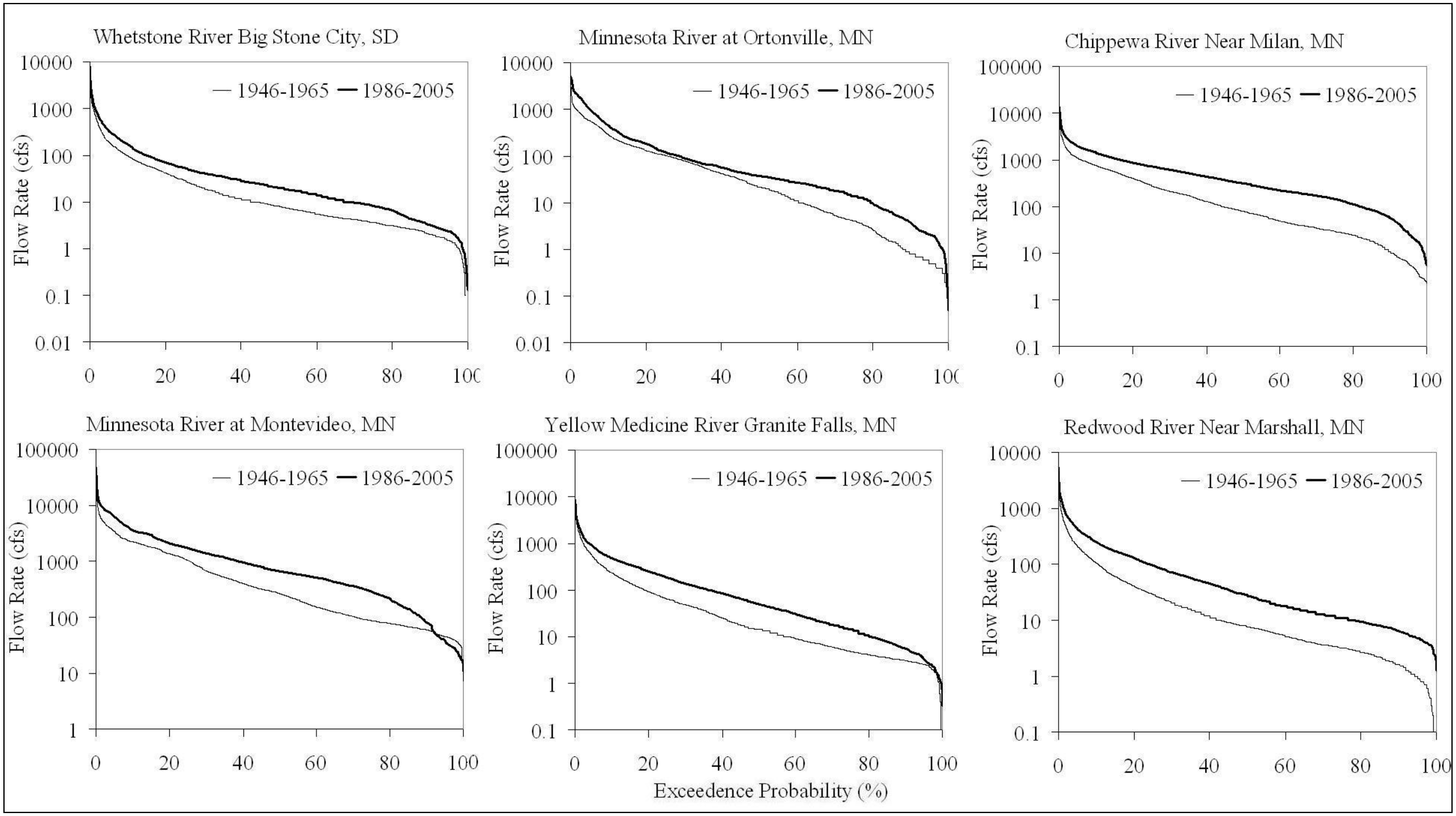

Figure 4.1a. FDCs at stream gauging stations in the Minnesota River Basin for the periods 1946 -1965 and 1986 -2005.

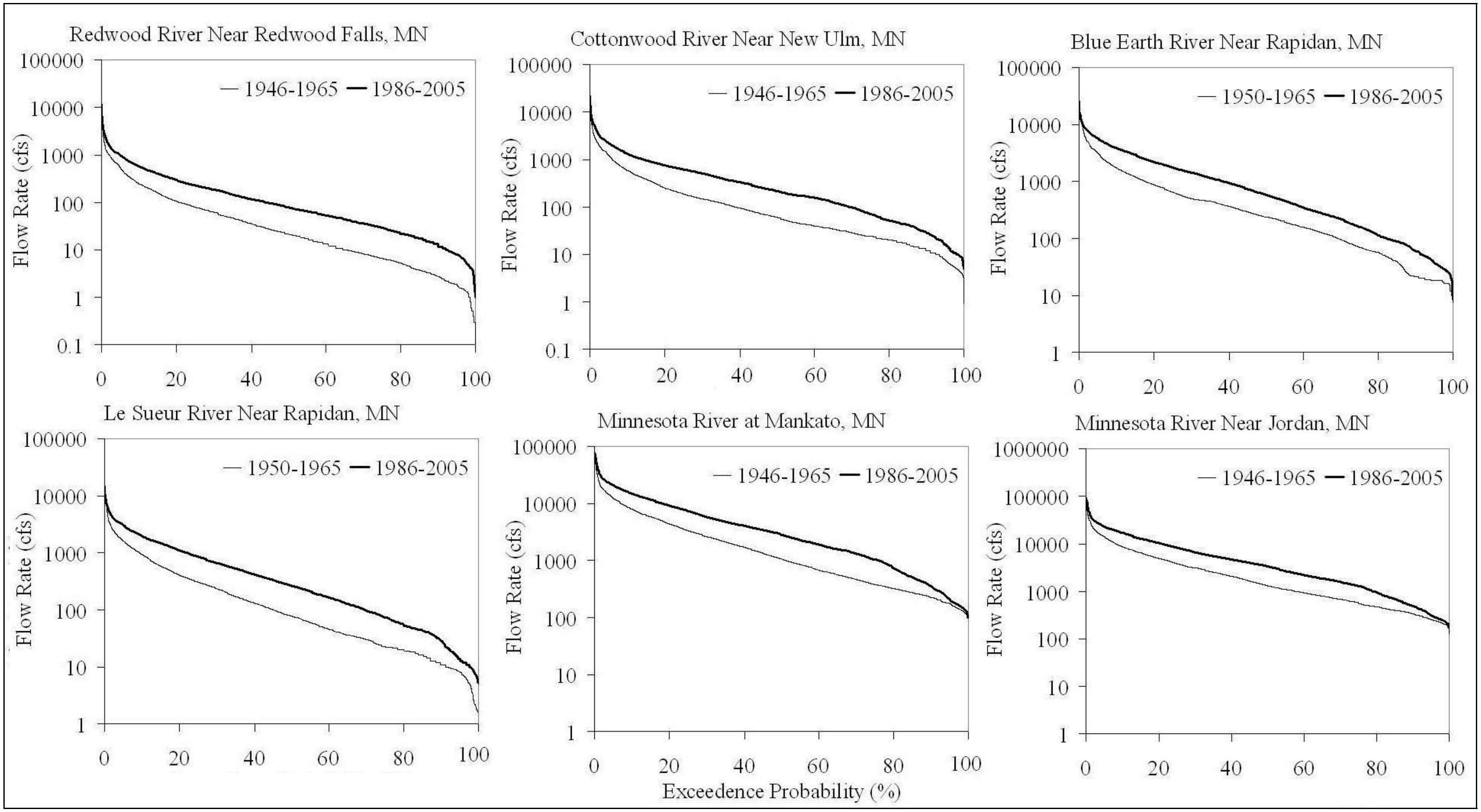

Figure 4.1b. FDCs at stream gauging stations in the Minnesota River Basin for the periods 1946 -1965 and 1986 -2005.

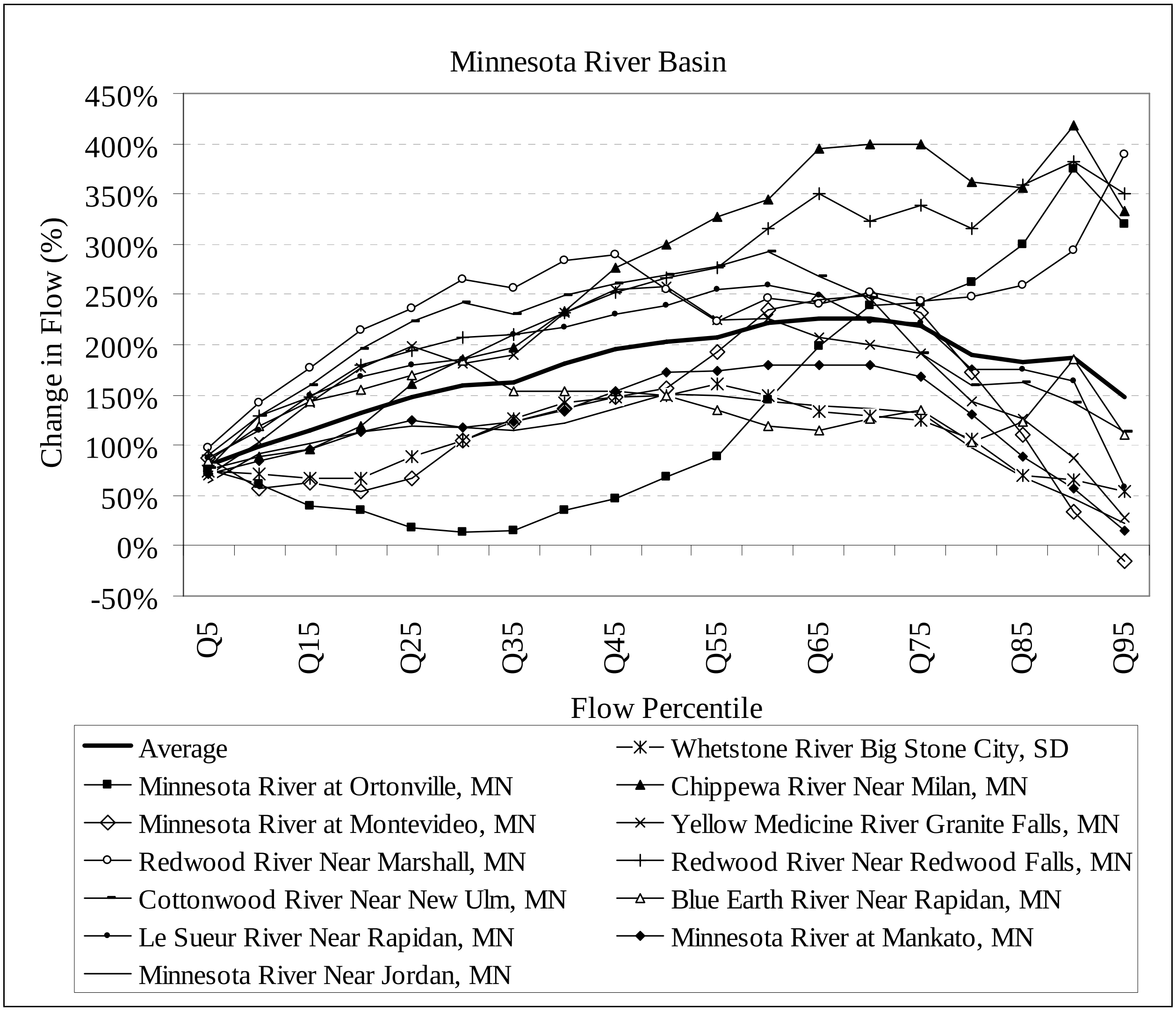

Figure 4.2. Change in flows at stream gauging stations in the Minnesota River Basin from the 1946 -1965 period to the 1986 -2005 period. Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

4.2. FDCs for the Red River of the North Basin

We analyzed stream flow data from 6 gauging stations in the Red River of the North Basin. High and medium flows in the FDCs (Q5-Q75) for all stations (Figures 4.3 and 4.4) were higher in the 1986 - 2005 period compared to the 1946 -1965 period. Low flows in the FDCs showed an increase at two of the stations (Red River of the North in Fargo and Buffalo River near Dilworth) and decrease at the four other stations in the latter period. Median flow in the 1986-2005 period was on average 78% (range from 14% to 141%) higher than the median flow in the 1946-1965 period (Table 4.2). The highest increases in medium to low flows were observed at the Buffalo River near Dilworth, MN and the highest increases in high flows were observed in the Red River of the North at Fargo, ND (Figure 4.4).

The changes in observed low flow indices, Q95 and Q90, varied over a large range for the 6 stations and the average changes for the basin were low (Table 4.2). Q95 varied in the range of -92% to 50% with an average of 0% and Q90 varied in the range of -77% to 70% with an average of 6%. The change in Q20/Q90 ratio was 98% (range from 5% to 366%) and the change in the Q90/Q50 ratio was -43% (range from -79% to -29%). The low flow results were inconsistent because two of the stations (Red River near Crookston and Roseau River Near Milung) showed a distinctly different behavior from the others (Figure 4.4).

High flows in the Red River of the North Basin shifted upwards at all stations. Q5 varied in the range of 13% to 86% with an average of 55% and Q10 varied in the range of 15% to 110% with an average of 62%.

In summary, the FDC indices for the Red River of the North Basin suggest that in the 60-year period from 1946 to 2005 high flows have, on average, increased about 60%, and median flows have increased about 80%. Low flows at 6 stream gauging stations showed inconsistent behavior. It must be considered that 6 individual stream gauging stations provide a small data base, and standard deviations from averages are large.

Table 4.2. Change in FDC index values in the Red River of the North Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Chang(%)	Maximum Change(%)
Q5	55	33	13	86
Q10	62	38	17	110
Q50	78	45	14	141
Q90	6	49	-77	71
Q95	0	52	-92	58
Q20/Q90	98	133	5	366
Q90/Q50	-43	18	-79	-29
Q50/Q90	112	134	40	385

Note; Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

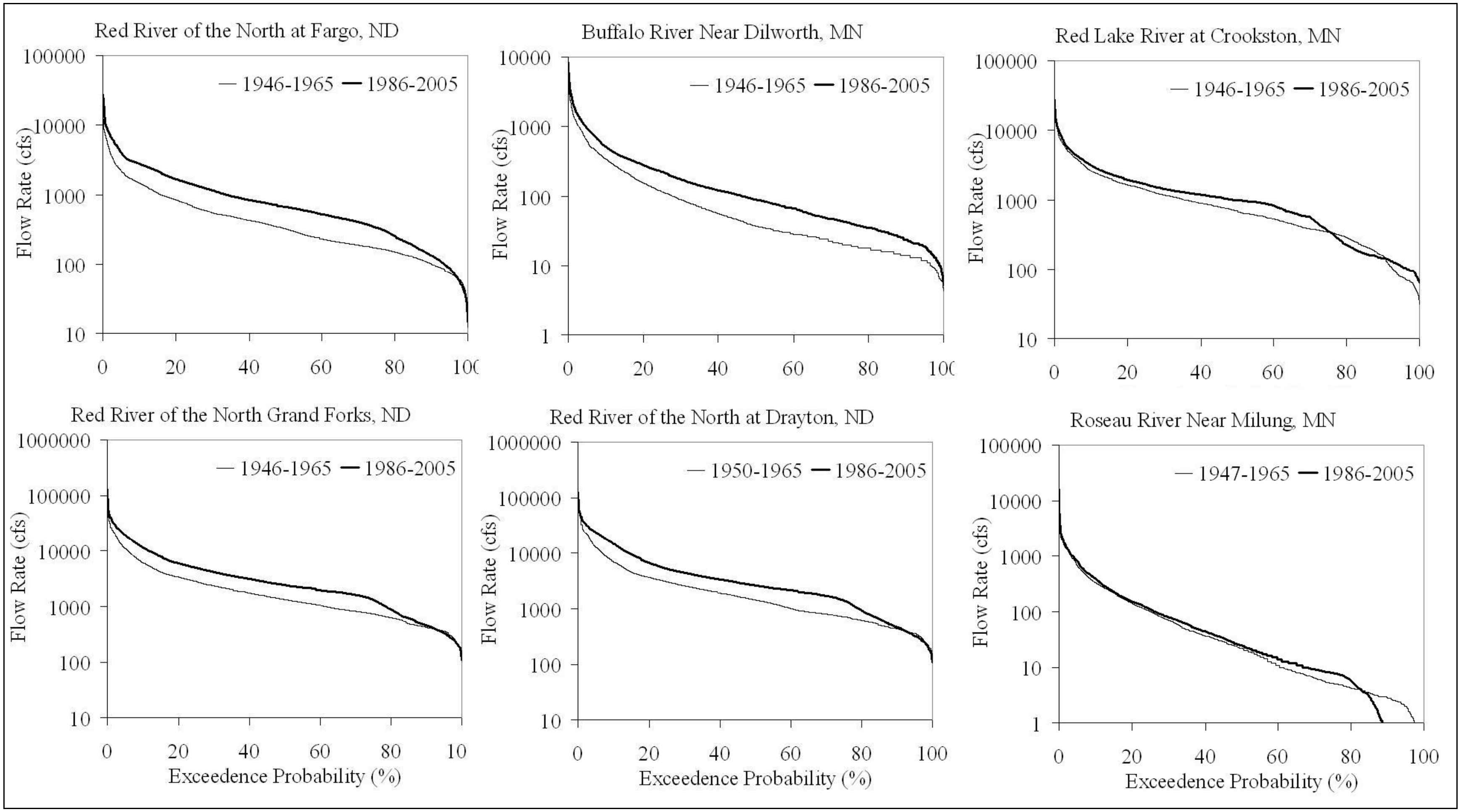

Figure 4.3. FDCs at stream gauging stations in the Red River of the North Basin for the periods 1946 -1965 and 1986 -2005.

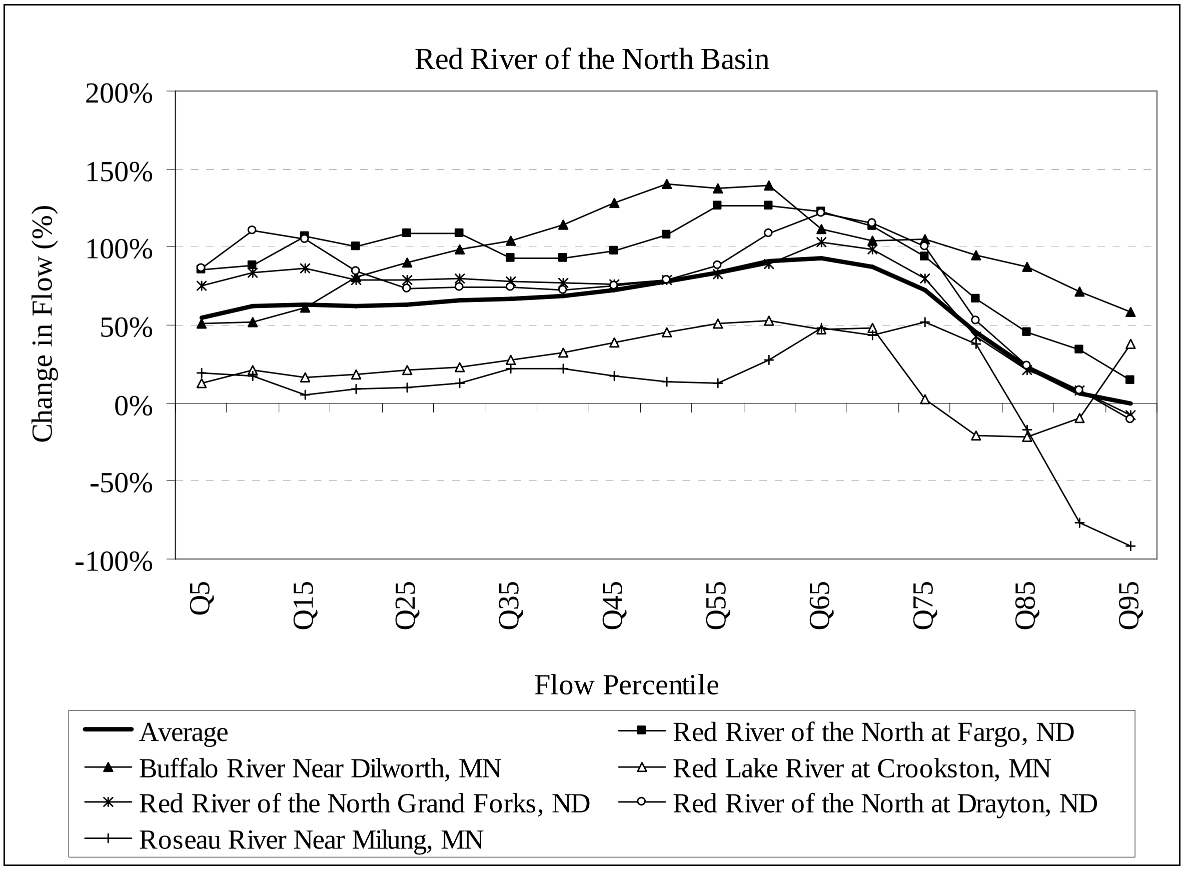

Figure 4.4. Change in flows between Q5 and Q95 at stream gauging stations in the Red River of the North Basin from the 1946 -1965 period to the 1986 -2005 period. Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

4.3. FDCs for the Rainy River Basin

Data from 5 gauging stations were analyzed in the Rainy River Basin. Medium and low flows (corresponding to the Q25-Q75 and Q75-Q95 ranges, respectively) increased, and high flows decreased at most of the stations between the 1946 -1965 and 1986 -2005 periods (Figures 4.5 and 4.6). An exception was the Rainy River near Manitou Rapids, where a downward shift was observed in the Q50-Q95 range, and an upward shift was observed in the Q5-Q50 range. Another exception was the Namakan River at the outlet of Lac La Croix, where decreases were observed in the Q5-Q55 and the Q95 flows, but increases were observed in other flows. The magnitudes of the shifts in the Rainy River Basin were not as large as those observed in the Minnesota River Basin and Red River of the North Basin. Median flow in the 1986 -2005 period was on average 22% (range from -4% to 56%) higher that the median flow in the 1946 -1965 period (Table 4.3). The largest increases in flows were observed in the Sturgeon River near Chisholm, MN and Little Fork River near Littlefork, MN (Figure 4.6).

Low flows, Q95 and Q90, had increased on average by 25% (range of -7% to 75%) and 23% (range of -17% to 73%), respectively, from 1946 - 1965 to 1986 - 2005. Changes in the flow variability index (Q50/Q90) were in the range of -10% to 16% with a basin average of 0%, and changes in the high to low flow ratio (Q20/Q90) were in the range of -35% to 22% with an average of -13% from 1946-1965 to 1986-2005. These numbers indicate that changes in low flow in the Rainy River Basin are far from uniform for the entire basin. Changes in high flows in the Rainy River Basin between 1946 -1965 and 1986 -2005 were low and negative. The average decreases in Q5 and Q10 were 9% (range from -14% to 5%) and 1% (range from -5% to 8%), respectively.

In summary, from 1946 to 2005, the low flows and median flows in the Rainy River Basin increased about 25%, while high flows decreased about 5%. Because the number of stations analyzed in the Rainy River Basin was only five and two of these stations showed patterns different from the others, the results are not conclusive.

Table 4.3. Change in FDC index values in the Rainy River Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change (%)	Maximum Change (%)
Q5	-9	8	-14	5
Q10	-1	5	-5	8
Q50	22	30	-4	56
Q90	23	36	-17	73
Q95	25	35	-7	75
Q20/Q90	-13	22	-35	22
Q90/Q50	1	11	-14	11
Q50/Q90	0	11	-10	16

Note: Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

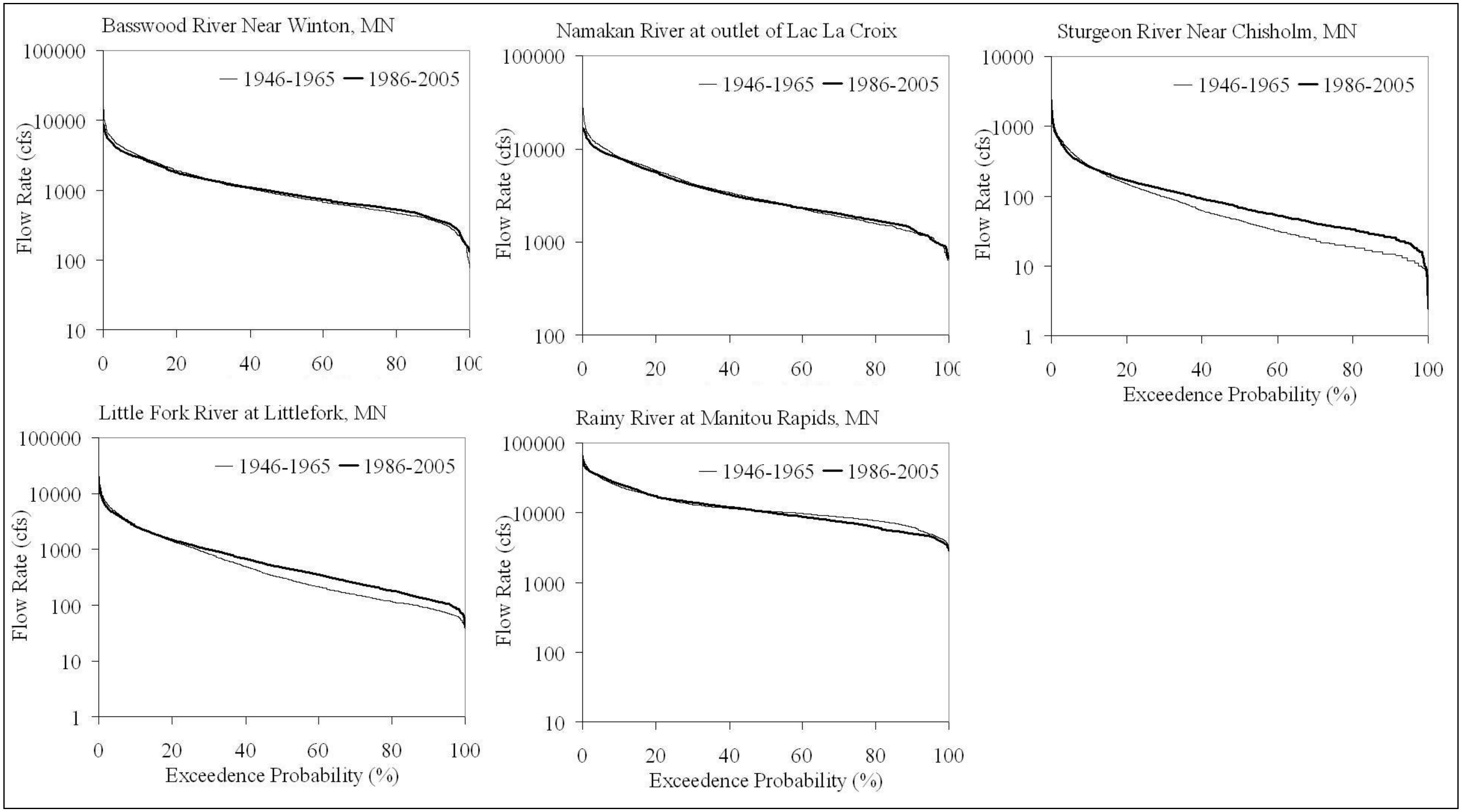

Figure 4.5. FDCs at stream gauging stations in the Rainy River Basin for the periods 1946-1965 and 1986-2005.

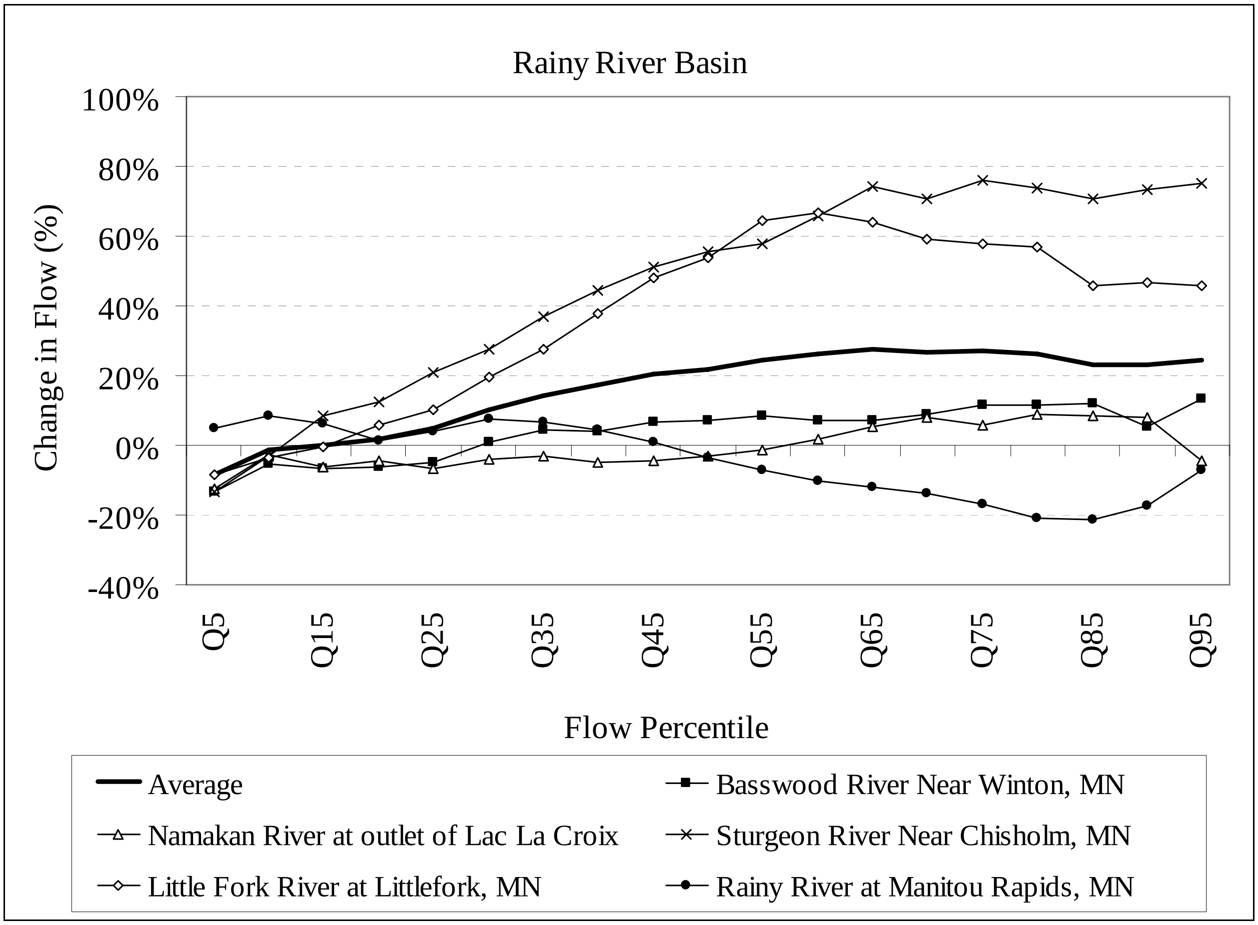

Figure 4.6. Change in flows between Q5 and Q95 at stream gauging stations in the Rainy River Basin from the 1946 -1965 period to the 1986-2005 period. Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

4.4. FDCs for Tributary Streams to Lake Superior

Data from 2 gauging station on tributaries to Lake Superior were analyzed. At both stations, medium flow portions of FDCs (Q25-Q75) showed an upward shift from 1946 -1965 to 1985 -2005, indicating that medium flows increased. The average increase in median flows was 13% (range from 11% to 15%) (Table 4.4).

Very low flows (i.e., Q95) showed a decrease in both streams between the two periods. The average decrease observed at the two stations was 19% (range from -29% to 8%). Q90 decreased by 9% in the Pigeon River at Middle Falls, MN and increased by 6% in the St. Louis River at Scanlon, MN from 1946 -1965 to 1986 -2005. The variability of low flows increased at both stations in the 1986 -2005 period by 15%. The Q20/Q90 index, which is a ratio of high flow to quick flow, increased by 12% and 17% at the two stations. The Q90/Q50 index, which indicates the base flow fraction of mean stream flow decreased by 18% and 8%. The results of the Q20/Q90 and Q90/Q50 indices are opposite to each other. Very high flows (i.e., Q5) decreased in both streams (range of 5% to 6%). Q10 decreased in the Pigeon River at Middle Falls, MN by 3%, but increased in St. Louis River at Scanlon by 5%.

In summary, the changes observed in flows from 1946 to 2005 were not consistent for the two stream gauging sites. The changes were, however, smaller than the changes observed in other river basins (about 10 to 20%).

Table 4.4. Change in FDC index values in tributaries (St. Louis River and Pigeon River) to Lake Superior from the 1946 -1965 period to the 1986 -2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change(%)	Maximum Change(%)
Q5	-5	0	-6	-5
Q10	1	5	-3	5
Q50	13	3	11	15
Q90	-2	10	-9	6
Q95	-19	14	-29	-8
Q20/Q90	15	4	12	17
Q90/Q50	-13	7	-18	-8
Q50/Q90	15	9	9	22

Note: Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

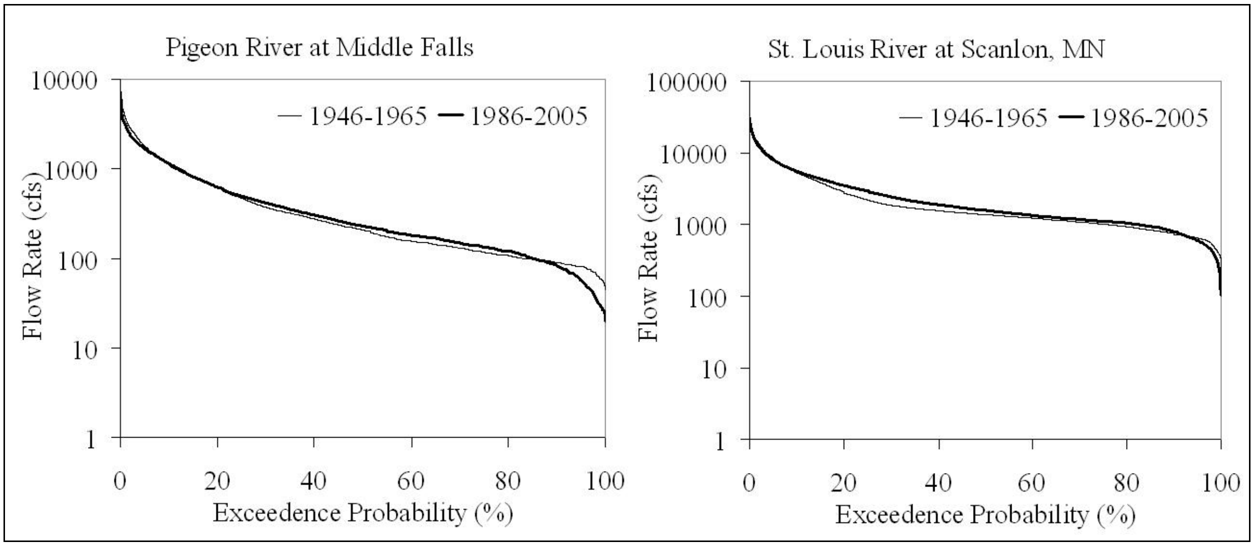

Figure 4.7. FDCs at stream gauging stations in tributaries to Lake Superior for the periods 1946 -1965 and 1986 -2005.

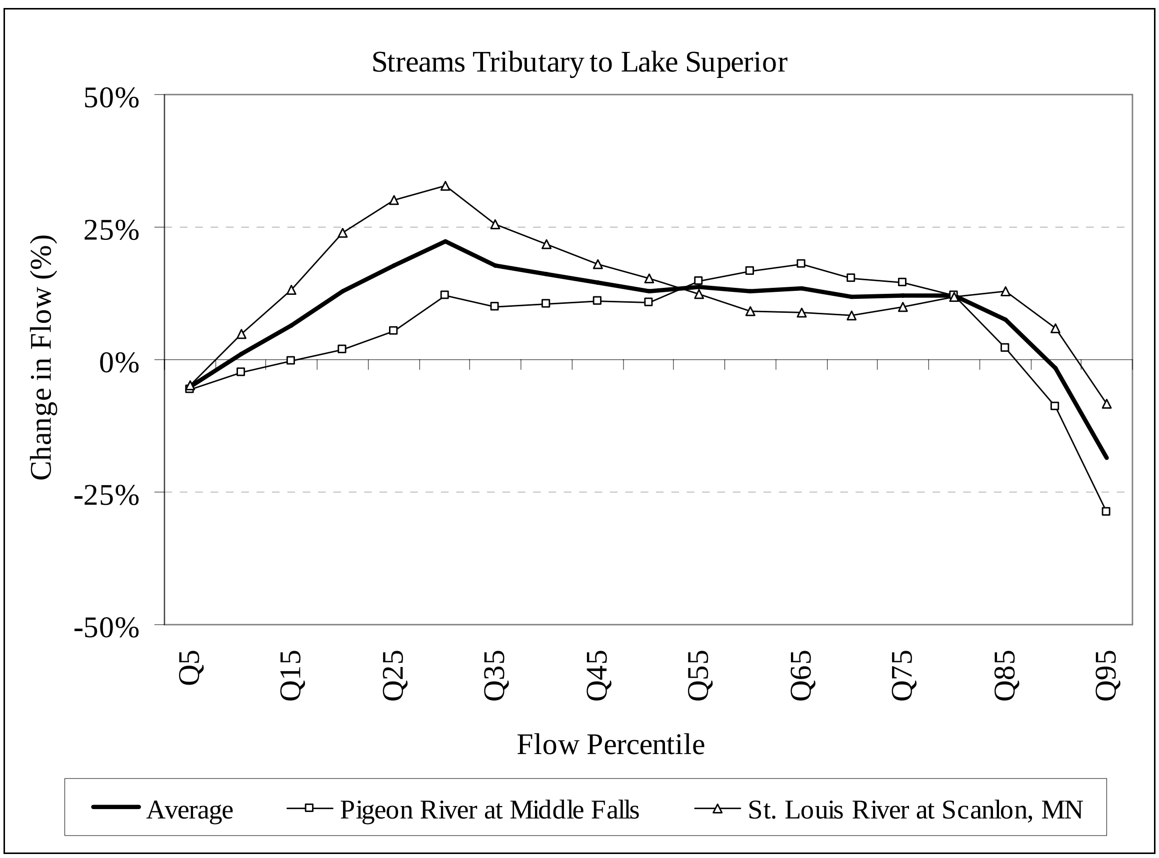

Figure 4.8. Change in flows at stream gauging stations in tributaries to Lake Superior from the 1946 -1965 period to the 1986 -2005 period. Change in flow (%) is the difference in flow

between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 - 1965 period.

4.5. FDCs for the Upper Mississippi River Basin

Data from 11 gauging stations in the Upper Mississippi River Basin were analyzed. The FDCs in the range of Q15 - Q95 made an upward shift for all stations from the 1946-1965 to the 1986-2005 period (Figures 4.9a and b). Median flow in the 1986-2005 period was on average 82% (range from 16% to 259%) higher than the median flow in the 1946-1965 period (Table 4.5). The largest increases in flows were observed in the Des Moines River at Jackson, MN; the Crow River at Rockford MN, and the Cedar River near Austin MN (Figure 4.10).

Low flow indices, Q95 and Q90, increased by 66% (range from 13% to 358%) and 435% (range from 5% to 4500%), respectively, in the latter period. The wide range of changes observed at the stations in the Upper Mississippi River Basin was caused by the changes in three of the stations, which have patterns not similar to the patterns observed in the other 8 stations. These stations were in the Cedar River near Austin, MN; the Crow River at Rockford, MN; and the Des Moines River at Jackson, MN. On average the variability of low flow (Q50/Q90) changed by 14% (range from -22% to 53%) between the 1946-1965 and 1986-2005 periods. Average changes in the Q20/Q90 and Q90/Q50 indices were 2% and -9%.

Q5 and Q10 made upward shifts for all stations except two. The exceptions were the Mississippi River at Aitkin, MN and the St. Croix River at St. Croix Falls, WI. The average increase in Q5 was 29% (range from -13% to 129%) and the average increase in Q10 was 41% (range from
-3% to 154%).

In summary, from 1946 to 2005, high flows in the Upper Mississippi River Basin increased about 35%, medium flows increased about 80%, and low flows increased about 60% (with one exception, the Des Moines River at Jackson, MN).

Table 4.5. Change in FDC index values in the Upper Mississippi River Basin from the 1946 - 1965 period to the 1986 - 2005 period.

Flow Percentile	Average Change (%)	Std. Dev. of Change (%)	Minimum Change(%)	Maximum Change (%)
Q5	29	43	-13	127
Q10	41	52	-3	154
Q50	82	85	16	259
Q90	66	102	13	358
Q95	435	1348	5	4500
Q20/Q90	2	24	-37	58
Q90/Q50	-9	19	-35	28
Q50/Q90	14	22	-22	53

Note; Change in flow (%) is the difference in flow between the 1986 -2005 period and the 1946 -1965 period divided by the flow in the 1946 -1965 period.

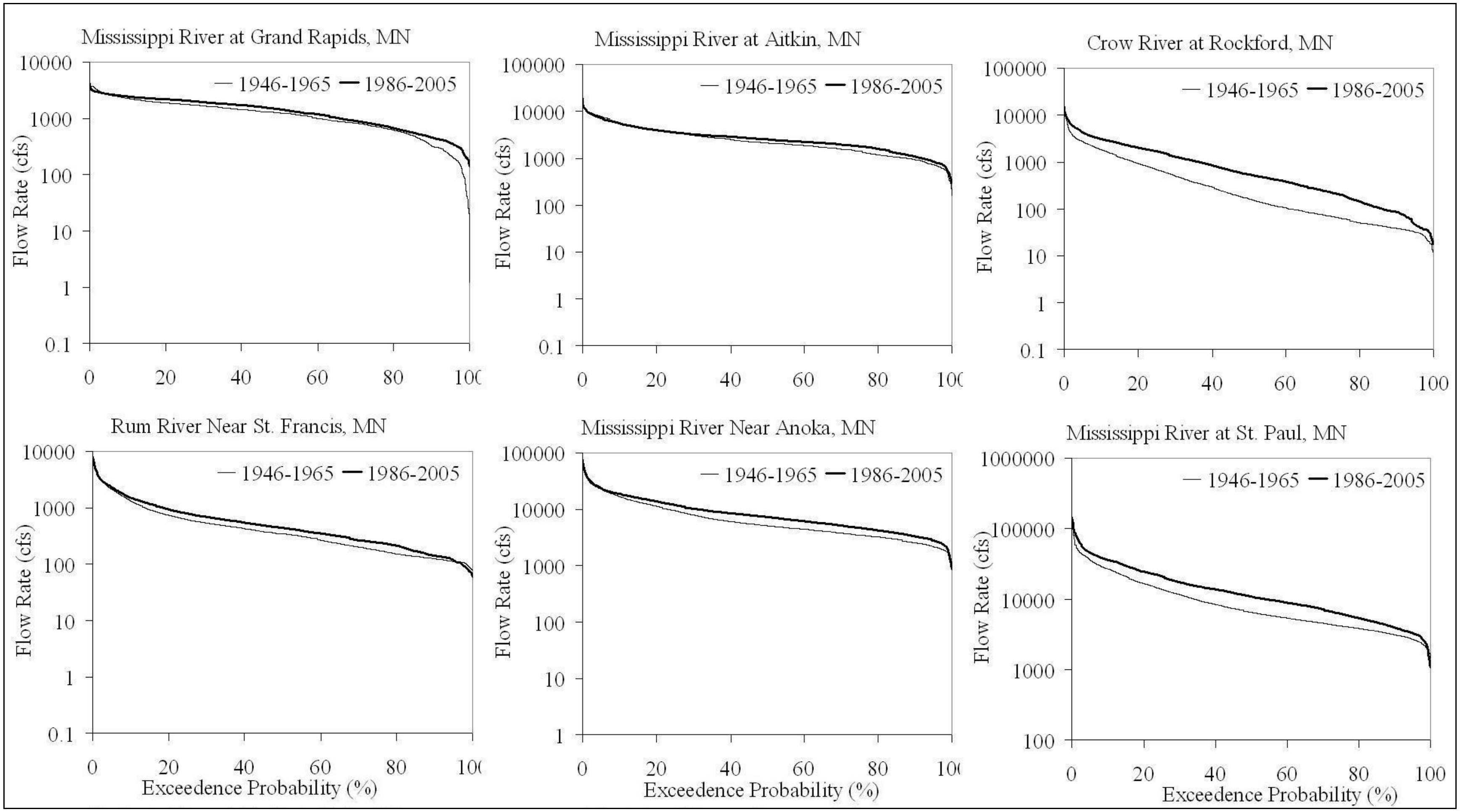

Figure 4.9a. FDCs at stream gauging stations in the Upper Mississippi River Basin for the periods 1946 -1965 and 1986 -2005.

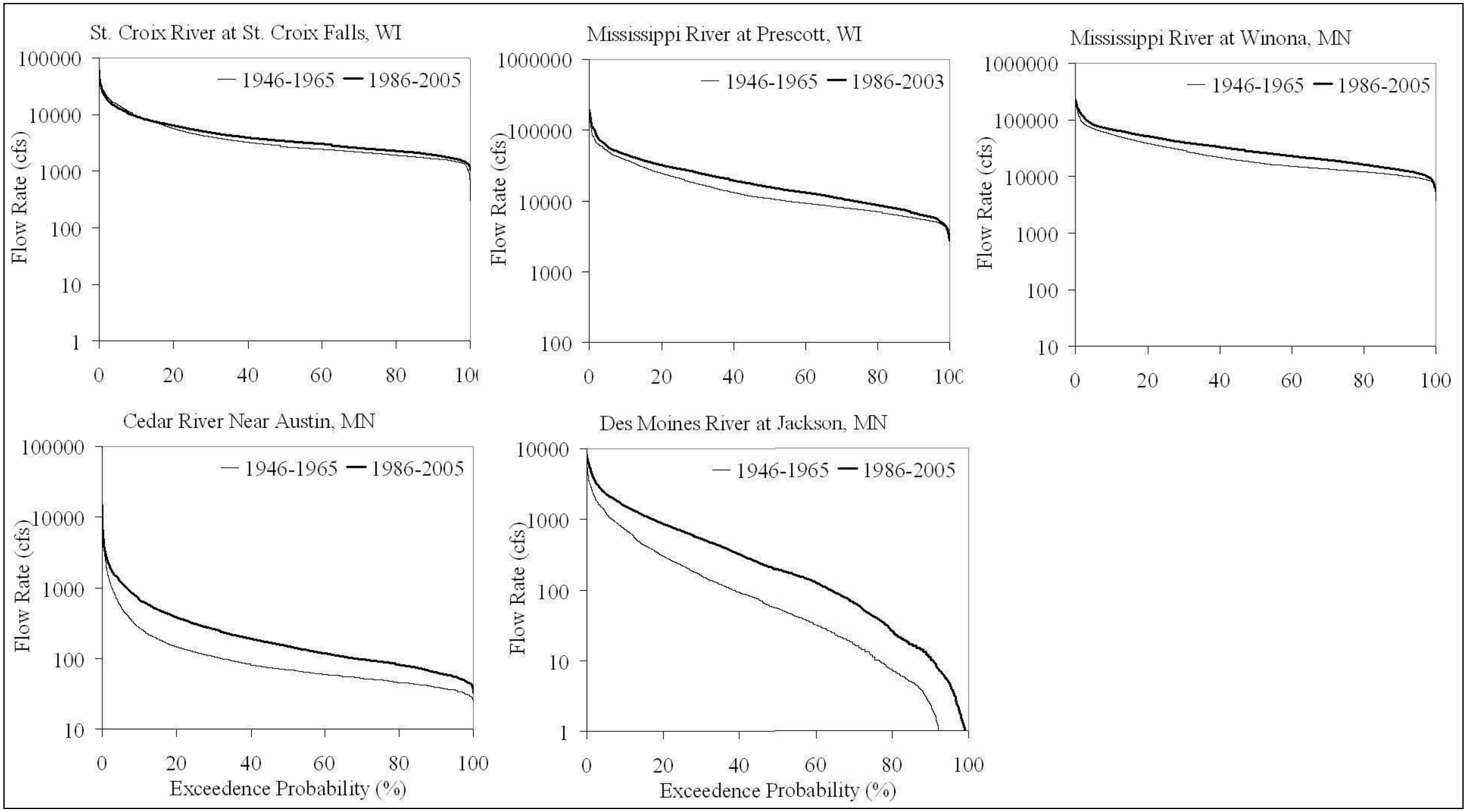

Figure 4.9b. FDCs at stream gauging stations in the Upper Mississippi River Basin for the periods 1946 -1965 and 1986 -2005.

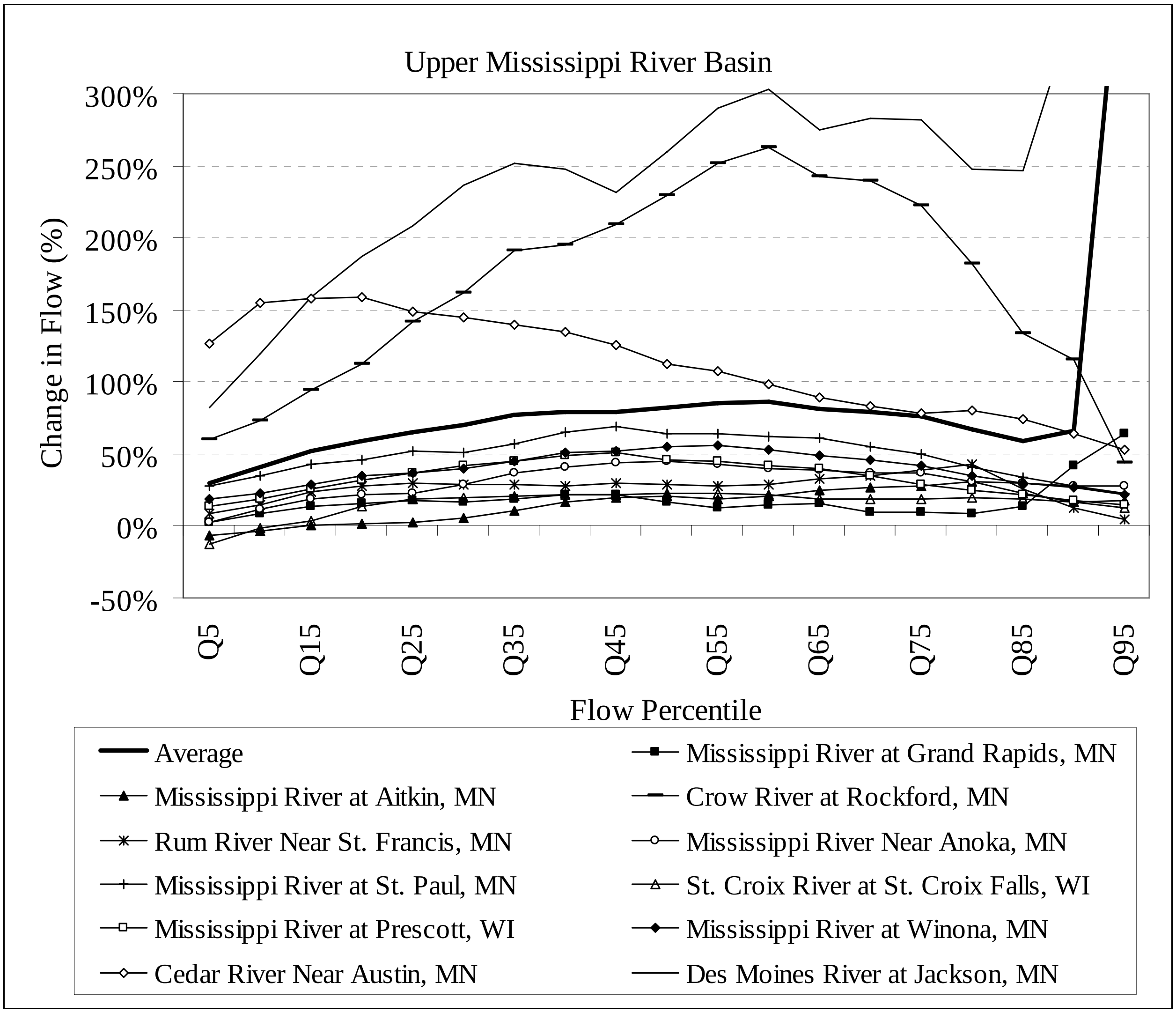

Figure 4.10. Change in flows between Q5 and Q95 at stream gauging stations in the Upper Mississippi River Basin from the 1946 - 1965 period to the 1986 - 2005 period. Change in flow (%) is the difference in flow between the 1986-2005 period and the 1946 - 1965 period divided by the flow in the 1946 - 1965 period.

4.6. Summary of Results from the FDC Analysis

Flow Duration Curves (FDCs) for 36 stream gauging stations in Minnesota showed significant changes from the period (1946-1965) to the period (1986-2005). The changes were mostly consistent for stream gauging stations located in the same river basin, although deviations from a typical river basin pattern were noted at a few gauging stations, e.g., for the Roseau River near Milung, in the Red River of the North Basin, or the Des Moines River at Jackson, and the

Crow River at Rockford in the Upper Mississippi River Basin. Consistency of changes observed in a river basin can be an indicator of climatic effects. However, the deviations from general patterns at some stations may have other causes, e.g., land-use/land cover changes.

The Minnesota River Basin has experienced the largest stream flow changes in the last 20 years compared to the other four basins. In that basin high, medium, and low flows have increased significantly. The increases in medium to low flows were larger than the increases in high flows. Considerable changes in flows were also observed in the Upper Mississippi River Basin and Red River of the North Basin. The changes, although smaller in magnitude, showed the same pattern as the Minnesota River Basin. Streams in the Rainy River Basin and tributaries to Lake Superior showed little change in stream flow distribution (10-20%). The changes observed in these river basins were also variable. In two tributaries to Lake Superior, average flows seem to have increased on the order of 10%, low flows seem to have decreased, and high flows seem to be unchanged.

5. RESULTS – OCCURRENCE OF RANKED ANNUAL PEAK FLOWS

When peak flows occur in streams or rivers, it is typical that flooding causes damage to infrastructure and buildings. In addition, water quality and habitat conditions for many aquatic organisms become stressed. Peak flow events are therefore economically and ecologically very significant. Annual peak flow events in a stream flow record can be ranked from highest to lowest, and the occurrence of the highest peak flows can be studied. The time series plots in Figures 5.1 to 5.5 identify the actual years in which the top 1, 3, 5, and 10 peak flow events have occurred at stream gauging stations of major Minnesota streams. Plots are provided for all stream gauging stations in the five major river basins of Minnesota. Have peak flows been more common in the recent 1986-2005 period compared to the longer 1946-2005 period? The number of stations where the observed number of annual peak flows during the 1986-2005 period was higher than the average number expected from the analysis of the full record (1946-2005) is therefore given in Table 5.1.

Figures 5.1 to 5.5 and Table 5.1 provide evidence that the occurrence of peak stream flow events may have shifted somewhat during the 1946 to 2005 period, at least in the Minnesota River Basin and the Red River of the North Basin. For example, up to 6 of the 12 stations in the Minnesota River Basin had more than the expected number of annual peak flow events in the

1986-2005 period (Table 5.1). The stream gauging station which experienced the changes are all in the upper reaches of the Minnesota River. The increase is readily apparent in the records for the Whetstone River near Big Stone City, SD, the Minnesota River at Ortonville and at Montevideo, and the Chippewa River near Milan (Figure 5.1). In the Red River of the North Basin, up to 5 of 6 stations had more than the expected number of annual peak flow events in the recent period (1986 to 2005). The temporal distribution of the top 1, 3, 5, and 10 peak flow events in the last 20 years is shown in Figure 4.13 for 4 of the 6 stations in the Rainy River Basin (Red Lake River at Crookston, MN and Red River of the North at Drayton, ND are excluded because peak flow data were not available for these stations). In the Rainy River Basin and in tributary streams to Lake Superior the temporal distribution of annual peak flow events does not seem to have changed. In the Upper Mississippi River Basin the evidence of change is mixed: only 2 of 11 stream gauging stations show a shift in the occurrence of the top 1, 3, and 5 peak flow events (Table 5.1), but peak flows that are in the top 10 have occurred more often at 6 of the 11 stream gauging stations on the Upper Mississippi River in the recent period (1986-2005).

Table 5.1. Number and percentage of stations which had more than the expected number of peak flow events in the 1986-2005 period.

	Number of peak flow events in (1946-2005) record	**1**	**3**	**5**	**10**
	Number of events expected in the (1986-2005) period	**0**	**1**	**2**	**3**
Minnesota River Basin (12 sta)	Number of sta above expected	5	5	6	6
	Percent of sta above expected	42	42	50	50
Red River of the North Basin (6 sta)	Number of sta above expected	4	3	3	5
	Percent of sta above expected	67	50	50	83
Rainy River Basin (4 sta)	Number of sta above expected	0	0	0	0
	Percent of sta above expected	0	0	0	0
Lake Superior Tributaries (2 sta)	Number of sta above expected	0	0	0	0
	Percent of sta above expected	0	0	0	0
Upper Mississippi River Basin (11)	Number of sta above expected	2	1	1	6
	Percent of sta above expected	18	9	9	55

Note: "Number above expected" is the number of stream gauging stations at which more than the expected number of peak flow events occurred. "Percent above expected" is the number of stream gauging stations at which more than the expected number of high flow events occurred, divided by the total number of stream gauging stations in the river basin.

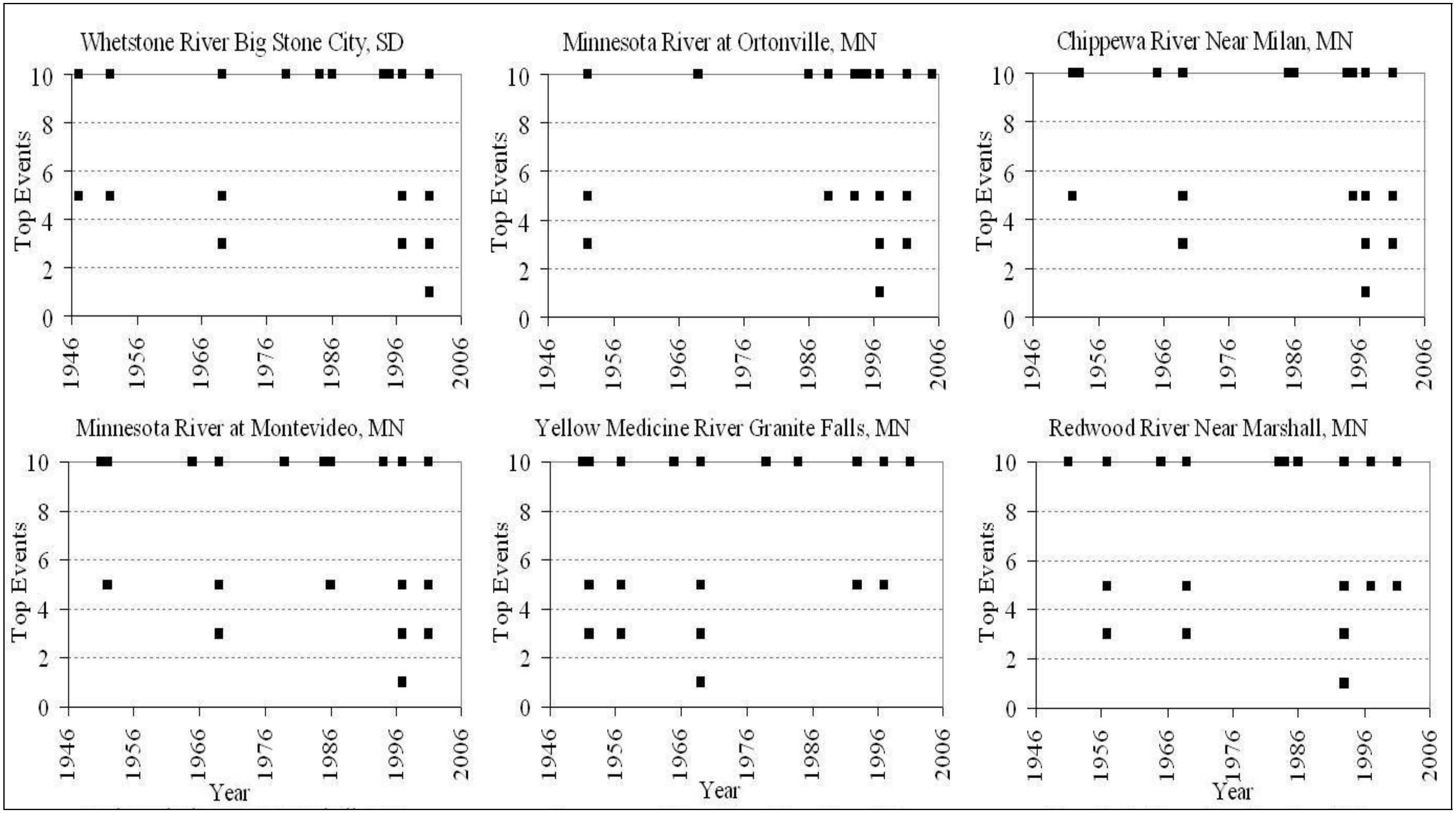

Figure 5.1a. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Minnesota River Basin

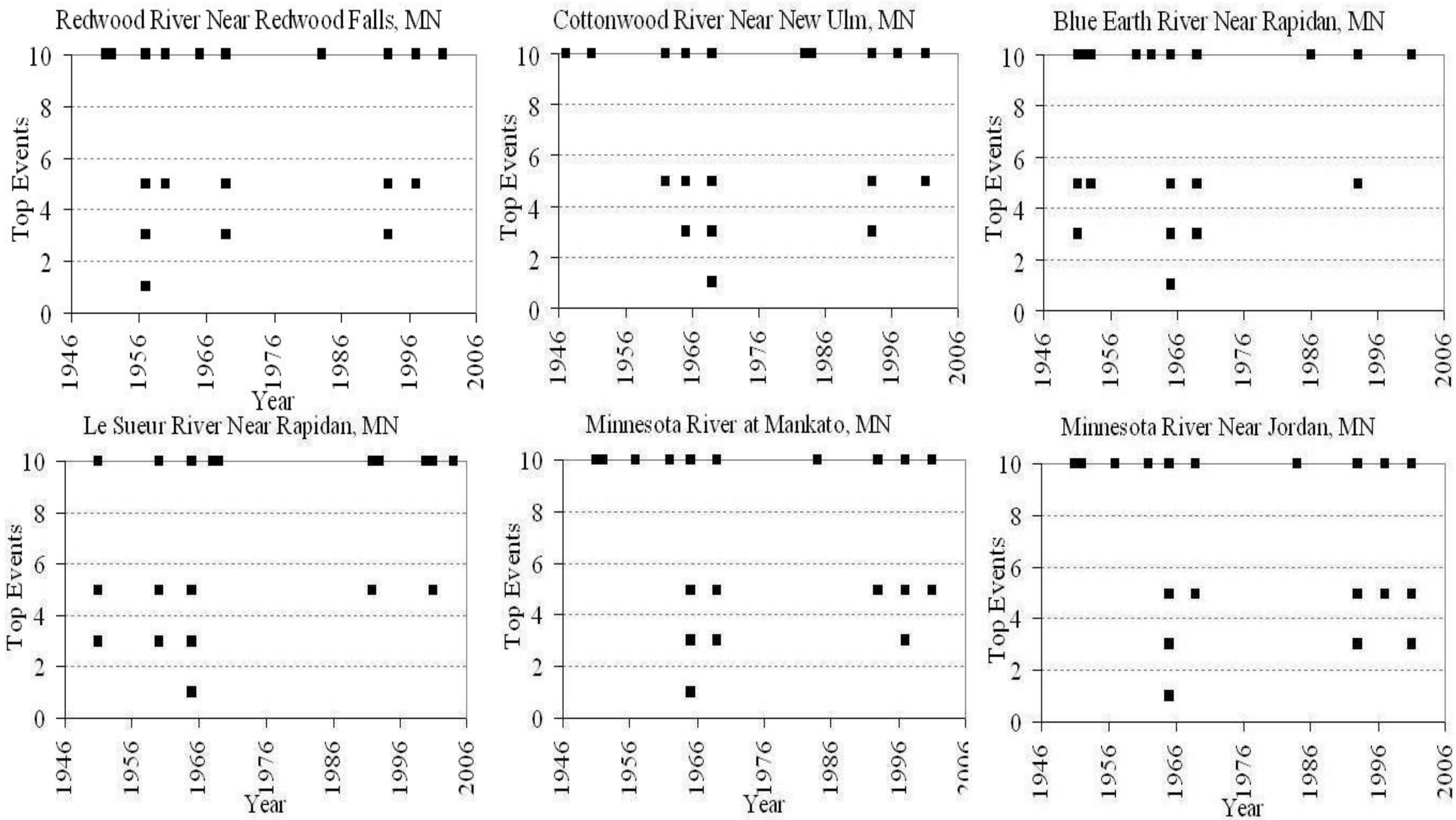

Figure 5.1b. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Minnesota River Basin

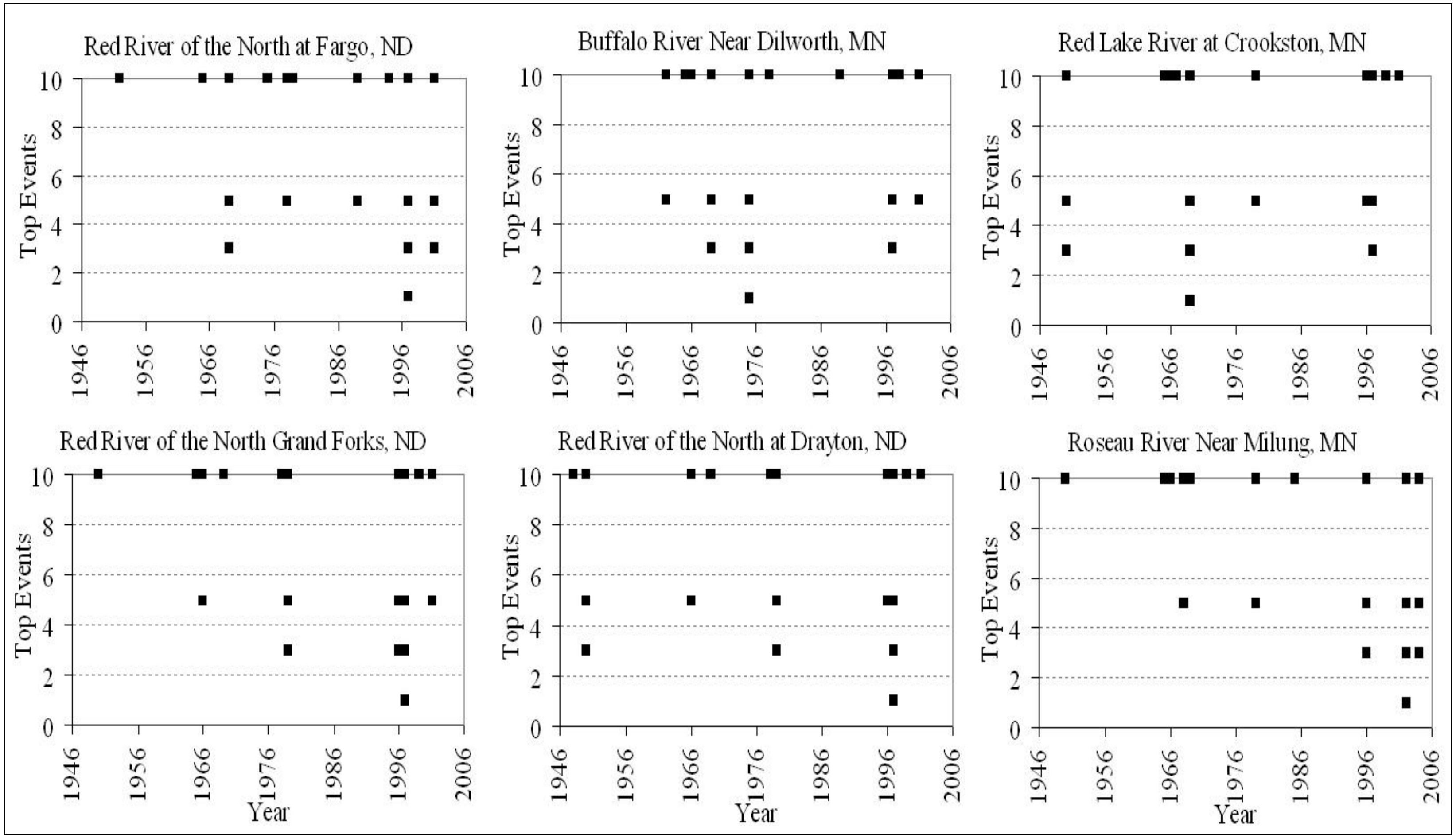

Figure 5.2. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Red River of the North Basin

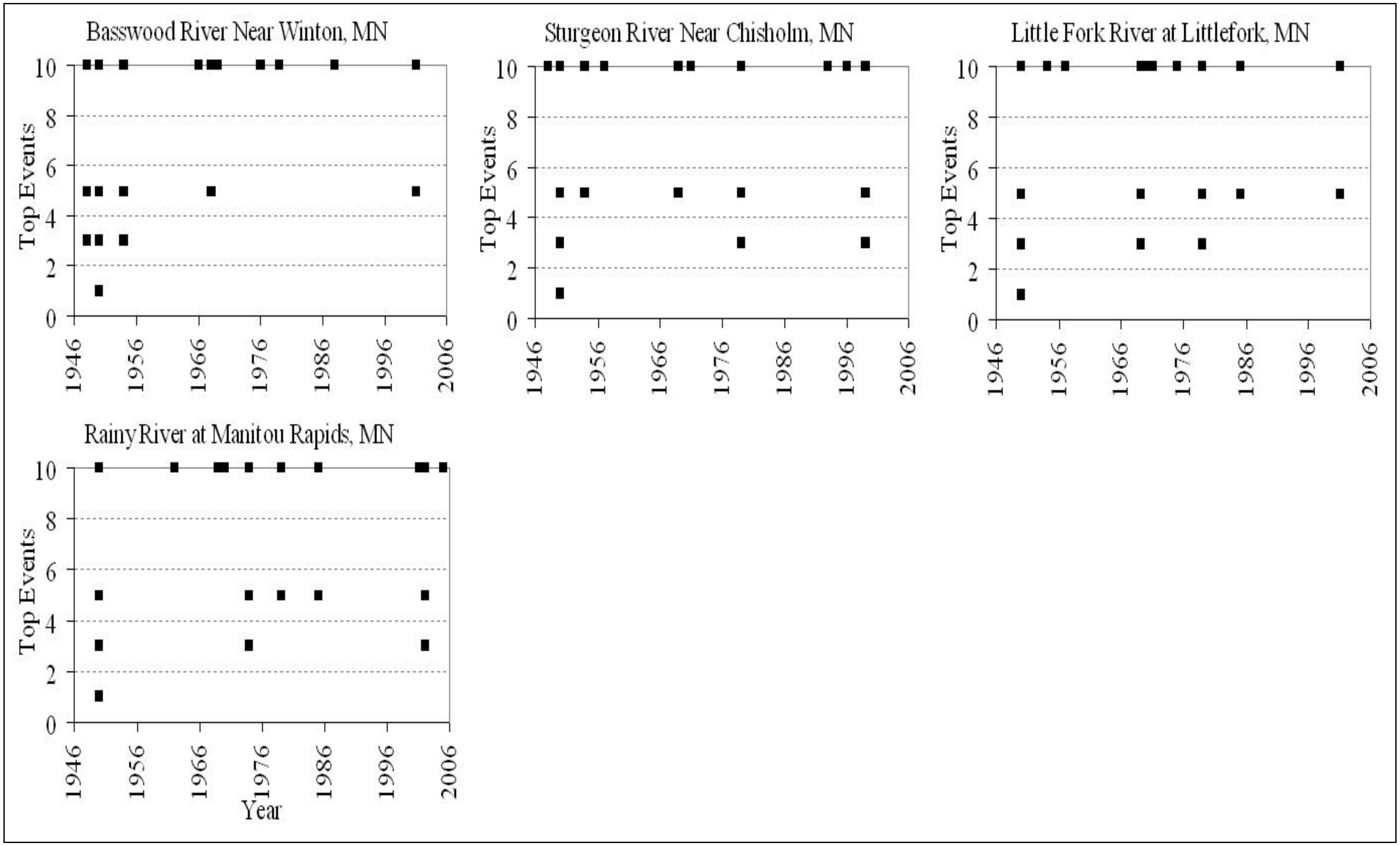

Figure 5.3. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Rainy River Basin

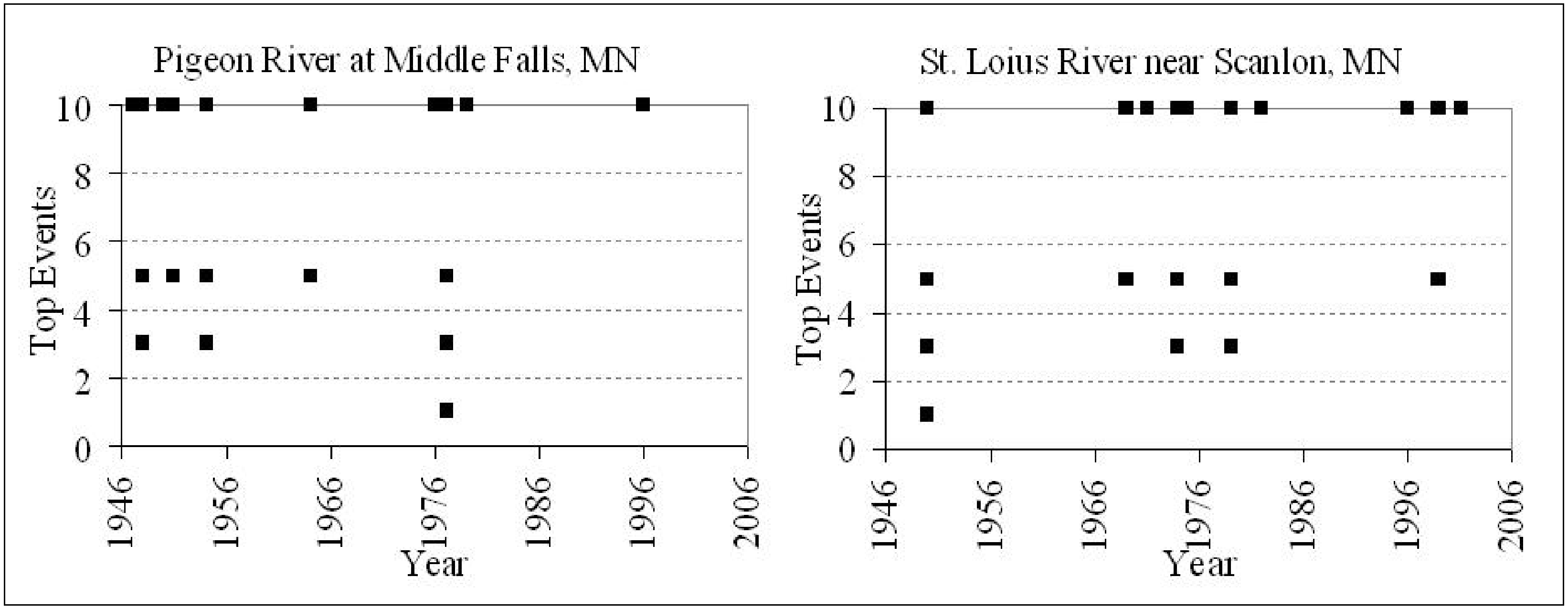

Figure 5.4. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in tributaries to Lake Superior.

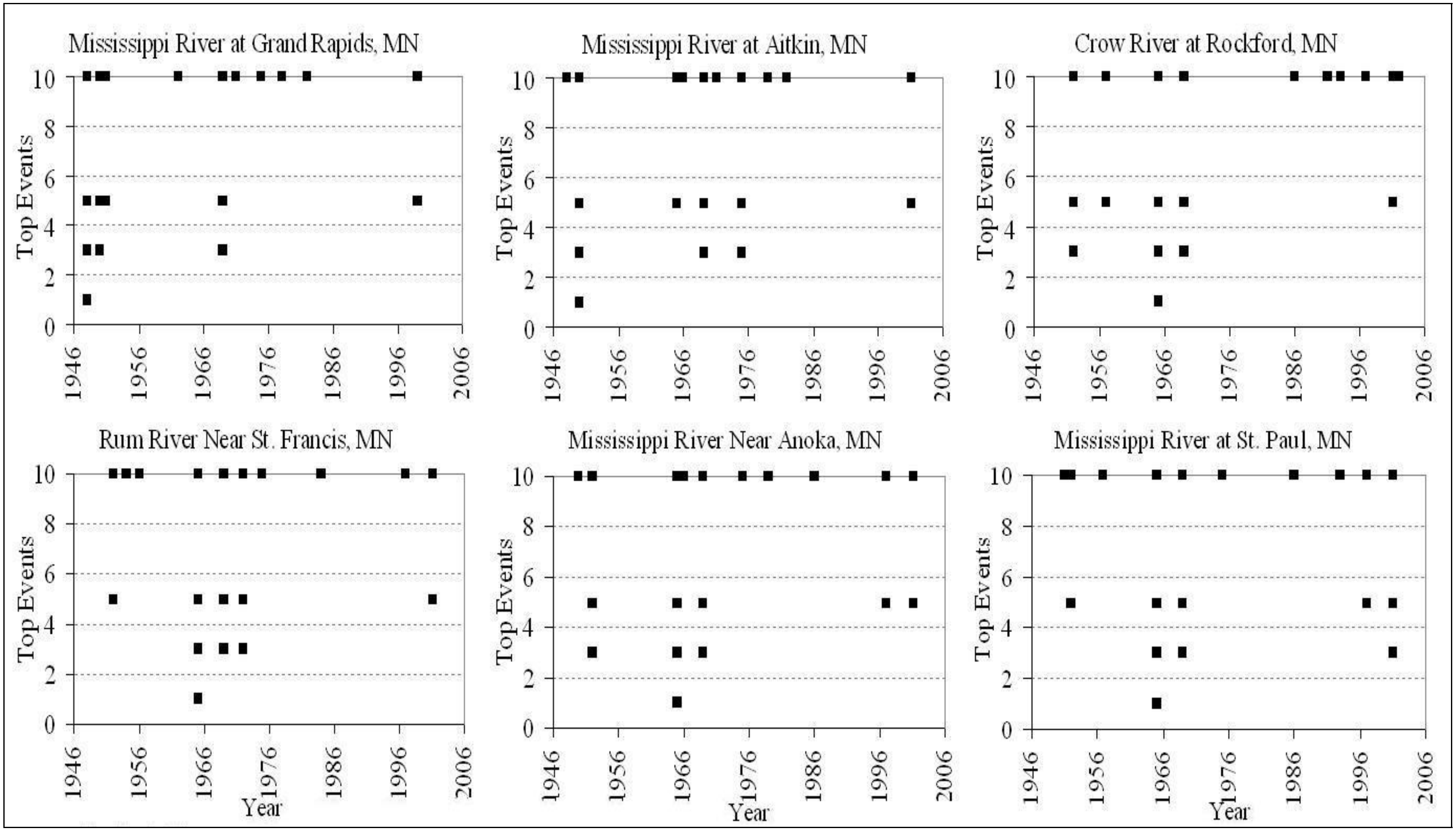

Figure 5.5a. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Upper Mississippi River Basin

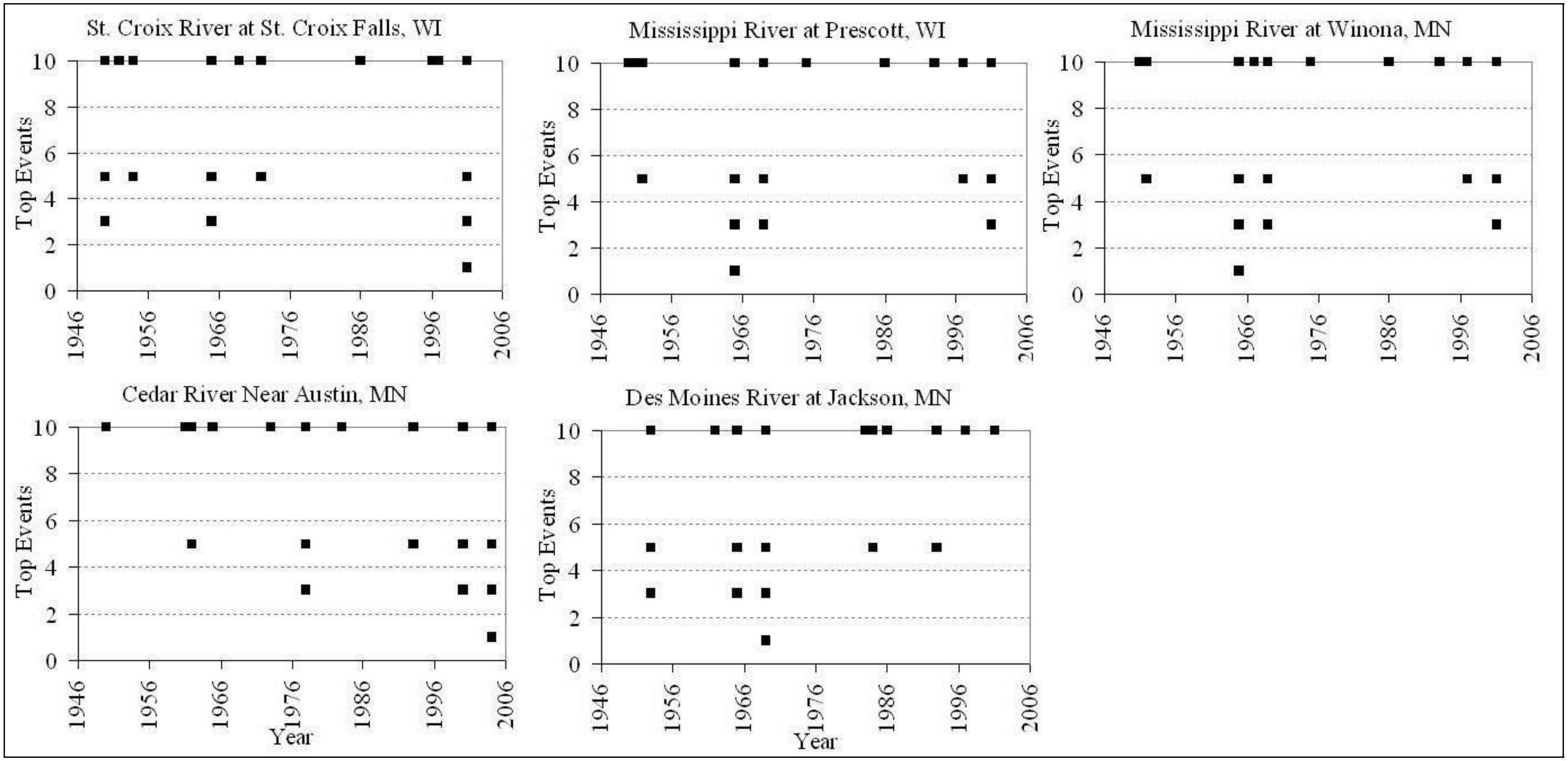

Figure 5.5b. Occurrence of the 1, 3, 5, and 10 highest annual flows in the 1946-2005 period in the Upper Mississippi River Basin

6. RESULTS – OCCURRENCE OF RANKED ANNUAL 7-DAY (AVERAGE) LOW FLOWS

When 7-day (average) low flows occur in a stream, it is typical that water quality deteriorates and habitat conditions for many aquatic organisms become stressed. 7-day low flow events are therefore ecologically very significant. The 7-day low flows in some small streams in Minnesota have been zero in some years. Table 6.1 gives the number of years when the 7-day low flow fell to zero at the 36 stream gauging stations investigated.

Table 6.1. Stations that had zero 7-day average low flows during the 1946-2005 period.

USGS Gauging Station No.	Stream/River Name	Number of years 7-day average flow is zero
Minnesota River Basin		
05291000	Whetstone River Big Stone City, SD	3
05313500	Yellow Medicine River Granite Falls, MN	2
05315000	Redwood River Near Marshall, MN	8
Red River of the North Basin		
05054000	Red River of the North at Fargo, ND	1
05104500	Roseau River Near Milung, MN	5
Upper Mississippi River Basin		
05476000	Des Moines River at Jackson, MN	7

Low flows can also be ranked – from the lowest annual low flow to the highest annual low flow in the record.. The temporal distributions of the lowest 1, 3, 5, and 10 7-day (average) annual low flows that occurred at stream gauging stations located in the five main river basins of Minnesota over the period of record (1946-2005) are provided in Figures 6.1 to 6.5. These plots show qualitatively if the occurrence of low flow conditions shifted over the period of record from 1946 to 2005. To quantify the shift, the number and the percentage of stream gauging stations which had a smaller than the expected number of lowest 7-day (average) low flow events during the recent 1986-2005 period are given in Table 6.2.

The analysis of flow duration curves in Section 4 showed that low flows increased within the last 20 years in some regions of Minnesota. We therefore also analyzed the distribution of the top 1, 3, 5, and 10 highest 7-day (average) annual low flow events that occurred in the 1946-2005 period (Figures 6.6 to 6.10). We also quantified the shift by calculating the number and the percentage of stream gauging stations where more than the expected number of the highest 7-day (average) low flow events occurred (Table 6.3).

According to this analysis changes in 7-day (average) low flows were most evident in the Minnesota River Basin and the Red River of the North Basin, and somewhat evident in the Upper Mississippi River Basin.

In the Minnesota River Basin, the highest 1, 3, 5 and 10 7-day (average) annual low flows occurred more than expected in the 1986-2005 period at all 12 stations (Table 6.3). In agreement with this finding is that only 1 in 12 stations had the single lowest 7-day (average) annual low flow in the 1986-2005 period (Table 6.2).

In the Red River of the North Basin, the highest 1 and 3 7-day annual (average) low flows at all 6 stations occurred during the 1986-2005 period. All stations showed more than the expected top 1, 3, 5 and 10 7-day annual (average) low flow events in the last 20 years. All but one stations had at least 4 of the 5 highest and 7 of the 10 highest 7-day average low flows after 1985 (Table 6.3).

In the Upper Mississippi River Basin, 6 of the 11 stations had the highest 7-day annual (average) low flow between 1986 and 2005 and 7 stations had at least 2 of the 3 highest 7-day annual (average) low flows after 1985.

The highest 7-day (average) low flow occurred on both gauged tributaries to Lake Superior in the last 20 years, the 3, 5, and 10 highest flows did not. Similarly, no convincing trend was observed in the records of the stations located in the Rainy River Basin. Only 40% of the stations had more than the expected highest 5 and 10 7-day annual (average) low flow in the 1986-2005 period.

In summary, the low flow occurrence results for all five major river basins agree with the results from the flow duration curves (FDCs) in Section 4 – as they should. Both analyses indicate that changes in low flows have occurred in 3 of the 5 major river basins (Minnesota River Basin, Red River of the North Basin, and Upper Mississippi River Basin).

Table 6.2. Number and percentage of stations which had more than the expected number of lowest 7-day (average) low flow occurrences in the 1986-2005 period.

	Number of lowest low flow events in (1946-2005) record	**1**	**3**	**5**	**10**
	Number of events expected in the (1986-2005) period	**0**	**1**	**2**	**3**
Minnesota River Basin (12 sta)	Number of sta below expected	1	0	0	1
	Percent of sta below expected	8	0	0	8
Red River of the North Basin (6 sta)	Number of sta below expected	2	0	0	1
	Percent of sta below expected	40	0	0	20
Rainy River Basin (4 sta)	Number of sta below expected	2	2	1	4
	Percent of sta below expected	33	33	17	67
Lake Superior Tributaries (2 sta)	Number of sta below expected	1	0	1	2
	Percent of sta below expected	50	0	50	100
Upper Mississippi River Basin (11 sta)	Number of sta below expected	2	2	1	1
	Percent of sta below expected	18	18	9	9

Note: “Number below expected” is the number of stream gauging stations at which fewer than the expected number of low flow events occurred. “Percent below expected” is the number of stream gauging stations at which fewer than the expected number of low flow events occurred, divided by the total number of stream gauging stations in the river basin

Table 6.3. Number and percentage of stations which had more than the expected number of highest 7-day (average) low flow occurrences in the 1986-2005 period.

	Number of low flow events in (1946-2005) record	**1**	**3**	**5**	**10**
	Number of events expected in the (1986-2005) period	**0**	**1**	**2**	**3**
Minnesota River Basin (12 sta)	Number of sta above expected	12	12	12	12
	Percent of sta above expected	100	100	100	100
Red River of the North Basin (6 sta)	Number of sta above expected	6	6	6	6
	Percent of sta above expected	100	100	100	100
Rainy River Basin (4 sta)	Number of sta above expected	0	0	2	2
	Percent of sta above expected	0	0	40	40
Tributaries to Lake Superior (2 sta)	Number of sta above expected	2	1	1	1
	Percent of sta above expected	100	50	50	50
Upper Mississippi River Basin (11 sta)	Number of sta above expected	6	7	7	9
	Percent of sta above expected	55	64	64	82

Note: "Number above expected" is the number of stream gauging stations at which more the expected number of low flow events occurred."Percent above expected" is the number of stream gauging stations at which more than the expected number of low flow events occurred, divided by the total number of stream gauging stations in the river basin.

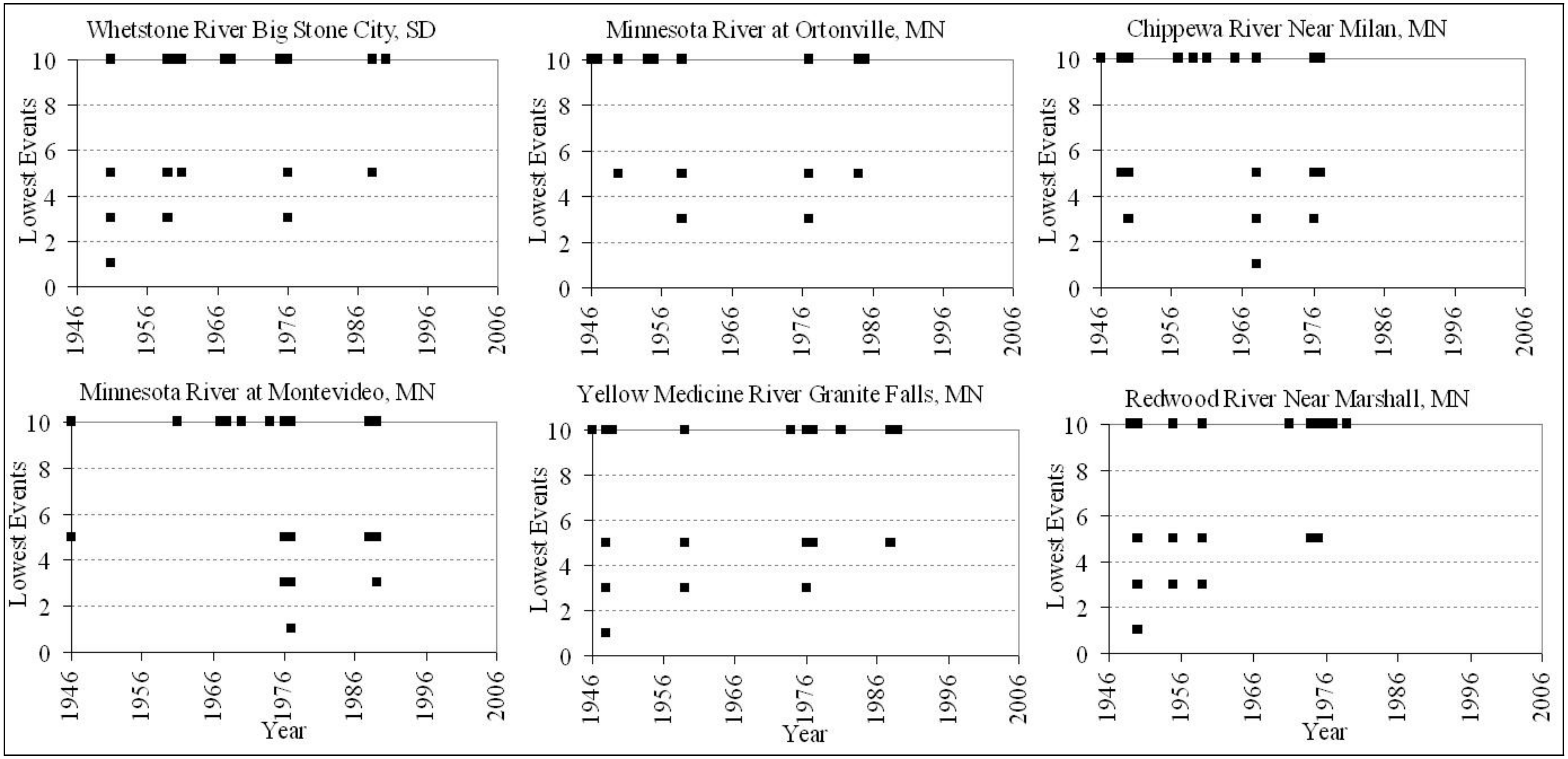

Figure 6.1a. Occurrence of the 1, 3, 5, and 10 lowest 7-day average low flows in the 1946-2005 period in the Minnesota River Basin

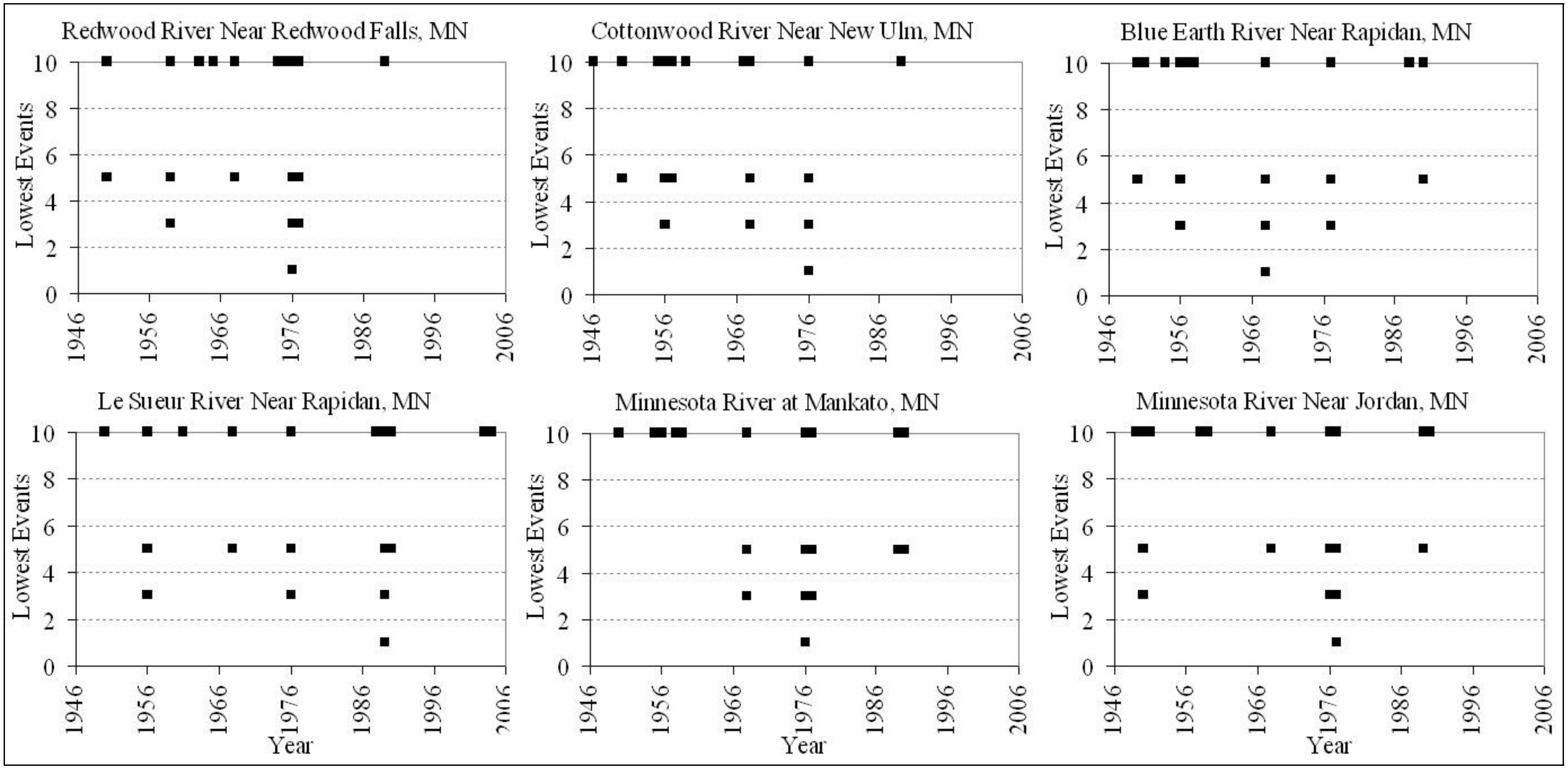

Figure 6.1b. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Minnesota River Basin

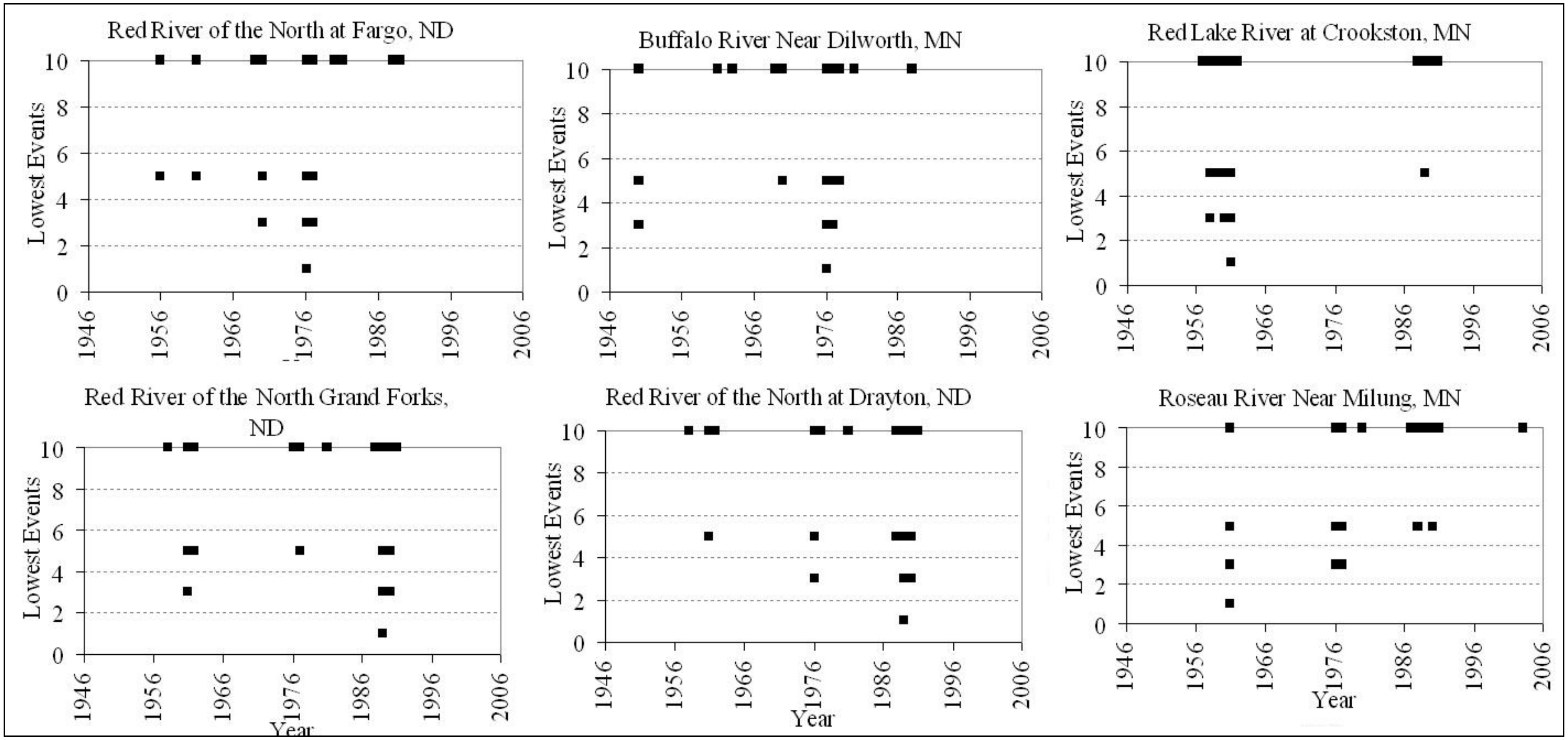

Figure 6.2. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Red River of the North Basin

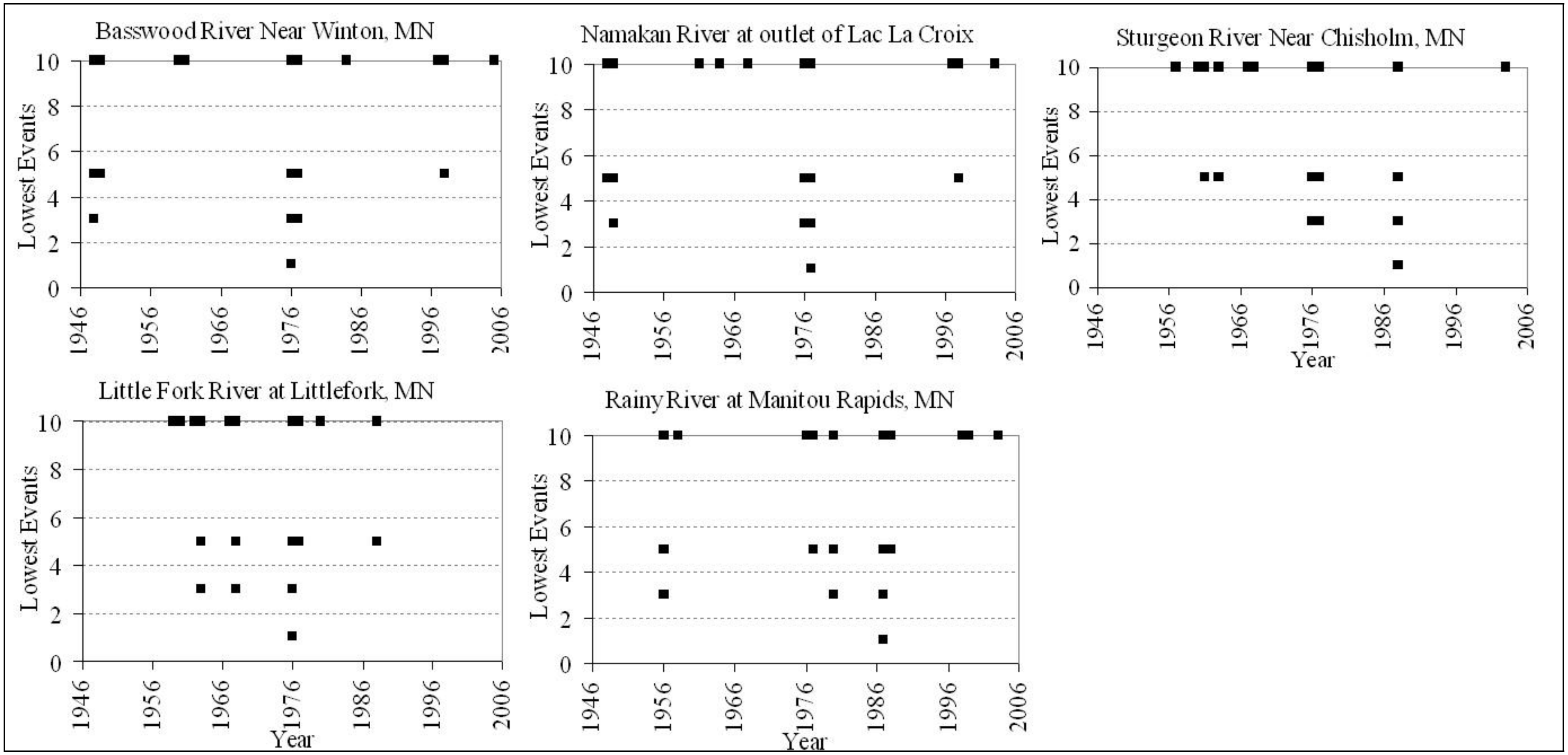

Figure 6.3. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Rainy River Basin

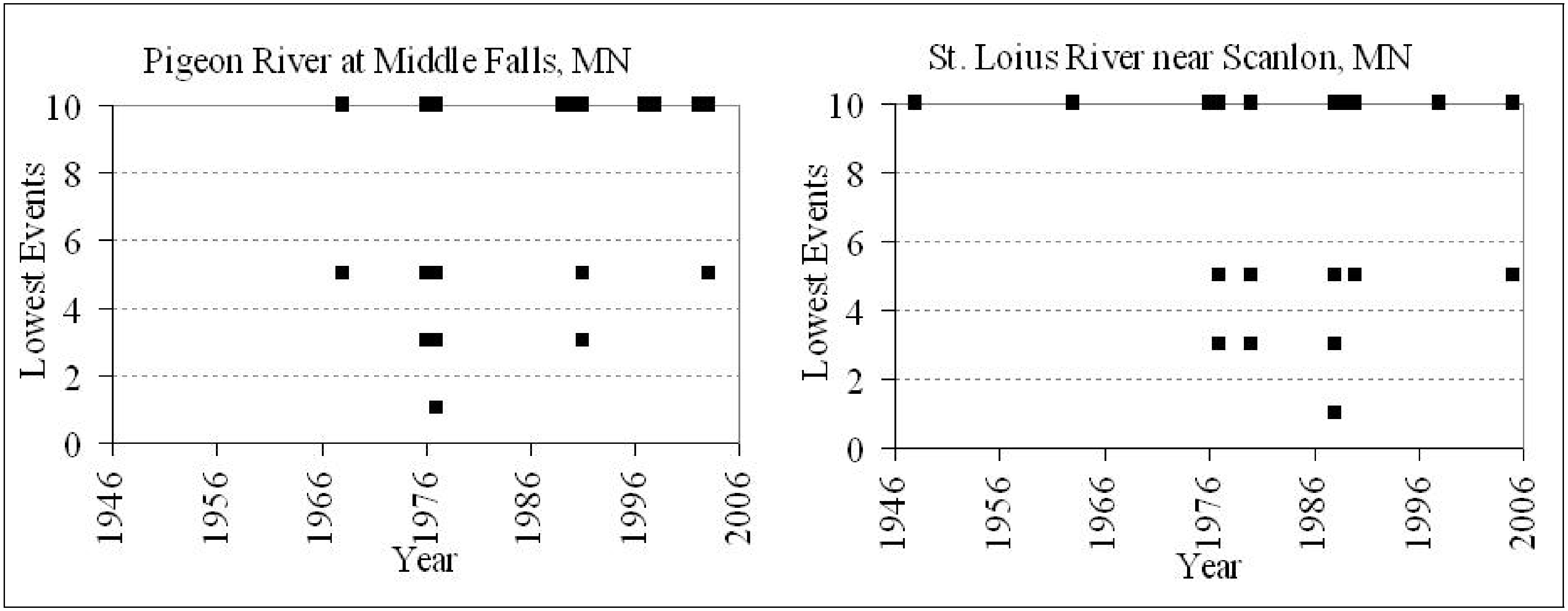

Figure 6.4. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in tributaries to Lake Superior

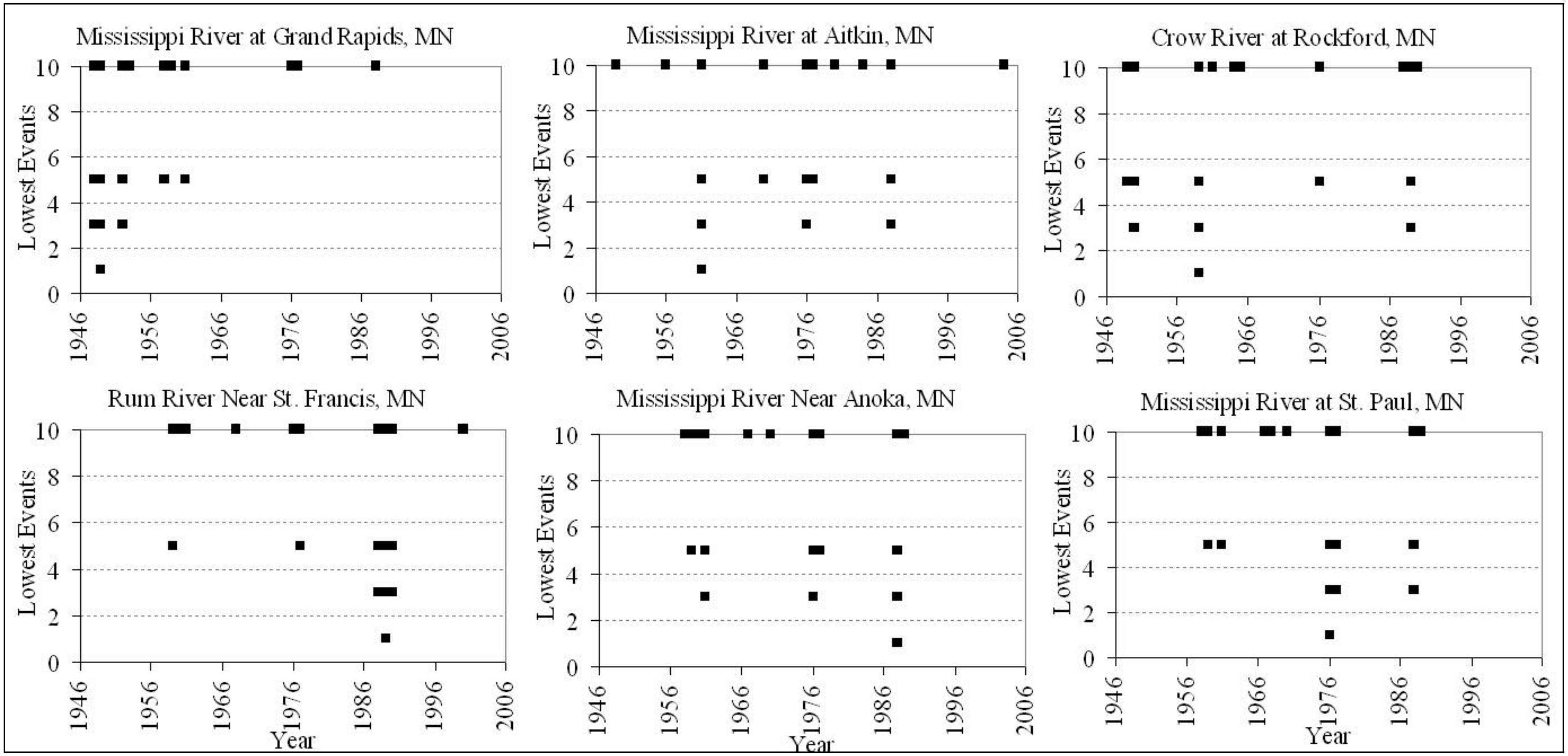

Figure 6.5a. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

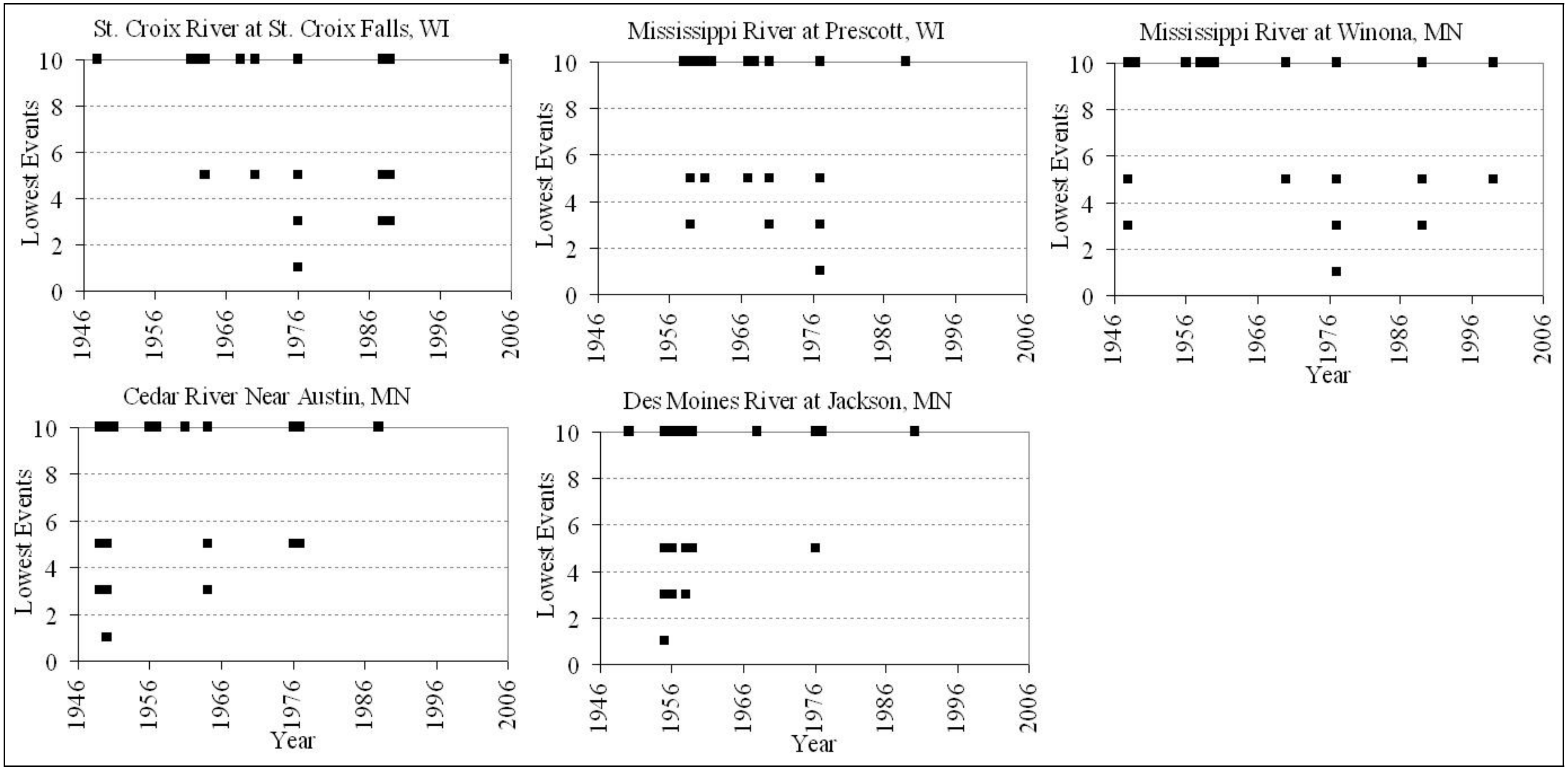

Figure 6.5b. Occurrence of the 1, 3, 5, and 10 lowest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

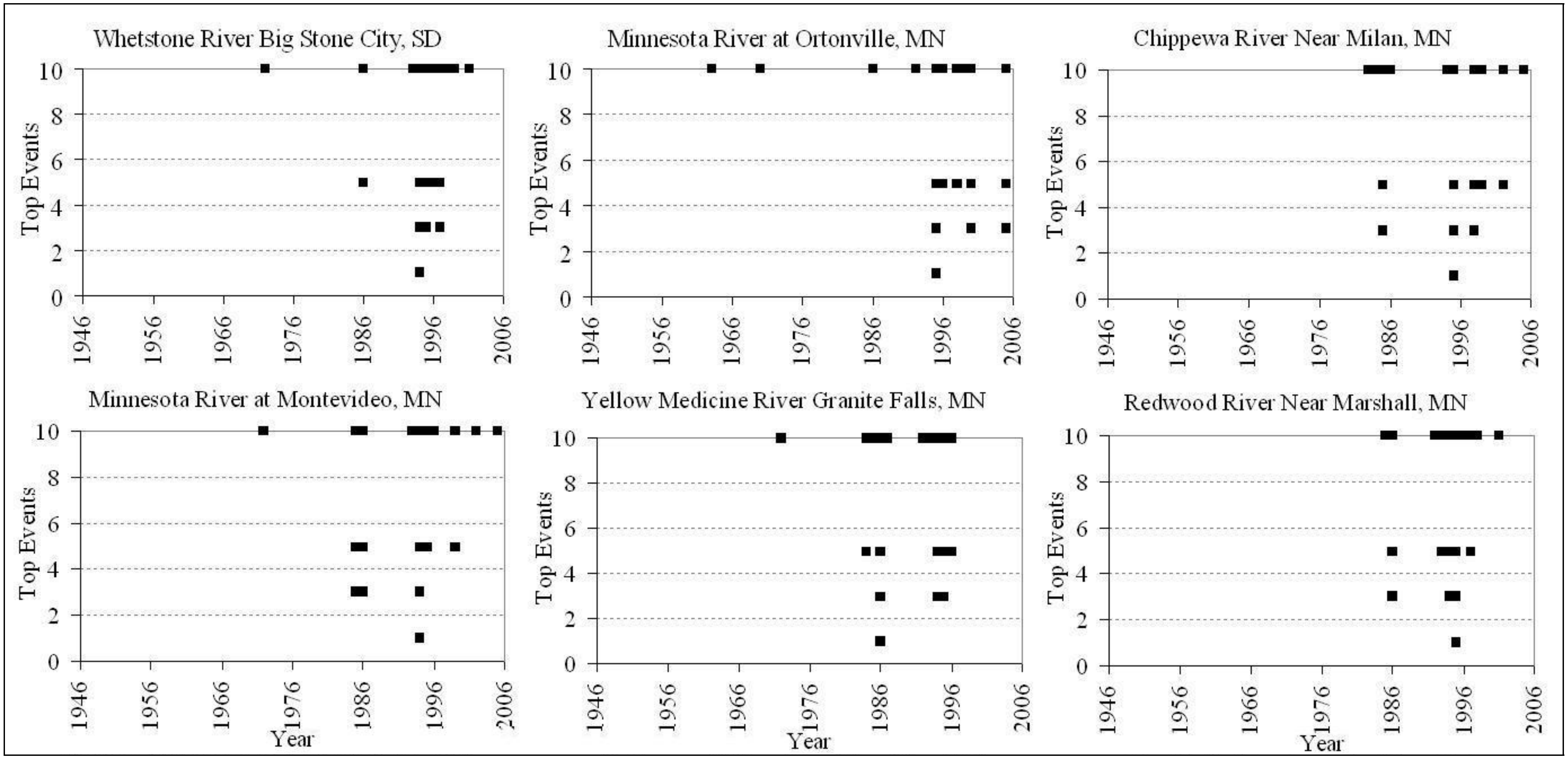

Figure 6.6a. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Minnesota River Basin

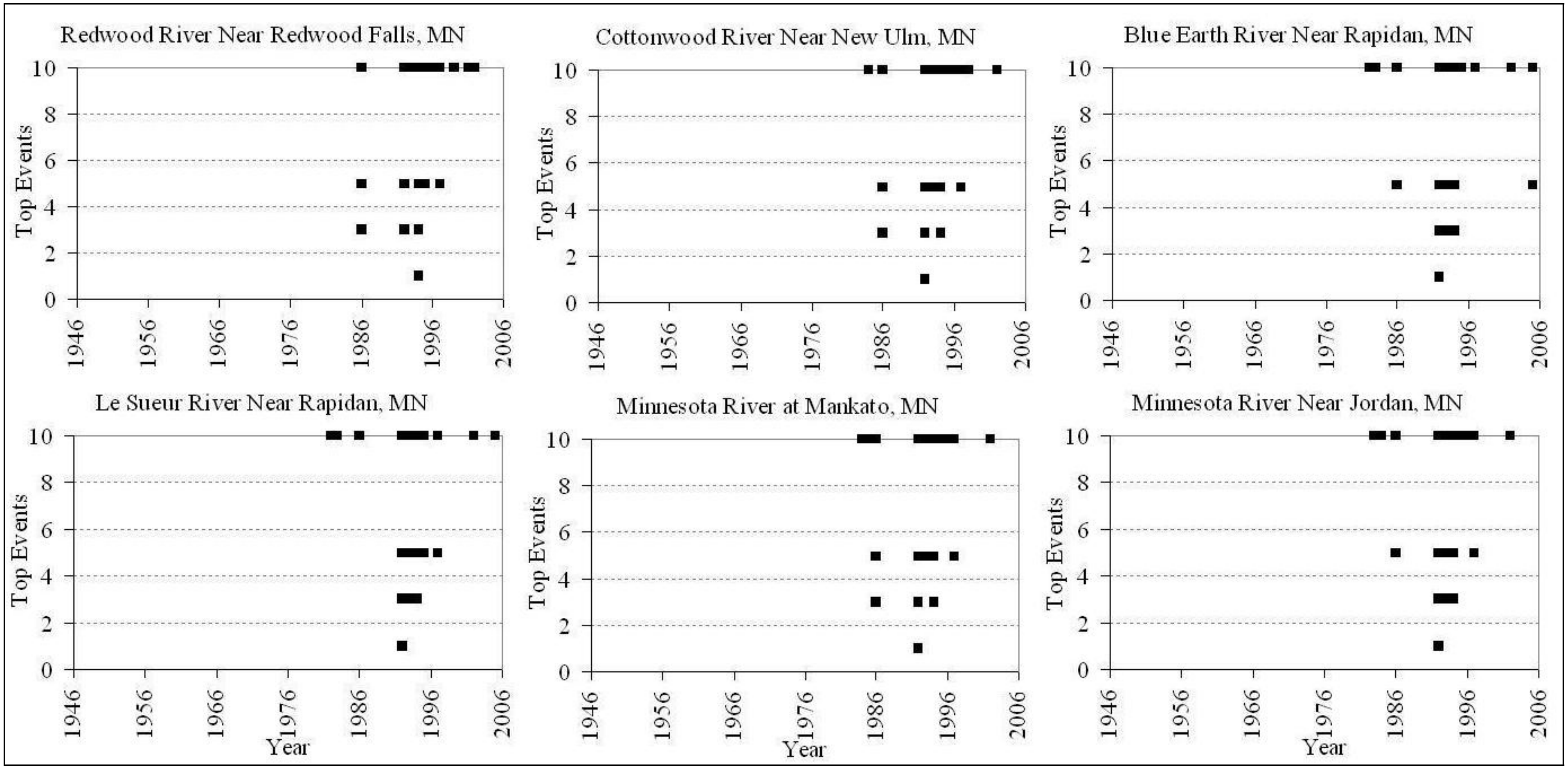

Figure 6.6b. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Minnesota River Basin

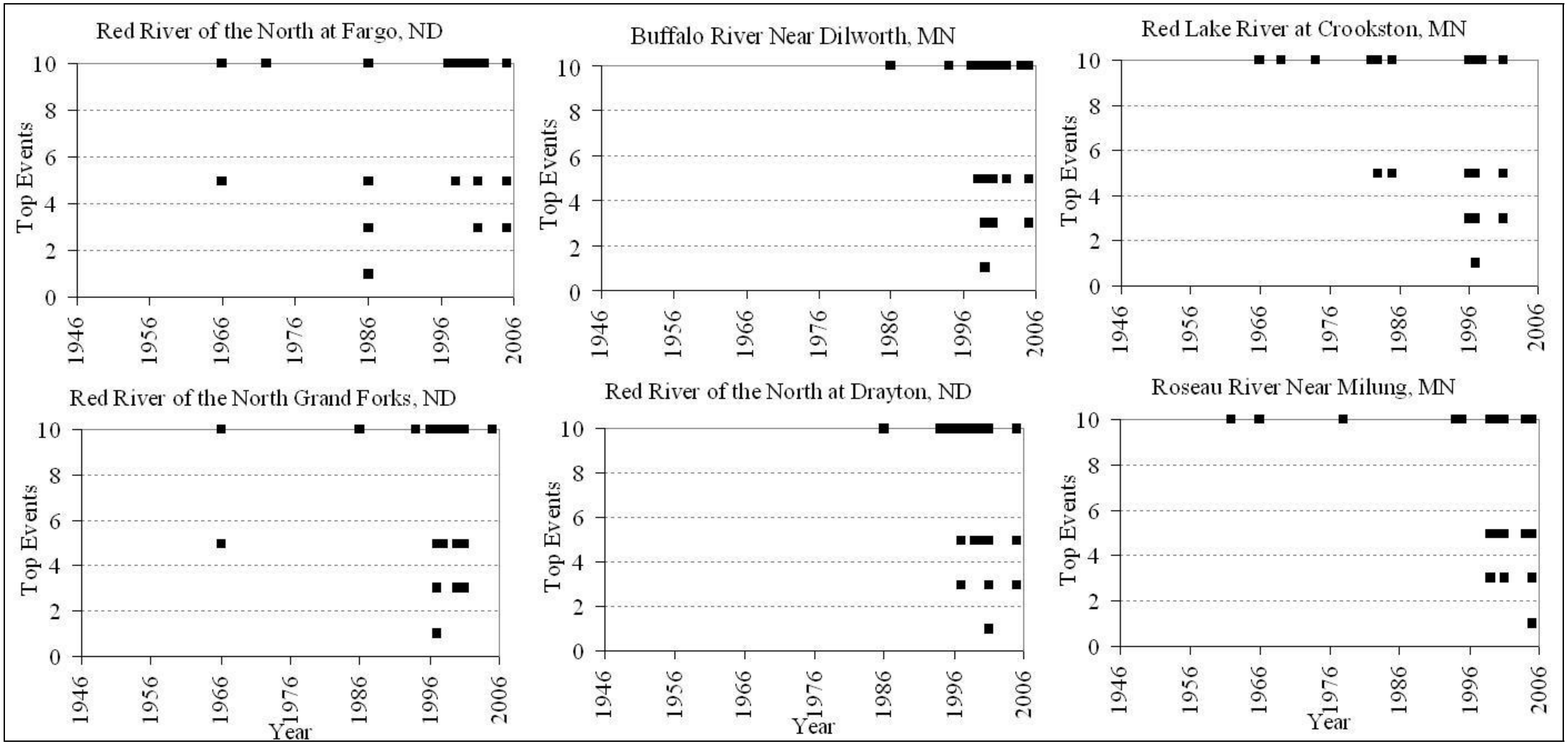

Figure 6.7. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Red River of the North Basin

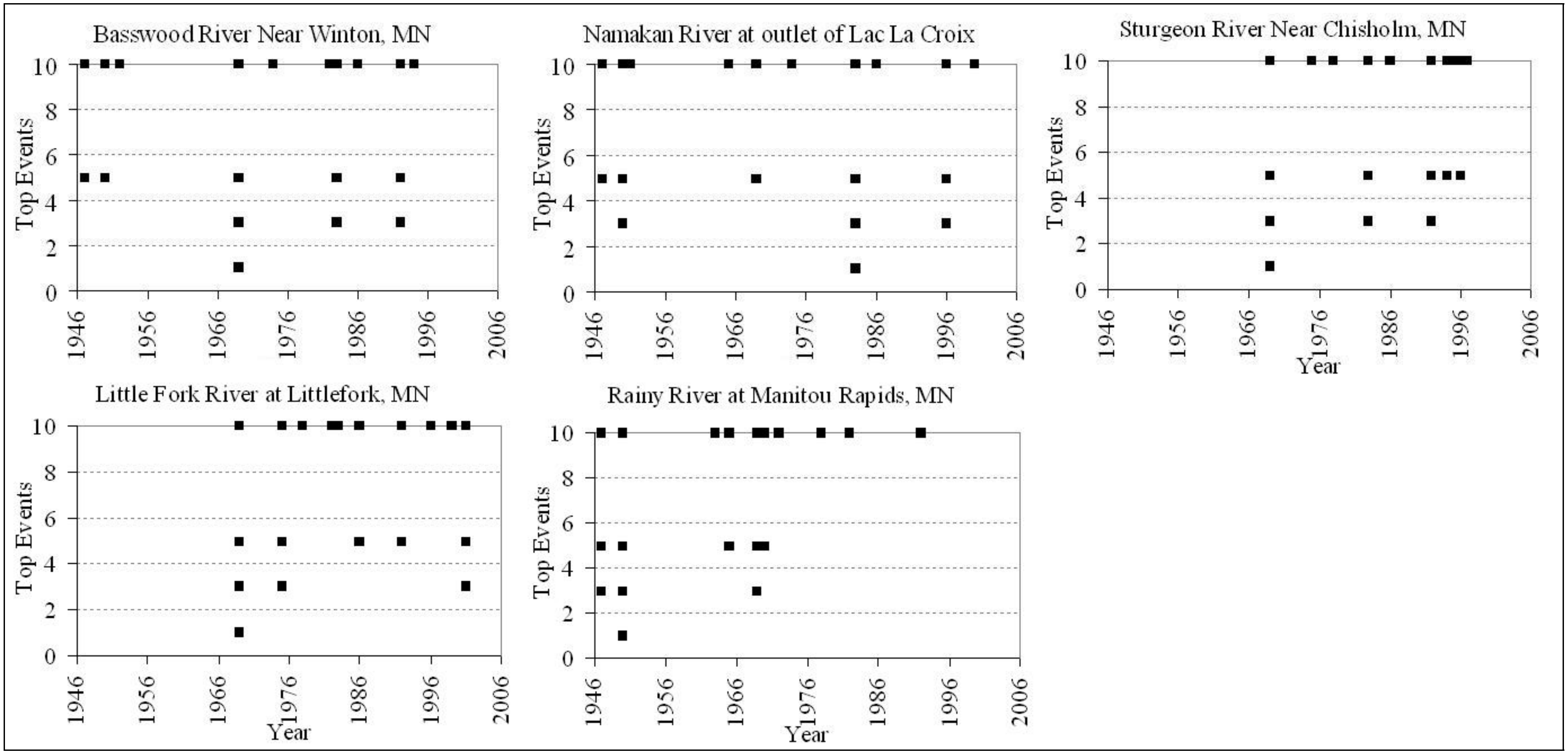

Figure 6.8. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Rainy River Basin

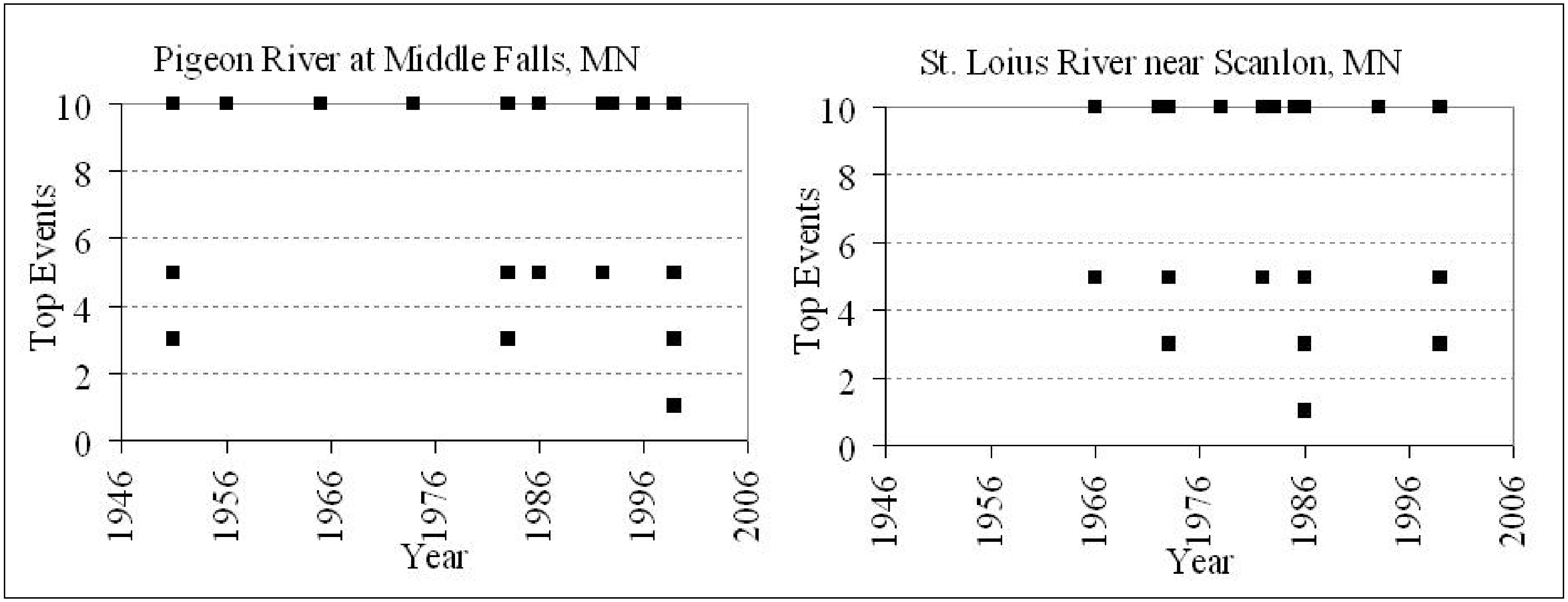

Figure 6.9. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in tributaries to Lake Superior

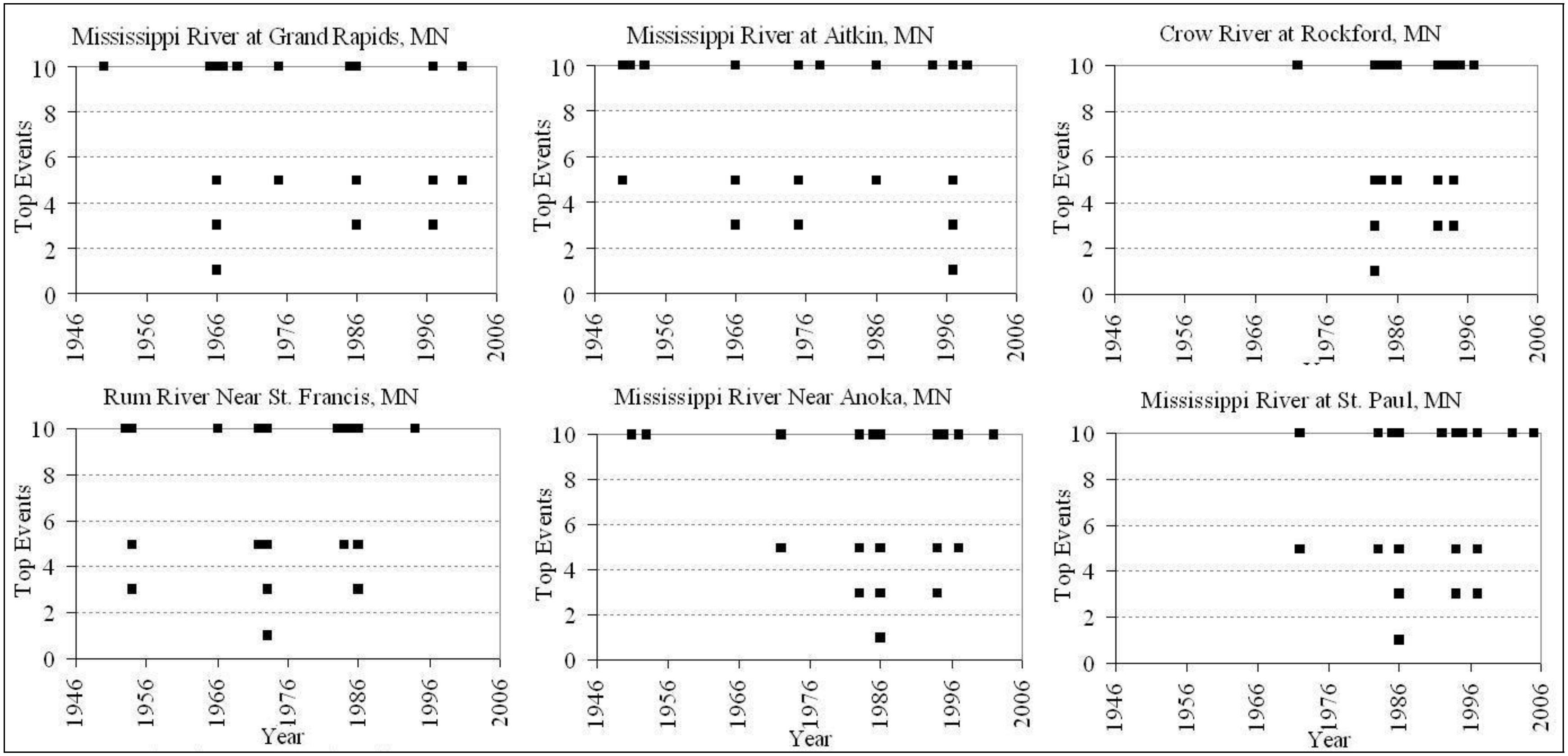

Figure 6.10a. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

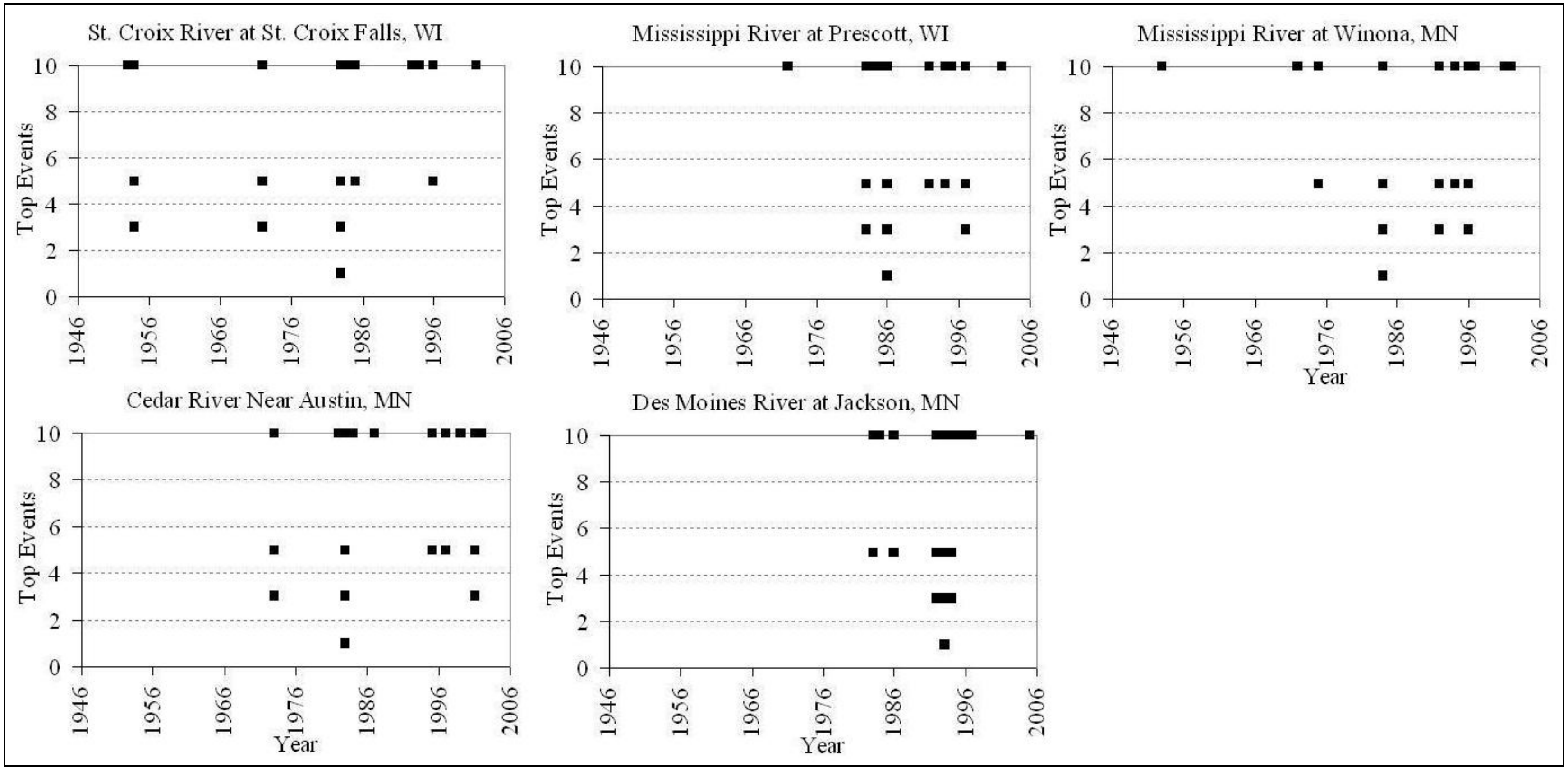

Figure 6.10b. Occurrence of the 1, 3, 5, and 10 highest 7-day (average) low flows in the 1946-2005 period in the Upper Mississippi River Basin.

7. RESULTS - FLOOD FREQUENCIES

Floods pose a risk to human life, they cause large economic losses, and they are disruptive to ecosystems. In an earlier section we analyzed the timing of peak flows in the period of record from 1946 to 2005. In this section we report results of flood frequency analyses (FFA) which were conducted on the annual peak flows in the 1946-1965 and 1986-2005 periods. Results for all stream gauging stations will be presented by river basin. Intermediate computational results are given in Appendix C. The magnitudes of floods with return periods from 1 to 25 years (small to moderate floods) were estimated in the analysis and provided in Appendix D. It would not make much sense to extrapolate flows of a higher recurrence interval from a data base of 20 years. Also many flow conveyance structures such as storm sewers in cities (not flood protection works) are designed to handle flows of this average recurrence.

7.1. Flood frequencies in the Minnesota River Basin

Flood frequency analysis (FFA) of the annual maximum flows in the periods 1946-1965 and 1986-2005 gave the results graphed in Figures 7.1a and b, and listed in Appendix D for the Minnesota River Basin. Table 7.1 summarized the changes in flood flows. Flood frequency distributions changed substantially from the 1946-1965 to the 1986-2005 period for eight of the 12 stream gauging stations in the Minnesota River Basin.

In a first group of stream gauging stations, representing the upstream portion of the Minnesota River Basin, flood flows with 1- to 25-year return periods were higher in the 1986-2005 period. This group includes stream gauging stations in the Minnesota River at Ortonville and at Montevideo, and the Chippewa River near Milan. The changes (%) in flood flows between the 1946-1965 and 1986-2005 periods for these three stations were in the range of 3% to 209% (Table 7.1).

In the second group of stream gauging stations representing the lower portion of the Minnesota River Basin magnitudes of the 1- to 5-yr floods became slightly higher but the magnitude of 25-yr flood remained pretty much the same in the 1986-2005 period. This group includes the Minnesota River near Jordan, the Minnesota River at Mankato, the Cottonwood River near New Ulm. The increases in the 1- to 10-yr flood flows were from 4% to 70%, and the decrease in the 25-yr flood floods from 1% to 7%.

In the third group of stream gauging stations, including the Redwood, the Blue Earth and the LeSueur Rivers in the middle reach of the Minnesota River, flood flows with 1- and 2-year return periods increased as for the second group, but flood flows with10- and 25-yr return periods became significantly lower in the last 20 years. The Yellow Medicine River showed the same behavior, except that the flood flows for all return periods showed a decrease.

Overall, in the Minnesota River Valley, floods with 1-yr and 2-yr return periods, i.e., floods of moderate magnitude that occur pretty much every year became, on average, 20-30% higher, while rarer floods with return periods of 10 to 25 years remained pretty much unchanged or became lower from 1946-1965 to 1986-2005 (Table 7.1). The median increase in 1-yr flood flows between 1946-1965 and 1986-2005 in the Minnesota River was 50% (with much variation between individual stream gauging stations), the median decrease in the 25-year flood flows was only 4% (range for individual stations was from -53% to 220%) (Table 7.1).

Table 7.1. Change (%) in flood flows in the Minnesota River Basins from (1946-1965) to (1986-2005).

	Return Period (years)				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Whetstone River Big Stone City, SD	-69	3	48	77	112
Minnesota River at Ortonville, MN	3	86	136	168	209
Chippewa River Near Milan, MN	50	72	73	72	70
Minnesota River at Montevideo, MN	12	38	54	64	77
Yellow Medicine River Granite Falls, MN	45	-12	-24	-29	-34
Redwood River Near Marshall, MN	505	25	-4	-11	-14
Redwood River Near Redwood Falls, MN	220	25	-10	-23	-35
Cottonwood River Near New Ulm, MN	48	13	3	-2	-7
Blue Earth River Near Rapidan, MN	153	4	-24	-35	-45
Le Sueur River Near Rapidan, MN	2760	94	-8	-35	-53
Minnesota River at Mankato, MN	44	21	10	4	-2
Minnesota River Near Jordan, MN	70	27	13	6	-1
Median	**49**	**25**	**6**	**1**	**-4**

Average	**320**	**33**	**22**	**21**	**23**
Standard Deviation	**782**	**34**	**47**	**62**	**79**

Note: Change (%) is the flow in the (1986-2005) period minus the flow in the (1946-1965) period divided by the flow in the (1946-1965) period times 100%.

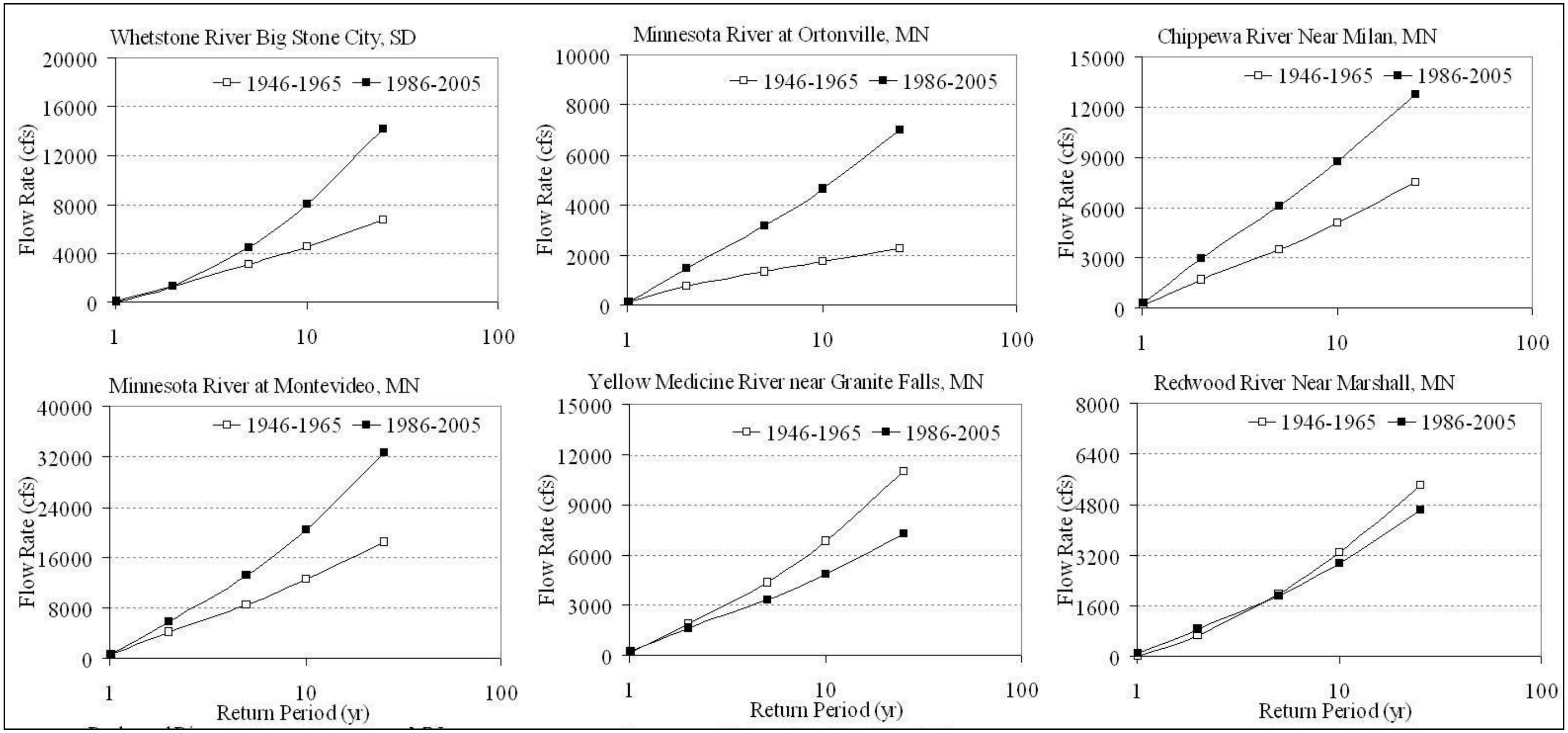

Figure 7.1a. Flood frequencies in the Minnesota River Basin

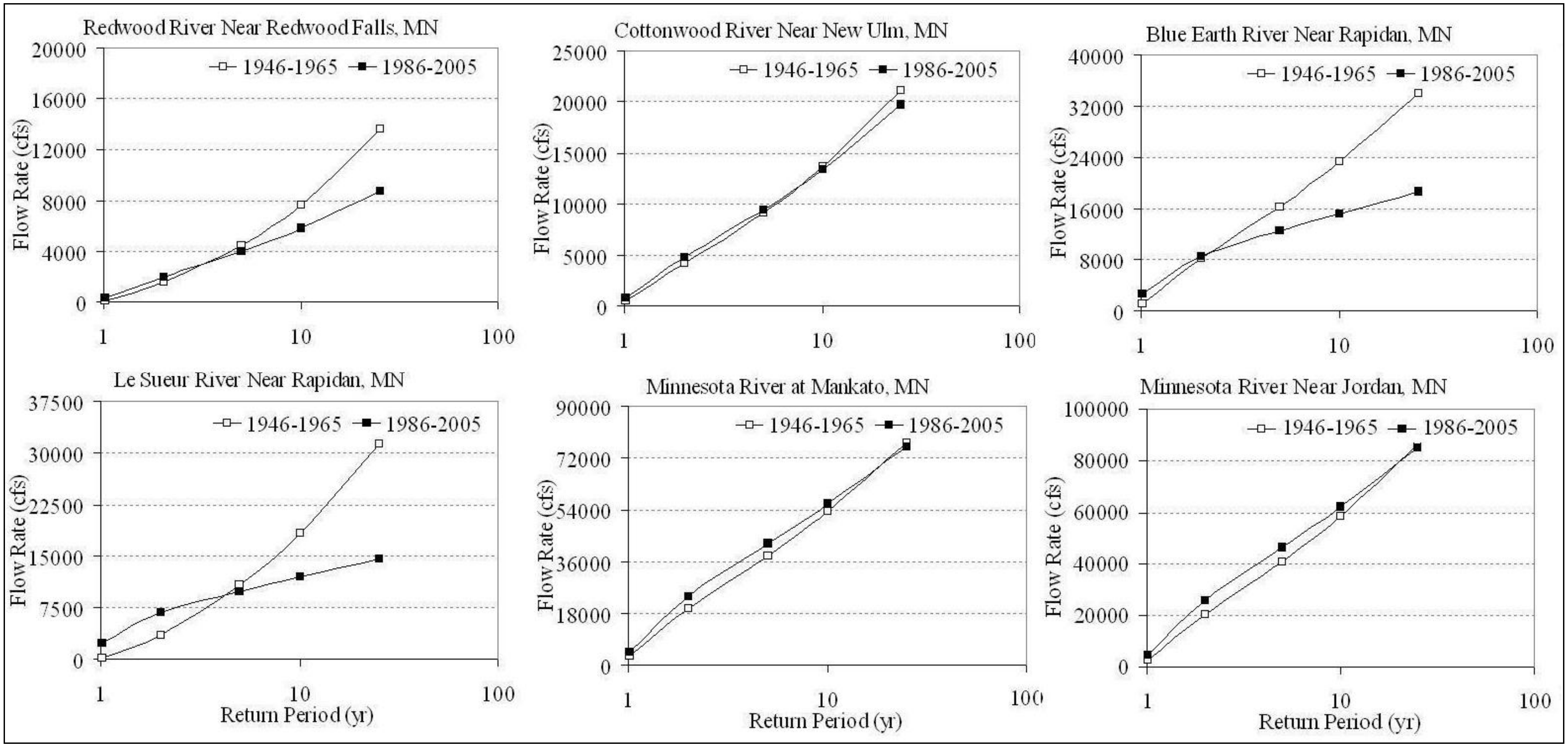

Figure 7.1b. Flood frequencies in the Minnesota River Basin

7.2. Flood frequencies in the Red River of the North Basin

In the Red River of the North Basin, 1-yr (annual) flood flows decreased in magnitude between the 1946-1965 and 1986-2005 periods while flood flows with higher return periods (2- to 25-year floods) became higher (Figure 7.2 and Table 7.2). The patterns and magnitudes of changes were consistent for all stations. The decrease in magnitude of 1-yr flood was in the range of 1% to 65% with a median of 11% (average of 21%) for the six stream gauging stations. The median and the average increases of flood flows with 2- to 25-yr return periods were from 30% to 60%.

Table 7.2. Change (%) in flood flows in the Red River of the North Basin from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Red River of the North at Fargo, ND	-1	57	70	74	76
Buffalo River Near Dilworth, MN	-18	22	34	38	42
Red Lake River at Crookston, MN	-35	6	17	21	25
Red River of the North Grand Forks, ND	-4	54	73	82	91
Red River of the North at Drayton, ND	-5	36	43	45	46
Roseau River Near Milung, MN	-65	27	66	84	100
Median	**-11**	**30**	**54**	**60**	**60**
Average	**-21**	**34**	**50**	**57**	**63**
Standard Deviation	**25**	**19**	**23**	**26**	**30**

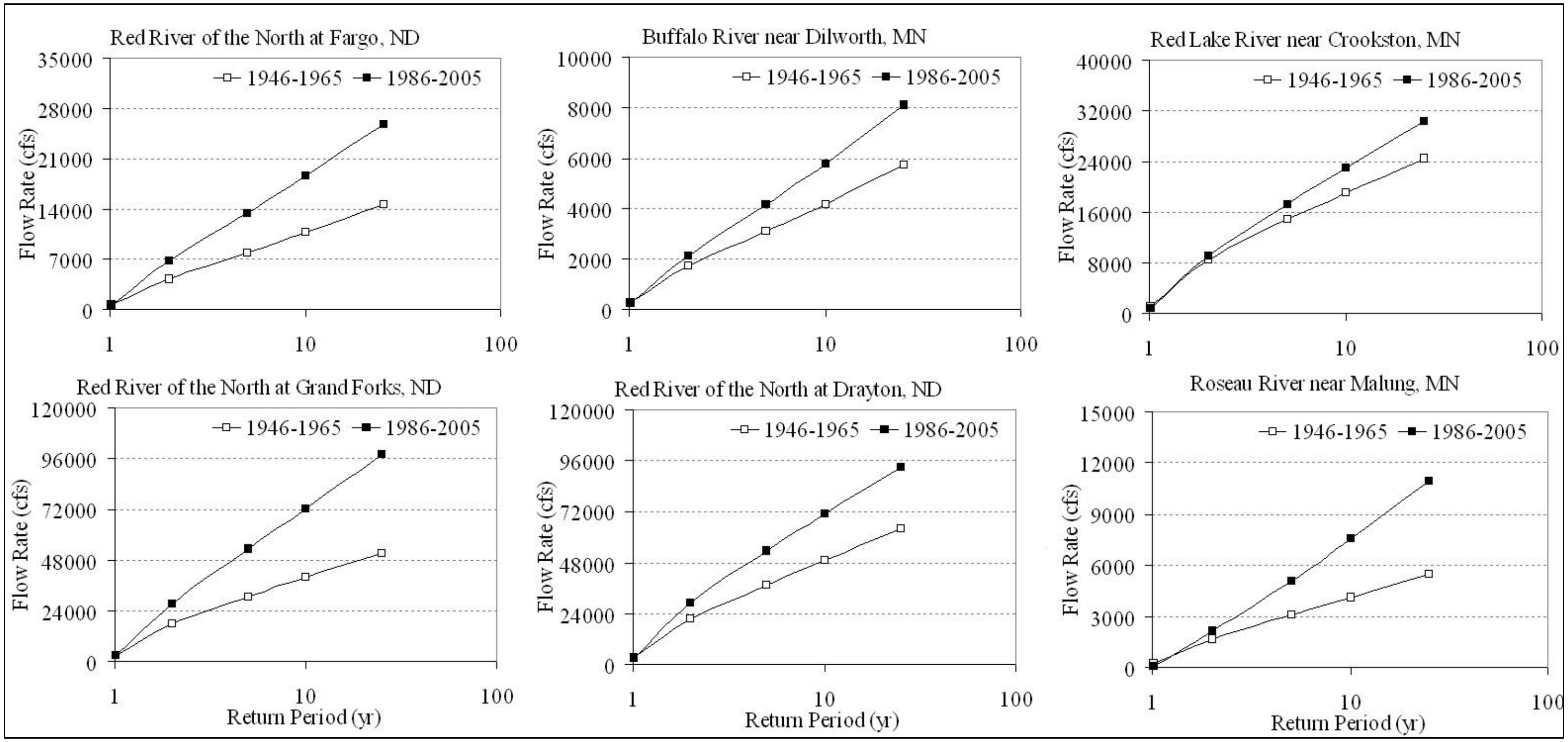

Figure 7.2. Flood frequencies in the Red River of the North Basin

7.3. Flood frequencies in the Rainy River Basin

In two of the station (Sturgeon River near Chisholm, MN, and Little Fork River at Littlefork, MN) in the Rainy River Basin, floods corresponding to 1, 2, 5, 10, and 25-yr floods became lower in the 1986-2005 period (Figure 7.3 and Table 7.3). The decrease in magnitude of 1-yr flood was the largest and the rate of decrease became smaller as return period increased (Table 7.3). In Basswood River near Winton, MN, magnitude of 1-yr flood became 19% lower in the 1986-2005 period, but 2 to 25-yr floods became higher. In Rainy River at Manitou Rapids, MN, magnitudes of 1 and 2-yr floods decreased with a rate of 47% and 19% respectively from 1946 to 2005 while 5, 10 and 25-yr floods increased by about 3-5% (Figure 7.3).

Overall, the flood frequency analysis indicated no increase in flood flows with 1- to 25-yr return periods in the Rainy River Basin. Flood flows on two of the tributaries (Basswood River and Little fork River) decreased, Flood flows on the mainstem (Rainy River at Manitou Rapids) and one tributary (Sturgeon River near Chisholm, MN) remained unchanged. On average, flood flows with 1- to 25-yr return periods were smaller in the 1986-2005 period compared to the 1946-1965 period. The median decreases were from 5% to 36% (average from 8 to 25%).

Table 7.3. Change (%) in flood flows in the Rainy River Basin from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Basswood River Near Winton, MN	19	-12	-21	-25	-29
Sturgeon River Near Chisholm, MN	-47	-11	-4	-3	-3
Little Fork River at Littlefork, MN	-46	-27	-18	-13	-7
Rainy River at Manitou Rapids, MN	-27	-2	3	5	5
Median	**-36**	**-12**	**-20**	**-8**	**-5**
Average	**-25**	**-13**	**-10**	**-9**	**-8**
Standard Deviation	**31**	**10**	**11**	**13**	**15**

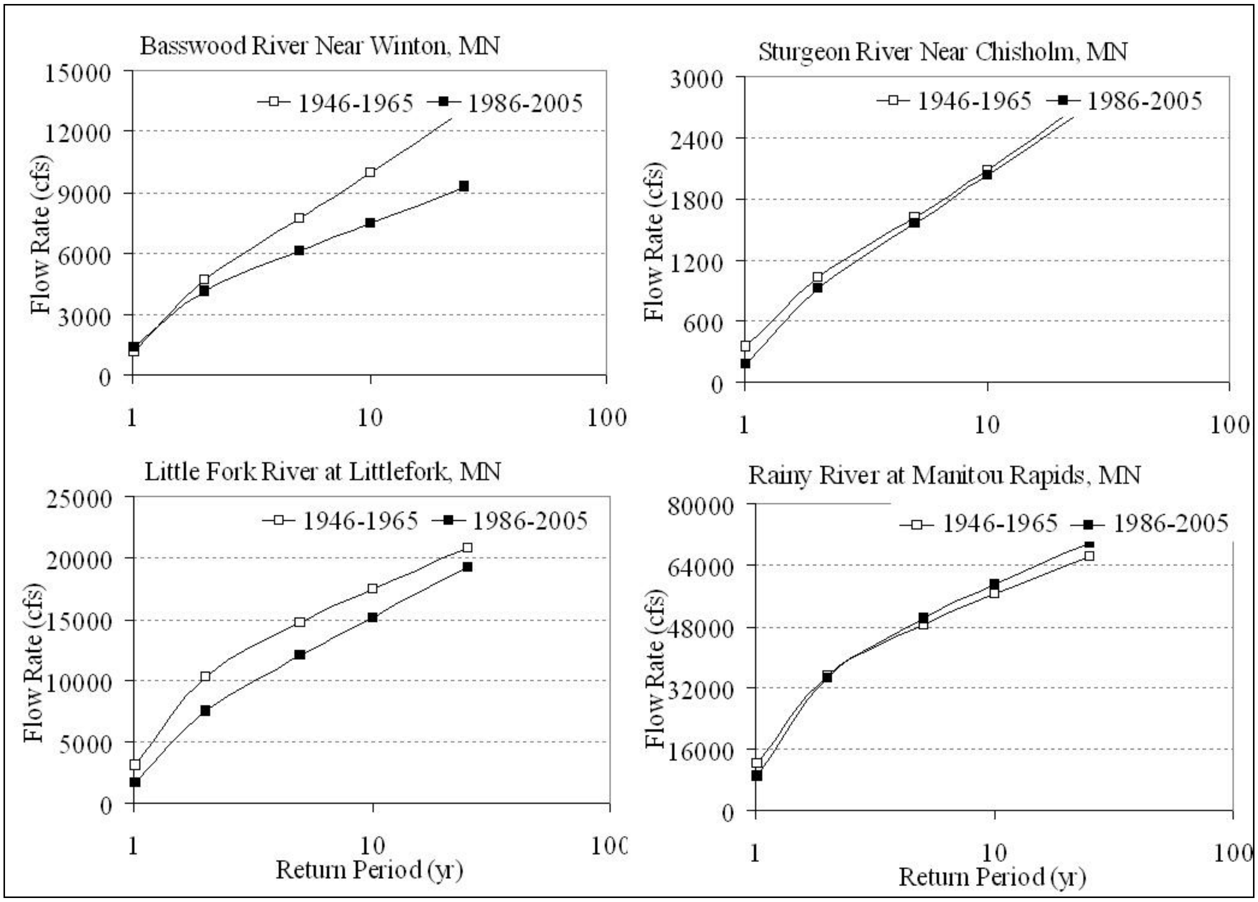

Figure 7.3. Flood frequencies in the Rainy River Basin

7.4. Flood frequencies in tributaries to Lake Superior

Two tributaries to Lake Superior showed inconsistent patterns of changes (Figure 7.4 and Table 7.4). At Pigeon River at Middle Falls, MN, the 1-yr flood flow increased (91%) in the 1986-2005 period, while the 2- to 25-yr flood flows decreased (range of 13% to 58%). In the St. Louis River near Scanlon, MN, the 1- and 2-yr flood flows became lower (38% and 9%, respectively), while the 10-yr and 25-yr floods became higher (4% and 8%, respectively). The 5-yr flood did not show any change. Overall, no significant increase in flood flows was found from the sparse data in the Lake Superior Basin.

Table 7.4. Change (%) in flood flows in tributaries to Lake Superior from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Pigeon River at Middle Falls	91	-13	-33	-41	-48
St. Louis River at Scanlon, MN	-38	-9	0	4	8
Average	**26**	**-11**	**-17**	**-19**	**-20**
Standard Deviation	**91**	**3**	**23**	**32**	**40**

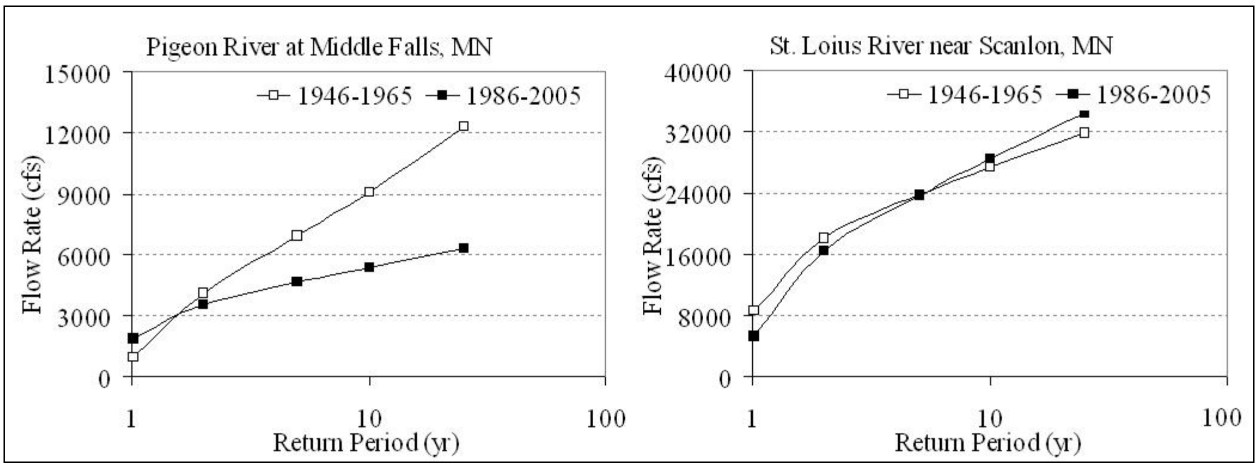

Figure 7.4. Flood frequencies in tributaries to Lake Superior

7.5. Flood frequencies in the Upper Mississippi River Basin

The flood frequency analysis predicted found no overwhelming changes in the 1- to 25-yr return flood flows in the Upper Mississippi River Basin. Although the identified changes were not consistent among all of the 11 stream gauging stations (Figure 7.5), some common patterns are apparent.

On the Mississippi main stem, changes between 1946-1965 and 1986-2005 in annual flood flows (1-year return period) varied from +51% (Grand Rapids,MN, to -9% Prescott,WI). Flood flows with return periods of 2- to 25-years decreased at the three upstream stations (Grand Rapids, Aitken, and Anoka, MN), showed only minor (almost 0%) change at the two stations in the middle reach (St. Paul,MN, and Prescott, WI), and an increase (between 2% for the 25-year return period and 20% for the 2-year return period) at the most downstream station (Winona, MN). The increases in flood flows at St. Paul and Winona, MN. for 2- to 25-year return periods were in the range of 1% to 20%. In other words, there is no indication in increases of major flood flows on the main stem of the Mississippi River.

On the five tributaries to the main stem the changes were relatively modest and mostly negative, i.e. lower flood flows in the 1986-2005 period. For the annual (1-yr return period) flood flow changes had a median of +26%. Floods with 2-year to 25-year return periods changed between +25% and -18% at individual stations with median values from -1% to -6% depending on the return period. The Crow River at Rockford had increased flood flows for all return periods and the Rum River at St. Francis and the St. Croix River at Croix Falls,WI, had decreased flood flows for all return periods above 2-years. The decreases in flood magnitudes were in the range of 3% and 20% (Table 7.5)

Table 7.5. Change (%) in flood flows in the Upper Mississippi River Basin from (1946-1965) to (1986-2005).

	Return Period				
Gauging Station	**1.01**	**2**	**5**	**10**	**25**
Mississippi River at Grand Rapids, MN	51	-1	-20	-30	-39
Mississippi River at Aitkin, MN	28	-14	-15	-12	-8
Crow River at Rockford, MN	26	25	14	6	-2
Rum River Near St. Francis, MN	-14	-18	-18	-16	-14
Mississippi River Near Anoka, MN	-3	-9	-11	-12	-14
Mississippi River at St. Paul, MN	11	13	8	5	1
St. Croix River at St. Croix Falls, WI	-19	-17	-13	-10	-6
Mississippi River at Prescott, WI	-9	0	0	-1	-2
Mississippi River at Winona, MN	16	20	13	8	2
Cedar River Near Austin, MN	82	-1	-3	-1	5
Des Moines River at Jackson, MN	80	17	1	-6	-13
Median	**16**	**-1**	**-3**	**-6**	**-6**

Median (6 stations on the mainstem)	**13**	**-5**	**-5**	**-6**	**-5**
Median (5 tributaries)	**26**	**-1**	**-3**	**-6**	**-6**
Average	**23**	**8**	**-1**	**-3**	**-4**
Standard Deviation	**34**	**15**	**12**	**11**	**12**

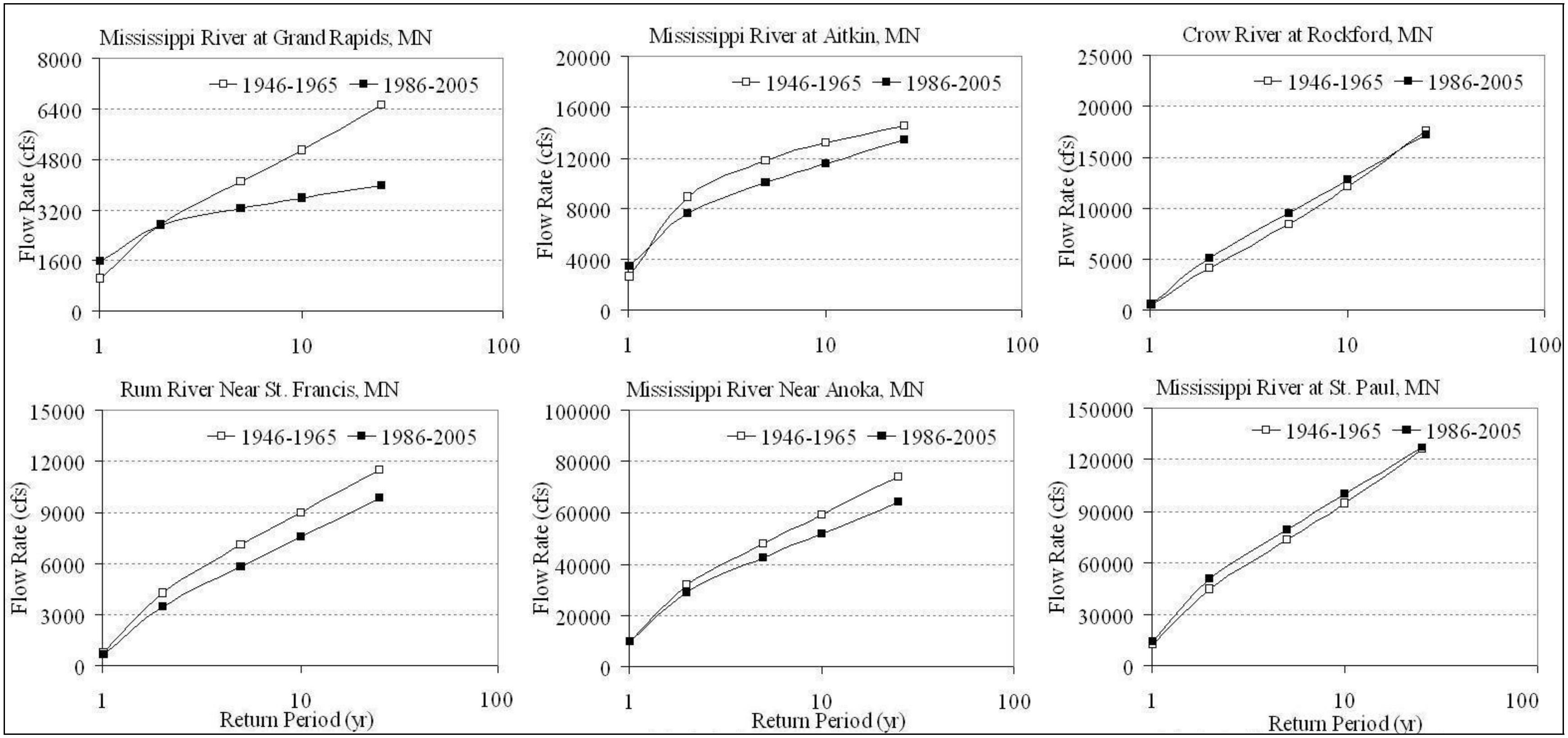

Figure 7.5a. Flood frequencies in the Upper Mississippi River Basin

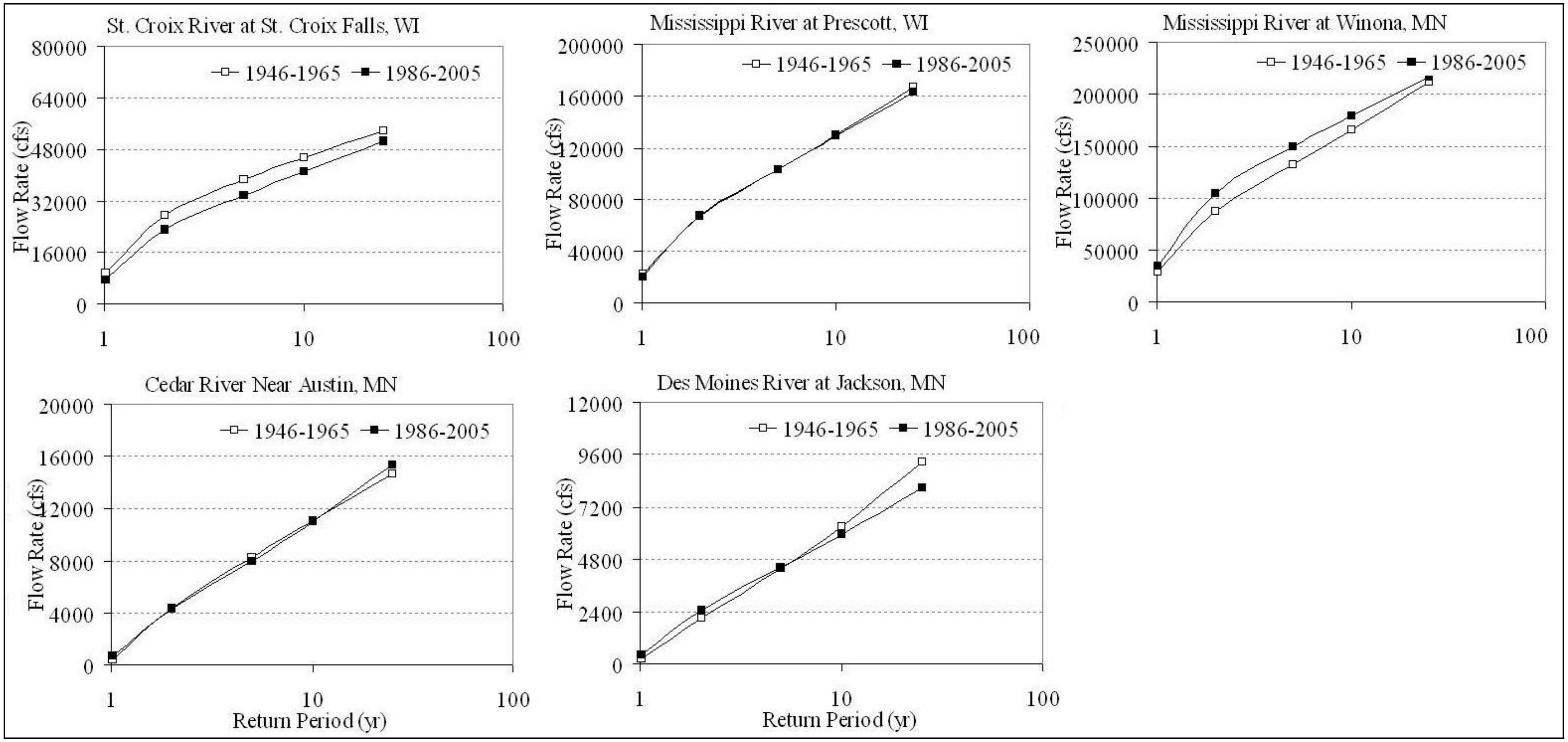

Figure 7.5b. Flood frequencies in the Upper Mississippi River Basin

7.6. Summary of results from flood frequency analysis

Floods with 1- to 25-yr return periods (small to moderate floods) were calculated using recorded stream flow data sets from 36 stream gauging stations in Minnesota for the two 20-year periods (1946-1965) and (1986-2005). The flood frequency analysis showed that observed flood flow characteristics in five river basins of Minnesota changed from 1946 to 2005, but the patterns and magnitudes of changes are not consistent throughout Minnesota. Changes in flood flows in the Rainy River Basin and the Lake Superior Basin had to be determined from a modest data base, and the results showed no consistent or alarming change in flood flows with return periods from 1- to 25-years. There are no definite patterns and the estimated changes are smaller than in the other three river basins. In these three other and major basins in area (Minnesota River, Red River of the North, and Upper Mississippi River Basins) changes were more detectable.

The analysis provided the most consistent results for the Red River of the North Basin. In this basin, magnitudes of 1-yr to 25-yr floods increased at all six stream gauging stations between the two periods analyzed. In the Minnesota River Basin and the Upper Mississippi River Basin, it was found that moderate increases in the magnitude of the most frequent and lowest floods (1-year to 5-year return period) had occurred, while floods of rarer occurrence (10-year and 25-yr return period) had decreased in the 1986-2005 period at many of the stream gauging stations. With regard to the 10- and 25-year floods, the Red River of the North Basin, and the upstream reach of the Minnesota River Basin (which together cover the northwestern portion of Minnesota) therefore showed results opposite to those found in the Upper Mississippi River and the lower Minnesota River Basins. In the Mississippi and lower Minnesota river Basins there were far more stream gauging stations where the 10- and 25-year floods had decreased in magnitude in the 1986-2005 period relative to the 1946-1965 period.

8. RESULTS – LOW FLOW FREQUENCIES

7-day annual (average) low flows corresponding to 2, 5, 10 and 20-year return periods were calculated for the 1946-1965 and 1986-2005 periods. Table 8.1 provides the changes in low flows from 1946-1965 to 1986-2005. We omitted the extreme values (i.e., values higher than 500%) from this table and provided the actual magnitudes of low flows in Appendix E.

The most consistent and largest changes in low flows were observed in the Minnesota River Basin. 7Q2, 7Q5, 7Q10, and 7Q20 values showed an increase at all stations from the 1946-1965 to the 1986-2005 period. The changes were largest for 2-year 7-day annual (average) low flows (most frequent low flows) and comparatively smaller for the 7-day annual (average) low flows of rarer occurrence (corresponding to 5-, 10- and 20-yr return periods). The largest changes in 7Q2, 7Q10 and 7Q20 values were observed at the Le Sueur River near Rapidan and the largest change in 7Q5 was observed in the Redwood River near Redwood Falls.

Considerable changes in 7-day average low flows were also observed in the Red River of the North and Upper Mississippi River Basins from the 1946-1965 to the 1986-2005 period. The changes although not as large as the changes observed in the Minnesota River Basin followed a similar pattern. In both river basins 7Q2, 7Q5, 7Q10, and 7Q20 values were larger in the 1986-2005 period at the majority of the stations. The changes were largest for most frequent low flows and smaller for rarer occurrence low flows.

Changes observed in the Rainy River Basin and Tributaries to Lake Superior were small and variable.

The results of the low flow frequency analysis support the findings obtained from flow duration curves and the analysis of 7-day annual (average) low flow occurrence in the earlier sections of this report. The Minnesota River Basin, the Red River of the North Basin, and the Upper Mississippi River Basin experienced bigger changes in low flows than the Rainy River Basin and Tributaries to Lake Superior.

Table 8.1. Changes (%) in 7-day (average) low flows of 2-, 5-, 10-, and 20- year return periods from 1946-1965 to 1986-2005.

	Return Period (yr)			
Stream/River Name	**2**	**5**	**10**	**20**
Minnesota River Basin				
Whetstone River Big Stone City, SD	131	63	33	11
Minnesota River at Ortonville, MN	159	69	30	4
Chippewa River Near Milan, MN	209	191	197	-
Minnesota River at Montevideo, MN	171	107	76	-
Yellow Medicine River Granite Falls, MN	319	198	148	112

Redwood River Near Marshall, MN	625	424	332	269
Redwood River Near Redwood Falls, MN	-	-	-	-
Cottonwood River Near New Ulm, MN	145	52	56	-
Blue Earth River Near Rapidan, MN	117	41	9	-13
Le Sueur River Near Rapidan, MN	-	-	-	360
Minnesota River at Mankato, MN	-	382	173	61
Minnesota River Near Jordan, MN	-	-	-	-
Average	**215**	**170**	**117**	**115**
Standard Deviation	**121**	**145**	**105**	**145**
<u>Red River of the North Basin</u>				
Red River of the North at Fargo, ND	-27	-86	-100	-
Buffalo River Near Dilworth, MN	81	24	-4	-
Red Lake River at Crookston, MN	78	30	3	-17
Red River of the North Grand Forks, ND	39	41	44	50
Red River of the North at Drayton, ND	124	81	61	45
Roseau River Near Milung, MN	110	64	40	22
Average	**68**	**26**	**8**	**25**
Standard Deviation	**50**	**54**	**53**	**26**
<u>Rainy River Basin</u>				
Basswood River Near Winton, MN	-13	-14	-14	-15
Namakan River at outlet of Lac La Croix	39	23	13	5
Sturgeon River Near Chisholm, MN	82	51	18	-13
Little Fork River at Littlefork, MN	9	10	9	7
Rainy River at Manitou Rapids, MN	6	5	4	5
Average	**25**	**15**	**6**	**-2**
Standard Deviation	**37**	**24**	**12**	**11**
<u>Tributaries to Lake Superior</u>				
Pigeon River at Middle Falls	-29	-	-54	-59
St. Louis River at Scanlon, MN	-4	-93	-35	-
Average	**-16**	**-**	**-44**	**-**

Standard Deviation	**18**	**-**	**13**	**-**
<u>Upper Mississippi River Basin</u>				
Mississippi River at Grand Rapids, MN	37	135	244	383
Mississippi River at Aitkin, MN	61	29	6	-
Crow River at Rockford, MN	373	-	-	-
Rum River Near St. Francis, MN	66	59	54	51
Mississippi River Near Anoka, MN	24	16	12	8
Mississippi River at St. Paul, MN	31	14	1	-
St. Croix River at St. Croix Falls, WI	9	3	-2	-6
Mississippi River at Prescott, WI	25	10	1	-8
Mississippi River at Winona, MN	9	7	2	-4
Cedar River Near Austin, MN	227	128	79	43
Des Moines River at Jackson, MN	-11	-1	10	23
Average	**77**	**40**	**41**	**61**
Standard Deviation	**117**	**51**	**76**	**132**

9. DISCUSSION

In the Minnesota River, Red River of the North, and Upper Mississippi River Basins an upward shift in stream flow rates appears to have occurred between 1946 and 2005. The 7-day average low flow appears to have become significantly higher, but annual peak flows have also increased at the majority of the stream gauging stations analyzed in these three basins. Annual (1-year return period) flood flows seem to fit this trend also, but rarer floods with 10- or 25-year return periods appear to have increased in magnitude only in the northwestern region of Minnesota (Red river of the North and upper Minnesota River). In the Rainy River Basin and in tributaries to Lake Superior, we found smaller and inconsistent changes in stream flow characteristics from 1946 to 2005.

These results are consistent with previous studies by Changnon and Kunkel (1995), Schilling and Libra (2003) in Iowa and Gebert and Klug (1996) in Wisconsin. Changnon and Kunkel (1995) found upward trends in flood flows that occur either in the warm-season (May-November) or in the cold-season (December-April) in Minnesota. An analysis of historical stream flow records from 38 USGS stream gauging stations in Minnesota (Novotny and Stefan, 2007) showed significant upward trends in seven stream-flow statistics including mean annual flows, peak and low flows, and number of days with high and low flows. Peak flows due to rainfall and low flows throughout the year were found to be increasing, but regional differences were pronounced. Stream flow changes in three river basins of Minnesota (Minnesota River, Upper Mississippi, and Red River of the North) were significantly larger than in two other basins (Rainy River and Lake Superior). This regional difference agrees with the findings of this study.

Although not an objective of this study, there are potentially multiple causes for the changes or the lack of changes in the observed stream flows. Precipitation is one obvious potential cause. An upward trend in precipitation in the midwestern region of the U.S. has been documented (Karl et al., 1996; Lettenmaier et al., 1994). The increase in precipitation for Minnesota was reported to be 10% to 20% per century (Karl et al., 1996). Heavy-precipitation amounts in Minnesota (e.g., from 7-day precipitation events at the 1-yr recurrence level) increased from 1921 to 1985 according to Changnon and Kunkel (1995). Novotny and Stefan (2007) reported strong correlations between mean annual stream flow changes and total annual precipitation changes. Figures 9.1 and 9.2 show annual average air temperature and annual precipitation in 9 climate divisions of Minnesota for the 1917-2002 period (Novotny and Stefan 2007).

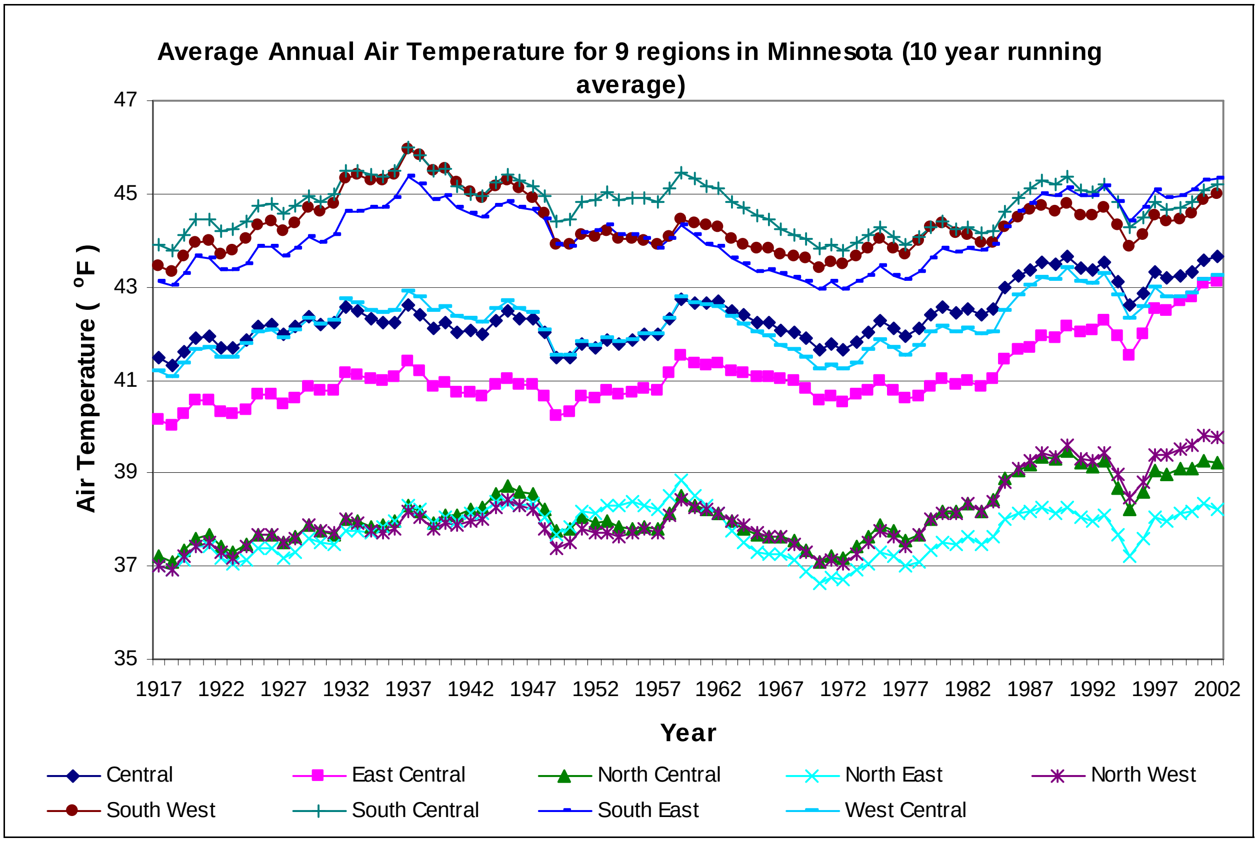

Figure 9.1. Average annual air temperature for 9 climate divisions of Minnesota (10 year running average) (from Novotny and Stefan 2007)

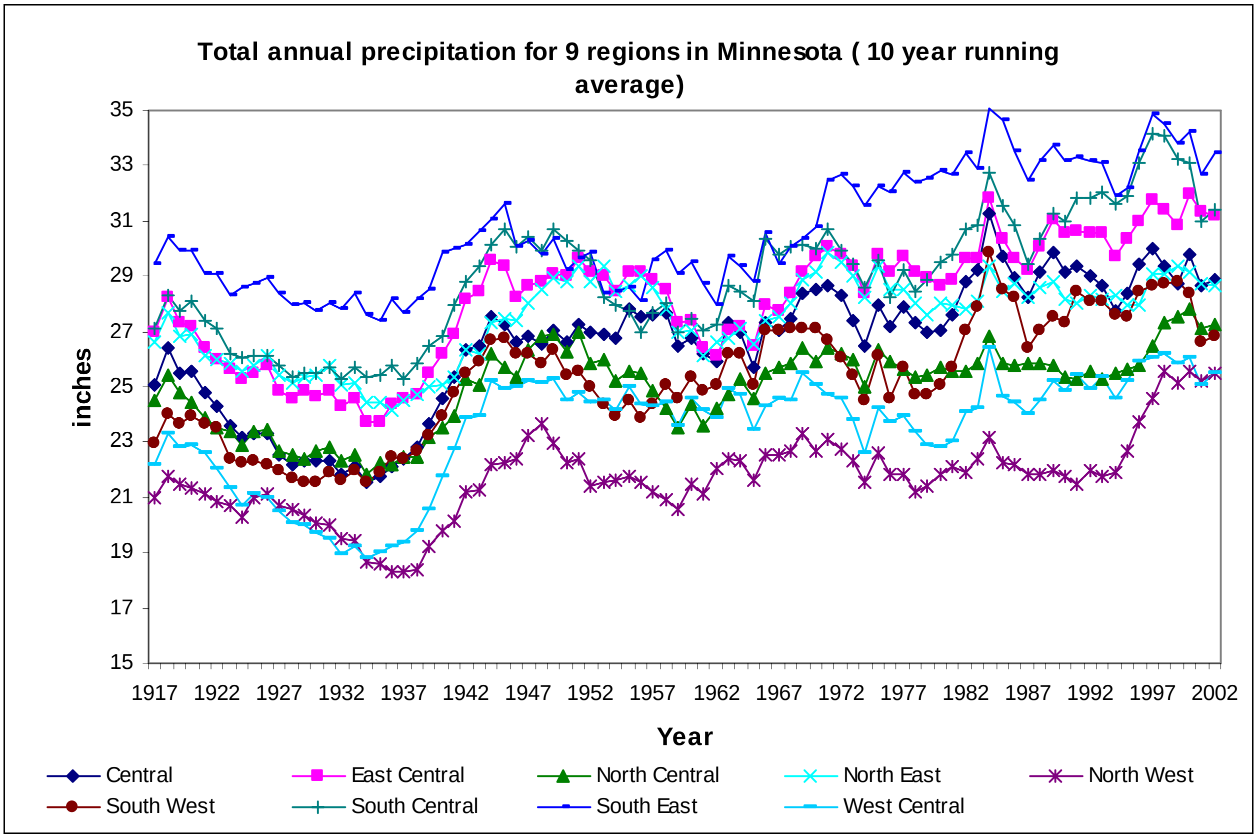

Figure 9.2. Total annual precipitation for 9 climate divisions of Minnesota (10 year running average) (from Novotny and Stefan 2007)

We also calculated the trends in precipitation and air temperature in the nine climate divisions of Minnesota (Figure 2.1) for the 1946-2005 period using a linear regression method. Precipitation showed an upward trend for all nine divisions from 1946 to 2005 (Table 9.1). The trends in precipitation in divisions 1, 5, 6, 7, 8, 9, and SD3 (South Dakota division 3) were significant at the 0.1 level. The largest increase in precipitation was in division 9 (0.114 in yr^{-1} or 2.89 mm yr^{-1}) and the lowest in division 3 (0.005 in yr^{-1} or 0.13 mm yr^{-1}). Precipitation trends, i.e., increases in precipitation, are more evident in the southern portions of the Minnesota. Air temperatures also had an upward trend for the 1946-2005 period (Table 9.1). All trends, except for divisions 3, 8, and SD4 (South Dakota division 4) were significant. The highest rate of temperature increase was observed in division 6 (0.047 ^{o}F yr^{-1} or 0.026^{o}C yr) and the lowest in division 3 (0.005^{o}F yr^{-1} or 0.003^{o}C yr). The rates of air temperature increase seem independent of geographic location. The increase in division 6 is probably linked to urbanization (Twin cities metropolitan area).

Table 9.1. Trends in precipitation and temperature from 1946 to 2005 (* indicates that the trend is significant at the 0.1 level).

Climate Division	Trend in Precipitation (in yr^{-1})	Trend in Temperature ($^{o}F\ yr^{-1}$)
1	0.060*	0.048*
2	0.032	0.035*
3	0.005	0.005
4	0.030	0.031*
5	0.068*	0.039*
6	0.079*	0.047*
7	0.072*	0.021*
8	0.094*	0.008
9	0.114*	0.030*
SD 3	0.077*	0.029*
SD 4	0.016	0.013
WI 1	0.053	0.026*

Our analysis showed that the river basins which showed the largest increases in stream flows drain climate divisions where significant increases in precipitation have been observed, while the basins which show little or no change in stream flows drain climate divisions where changes in precipitation have not been significant. For example, the drainage area of the Minnesota River Basin includes the climate divisions 4, 5, 7, 8 of Minnesota (Figure 2.1) and two climate divisions of South Dakota (SD 3, and SD4). Upward trends in precipitation were observed in climate divisions 5, 7 and 8 and SD4. Climate division 1 had a significant increase in precipitation, and covers the Red River of the North Basin. The Rainy River Basin and the Lake Superior Basin drain climate divisions 2 and 3, where no significant increase in precipitation has been recorded.

Changes in agricultural drainage and crop patterns can contribute significantly to changes in stream flows. A study conducted in the LeSueur and Cottonwood River watersheds in the Minnesota River Basin indicated that increases in baseflow, stormwater runoff, and 7-day low flows after 1950s are most likely due to the intensification of agricultural drainage and corn and soybean cultivation rather than climatic change (Ennaanay, 2006).

10. SUMMARY & CONCLUSIONS

We analyzed historical (1946 to 2005) flow records from 36 USGS stream gauging stations in Minnesota to identify changes in flow characteristics over the period of record. Flow duration curves, the occurrence of extreme peak and low stream flows, and flood and low-flow frequencies were analyzed. The basic data were mean and peak daily flow data from 36 USGS stream gauging stations (Table 3.1) located in five river basins of Minnesota (Minnesota River, Rainy River, Red River of the North, Lake Superior, Upper Mississippi River Basins). From these basic data, 7-day average low flows were extracted. The analysis period was 60 years, from 1946 to 2005. Because this study followed a previous study of Minnesota stream flows (Novotny and Stefan, 2007) this study focused on changes in two distinct periods, one from 1946-1965, and the other from 1986 to 2005. Most of the analysis was conducted on the data sets (7220 daily and peak stream flows) for these two 20-year sample periods. The results can be summarized as follows:

1) The largest stream flow changes were observed in the Minnesota River Basin, the Red River of the North Basin, and the Upper Mississippi River Basin from 1946 to 2005. In these river basins, low, medium, and high daily stream flows increased.
2) Magnitudes of floods, as exemplifies by the 25-yr floods, increased in the 1986-2005 period only in the Red River of the North and the Upper Minnesota River Basin. In all other Basins the magnitude of the 25-year floods decreased or remained more or less the same. Floods in Minnesota have often been due to snowmelt, sometimes combined with rainfall.
3) The occurrence of peak stream flow events may have shifted somewhat during the 1946 to 2005 period, at least in the Minnesota River Basin and the Red River of the North Basin. Six of the twelve stream gauging stations, all in the upper reaches of the Minnesota River Basin, had more than the expected number of annual peak flow events in the 1986-2005 period. In the Red River of the North Basin, up to 5 of 6 stations had more than the expected number of annual peak flow events in the recent period (1986 to

2005). In the Rainy River Basin and in tributary streams to Lake Superior the temporal distribution of annual peak flow events does not seem to have changed. In the Upper Mississippi River Basin the evidence of change is mixed: only 2 of 11 stream gauging stations show a shift in the occurrence of the rarest peak flow events, but peak flows that are in the top 10 have occurred more often at 6 of the 11 stream gauging stations on the Upper Mississippi River in the recent period (1986-2005).

4) The 7-day average low flows were higher in the 1986-2005 period than in the 1946-1965 period. Frequent 7-day annual (average) lows flows (i.e., low flows with 2-yr return period) increased more than the 7-day low flows of rarer occurrence (i.e., 20-yr return period).
5) Of the five river basins analyzed, the Minnesota River Basin has experienced the largest stream flow changes compared to the other four basins. In that basin high, medium, and low flows increased significantly from the 1946-1965 period to the1986-2005 period. The increases in Q5, Q50, and Q95 were on average 79%, 203%, and 148%, respectively. All 12 stations in this river basin had more than the expected number of 7-day (average) low flow events in the 1986-2005 period. Frequencies of occurrence of 7-day annual (average) low flows having 2 to 20 yr return periods were higher for all stations in the recent period too. At about half of the stream gauging stations, more than expected number of annual peak flow events was observed in the 1986-2005 period. Flood frequency analysis showed that, on average, magnitudes of the 1-, 2-, 5-, 10- and 25-yr floods increased by about 20 to 30%. The likely cause for these changes is not only the change in precipitation (climate) but also the change in agricultural practices.
6) In the Red River of the North Basin, Q5, Q50, and Q95 increased on average 55%, 62%, and 0%, respectively, from the 1946-1965 period to the1986-2005 period. All 6 stations in this river basin had higher than expected 7-day average low flows in the 1986-2005 period. At about 60% of the stations, more than expected number of annual peak flow events occurred in the 1986-2005 period. The 1-yr flood flow decreased on average about 20% while the 2-, 5-, 10- and 25-yr floods increased on the order of 30% to 60% in the 1986-2005 period.
7) In the Upper Mississippi River Basin, Q5, Q50, and Q95 increased on average 29%, 82%, and 435%, respectively, from the 1946-1965 period to the1986-2005 period. About

60% of the gauging station in this river basin had higher than expected 7-day average low flow events in the 1986-2005 period. An increase in the occurrence of peak flow events was not found. The 1- and 2-yr flood flows became, on average, about 20% and 8% higher, while the 5-, 10- and 25-yr flood flows did not change significantly in magnitude.

8) Changes in low, medium, and high flows in the Rainy River Basin and in tributaries to Lake Superior from 1946 to 2005 were determined from a relatively sparse data base, and were found to be lower (about 10 to 30%) compared to the other three basins.
9) There are potentially multiple causes for the changes or the lack of changes in the observed stream flows. Precipitation and land use changes are two potentially major causes for changes. Trends observed in precipitation data in the climate divisions of Minnesota support the findings from the analysis of stream flow records. However, more analysis is required to identify their roles individually.

ACKNOWLEDGMENTS

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Appendix A: Flow Duration Curves for the exceedence of a given flow on Log-log plots for the periods 1946 - 1965 and 1986 - 2005.

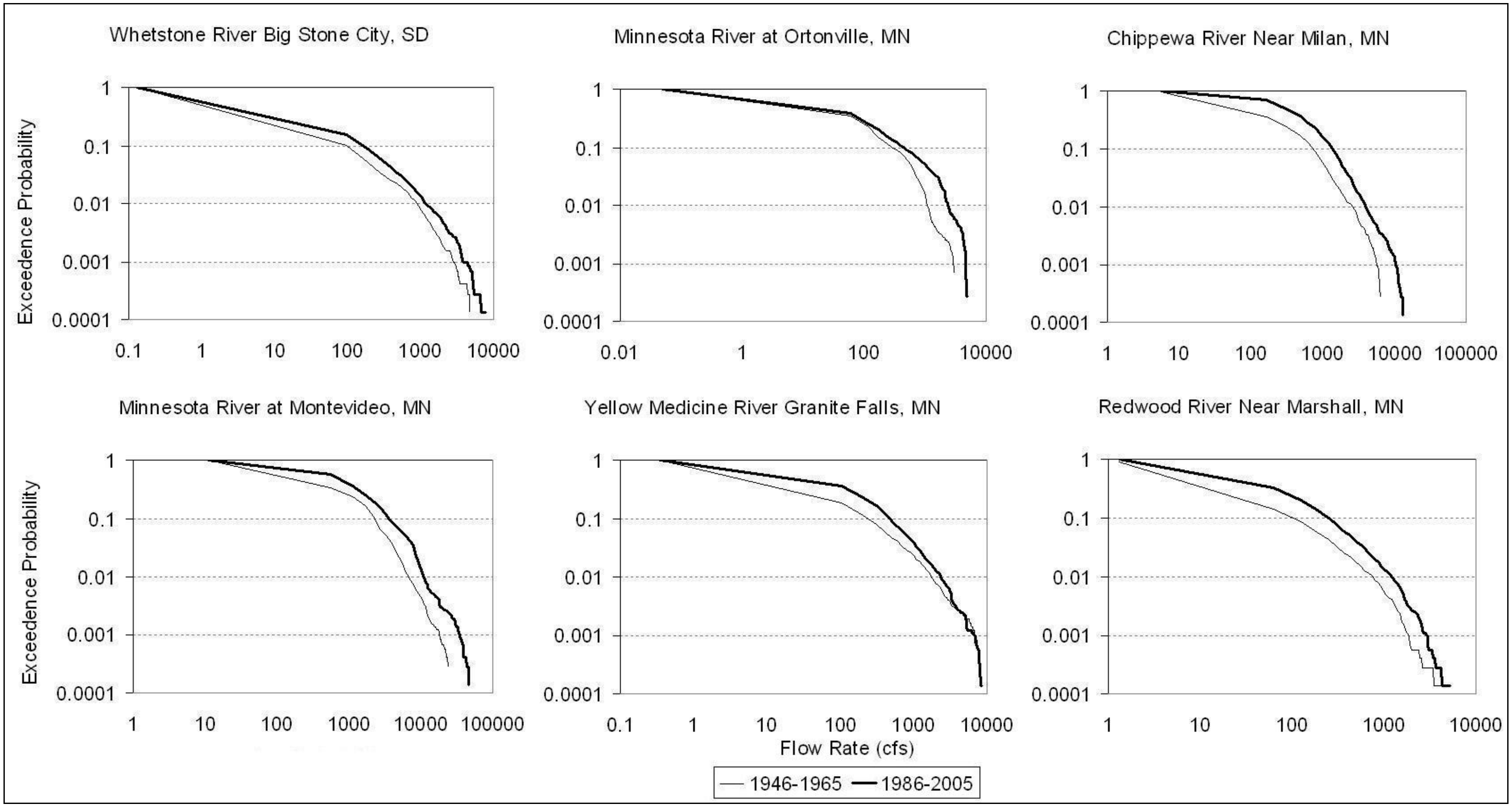

Figure A.1a. Flow Duration Curves for the Minnesota River Basin on Log-log plots.

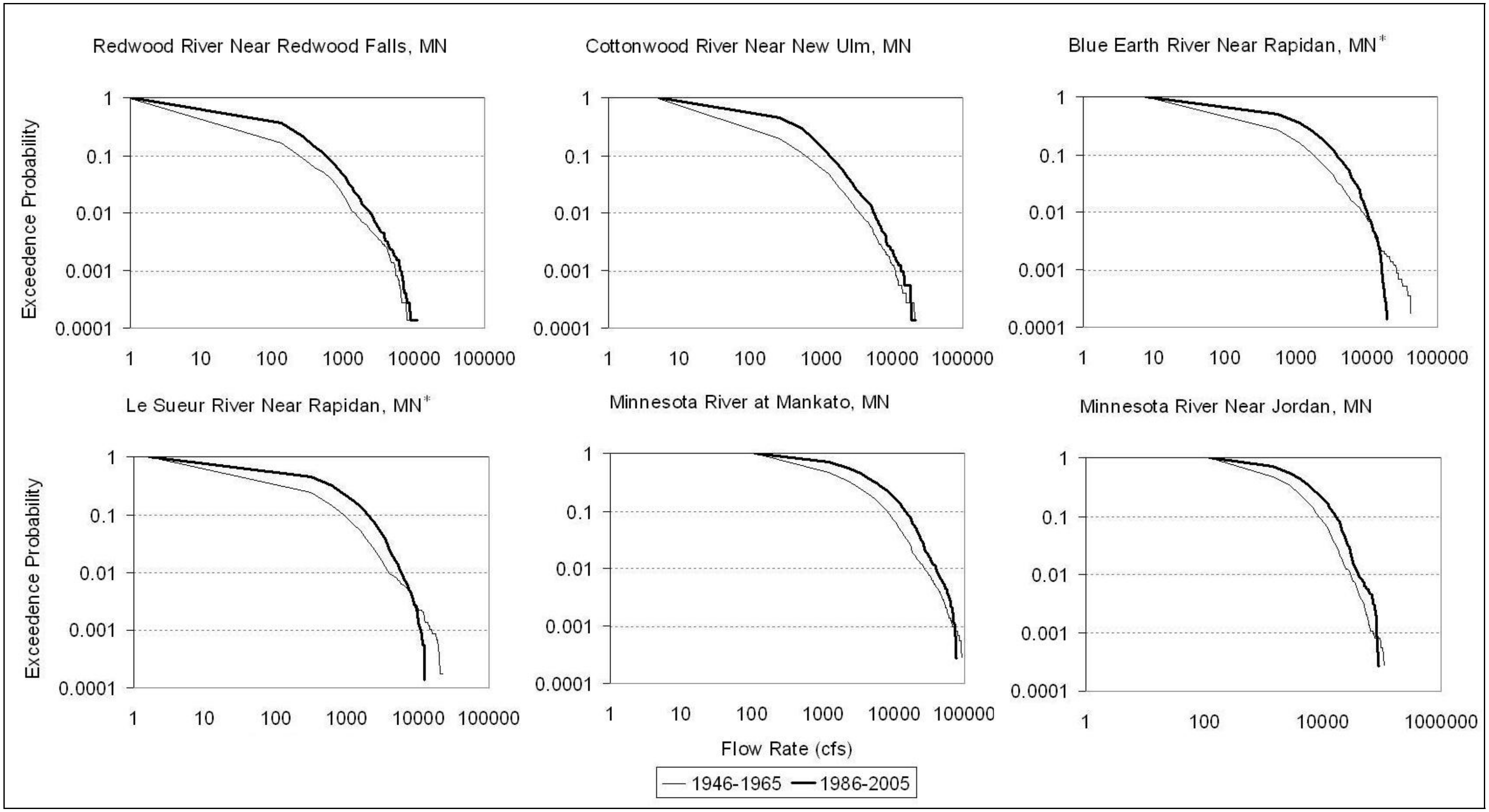

Figure A.1b. Flow Duration Curves for the Minnesota River Basin on Log-log plots.

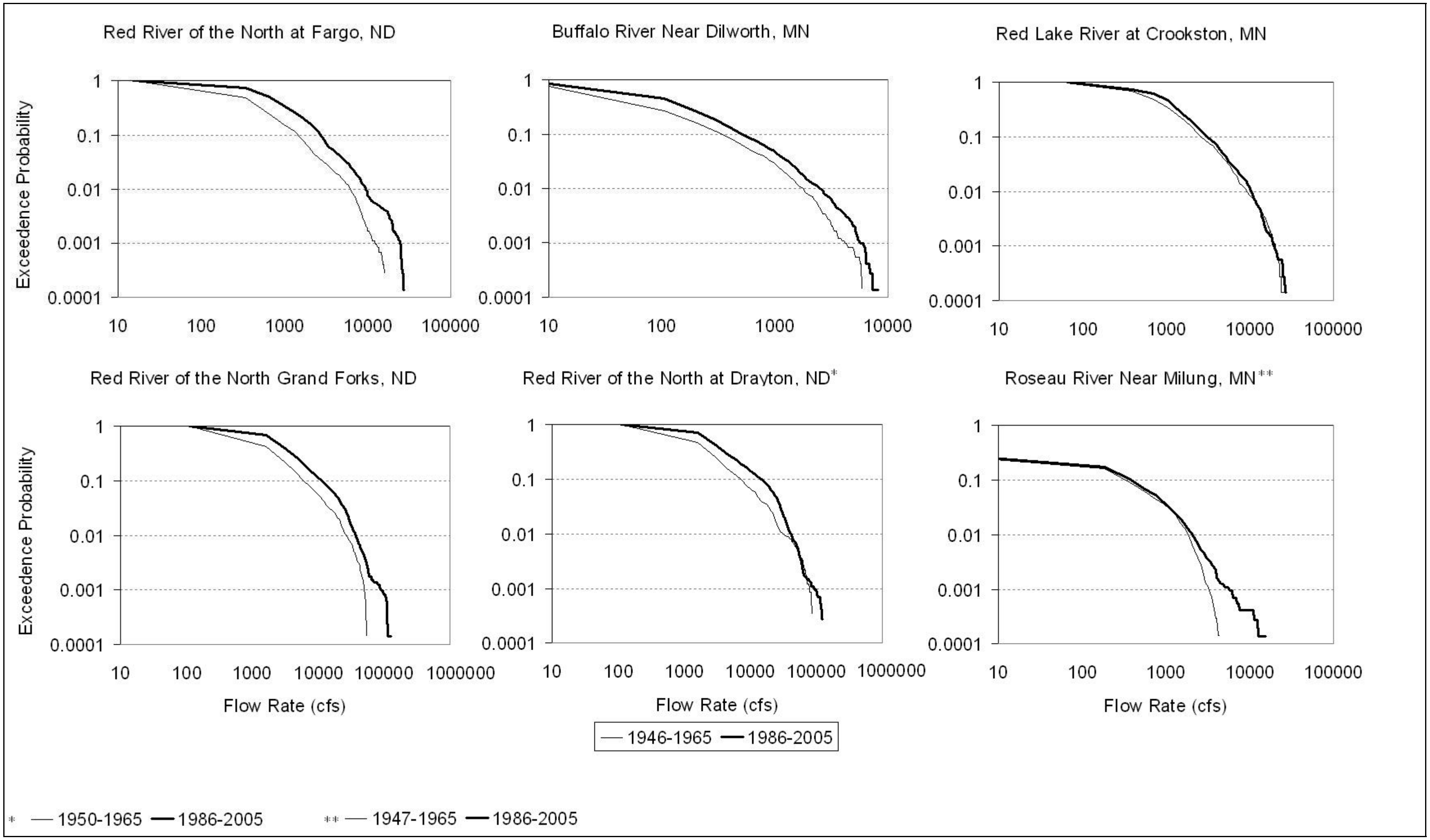

Figure A.2. Flow Duration Curves for the Red River of the North Basin on Log-log plots.

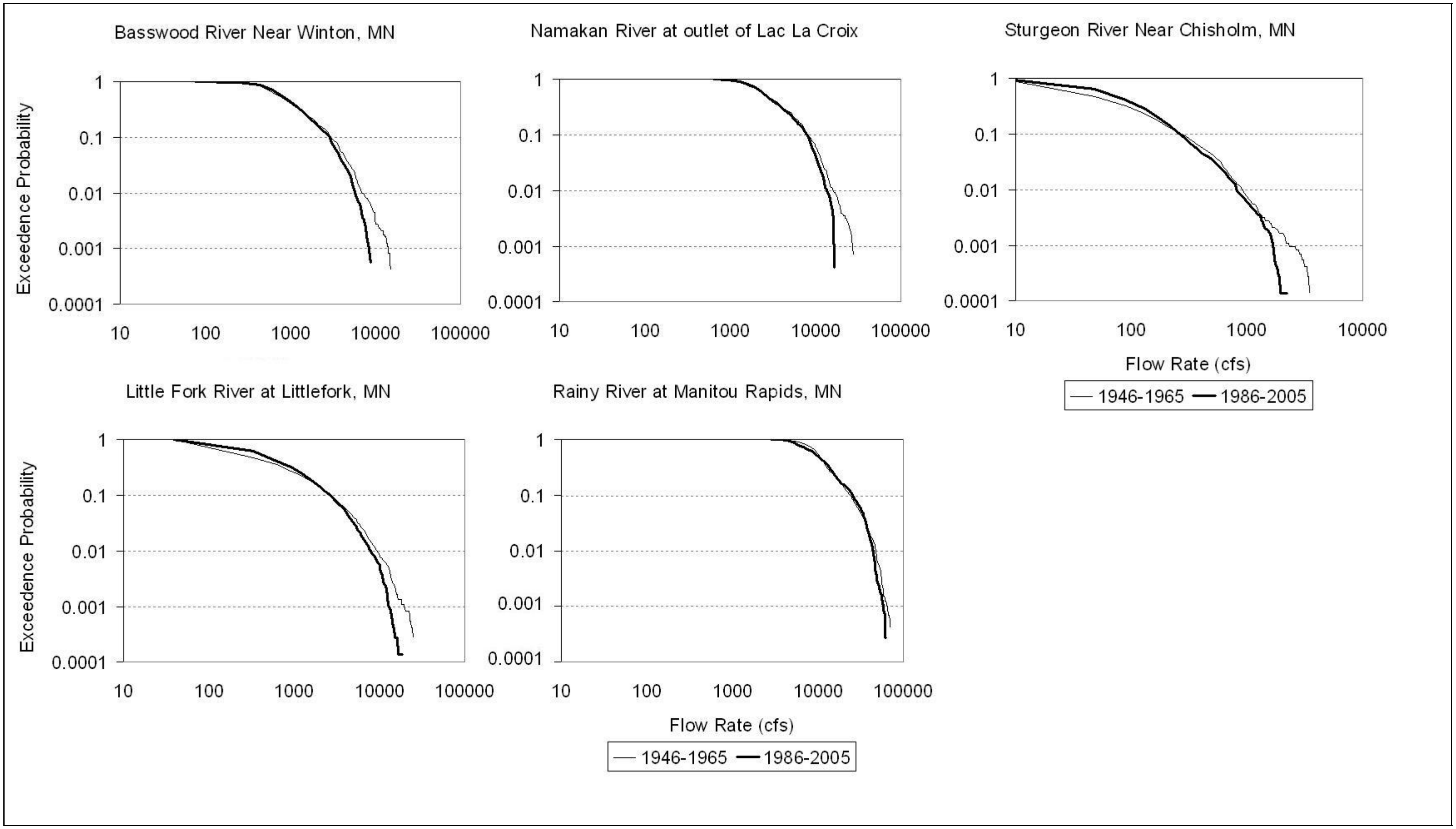

Figure A.3. Flow Duration Curves for the Rainy River Basin on Log-log plots.

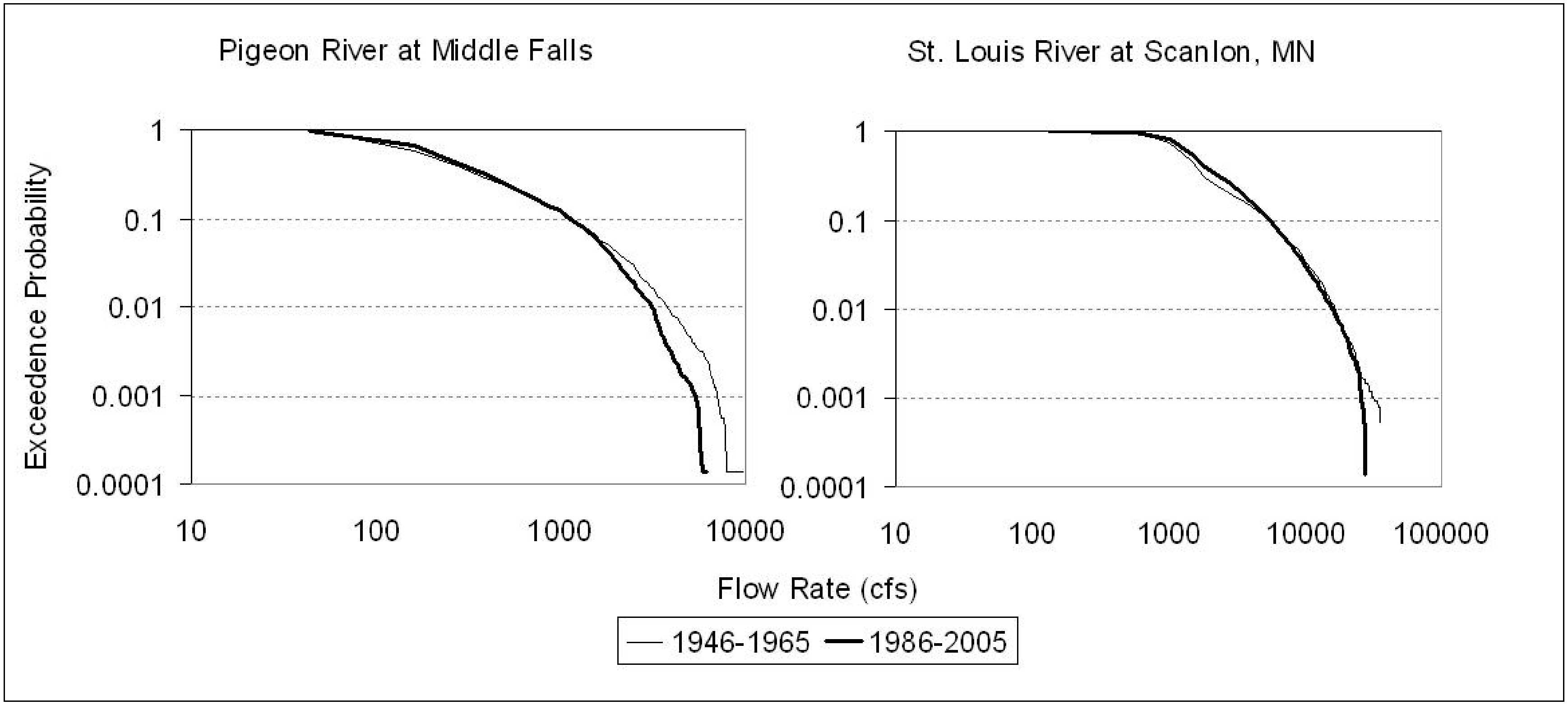

Figure A.4. Flow Duration Curves for tributaries to Lake Superior on Log-log plots.

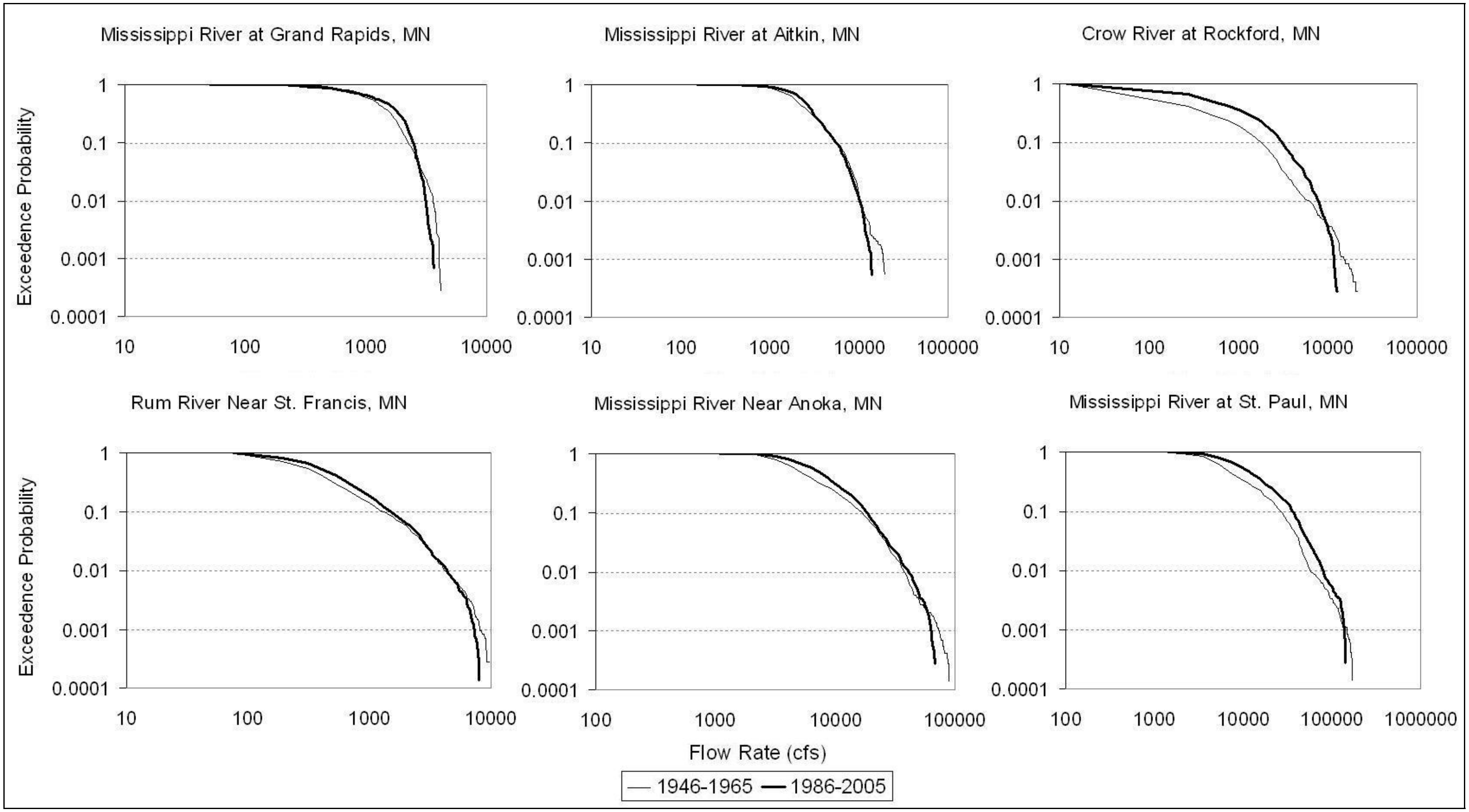

Figure A.5a. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots.

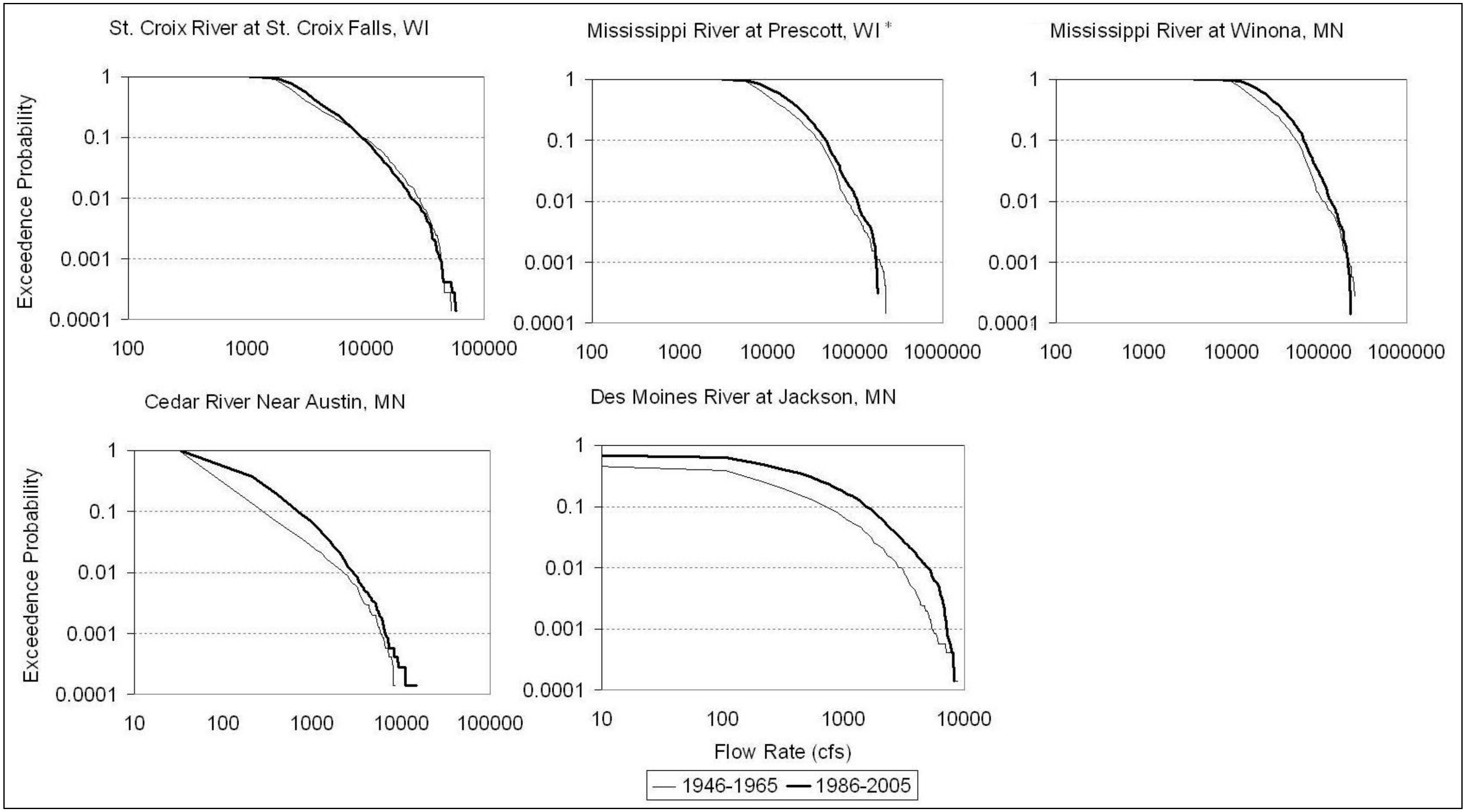

Figure A.5b. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots.

Appendix B: Flow Duration Curves for the non-exceedence of a given flow on Log-log plots for the periods 1946 - 1965 and 1986 - 2005.

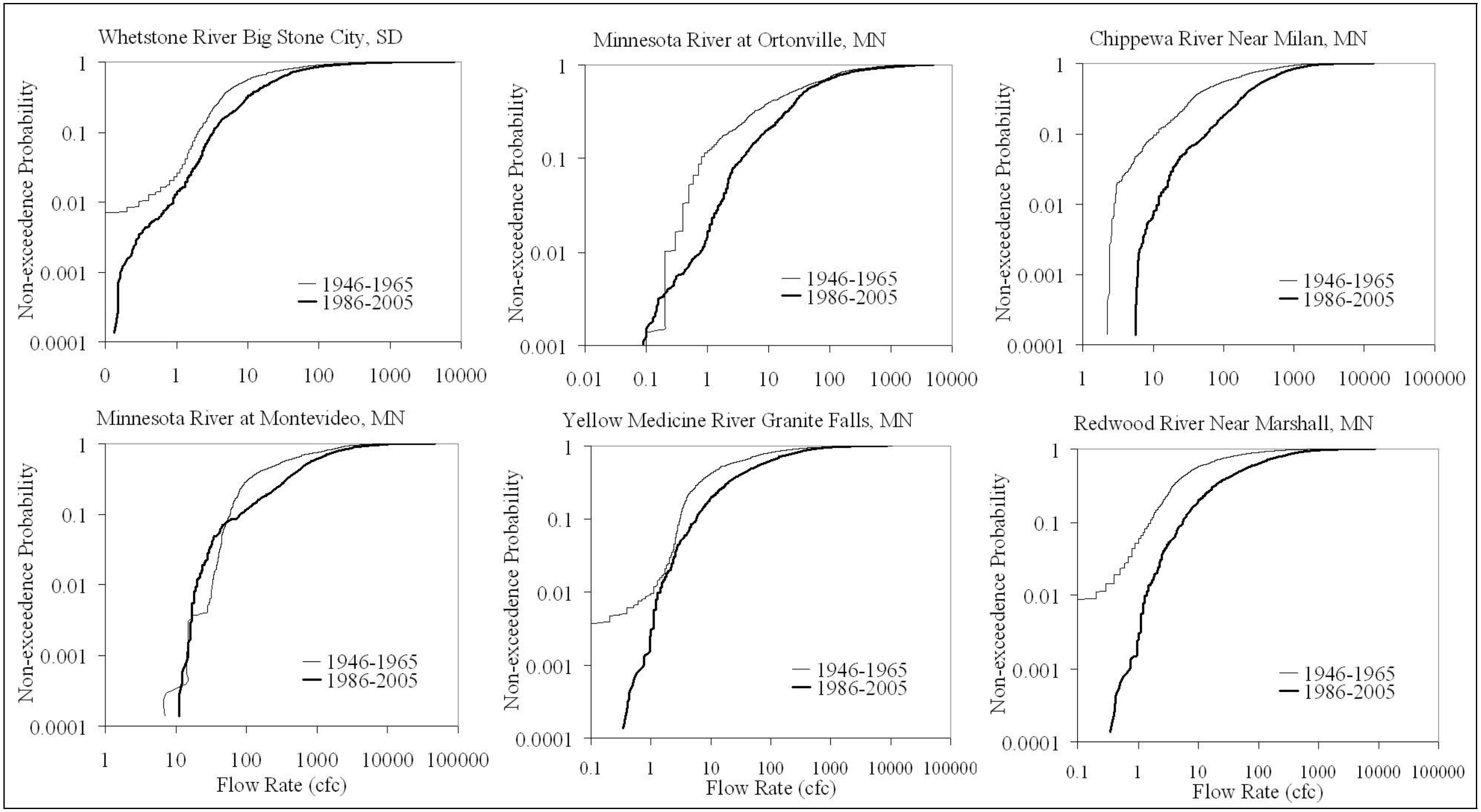

Figure B.1a. Flow Duration Curves for the Minnesota River Basin on Log-log plots for non-exceedence of a given flow.

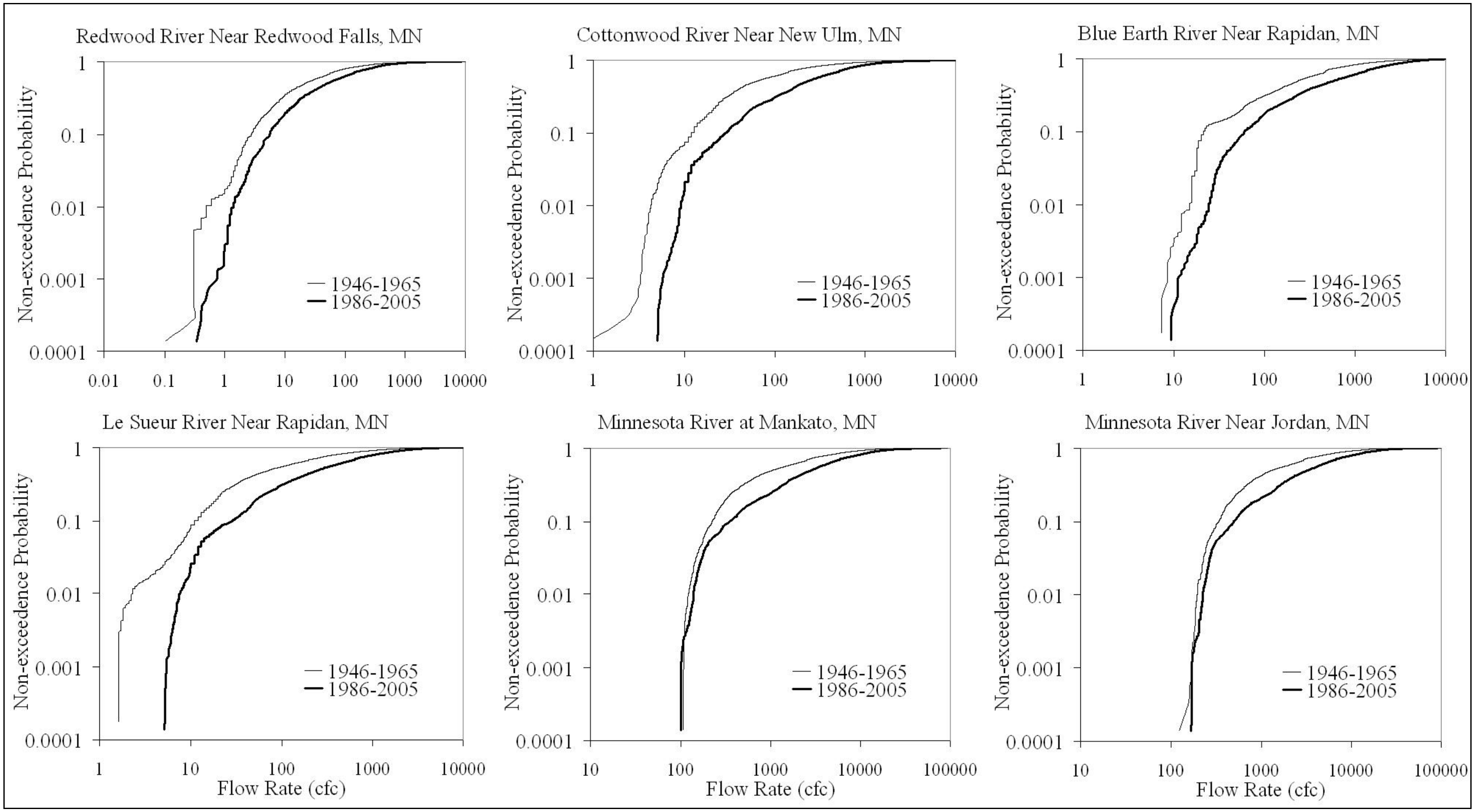

Figure B.1b. Flow Duration Curves for the Minnesota River Basin on Log-log plots for non-exceedence of a given flow.

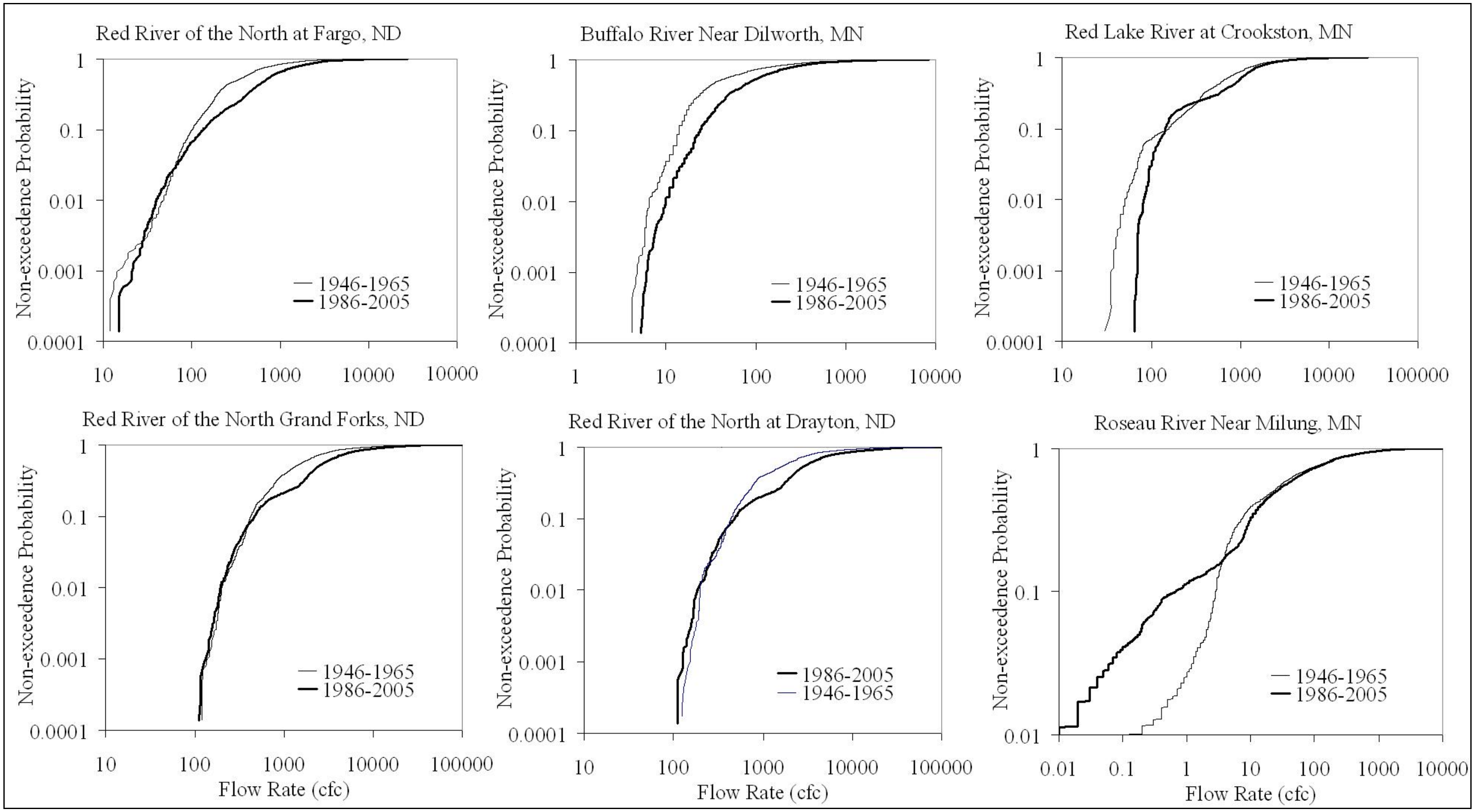

Figure B.2. Flow Duration Curves for the Red River of the North Basin on Log-log plots for non-exceedence of a given flow.

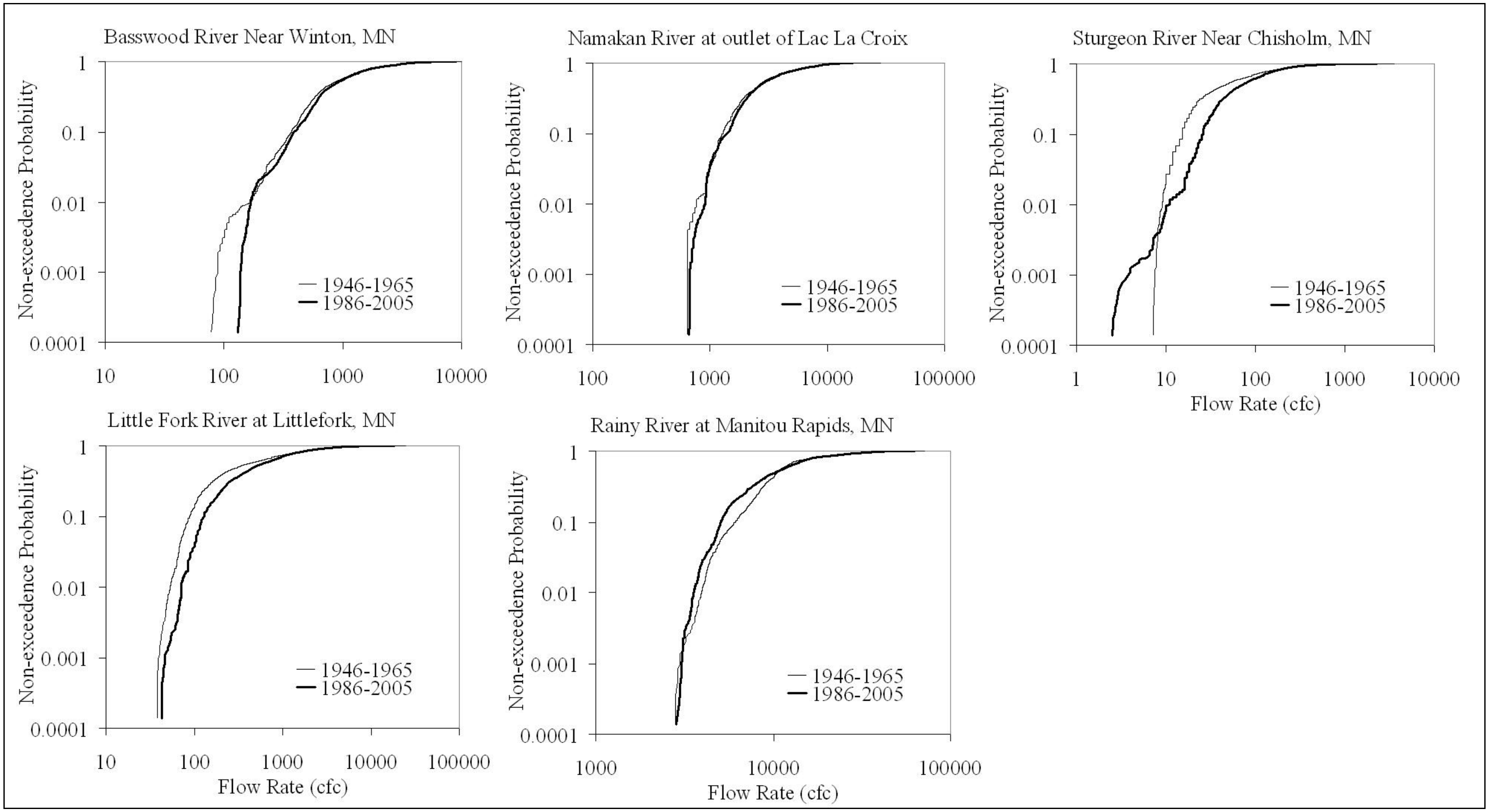

Figure B.3. Flow Duration Curves for the Rainy River Basin on Log-log plots for non-exceedence of a given flow.

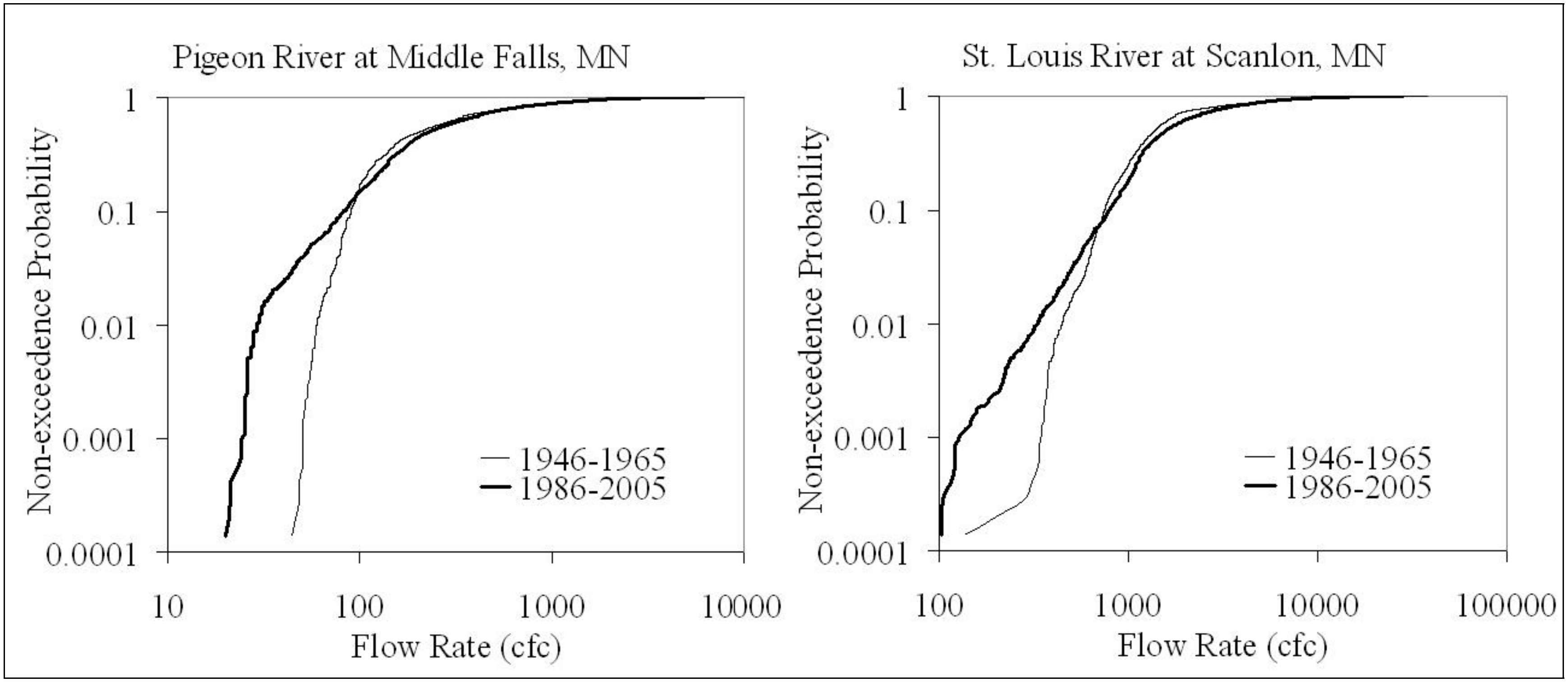

Figure B.4. Flow Duration Curves for tributaries to Lake Superior on Log-log plots for non-exceedence of a given flow.

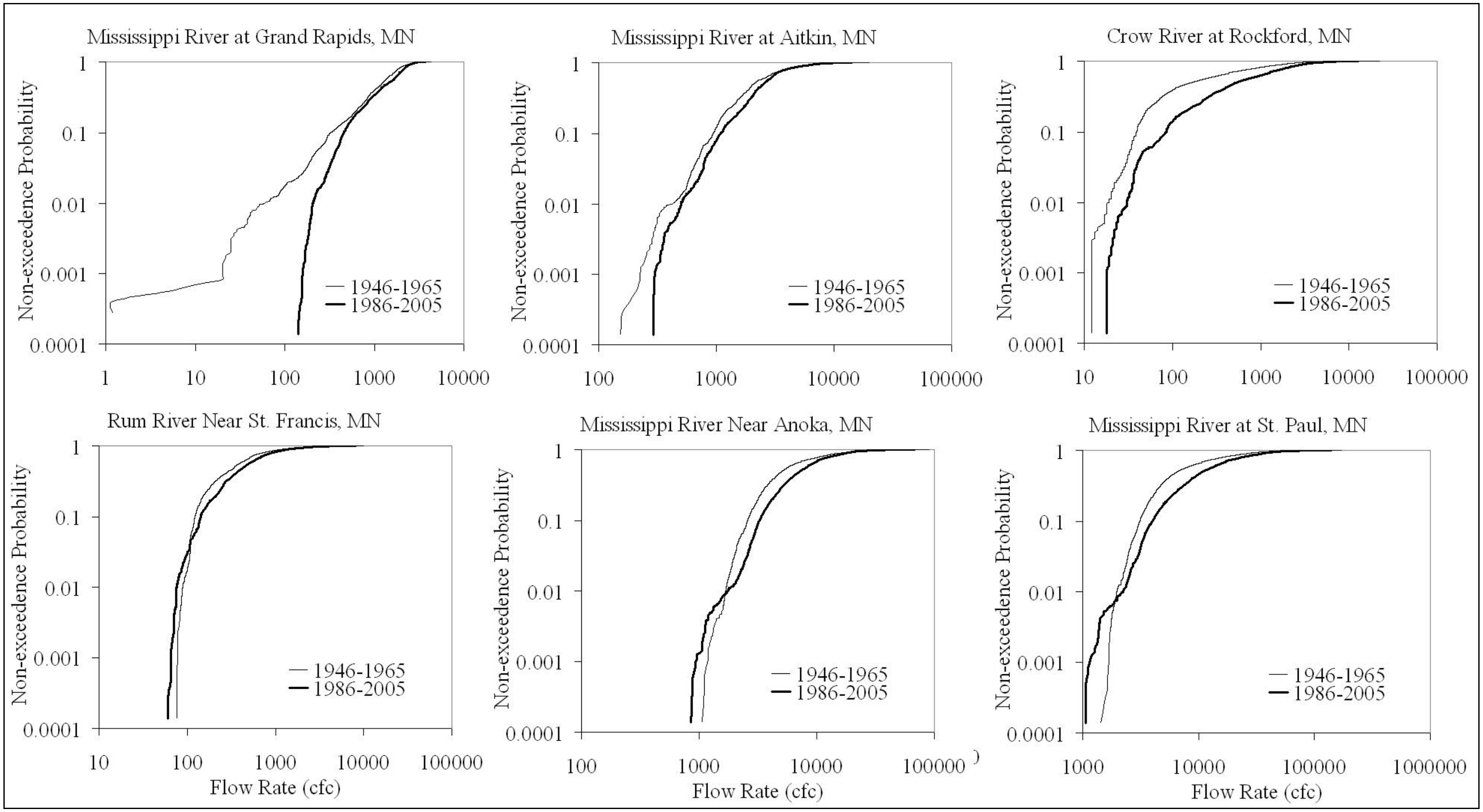

Figure B.5a. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots for non-exceedence of a given flow.

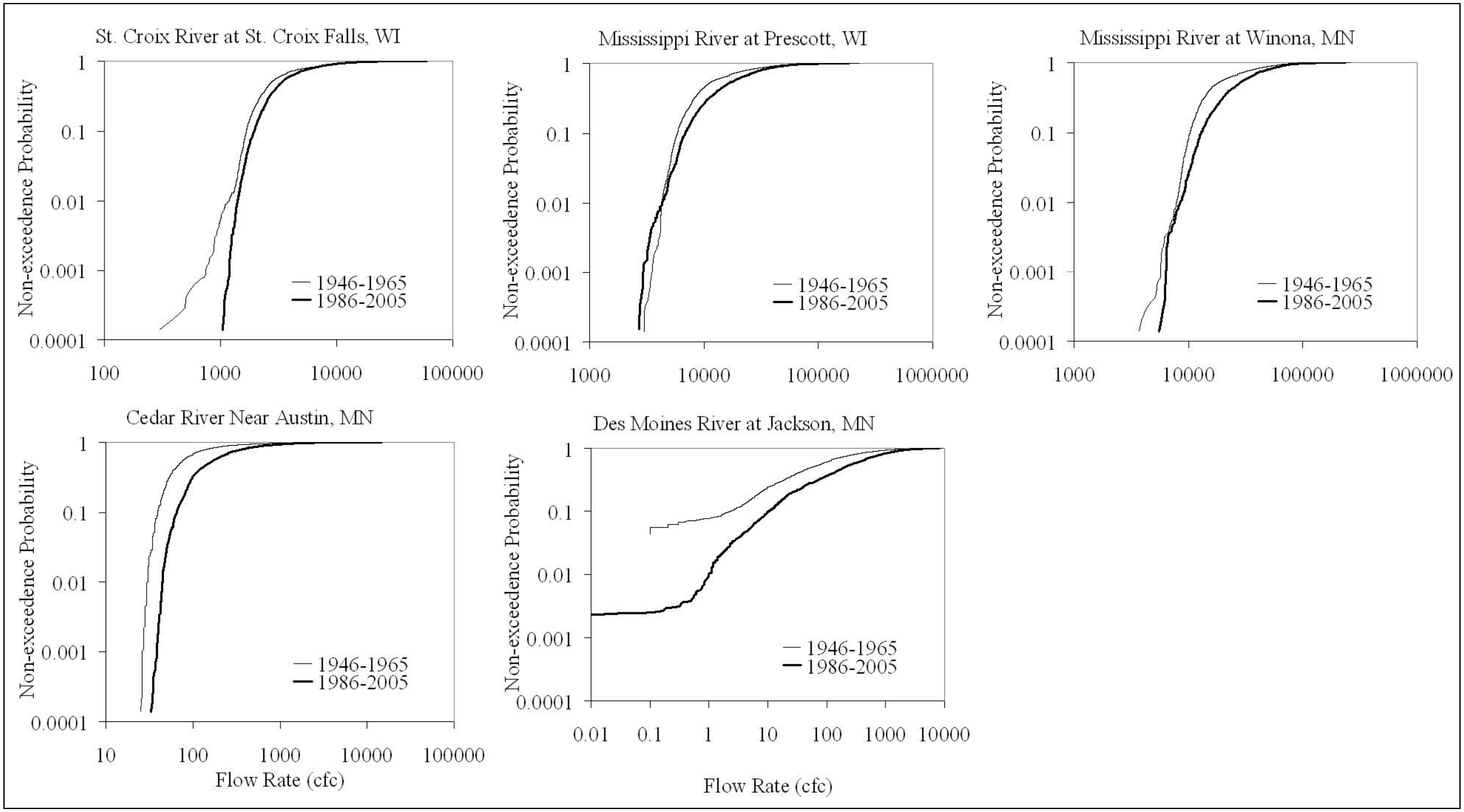

Figure B.5b. Flow Duration Curves for the Upper Mississippi River Basin on Log-log plots for non-exceedence of a given flow.

Appendix C: Mean, standard deviation, skew coefficient, and weighted skew coefficients of log-transformed stream flow data (log Q) for the 1946-1965 and 1986-2005 periods for 36 USGS stream gauging stations in Minnesota.

Stream/River name	**1946-1965**				**1986-2005**			
	Mean	**Std. Dev.**	**Skew Coeff.**	**Weighted Skew Coeff.**	**Mean**	**Std. Dev.**	**Skew Coeff.**	**Weighted Skew Coeff.**
Minnesota River Basin								
Whetstone River Big Stone City, SD	3.08	0.47	-0.78	-0.48	3.08	0.67	-0.64	-0.43
Minnesota River at Ortonville, MN	2.88	0.29	-0.30	-0.31	3.15	0.41	-0.74	-0.47
Chippewa River Near Milan, MN	3.23	0.38	0.03	-0.12	3.46	0.39	-0.21	-0.22
Minnesota River at Montevideo, MN	3.62	0.37	0.26	-0.02	3.77	0.42	0.49	0.06
Yellow Medicine River Granite Falls, MN	3.27	0.44	0.30	0.00	3.22	0.36	0.54	0.08
Redwood River Near Marshall, MN	2.79	0.60	-0.89	-0.47	2.94	0.41	0.48	0.04
Redwood River Near Redwood Falls, MN	3.21	0.53	0.35	0.04	3.31	0.36	0.57	0.11
Cottonwood River Near New Ulm, MN	3.62	0.40	0.25	0.03	3.68	0.35	0.28	0.04
Blue Earth River Near Rapidan, MN	3.91	0.36	-0.04	-0.09	3.93	0.20	-0.08	-0.11
Le Sueur River Near Rapidan, MN	3.51	0.61	-0.90	-0.37	3.83	0.19	0.06	-0.05
Minnesota River at Mankato, MN	4.30	0.34	0.29	0.00	4.38	0.29	0.02	-0.11
Minnesota River Near Jordan, MN	4.31	0.36	0.20	-0.03	4.41	0.30	0.07	-0.08
Rainy River Basin								

Stream/River name	1946-1965				1986-2005			
	Mean	Std. Dev.	Skew Coeff.	Weighted Skew Coeff.	Mean	Std. Dev.	Skew Coeff.	Weighted Skew Coeff.
Basswood River Near Winton, MN	3.67	0.26	-0.30	-0.06	3.61	0.20	-0.24	-0.04
Namakan River at outlet of Lac La Croix								
Sturgeon River Near Chisholm, MN	3.02	0.23	0.75	0.27	2.96	0.28	-0.47	-0.18
Little Fork River at Littlefork, MN	4.00	0.19	-0.55	-0.35	3.87	0.25	-0.29	-0.25
Rainy River at Manitou Rapids, MN	4.54	0.17	-0.39	-0.35	4.52	0.21	-1.08	-0.56
Red River of the North Basin								
Red River of the North at Fargo, ND	3.62	0.33	-0.06	-0.23	3.80	0.38	-0.51	-0.41
Buffalo River Near Dilworth, MN	3.23	0.31	0.13	-0.16	3.31	0.37	-0.19	-0.29
Red Lake River at Crookston, MN	3.91	0.31	-0.65	-0.52	3.92	0.37	-1.01	-0.63
Red River of the North Grand Forks, ND	4.23	0.30	-0.41	-0.43	4.41	0.37	-0.55	-0.49
Red River of the North at Drayton, ND	4.31	0.31	-0.29	-0.40	4.43	0.35	-0.69	-0.56
Roseau River Near Milung, MN	3.20	0.33	-0.23	-0.39	3.27	0.50	-0.85	-0.63
Streams Tributary to Lake Superior								
Pigeon River at Middle Falls	3.61	0.27	-0.84	0.03	3.55	0.13	-0.06	0.26
St. Louis River at Scanlon, MN	4.26	0.14	-0.01	-0.01	4.21	0.20	-0.59	-0.22
Upper Mississippi River Basin								
Mississippi River at Grand Rapids, MN	3.45	0.20	1.68	0.25	3.43	0.10	-0.13	-0.14
Mississippi River at Aitkin, MN	3.93	0.17	-0.45	-0.31	3.88	0.14	0.05	-0.11

Stream/River name	1946-1965				1986-2005			
	Mean	**Std. Dev.**	**Skew Coeff.**	**Weighted Skew Coeff.**	**Mean**	**Std. Dev.**	**Skew Coeff.**	**Weighted Skew Coeff.**
Crow River at Rockford, MN	3.60	0.38	-0.18	-0.18	3.68	0.35	-0.95	-0.44
Rum River Near St. Francis, MN	3.61	0.28	-0.67	-0.39	3.53	0.28	-0.67	-0.39
Mississippi River Near Anoka, MN	4.50	0.21	0.25	-0.02	4.46	0.20	0.17	-0.05
Mississippi River at St. Paul, MN	4.66	0.25	0.69	0.13	4.70	0.23	0.18	-0.05
St. Croix River at St. Croix Falls, WI	4.43	0.18	-0.46	-0.30	4.36	0.20	0.11	-0.07
Mississippi River at Prescott, WI	4.83	0.22	0.69	0.13	4.83	0.22	0.20	-0.04
Mississippi River at Winona, MN	4.95	0.21	0.68	0.12	5.01	0.19	-0.23	-0.21
Cedar River Near Austin, MN	3.60	0.36	-1.37	-0.55	3.63	0.32	0.29	-0.05
Des Moines River at Jackson, MN	3.31	0.38	-0.13	-0.15	3.38	0.31	-0.14	-0.15

Appendix D: Floods (in cubic feet per second) with 1-, 2-, 5-, 10-, and 25-year return periods for (1946-1965) and (1986-2005)

Return Period	1.01		2		5		10		20	
Stream/River Name	1946-1965	1986-2005	1946-1965	1986-2005	1946-1965	1986-2005	1946-1965	1986-2005	1946-1965	1986-2005
Minnesota River Basin										
Whetstone River Big Stone City, SD	65	20	1,305	1,341	3,048	4,521	4,535	8,037	6,693	14,210
Minnesota River at Ortonville, MN	136	140	780	1,450	1,338	3,163	1,741	4,672	2,274	7,016
Chippewa River Near Milan, MN	205	308	1,716	2,951	3,529	6,113	5,094	8,779	7,486	12,745
Minnesota River at Montevideo, MN	569	638	4,199	5,785	8,584	13,189	12,453	20,411	18,495	32,645
Yellow Medicine River Granite Falls, MN	176	254	1,863	1,645	4,378	3,330	6,842	4,846	11,012	7,262
Redwood River Near Marshall, MN	16	97	687	857	1,999	1,919	3,300	2,937	5,401	4,633
Redwood River Near Redwood Falls, MN	100	319	1,597	1,989	4,445	4,014	7,624	5,847	13,594	8,785
Cottonwood River Near New	509	755	4,196	4,752	9,100	9,382	13,674	13,430	21,139	19,730

Ulm, MN										
Blue Earth River Near Rapidan, MN	1,093	2,765	8,169	8,496	16,349	12,471	23,332	15,170	33,937	18,638
Le Sueur River Near Rapidan, MN	84	2,399	3,518	6,821	10,720	9,862	18,292	11,935	31,250	14,607
Minnesota River at Mankato, MN	3,240	4,669	19,857	24,082	38,216	42,179	53,789	56,152	77,418	75,845
Minnesota River Near Jordan, MN	2,876	4,882	20,429	25,980	40,995	46,318	58,838	62,320	86,335	85,208
Red River of the North Basin										
Red River of the North at Fargo, ND	640	634	4,297	6,734	7,929	13,441	10,479	18,667	14,702	25,882
Buffalo River Near Dilworth, MN	292	238	1,722	2,109	3,112	4,159	4,195	5,797	5,725	8,127
Red Lake River at Crookston, MN	1,178	772	8,554	9,064	14,801	17,286	19,083	23,104	24,427	30,447
Red River of the North Grand Forks, ND	2,767	2,655	17,957	27,591	30,836	53,260	39,822	724,411	51,297	97,779
Red River of the North at Drayton, ND	3,145	2,990	21,360	28,983	37,516	53,672	49,062	71,181	64,110	93,460
Roseau River Near Milung, MN	213	75	1,669	2,117	3,067	5,083	4,101	7,534	5,481	10,956

Rainy River Basin										
Basswood River Near Winton, MN	1,148	1,370	4,705	4,131	7,713	6,111	9,954	7,485	13,036	9,283
Namakan River at outlet of Lac La Croix		186		920		1,558		2,029		2,669
Sturgeon River Near Chisholm, MN	351	186	1,034	920	1,624	1,558	2,085	2,029	2,749	2,669
Little Fork River at Littlefork, MN	3,157	1,704	10,311	7,517	14,733	12,032	17,500	15,176	20,809	19,249
Rainy River at Manitou Rapids, MN	12,231	8,915	35,304	34,666	48,576	50,052	56,650	59,209	66,124	69,611
Tributaries to Lake Superior										
Pigeon River at Middle Falls	970	1,847	4,081	3,534	6,914	4,631	9,122	5,376	12,270	6,342
St. Louis River at Scanlon, MN	8,582	5,286	18,156	16,468	23,793	23,757	27,399	28,502	31,843	34,385
Upper Mississippi River Basin										
Mississippi River at Grand Rapids, MN	1,044	1,579	2,750	2,723	3,270	3,270	3,587	3,587	3,952	3,952
Mississippi River at Aitkin, MN	2,686	3,427	8,939	7,644	10,057	10,057	11,570	11,570	13,406	13,406
Crow River at Rockford, MN	459	577	4,092	5,097	9,549	9,549	12,845	12,845	17,219	17,219
Rum River Near St. Francis, MN	750	646	4,235	3,457	5,811	5,811	7,535	7,535	9,854	9,854

Mississippi River Near Anoka, MN	10,138	9,804	31,809	29,082	42,638	42,638	51,960	51,960	64,059	64,059
Mississippi River at St. Paul, MN	12,760	14,209	44,880	50,556	79,154	79,154	99,827	99,827	127,655	127,655
St. Croix River at St. Croix Falls, WI	9,371	7,607	27,641	22,941	33,700	33,700	41,077	41,077	50,628	50,628
Mississippi River at Prescott, WI	22,211	20,157	67,201	67,369	103,363	103,363	129,049	129,049	163,307	163,307
Mississippi River at Winona, MN	29,573	34,284	87,260	104,579	150,070	150,070	179,634	179,634	216,256	216,256
Cedar River Near Austin, MN	408	4,338	4,338	8,244	8,244	11,066	11,066	14,702	14,702	15,422
Des Moines River at Jackson, MN	239	2,108	2,108	4,369	4,369	6,316	6,316	9,281	9,281	8,055

Appendix E: 7-day (average) low flow (in cubic feet per second) with 2-, 5-, 10-, and 20-year return periods for (1946-1965) and (1986-2005)

	7Q2		**7Q5**		**7Q10**		**7Q20**	
Stream/River Name	**1946-1965**	**1986-2005**	**1946-1965**	**1986-2005**	**1946-1965**	**1986-2005**	**1946-1965**	**1986-2005**
Minnesota River Basin								
Whetstone River Big Stone City, SD	299	690	221	360	189	251	166	184
Minnesota River at Ortonville, MN	192	498	140	236	119	155	104	108
Chippewa River Near Milan, MN	11	35	4.99	14.5	3.05	9.05	-	6.1
Minnesota River at Montevideo, MN	29	79	16.2	33.6	11.9	21	-	14
Yellow Medicine River Granite Falls, MN	9	39	5.37	16	3.96	9.83	3.06	6.5
Redwood River Near Marshall, MN	2	15	1.11	5.82	0.75	3.24	0.52	1.92
Redwood River Near Redwood Falls, MN	1	6	0.14	3.54	0	2.65	0	2.1
Cottonwood River Near New Ulm, MN	3	6	1.57	2.39	0.91	1.42	0	0.91
Blue Earth River Near Rapidan, MN	51	110	32.7	46.1	25.4	27.7	20.3	17.6
Le Sueur River Near Rapidan, MN	8	78	3.68	30	2.52	15.8	1.87	8.61
Minnesota River at Mankato, MN	1	5	0.28	1.35	0.22	0.6	0.18	0.29
Minnesota River Near Jordan, MN	0	5	-	1.55	-	0.77	-	0.41
Red River of the North Basin								
Red River of the North at Fargo, ND	2	1.3	0.51	0.07	0.2	0	0	0
Buffalo River Near Dilworth, MN	460	834	277	344	209	201	-	124

Red Lake River at Crookston, MN	457	814	276	358	210	217	167	139
Red River of the North Grand Forks, ND	216	301	93.9	132	57.9	83.5	37.8	56.7
Red River of the North at Drayton, ND	12	28	8.43	15.3	6.75	10.9	5.54	8.02
Roseau River Near Milung, MN	82	173	42.1	68.9	28.6	40	20.4	24.8
Rainy River Basin								
Basswood River Near Winton, MN	5450	4720	4330	3740	3850	3310	3500	2990
Namakan River at outlet of Lac La Croix	77	107	59.3	72.8	51	57.7	44.7	46.8
Sturgeon River Near Chisholm, MN	13	23	9.85	14.9	8.58	10.1	7.65	6.68
Little Fork River at Littlefork, MN	1270	1390	966	1060	838	911	744	795
Rainy River at Manitou Rapids, MN	357	377	221	231	161	168	119	125
Tributaries to Lake Superior								
Pigeon River at Middle Falls	82	58	63.7	396	56.6	26.3	51.7	21.2
St. Louis River at Scanlon, MN	681	657	524	34.4	446	289	-	-
Upper Mississippi River Basin								
Mississippi River at Grand Rapids, MN	289	396	110	259	60.8	209	35.4	171
Mississippi River at Aitkin, MN	2750	4440	2180	2810	1930	2040	-	-
Crow River at Rockford, MN	3	14	0.04	2.63	0	0.82	0	0.04
Rum River Near St. Francis, MN	38	63	31.3	49.7	28.3	43.7	26.1	39.3
Mississippi River Near Anoka, MN	9740	12100	7970	9230	7110	7940	6440	6980
Mississippi River at St. Paul, MN	5450	7130	4630	5260	4280	4310	4020	-
St. Croix River at St. Croix Falls, WI	1650	1800	1440	1490	1350	1320	1280	1200
Mississippi River at Prescott, WI	2570	3200	1940	2140	1660	1670	1440	1330

Mississippi River at Winona, MN	147	160	98.2	105	81.5	82.9	70.6	67.5
Cedar River Near Austin, MN	34	112	21.8	49.6	17.4	31.1	14.5	20.8
Des Moines River at Jackson, MN	1030	920	587	583	418	460	308	379