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CLIMATE VARIABILITY AND FLOOD FREQUENCY ESTIMATION FOR THE UPPER MISSISSIPPI AND LOWER MISSOURI RIVERS[1]

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ABSTRACT: This paper considers the distribution of flood flows in the Upper Mississippi, Lower Missouri, and Illinois Rivers and their relationship to climatic indices. Global climate patterns including El Niño/Southern Oscillation, the Pacific Decadal Oscillation, and the North Atlantic Oscillation explained very little of the variations in flow peaks. However, large and statistically significant upward trends were found in many gauge records along the Upper Mississippi and Missouri Rivers: at Hermann on the Missouri River above the confluence with the Mississippi ($p = 2$ percent), at Hannibal on the Mississippi River ($p < 0.1$ percent), at Meredosia on the Illinois River ($p = 0.7$ percent), and at St. Louis on the Mississippi below the confluence of all three rivers ($p = 1$ percent). This challenges the traditional assumption that flood series are independent and identically distributed random variables and suggests that flood risk changes over time.
(KEY TERMS: surface water hydrology; floods; climate variability; climate trends; climate change; Upper Mississippi River, Lower Missouri River.)

INTRODUCTION

The Corps of Engineers is currently conducting a major flood frequency analysis for the Upper Mississippi River upstream of the confluence with the Ohio River and the Lower Missouri River downstream of Gavins Point Dam (see Figure 1). The drainage area above Gavins Point Dam is highly regulated by six major reservoirs, so the gauges from that area are not included in the study. The locations of the gauges used in the study are shown in Figure 2. The last major flood frequency study of the Upper Mississippi River Basin was completed in 1979. The flood profiles available for the Missouri River were developed in 1962. With the additional 20 years of data available for the upper Mississippi river basin and 40 years for the Missouri, the experience of the 1993 flood, and the availability of improved hydraulic models, now is an appropriate time to update flood profiles for the region. To address the fact that flows on the Missouri River and several of the tributaries of the Upper Mississippi are regulated, the U.S. Army Corps of Engineers has developed a set of "natural flows" for the basin, which to the extent possible have the effects of such regulation removed. In some cases, other adjustments have been made in reported flows to reflect suspected biases in older measurement algorithms, and inconsistencies between gauges. The statistical results reported in this paper are throughout based upon these adjusted flow sequences.

This paper begins by exploring the flood hydrology of the basin, snowmelt versus rainfall floods, and possible variation in flood risk that can be explained with indices of global climate patterns including El Niño/Southern Oscillation, the Pacific Decadal Oscillation, and the North Atlantic Oscillation. A major result of the investigations reported in this paper is documentation of variations in flood risk over time that result in statistically significant trends at some sites. These appear in both the northern region of the Mississippi basin and around St. Louis. These results challenge the traditional assumption in hydrology that floods are a sequence of random independently and identically distributed random variables and suggest that water management agencies may need to rethink their paradigm for flood frequency analysis to allow for flood risk variations over time.

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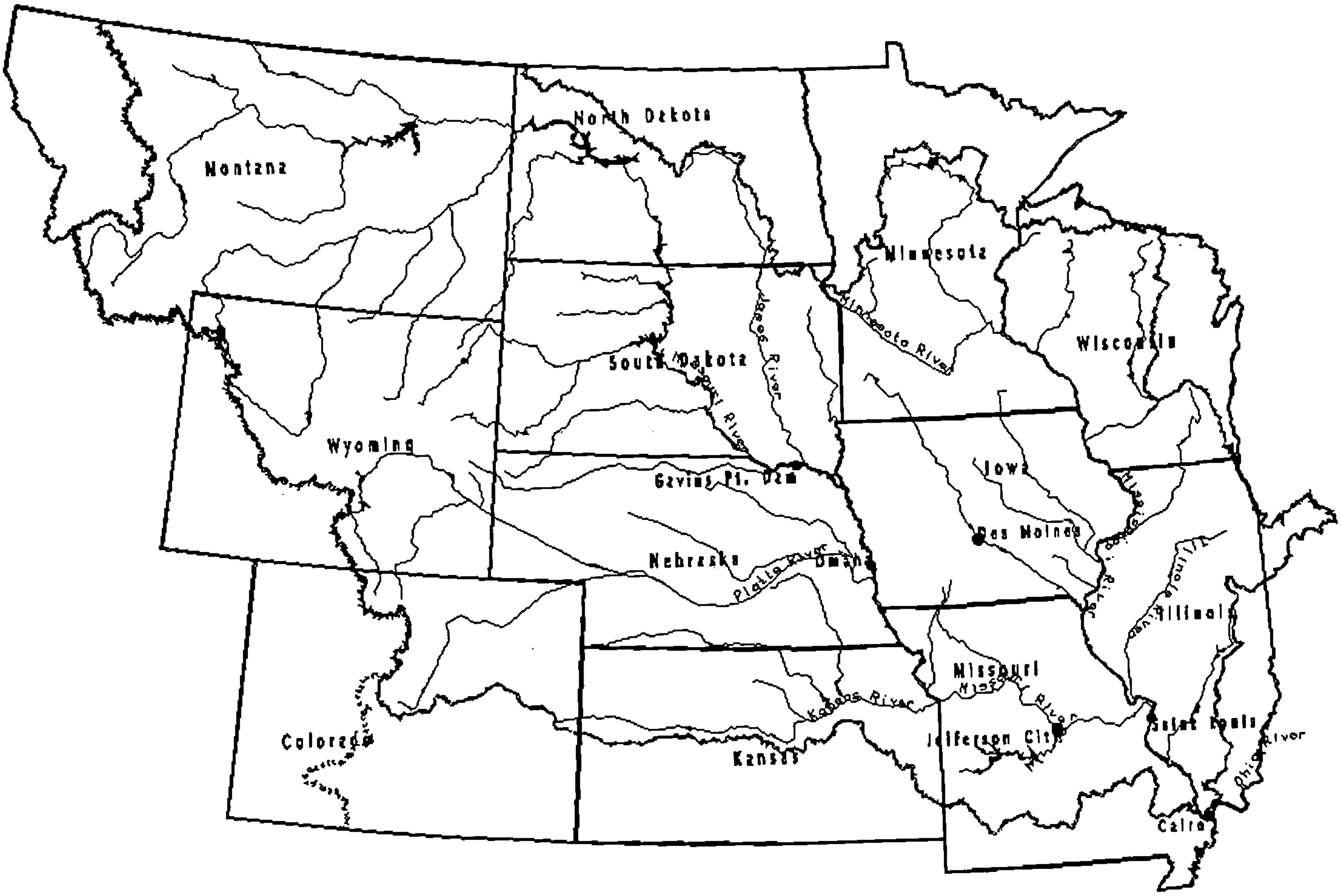

Figure 1. The Upper Mississippi and Missouri River Basin (SAST Report, 1994).

HYDROLOGY OF BASIN

The Missouri River drains about 73 percent of the Upper Mississippi River basin but on average accounts for only about 36 percent of the total annual streamflow. The average flow for the Missouri River at Hermann, Missouri, is 80,000 cubic feet per second (cfs), while the average for the Mississippi River at Alton-Grafton, Illinois (upstream of the Missouri confluence) is 111,000 cfs. Figure 3 shows that during major floods the Missouri produces a larger percentage of the flood peak downstream of the confluence of the two rivers than the Mississippi. The average annual flood at the Hermann gage on the Missouri River is about 350,000 cfs; the average annual flood for the Upper Mississippi River at Alton above the confluence is about 300,000 cfs, whereas the average is 550,000 cfs for St. Louis downstream of the confluence of the two rivers.

The largest floods in the northern part of the Mississippi River basin (1965 and 1969) were caused by snowmelt. Figure 4 shows the peaks at sites along the Mississippi River corresponding to these and more recent flood events. The maximum flood discharges downstream do not increase significantly for these snowmelt floods. The mean snowfall in Minnesota is about four times the value for St. Louis (UMRCBS, 1972). On the other hand, the rainfall floods of 1973, 1993, and 1995 increase significantly as one moves downstream. The state of Missouri receives about twice the annual rainfall as Minnesota in the northern part of the Mississippi basin (UMRCBS, 1972). Large floods on the Mississippi River have broad peaks with durations of a month or longer.

That snowmelt floods predominate above Keokuk, and rainfall floods predominate farther south, suggest that the annual maximum flood series near Keokuk might represent a mixture of two very different populations. (For a discussion of mixtures, see Stedinger *et al.*, 1993, Section 18.6.2). The floods at Keokuk are displayed in Figure 5 to see if they should be split into separate distributions for rainfall and snowmelt events. The year was divided into three periods: October to February, March to April, and May to September. The largest flows in each water year from 1901 to 1997 were determined and plotted using Weibull plotting positions. The March-April period generally corresponds to snowmelt floods while May-September period would contain rainfall floods. The distributions of these spring snowmelt and rainfall events have the same coefficient of variation, and at this location, almost the same mean as well. Thus there is no need to model them separately. There is a large correlation between the March-April and May-September floods ($\rho = 0.6$). Large rainfall floods often follow large snowfall floods due to increased soil moisture and baseflow.

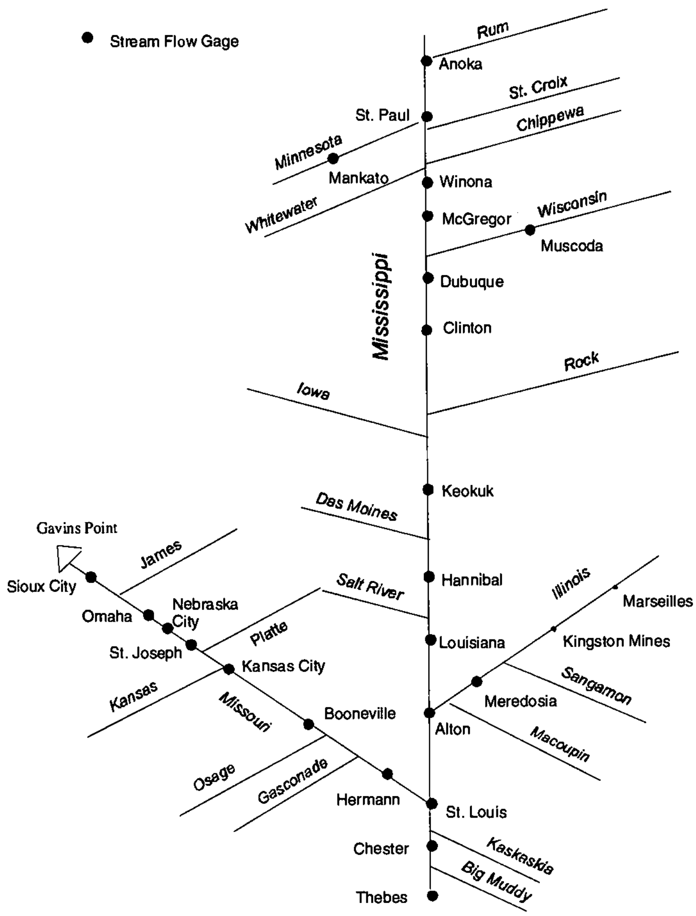

Figure 2. Streamflow Gages and Locations Used in the Upper Mississippi, Lower Missouri, and Illinois Flow Frequency Study (HEC, 1998).

CLIMATE PATTERNS AND MISSISSIPPI AND MISSOURI FLOODS

El Niño

The influence of El Niño on Mississippi River floods was explored by plotting annual floods at several stations on the Mississippi and Missouri Rivers against the average equatorial Pacific sea surface temperature anomaly (SST) during the months of March through June. For the more recent period (1950-1996) shown in Figure 6, El Niño events appear to be associated with larger floods and La Niña events with smaller peak annual floods. However, Figure 7 shows that there is relatively little relationship between the two over the longer period (1868-1996). There are several possible explanations of this difference: climate patterns may be different in the more recent period, the data before 1949 may not be as accurate, or the short and more recent period may not be representative of the larger population of El Niño years.

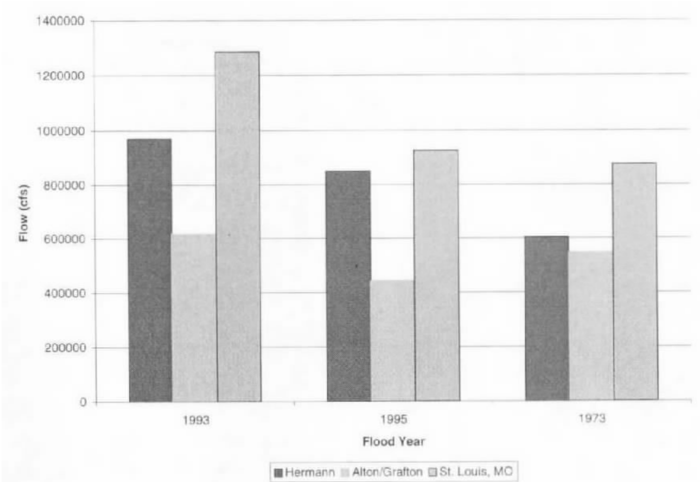

Figure 3. Relative Size of Flood Peaks During Three Major Floods.

Figure 8 displays the 129-year annual peak flood record using Weibull plotting positions and the fitted log Pearson type III distribution for the Mississippi River at Hannibal. The El Niño years (displayed as circles) are the fifteen years with the highest average positive sea surface temperature anomalies for the March-June period. The 1993 flood is the largest flood of record at Hannibal and is classified as an El Niño flood. The El Niño events fit in with the other observations. As long as the frequency and intensity of El Niño events are not changing over time, flood frequency analysis naturally accounts for climate variability associated with El Niño events.

Other Climate Patterns

Natural interdecadal climate variation is a potential cause of apparent non-stationarity in the flood process (NRC, 1998). Climate in the north Pacific may affect the storm track across North America. Conditions in the north Atlantic may influence the low-level jet bringing moisture to the Midwest. Global climate patterns including the Pacific Decadal Oscillation (PDO) and the North Atlantic Oscillation (NAO)

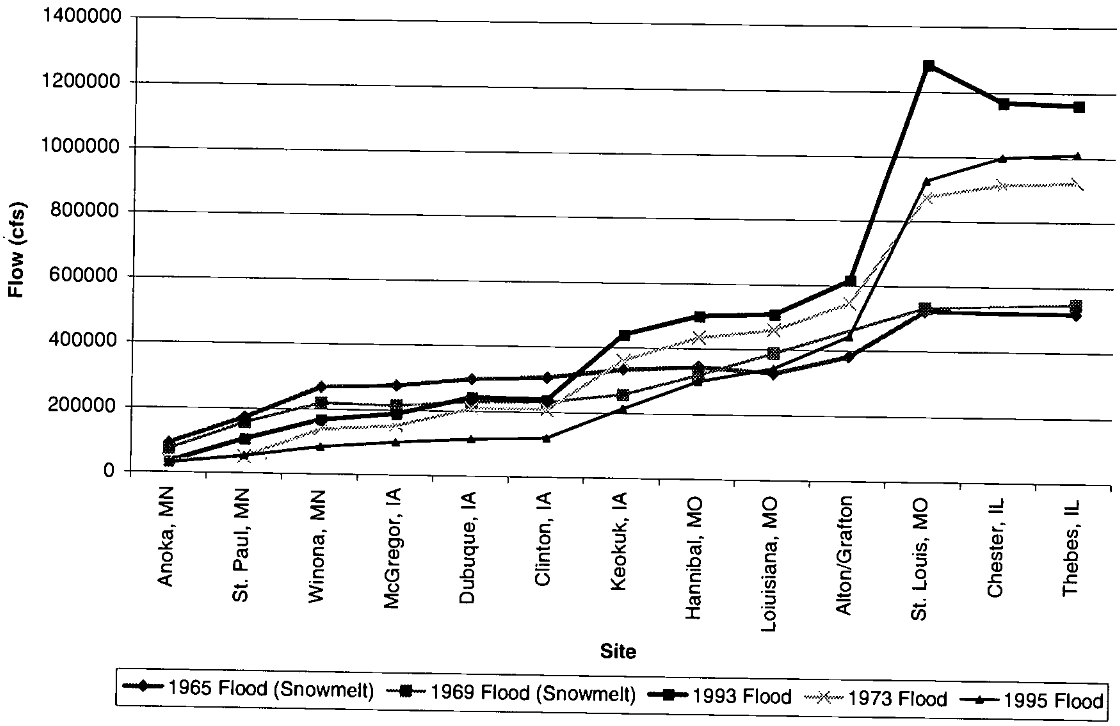

Figure 4. The Peak Flow at Sites Along the Mississippi River for Five Large Flood Events. The 1965 and 1969 are snowmelt floods while the other floods were caused by rainfall.

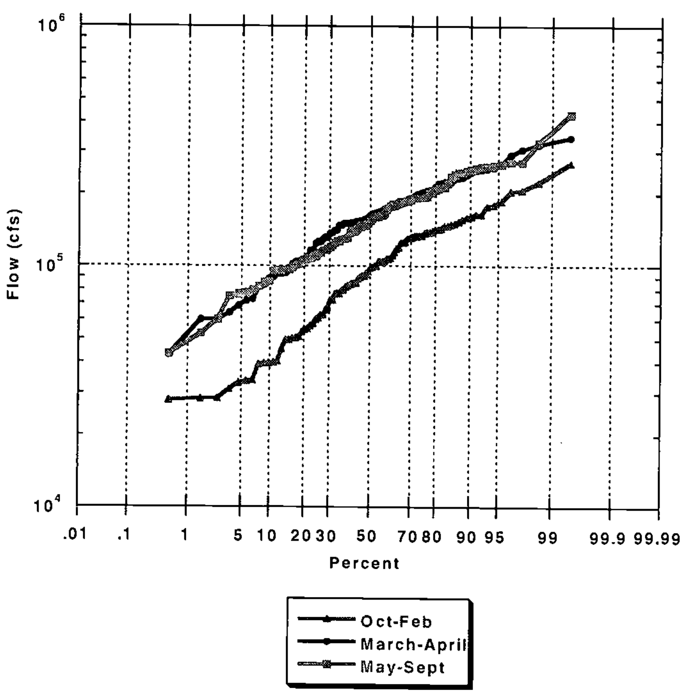

Figure 5. A Plot of the Largest Flows for the Mississippi River at Keokuk for Three Different Periods in a Water Year Sorted by Size.

exhibit low frequency variability with recent excursions above and below their median lasting a decade or more. To examine the relationship between Mississippi and Missouri River floods and these large-scale climate patterns, the annual flood for three gages were regressed on three climate indices and interaction terms. The gages were the Mississippi River at Hannibal, the Missouri River at Hermann, and the Mississippi River at St. Louis. The three climate indices were tropical Pacific sea surface temperature anomaly (SST), Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO). In addition, the squares of the indices was included (SST*SST, PDO*PDO, NAO*NAO) along with interaction terms (SST*NAO, SST*PDO, PDO*NAO). The analysis used data from two time periods 1900-1996 and 1950-1996.

As shown in Table 1, using the entire 1900-1996 period, there is little relationship between the best explanatory variable identified by stepwise regression and the observed floods. The R^2 for each site is less than 10 percent. The interaction term for SST and NAO (SST*NAO) and SST are significant at the 10 percent level in the Hannibal model. PDO is significant at the 10 percent level for Hermann. PDO and the PDO*NAO are significant at the 5 percent level for St. Louis.

Table 2 considers the more recent and shorter data set for 1950-1996. The data after 1949 may be more accurate; sea surface temperature data were directly observed after 1949, while the data prior to 1949 is reconstructed. The R^2 values increase for Hermann and St. Louis. Now only SST is significant for Hannibal. PDO, PDO*SST, SST and SST*SST are significant at the 5 percent level for Hermann. Either PDO or SST is significant for St. Louis, though PDO provides a much better model.

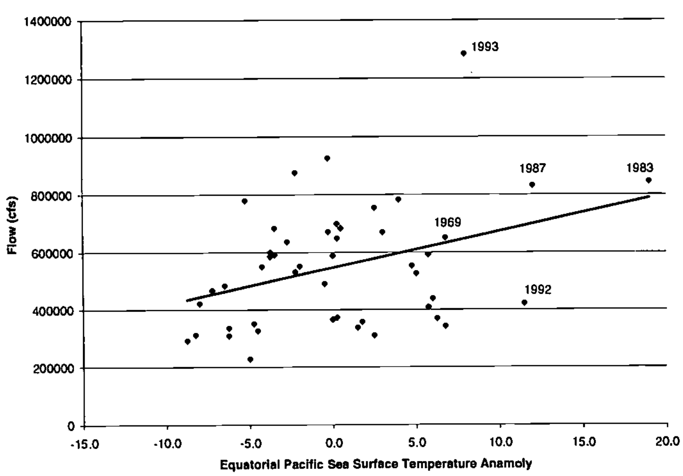

Figure 6. Annual Floods (1950-1996) for the Mississippi River at St. Louis and Tropical Pacific Sea Surface Temperature Anomalies.

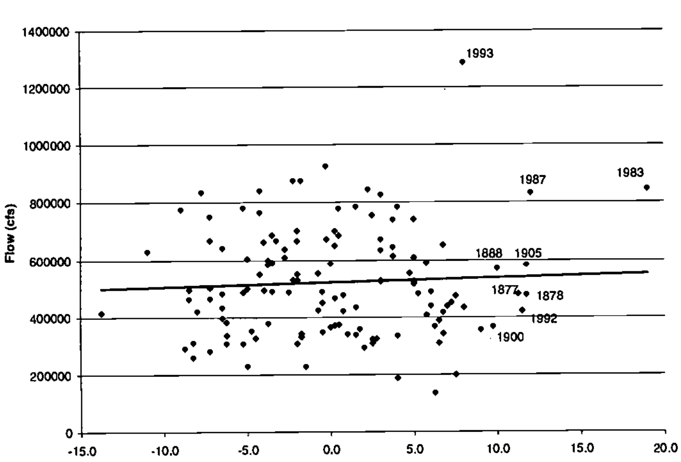

Figure 7. Annual Floods (1868-1996) for the Mississippi River at St. Louis and Tropical Pacific Sea Surface Temperature Anomalies.

Our simple regression analyses involving equatorial Pacific sea surface temperature, the Pacific Decadal Oscillation, and the North Atlantic Oscillation found little signal over the entire 97-year record. A significant signal could be observed over the last 47 years, so that PDO, SST and NAO values could explain partially the occurrence of large floods. However, even during this more recent period, the regression analyses could explain only a small percentage of the variability in the annual maximum floods. These factors do not appear to have a major influence of the magnitude of floods in the upper Mississippi River basin.

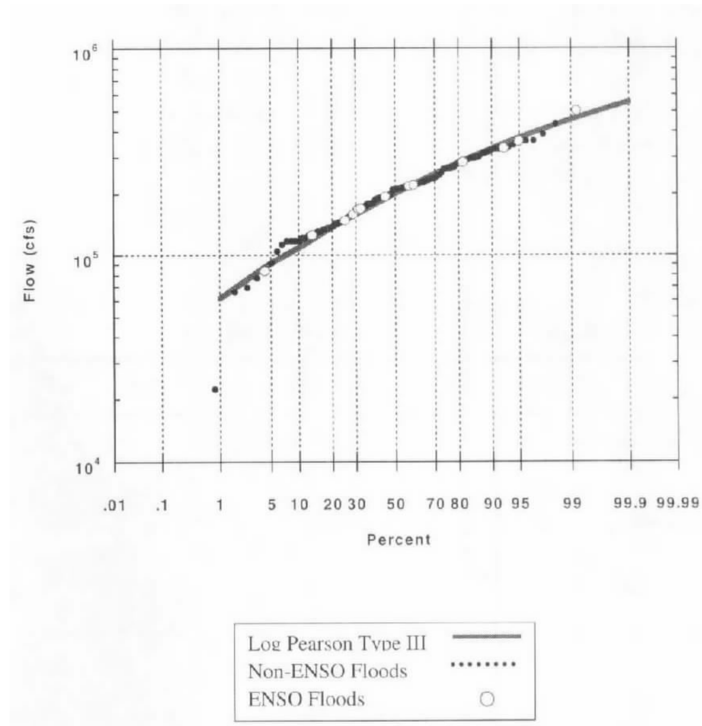

Figure 8. El Niño Floods and Other Floods Plotted With the Log-Pearson III Distribution Fitted to the Peak Annual Floods for the Mississippi River at Hannibal, Missouri, 1879-1996. Note the one low outlier.

REPORTS OF CLIMATE AND STREAMFLOW TRENDS

There is evidence of a historical trend of increasing temperatures and precipitation in the Upper Midwest since 1900 (Karl *et al.*, 1996; Lettenmaier *et al.*, 1994). Much of the Midwest showed an increasing trend in annual total precipitation of 10 to 20 percent per century from 1900 to 1994 (Karl *et al.*, 1996). Average annual snow cover in the region may have decreased in the past 20 years partly due to higher temperatures (Karl *et al.*, 1993). Less snow cover may reduce the severity of spring snowmelt floods. Karl *et al.* (1995) reported that the frequency of heavy rainfall (defined as more than 2 inches per day) may be increasing. Angel and Huff (1997) also found an approximately 20 percent increase from 1901 to 1994 in the number of daily precipitation events of 2 inches or more. They also noted that between the periods 1901-1947 and 1948-1994, the number of stations with a statistically significant increase in daily, 2-, 3-, 5- and 10-day annual maximum rainfall outnumbered stations with significant decreases by a ratio of 5 to 1. In another analysis, Karl and Knight (1998) showed an annual increase in the upper 10 percentile of daily precipitation amounts in the Upper Mississippi region, including increases in the spring, summer, and autumn, but a decrease in the winter. In the Missouri River region, there was a smaller annual increase, increases in the spring and summer, and decreases in the autumn and winter.

TABLE 1. Terms With the Most Significance in Multiple Regression Using 97-Year (1900-1996) Record.

Gage	Terms	P Value	R^2
Mississippi River at Hannibal	SST*NAO	0.03	0.06
	SST	0.09	
Missouri River at Hermann	PDO	0.06	0.04
Mississippi River at St. Louis	PDO	0.04	0.07
	PDO*NOA	0.04	

TABLE 2. Terms With the Most Significance in Multiple Regression Using 47-Year (1950-1996) Record.

Gage	Terms	P Value	R^2
Mississippi River at Hannibal	SST	0.065	0.07
Missouri River at Hermann	PDO	0.024	0.31
	PDO*SST	0.028	
	SST	0.040	
	SST*SST	0.044	
Mississippi River at St. Louis (Model 1)	PDO	0.001	0.21
Mississippi River at St. Louis (Model 2)	SST	0.013	0.13

Despite evidence of a small increase in frequency of heavy rainfall, Lins and Slack (1999) reported that the annual maximum floods at stream gages in the Upper Midwestern region do not show a consistent pattern of increasing trends. Karl *et al.* (1995) and Lins and Slack's results are not necessarily inconsistent. The extreme precipitation category used by Karl et al. is daily rainfall greater than 2 inches. A 24-hour precipitation of 2 inches (50 mm) happens every year in almost every location east of the Mississippi and across much of the west and south (see Hershfield, 1961). The timing of the increased extreme precipitation is also important. Extreme rainfall in the late summer has less likelihood of causing flooding due to lower antecedent soil moisture. Antecedent soil moisture conditions are typically higher in the fall than in the summer because of plant senescence and lower evapotranspiration rates. However, rainfall amounts have typically been lower in the autumn than in the summer.

Several studies have addressed trends in the watersheds of the Mississippi River. For example, Potter (1991) shows that since 1951 flood peaks have decreased in some small agricultural catchments in Wisconsin due to changing land management practices. Knox (1984) discusses flood risk at St. Paul from 1860 to 1981. He suggests a period from 1860 to 1895 with higher flood risk, a period from 1896-1949 with significantly depressed flood risk, and then a period from 1950-1981 when flood risks increase to the highest level over the period. Knapp (1994) observed that the Upper Mississippi River basin has experienced above-average precipitation since 1965 resulting in increased annual peak discharges and annual flood volumes at several gauges.

TREND ANALYSIS OF MISSISSIPPI AND MISSOURI RIVER FLOODS

Analysis of a number of climate variables by Karl *et al.* (1996), Angel and Huff (1997), and Lettenmaier *et al.* (1994) suggest that positive trends may be present in hydrologic series in the Upper Mississippi River Basin. The possibility of such trends in Mississippi and Missouri Rivers gauge records to be used in the USACE flood-flow frequency study of the Upper Mississippi River basin was investigated. Table 3 summarizes the results of linear regression analyses of flow (annual flood) on time (year), that are described more fully in Tables A-1 through A-5. Table 3 also includes the significance of a Spearman rank correlation test for an upward trend (Gibbons and Chakraborti, 1992). The Spearman results are generally consistent with the results obtained with regression analysis.

High in the basin, the St. Croix River, the Minnesota River, and the Mississippi River at St. Paul all show significant trends at the 5 percent level using a one-sided regression test. The trend at Anoka, Minnesota, which is a gauge much higher in the basin and with half the drainage area of St. Paul, is not significant. The record at Anoka is 64 years in length, whereas St. Paul has a 129-year record (see Table A-1). Table A-1 shows that the trend is also statistically

TABLE 3. Linear Trend Analyses for Upper Mississippi Basin Gauges.

Station	Location	Record Length	R^2	Correlation	Significance Level	Spearman Significance Level
Anoka, Minnesota	Upper Upper Mississippi	64	0.01	0.11	0.18	0.16
St. Croix Falls, Wisconsin	St. Croix River	86	0.09	0.30	*0.003*	*0.0009*
Jordan, Minnesota	Minnesota River	63	0.06	0.24	*0.03*	*0.007*
St. Paul, Minnesota	Upper Upper Mississippi	129	0.03	0.16	*0.03*	*0.03*
Clinton, Iowa	Upper Upper Mississippi	122	0.00	0.01	0.47	0.47
Keokuk, Iowa	Middle Upper Mississippi	117	0.02	0.15	*0.06*	*0.09*
Hannibal, Missouri	Middle Upper Mississippi	118	0.20	0.45	$< 1x10^{-6}$	*0.00001*
Alton/Grafton, Missouri	Middle Upper Mississippi	67	0.17	0.42	*< 0.001*	*0.0003*
Nebraska City, Nebraska	Missouri	100	0.01	-0.08	0.22	0.86
Booneville, Missouri	Missouri	100	0.01	0.10	0.16	0.24
Hermann, Missouri	Lower Missouri	100	0.05	0.22	*0.02*	*0.04*
Meredosia, Illinois	Illinois River	63	0.10	0.31	*0.01*	*0.005*
Meremac River Near Eureka, Missouri	Between St. Louis and Chester	73	0.06	0.27	*0.02*	*0.017*
St. Louis	Below Junction Mississippi and Missouri	136	0.04	0.19	*0.01*	*0.03*

significant at Winona, McGregor, and Dubuque. For the most part this is the region dominated by snowmelt floods. Table 3 and Table A-1 show that a trend at Clinton is not significant. A trend is significant at the 6 percent level at Keokuk farther downstream. Table A-1 categorizes this as the transition region between the area dominated by snowmelt floods to the north, and the region dominated by rainfall events to the south.

Table 3 and Table A-2 report regression results for the Missouri River. For sites reflecting flood flows from the West, corresponding to Sioux City, Omaha, Nebraska City, and Kansas City, there is no significant trend. A trend was significant at St. Joseph, but was lost after the Kansas River enters the Missouri River before Kansas City. The trend starts to show up again at Booneville, and is significant at the 2 percent level at Hermann using a one-sided regression test (see Figure 9). In the Missouri River basin, the local inflow above St. Joseph and the floods at the bottom of the basin at Hermann exhibit a statistically significant and potentially important upward trend over the 100-year period. Table A-2 reports the drainage areas for each gauge; however, one needs to recognize that remote areas to the west do not contribute as much to flood peaks as areas nearer the Missouri channel due to the large spatial gradient in rainfall rates. The Nishnabota and Thompson Rivers, tributaries to the Missouri River included in Table A-4, show significant trends. These tributaries join the Missouri above St. Joseph and above Boonesville. A positive trend for the Gasconade River was evident, but not statistically significant. These tributaries were chosen because they have good gauged records and have relatively little regulation (Slack *et al.*, 1993).

The Hannibal and Alton/Grafton gages above the confluence of the Missouri River have highly significant trends with $p < 0.1$ percent. The trend in the Hannibal record shown in Figure 10 is extraordinary. The 300,000 cfs flow threshold was never crossed until the 1940s, and was exceeded almost every-other-year in the 1970-1997 period (see the nonparametric exceedance analysis in Appendix B). The Hannibal gauge is not a USGS recording station and some have expressed concern that the rating curve has shifted and was not updated. Table 3 reports results for Meredosia on the Illinois River (Figure 11) and the Meremac River, which enters the Mississippi

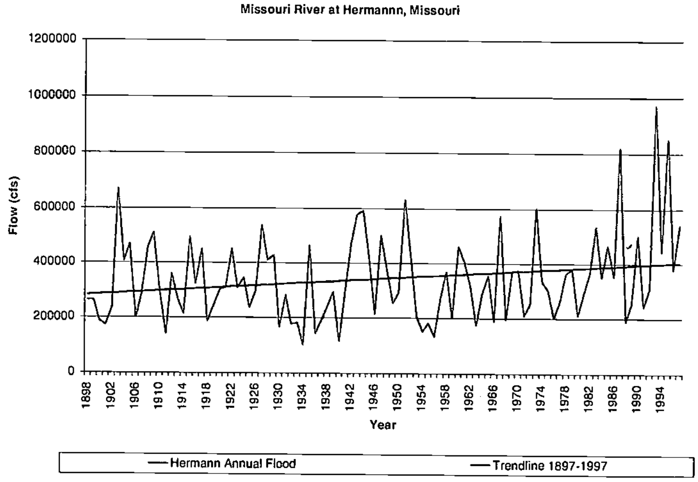

Figure 9. Annual Floods for the Missouri River at Hermann and Trendline.

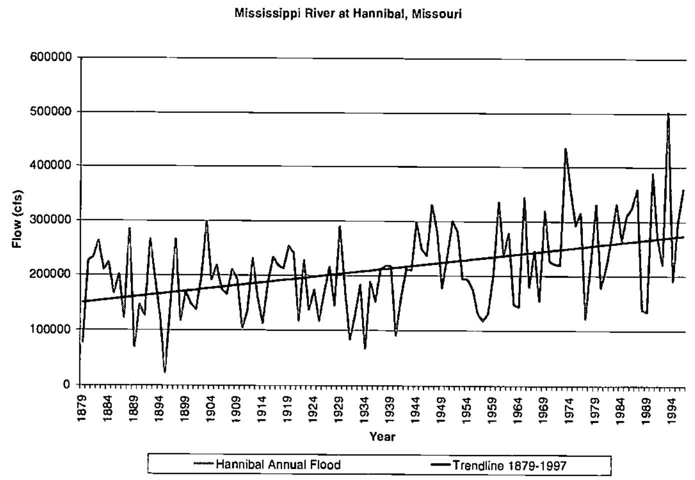

Figure 10. Annual Floods for the Mississippi River at Hannibal and Trendline.

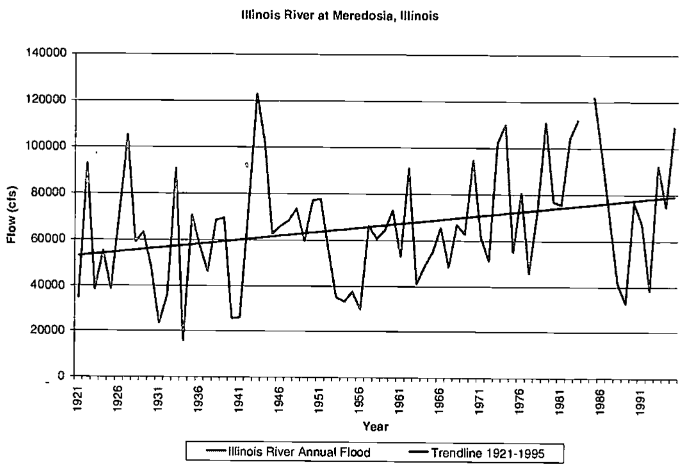

Figure 11. Annual Floods for the Illinois River at Meredosia and Trendline.

below St. Louis. These two rivers also show highly significant trends.

Table A-3 shows the three gauges downstream of the confluence of the Missouri and Mississippi: St. Louis, Chester, and Thebes. These gauges also have significant trends, but are highly correlated ($\rho > 0.975$) and thus represent essentially the same hydrologic experience over the recent period of record for which the Chester and Thebes gauges have been active. The longest record is at St. Louis (Figure 12).

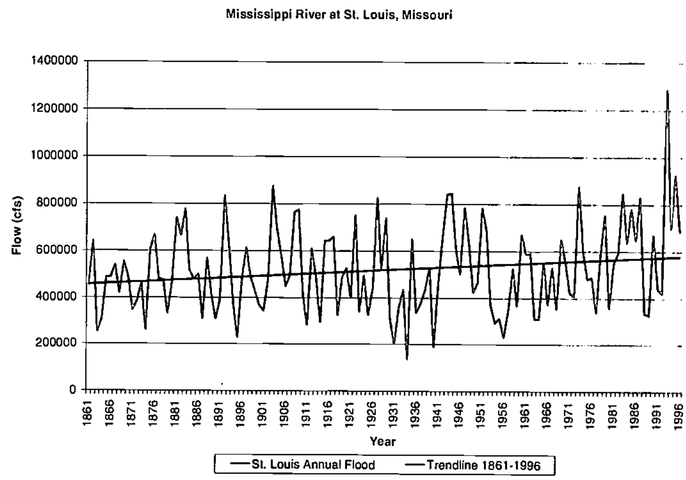

Figure 12. Annual Floods for the Mississippi River at St. Louis and Trendline.

Correlations among the annual floods at Hermann, Hannibal, and St. Louis are 0.65 (Hermann-Hannibal), 0.90 (Hermann-St. Louis), and 0.77 (Hannibal-St. Louis). This reflects the observation that the Missouri contributes more to the flood peaks at St. Louis than does the Upper Mississippi River. The three records do not constitute independent experiences. However the data provide very strong evidence that flood risk has increased in recent decades in the lower part of the Missouri basin, on the Mississippi near Hannibal, on the Illinois River, and at St. Louis below the junction of the two rivers. Analysis of flows on tributaries of the Missouri and Meremac River add to the evidence of a significant increase in flood risk over time in the last century.

Examination of the residuals in the regression analysis revealed that they were well-described by a normal distribution at Dubuque, Clinton, Keokuk, Hannibal, and St. Louis. The approximation was less satisfactory at St. Paul and on the Missouri River where residuals were positively skewed. However, with more than 100 years of data the normality assumption is not too critical, as the consistency with the Spearman non-parametric rank correlation results revealed.

This discussion has emphasized the results of a linear regression or equivalently use of Pearson's correlation coefficient with the raw flows. An analysis using Spearman's rank correlation test was also conducted (Gibbons and Chakraborti, 1992), with little change in the significance of the results reported in Table 3. In a few cases, the trends are even more significant. The non-parametric exceedance analysis in Appendix B also supports the conclusion that flood risk has increased in recent decades.

PRESENT-TO-PAST AND PAST-TO-PRESENT TREND ANALYSIS FOR BASINS

The assessment of trend can be extended by considering its evolution to determine how the trend assessment would have changed over time. A *past-to-present* view is complimented by a *present-to-past* view, i.e., by an assessment of trend considering alternate dates at which the sequence began, where the alternate dates can be taken within the historical time span of the historical flood record. The two views remind us that the future remains unknown, and may eventually contradict the past.

An evolutionary trend assessment was undertaken for annual flood sequences available for sites in the Upper Mississippi and Missouri Basins. The sequences are examined to determine if they are characterized by statistically meaningful trends. Trends are limited to those in the mean defined by the linear regression of flow (annual flood) on time (year). A statistically meaningful trend is taken to be a statistically significant regression at the 5 percent level and at the 1 percent level. Each sequence is assessed under this null hypothesis that the regression coefficient is equal to zero versus it is positive (a one-sided test). In the case of a simple regression, the null hypothesis is equivalent to the null hypothesis that the coefficient of correlation between time and flow is equal to zero.

Tables 4 through 7 report an evolutionary trend analysis for the gauge records at Hermann, Keokuk, Hannibal, and St. Louis. As one can see, a trend that may not be significant over a period of moderate length may be significant if a longer or a shorter record is employed. A time trend with the Keokuk record ending in 1997 was significant for a record beginning in 1928 to as early as 1888, but was not significant at the 5 percent level if the period of record was extended back to 1879. For many gauges in the basin, such as Hermann and St. Louis, a trend is only significant if the wet 1988-1997 period is included in the analysis. The interpretation of trend analyses such as those in Tables A-1 through A-6 should be sensitive to the total record length available, as well as the particular period of record employed for each gauge.

TABLE 4. Past-to-Present and Present-to-Past Trend Analysis for Hermann.

Length of Record	Period of Record	Correlation
	Past to Present	
10	1898-1907	0.266
20	1898-1917	0.179
30	1898-1927	0.100
40	1898-1937	-0.159
50	1898-1947	0.051
60	1898-1957	-0.033
70	1898-1967	0.002
80	1898-1977	-0.005
90	1898-1987	0.114
100	1898-1997	0.224*
	Present-to-Past	
10	1997-1988	0.495
20	1997-1978	0.374*
30	1997-1968	0.435**
40	1997-1958	0.381**
50	1997-1948	0.372**
60	1997-1938	0.263*
70	1997-1928	0.325**
80	1997-1918	0.296**
90	1997-1908	0.234*
100	1997-1898	0.224*

*5 Percent Level of Significance.
**1 Percent Level of Significance (for a one-sided test).

The past-to-present and present-to-past analysis captures, to a degree, effects of past periods of dryness and wetness, whereby the trends seen today were not necessarily there in the past and they may not be there tomorrow. Trends can be associated with (1) independent, nonidentically distributed random variables, (2) nonindependent, identically distributed random variables, or (3) nonindependent and nonidentically distributed random variables. The past-to-present and present-to-past analysis suggests the plausibility of using stationary persistence to describe the episodic movement of varying flood frequencies and amplitudes.

TABLE 5. Past-to-Present and Present-to-Past Trend Analysis for Keokuk.

Length of Record	Period of Record	Correlation
	Past to Present	
9	1879-1887	-0.151
19	1879-1897	-0.250
29	1879-1907	-0.139
39	1879-1917	-0.226
49	1879-1927	-0.234
59	1879-1937	-0.326**
69	1879-1947	-0.184
79	1879-1957	-0.146
89	1879-1967	-0.046
99	1879-1977	0.044
109	1879-1987	0.110
118	1879-1996	0.147
	Present-to-Past	
9	1996-1988	0.364
19	1996-1978	0.196
29	1996-1968	0.104
39	1996-1958	0.130
49	1996-1948	0.188
59	1996-1938	0.202
69	1996-1928	0.321**
79	1996-1918	0.309**
89	1996-1908	0.316**
99	1996-1898	0.270**
109	1996-1888	0.223**
118	1996-1878	0.147

*5 Percent Level of Significance.
**1 Percent Level of Significance (for a one-sided test).

TABLE 6. Past-to-Present and Present-to-Past Trend Analysis for Hannibal.

Length of Record	Period of Record	Correlation
	Past to Present	
9	1879-1887	-0.151
19	1879-1897	-0.189
29	1879-1907	-0.034
39	1879-1917	-0.012
49	1879-1927	0.016
59	1879-1937	-0.065
69	1879-1947	0.123
79	1879-1957	0.159
89	1879-1967	0.221*
99	1879-1977	0.329**
109	1879-1987	0.428**
118	1879-1996	0.447**
	Present-to-Past	
9	1996-1988	0.456
19	1996-1978	0.228
29	1996-1968	0.168
39	1996-1958	0.290*
49	1996-1948	0.340**
59	1996-1938	0.341**
69	1996-1928	0.450**
79	1996-1918	0.458**
89	1996-1908	0.475**
99	1996-1898	0.475**
109	1996-1888	0.477**
118	1996-1878	0.447**

*5 Percent Level of Significance.
**1 Percent Level of Significance (for a one-sided test).

CLIMATE VARIABILITY AND WATER RESOURCES MANAGEMENT

Bulletin 17-B, *Guidelines for Determining Flood Flow Frequency*, observes that traditional flood frequency analysis employs an assumption that is often described as stationarity: "Necessary assumptions for a statistical analysis are that the array of flood information is a reliable and representative time sample of random homogeneous events" (IACWD, 1981, p. 6). The annual maximum peak floods are considered to be a sample of random, independent and identically distributed (iid) events. Thus one implicitly assumes that climatic trends or cycles are not affecting the distribution of flood flows in a significant way.

Studies devoted to improving methodology for flood frequency analysis continue to be based on the iid assumption (NRC, 1999). Current interest in climate change and its potential impacts on hydrology in general and on floods in particular calls into question the iid assumption (NRC, 1998). Whether flood frequency analysis should continue to be pursued under the assumption or not is presently unsettled. A few studies have addressed the issue of nonstationarity described as trend in flood flows over time. However, little attention has been given to whether or not the assumption of temporal independence should continue to be accepted or if it should be rejected.

A trend, positive or negative, has a beginning and an end. A sustained positive trend would in time become limited by the carrying capacity of the stream's drainage area and a sustained negative trend would in time render the stream dry. It is reasonable to assume that between these extreme hydrologic states, the slope of a positive (negative) trend decreases (increases) as the flood flow distribution approaches a new regime. For hydrologic sequences, it is unlikely that such episodic behavior would have a fixed periodicity. Trend assessment should be pursued in conjunction with exploration of flood-flow series persistence.

TABLE 7. Past-to-Present and Present-to-Past Trend Analysis for St. Louis.

Length of Record	Period of Record	Correlation
	Past to Present	
7	1861-1867	0.087
17	1861-1877	0.146
27	1861-1887	0.228
37	1861-1897	0.112
47	1861-1907	0.152
57	1861-1917	0.202
67	1861-1927	0.134
77	1861-1937	-0.024
87	1861-1947	0.090
97	1861-1957	0.020
107	1861-1967	0.002
117	1861-1977	0.020
127	1861-1987	0.139
137	1861-1996	0.194*
	Present-to-Past	
9	1996-1988	0.598*
19	1996-1978	0.231
29	1996-1968	0.344*
39	1996-1958	0.393**
49	1996-1948	0.391**
59	1996-1938	0.243**
69	1996-1928	0.325**
79	1996-1918	0.297**
89	1996-1908	0.211*
99	1996-1898	0.185*
109	1996-1888	0.188*
119	1996-1878	0.160*
129	1996-1868	0.179*
137	1996-1861	0.194*

*5 Percent Level of Significance.
**1 Percent Level of Significance (for a one-sided test).

Climate is a nonlinear dynamic system. Such nonlinear systems can exhibit apparently periodic behavior over an interannual time scale and/or slowly-varying episodic behavior over decades or centuries (NRC, 1998). Nonlinear systems such as the earth's climate system can follow similar patterns for many years, but these systems are capable of abrupt shifts. In addition to natural climatic variability, man is influencing the climate system by increasing the concentration of carbon dioxide and other greenhouse gases in the atmosphere, as well as changing land cover and associated fluxes of gases, water vapor and energy. This further increases the uncertainty associated with climate.

The objective of flood frequency analysis is to estimate the magnitude and probability of floods for approximately the next 30-50 years, which will depend on the prevailing climate during that period. The analysis generally assumes that future climate will be similar to past climate. One response to possible climate variability is to employ only the record for more recent years. In its discussion of such a proposal, a recent National Research Council (NRC) committee observed:

> "At this time, given the limited understanding of the low frequency climate-flood connection, the traditional approach to flood frequency estimation entails a tradeoff between potential bias and variance. Bias arises from the use of long periods of record that are more likely to include time periods during which flood risk is different from that during the immediate planning period. On the other hand, longer periods of record allow the construction of risk estimators with less variance due to the larger sample with which the estimators are constructed" (NRC, 1999).

The most serious problem would be if the nonlinear climate system determining flood risk were nonstationary and thus drifted over time without internal feedbacks that kept the variability from year-to-year within some bounds around a stable regime. In such a case, the past might be a poor guide to the future. A second concern, even if climate is stationary in a statistical sense, is the time scale over which natural variations in climate persist. Do the ebbs and flow of climate variation have a short enough memory so that the historical flood risk observed over the last 100 years is a good guide for the estimation of flood risk over the planning period? One needs to recognize that from year-to-year the magnitude of the flood that occurs is highly variable. With modest records it would be very difficult to detect any systematic trend in the mean or the variances of floods from the random variation that might have occurred by chance. In fact, long records are needed to estimate reliably statistical parameters such as the mean and variances of flood flows.

CONCLUSIONS

This study found statistically significant trends in the northern part of the Upper Mississippi basin on both the main stem and tributaries. The major floods in this region generally are snowmelt floods. There are also trends in the lower part of the Upper Mississippi basin around St. Louis. The gauge records for the Missouri River at Hermann, the Mississippi River at Hannibal, at Alton/Grafton and at St. Louis, and the Illinois River at Meredosia all show statistically significant trends. Long duration precipitation over a large area is the cause of major floods in this part of the basin. There is no consistent pattern of trends on the Missouri River. The time period that one uses for trend analysis has a major effect on the size and significance of the trend. For example, major floods in the 1990s have a large influence on the observed trends at St. Louis.

There are several possible causes for the apparent trends on the Upper Mississippi and Lower Missouri Rivers. One possibility is increased precipitation in the more recent period. This climate variability is not clearly associated with global climate indices, which explain only a small fraction of the variability in annual floods. Land use changes and channel modifications may increase flood peaks, but these changes would probably have more effect at the upstream gauges that have smaller drainage areas. Measurement errors at stage-only gauges such as Hannibal should be investigated. In addition, corrections made by the Corps of Engineers to account for regulation could also have an influence on observed trend. The least likely cause of the trend is anthropogenic climate change associated with increased greenhouse gases: simulations of the Missouri River basin using General Circulation Model predictions indicate that average monthly runoff may decrease in that basin (Lettenmaier *et al.*, 1996).

The apparent increased flood risk in recent decades in the lower part of the basin suggests a need for reexamination of the implicit assumptions of independence and perhaps stationarity used in traditional flood frequency analysis. If a trend exists, a decision must be made as to how to extend the trend into the future. The estimates of the parameters would need to be adjusted to reflect the future trend. If trend is considered to be a manifestation of non-stationarity, then the amount of adjustment will affect the expected values of flood quantiles. It is unlikely that flood analysts will agree on the appropriate degree of adjustment due to the large uncertainty. An alternative approach is to describe the episodic movement of varying flood frequencies and amplitudes as a stationary persistent process. Research is needed on how to incorporate interdecadal variation in flood risk into flood frequency analysis so that state and federal water agencies can move to adopt procedures that appropriately reflect such variations.

APPENDIX A
ADDITIONAL TABLES

See Tables A-1 through A-5.

TABLE A-1. Mississippi River (USACE Records).

Station	Location	Drainage Area	Record Length	R^2	Correlation	Significance Level
	Northern Upper Mississippi River (Snow Melt Floods Dominate)					
Anoka	Upper Mississippi (Minnesota)	19,600	64	0.01	0.11	0.18
St. Paul	Upper Mississippi (Minnesota)	36,800	129	0.03	0.16	***0.03***
Winona	Upper Mississippi (Minnesota)	59,200	109	0.02	0.16	0.06
McGregor	Upper Mississippi (Iowa)	67,500	60	0.05	0.21	0.05
Dubuque	Upper Mississippi (Iowa)	82,000	117	0.10	0.31	***0.001***
	Transition Region Snowmelt and Rainfall Floods					
Clinton	Upper Mississippi (Iowa)	85,600	121	< 0.001	0.01	0.47
Keokuk	Upper Mississippi (Iowa)	119,000	117	0.02	0.15	0.06
	Upper Mississippi River Above Confluence With Missouri (Rainfall Floods Dominate)					
Hannibal	Upper Mississippi (Missouri)	137,000	117	0.20	0.45	***< 0.001***
Alton/Grafton	Upper Mississippi (Missouri)	171,300	67	0.17	0.42	***< 0.001***

TABLE A-2. Missouri River (USACE Records).

Station	Location	Drainage Area	Record Length	R^2	Correlation	Significance Level
Sioux City	Missouri	314,600 (35,120)	100	0.03	-0.17	0.95
Omaha	Missouri	322,820 (43,340)	100	< 0.001	-0.01	0.93
Nebraska City	Missouri	414,420 (134,940)	100	0.01	-0.08	0.22
St. Joseph	Missouri	429,340 (149,860)	100	0.05	+0.22	***0.01***
Kansas City	Missouri	489,162 (209,860)	100	< 0.001	-0.02	0.44
Booneville	Lower Missouri	505,710 (226,230)	100	0.01	+0.10	0.16
Hermann	Lower Missouri	528,200 (248,720)	100	0.05	+0.22	***0.02***

TABLE A-3. Upper Mississippi River Below Confluence With Missouri (USACE Records).

Station	Location	Drainage Area	Record Length	R^2	Correlation	Significance Level
St. Louis	Below Junction of Mississippi and Missouri	397,013 (417,520)	135	0.04	0.19	***0.01***
Chester	Below Junction of Mississippi and Missouri	708,563 (429,120)	70	0.07	0.26	***0.02***
Thebes	Below Junction of Mississippi and Missouri	713,200 (433,720)	63	0.10	0.32	***0.01***

TABLE A-4. Missouri River Tributaries (USACE Records).

Station	Confluence	Record Length	R^2	Correlation	Significance Level
Nishnabota River Above Hamburg, Iowa*	Between Nebraska City and St. Joseph	71	0.01	0.29	***0.09***
Thompson River at Trenton, Missouri*	Tributary of Grand River (Between Booneville and Hermann	69	0.08	0.29	***0.01***
Gasconade River at Jerome, Missouri*	Between Booneville and Hermann	73	0.02	0.16	0.09

*HCDN streamflow gage with the entire record having acceptable (relatively unimpaired) values and a daily minimum averaging time unit for acceptable values.

TABLE A-5. Mississippi River Tributaries (USACE Records).

Station	Confluence	Record Length	R^2	Correlation	Significance Level
Minnesota River Near Jordan, Minnesota	At St. Paul	63	0.06	0.24	***0.03***
St. Croix River, St. Croix Falls, Wisconsin*	Between St. Paul and Winona	86	0.09	0.30	***0.003***
Chippewa River at Chippewa Falls, Wisconsin	Between St. Paul and Winona	96	< 0.001	0.02	0.44
Wisconsin River at Muscoda, Wisconsin	Between McGregory and Dubuque	83	0.03	0.16	0.07
Iowa River, Wapello, Iowa	Between Clinton and Keokuk	95	0.01	0.09	0.20
Cedar River Near, Conesville, Iowa	Tributary of Iowa River	58	< 0.001	0.01	0.47
Des Moines River at Keosauqua, Iowa	Between Keokuk and Hannibal	86	0.005	0.07	0.27
Illinois River at Meredosia, Illinois	At Grafton	63	0.10	0.31	***0.01***
Meremac River Near Eureka, Missouri*	Between St. Louis and Chester	73	0.06	0.27	***0.02***

*HCDN streamflow gage with the entire record having acceptable (relatively unimpaired) values and a daily minimum averaging time unit for acceptable values.

APPENDIX B
NONPARAMETRIC TREND ANALYSIS AT SELECTED SITES

Tables A-1 through A-5 report the results of a trend analysis using linear regression. A nonparametric analysis of the frequency of large floods also supports the conclusion that the risk of large floods seems to have been increased. A summary appears in Table B-1. The pattern is clearest for Hannibal at the lower end of the Upper Mississippi. In the 56 years from 1941-1996 after the dry 1930s, a threshold of 300,000 cfs was crossed 17 times – however in the earlier 62 years from 1879-1940, no floods are recorded that exceeded 300,000 cfs. Thus, even though the two periods are of roughly equal length, all 17 floods in excess of 300,000 cfs occurred in the second half of the record. That such a result (all 17 floods occur in the second 56-year period) is due to chance has a probability of less than one-in-100,000 (one-sided hypergeometric test).

At Hermann on the lower Missouri, the three largest floods, and the only floods to even approach 1,000,000 cfs, all occurred in the last decade. Overall 12 floods exceeded a threshold of 500,000 cfs in the 57 year period from 1941-1997, whereas only three floods exceeded 500,000 cfs in the 43 years from 1898-1940. That such a result (12 or more of the 15 floods in excess of 500,000 cfs fall in the second period) is due to chance has a probability of 5 percent (one-sided hypergeometric test).

The St. Louis record is unusual. The last decade has the two largest floods of record, and the 1993 event is 20 percent larger than anything that occurred before. Consider again the division of floods before and after 1940. At St. Louis in the 56 year period from 1941-1996 some 22 floods exceeded a threshold of 600,000 cfs, whereas in the 80 years from 1861-1940, 21 floods exceeded 600,000. That such a result is due to chance has a probability of 7.8 percent (one-sided hypergeometric test). In fact, during the recent 20 years from 1977-1996, 11 annual floods exceeded 600,000 cfs, whereas during the 40 years from 1861-1900 that threshold was crossed only nine times! This result is significant at the 1.4 percent level (using a one-sided hypergeometric test). The thresholds employed in this analysis are convenient round numbers useful for differentiating between large floods and other events.

TABLE B-1. Statistical Analysis of Large Flood Occurrences.*

Gauge	Threshold (csf)	Floods After 1941	Flood Before 1940	Years After 1941	Years Before 1940	Significance Level of Test
Hannibal	300,000	17	0	56	62	$< 10^{-5}$
Herman	500,000	12	3	57	43	*0.045*
St. Louis	600,000	22	21	56	80	*0.078*
St. Louis	600,000	11**	9**	20	40	*0.014*

*The test considered the number of floods above the indicated threshold from 1941 through the end of the record, and from the beginning of the record through 1940. Columns 3 and 4 report the number of floods in each period. Columns 5 and 6 report the number of years in each period. A one-sided significance or P-value for each case is computed using a hypergeometric distribution to determine the probability that a given total number of large floods would by chance be randomly distributed to yield the observed division, or one more extreme.

**This special case considers the periods of 1977-1996 versus 1861-1900 to illustrate how different the frequencies of large floods were before the turn of the century and in the last two decades.

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