Uncertainty of Flood Frequency Estimates: Examining Effects of Land Use Changes, Climate Variability, and Climate Change: Synthesis Report

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Synthesis Report

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Findings

- The results of General Circulation Models used to project future climate are ambiguous. Although flood magnitudes and frequencies may change as a result of global warming, the evidence is not strong enough to project even the direction of change for the Upper Mississippi and Missouri River basins.

- There is 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.

- Reduced forest in the watersheds and floodplains and other channel modifications tend to increase the magnitude of floods. However, conclusions concerning changes in the flood frequency distribution due to land cover changes lack credibility.

- Flood sequences affected by trends and interdecadal climate variability may be described as realizations of stationary persistent processes. Stationary time series allow risk to vary over time but preserve the assumption that hydrology is stationary in the long run. When stationary time series models are used for risk forecasting, the predicted risk returns to the unconditional long-run average as the forecasting horizon increases.

Recommendations

- For the purposes of the Upper Mississippi River System Flow Frequency Study, there is not enough compelling evidence to deviate from application of the log-Pearson III distribution estimated by application of the method of moments to log flows. Although flood risk may have changed over time for some of the stations in the Upper Mississippi basin, there is currently no viable alternative in flood frequency analysis to using the assumption that flood flows are independent and identically distributed random variables.

- However, climate change and variability increase the uncertainty in the estimate of the 1% flood. The uncertainty in flood risk estimates should be communicated to floodplain communities, local sponsors of flood control projects, and participants in the National Flood Insurance Program.

- Federal agencies should consider updating Bulletin 17-B with one topic of consideration being how to treat interdecadal climate variability and climate change in flood risk assessment.

- What is beneficial for floodplain management under contemporary climate variability will also be useful under future climate uncertainty. For example, implementing the recommendations of the Galloway report (Interagency Floodplain Management Review Committee, 1994) will reduce vulnerability to flood damages under both current conditions and possible future climates.

Uncertainty of Flood Frequency Estimates: Examining Effects of Land Use Changes, Climate Variability, and Climate Change:

Synthesis Report

1. Introduction

Changes in the frequency and magnitudes of floods have been repeatedly emphasized as a potential consequence of global warming. The most recent report from the Intergovernmental Panel on Climate Change (IPCC, 2001) states that

> Flood magnitude and frequency are likely to increase in most regions, and low flows are likely to decrease in many regions. The general direction of change in extreme flows is broadly consistent among climate change scenarios, although confidence in the potential magnitude of change in any catchment is low (IPCC, 2001).

The United States National Assessment on the Potential Consequences of Climate Variability and Change stated with medium confidence that "research to date suggests that there is a risk of increased flooding in parts of the U.S. that experience large increases in precipitation" (Gleick, 2000).

The same report says "water managers and policymakers must start considering climate change as a factor in all decisions about water investments and the operation of existing facilities and systems." The Upper Mississippi River System Flow Frequency Study is a major Corps of Engineers study formed to update the flood profiles for the Mississippi River between St. Paul, Minnesota and Cairo, Illinois, the Missouri River south of Gavins Point Dam, and the Illinois River. The study coordinator considered climate change and variability, land cover changes, and the consequent uncertainty to be important issues to be evaluated as part of the study in addition to traditional flood frequency analysis. Indeed one of the motivating factors behind the study was that several communities questioned the adequacy of their flood protection and whether their flood risk had changed. The flood frequencies developed in 1979 showed that Hannibal, Missouri had a “200-year” flood and a “500-year” flood in the time span of 29 years (POS, 1998). This study provides an opportunity to address how water resources practitioners should accommodate uncertainties related to climate variability and change in flood frequency analysis and floodplain management.

The issue of the effect of climate change uncertainty on flood frequency analysis must be considered in the context of current floodplain management institutions. Flood frequency analysis is used to support sound floodplain management. Flood frequency estimates are used in engineering design for levees and other flood control structures. Flood profiles are used to delineate the Special Flood Hazard Area (SFHA), which is defined as an area of land that would be inundated by a flood having a 1-percent chance of occurring in any given year (also referred to as the base flood or 100-year flood). The regulatory floodplain is used by the Federal Emergency Management Agency (FEMA) for administering the National Flood Insurance Program (NFIP). Flood frequency estimates are also required for certifying that a levee has been adequately designed and constructed to provide 100-year flood protection for purposes of the flood insurance program.

Floodplain management is based on estimating the probability of future floods. Where adequate streamflow records are available, a statistical analysis is employed to determine the flood flow frequencies used in floodplain management decisions. The approach assumes that future climate conditions will have the same variability as the past. Potential global warming brings this assumption into doubt. According to the report of the Water Sector of the National Assessment (Gleick, 2000), the “reliance on the past record now may lead us to make incorrect - and potentially dangerous or expensive - decisions.”

The Institute for Water Resources (IWR) was tasked to examine land cover changes, climate change, and climate variability in the Upper Mississippi basin and their implications for floodplain management policy. This report summarizes the IWR studies and discusses the implications of climate uncertainty on floodplain management. This report is organized as follows. Section 2 discusses flood frequency analysis and uncertainty in flood frequency estimates. Section 3 examines recent studies of projected future climate change and their implications for flooding in the Mississippi River system. Section 4 discusses the variability in precipitation, streamflow, and flood records in the region. Since land cover changes also affect the hydrological cycle and the potential for floods, land cover issues are addressed in section 5. The effect of episodic climatic variability on flood risk analysis is then discussed in section 6. Finally, the implications of climatic uncertainty on floodplain management are assessed in section 7.

2. Flood Frequency Analysis and Uncertainty

2.1. Flood Frequency Analysis

Bulletin 17-B (1982), the Federal *Guidelines for Determining Flood Flow Frequency*, observes that traditional flood frequency analysis employs a “stationarity” assumption: “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 (i.i.d.) events. One implicitly assumes that climatic trends or cycles are not affecting the distribution of flood flows in an important way:

> In hydrologic analysis it is conventional to assume flood flows are not affected by climatic trends or cycles. Climatic time invariance was assumed when developing this guide (IACWD, 1982).

Watershed changes can also affect the homogeneity of the flood record. Bulletin 17-B states that “special effort should be made to identify those records which are not homogeneous” (IACWD, 1981, p. 7). The *Guidelines* assume a relatively homogeneous land cover over the record used for the flood frequency analysis. There are thus two related questions concerning climate change and variability: whether the future flooding will look like the past, and whether the assumptions for a statistical analysis using the methods of Bulletin 17-B are met.

Bulletin 17-B (1982) recommends fitting a Pearson type III distribution to the logarithms of observed annual peak discharges. The mean, standard deviation, and skew of the logarithms are obtained using the method of moments. The guidelines include procedures for obtaining a generalized skew coefficient and for censoring outliers.

Bulletin 17-B was adopted to provide a uniform method for Federal agencies to use for flood frequency estimation. Thomas (1985) lists several reasons for the adoption of a uniform method. The uniform technique is desirable to compare the relative benefits of flood control projects proposed by the same or different Federal agencies. It is also necessary to equitably compute flood insurance rates. According to Thomas (1985), "a uniform technique minimizes public confusion and discourages legal litigation that might result from Federal agencies advocating different estimates of the same frequency flood."

2.2. Uncertainty in Water Resources Planning

2.2.1. Definitions

The *Economic and Environmental Principles and Guidelines for Water and Related Land Resources Implementation Studies* (*Principles and Guidelines*) (P&G; 1983) is the governing document for Corps of Engineers planning. It states "the Federal objective of water and related land resources project planning is to contribute to national economic development consistent with protecting the Nation's environment" (P&G, 1983). It also states that "planners shall identify areas of risk and uncertainty in their analysis and describe them clearly." The *Principles and Guidelines* defines situations of risk "as those in which the potential outcomes can be described in reasonably well known probability distributions" and situations of uncertainty as those where "potential outcomes cannot be described in objectively known probability distributions."

A National Research Council (NRC) assessment of the Corps of Engineers risk analysis procedures noted that the *Principles and Guideline*'s definitions of risk and uncertainty are no longer commonly used (NRC, 2000). The NRC study defines uncertainty as "a lack of sureness about something or someone" whether or not the outcome can be described as a probability distribution. (The study notes that "'risk' is generally understood to describe the probability that some undesirable event occurs, and is sometimes used to describe the combination of that probability and the corresponding consequence of the event.")

The NRC report further differentiated between natural variability and knowledge uncertainty. Natural variability "deals with inherent variability in the physical world" which by assumption is irreducible. Knowledge uncertainty "deals with a lack of understanding of events and processes, or with a lack of data from which to draw inferences." This uncertainty supposedly can be reduced with additional information. The NRC study argues that the distinction between natural variability and knowledge uncertainty is hypothetical and dependent on the model used by the analyst.

The 2001 Intergovernmental Panel on Climate Change study (IPCC, 2001) explicitly treated the uncertainties in the assessment of climate change and attempted to state the "level of confidence" in their conclusions. The report defined three sources of uncertainty: problems with data, problems with model, and other sources, which included uncertainty from the projections of human behavior. The study noted that the confidence levels are subjective probabilities, and experts tend to be inept at making judgments under conditions of high uncertainty. Although the IPCC notes "that judgments of likelihood should be considered only with caution," they conclude that subjective probabilities are necessary in the decision analytic frameworks necessary for policy analysis.

Matalas (2001) provides an alternative definition of uncertainty based on Davidson (1991). Davidson defines three types of decisionmaking environment. The "objective probability environment" holds that the past is a statistically reliable guide to the future. The "subjective probability environment" refers to subjective probabilities in an individual's mind regarding future outcomes. The third environment is the "true uncertainty environment," where the decisionmaker believes that "unforeseeable changes will occur" regardless of whether objective relative frequencies existed in the past or subjective probabilities exist today (Davidson, 1991). As Matalas notes, true uncertainty implies that some of the outcomes are unknown at the time a decision is made. The National Assessment on Climate Change notes "there are also likely to be unanticipated impacts of climate change during the 21st century." These "surprises" include unforeseen changes in the physical climate system, unpredicted biological consequences, and unexpected social and economic changes (NAST, 2001). "Because the sample space is incomplete, probabilities, personalistic or otherwise, cannot be assigned to those outcomes that are not known" (Matalas, 2001).

How one classifies climate change uncertainty will influence how one approaches the effect of climate change on floodplain management and the role of climate modeling in flood frequency analysis. The National Research Council study on the Corps' risk analysis methods implied that future flood risk analysis could in theory be based on climatic modeling:

> In the future--at least in principle--the sophistication of atmospheric models might improve sufficiently such that flood time series could be modeled and forecast with great accuracy. All the uncertainty currently ascribed to natural variation might become knowledge uncertainty in the modeling, and thus reflect incomplete knowledge rather than randomness (NRC, 2000).

Most would concede that a better knowledge of climate and more accurate General Circulation Models will reduce the uncertainty of future climate. On the other hand, climate is a nonlinear dynamic system, so without perfect knowledge of the initial conditions, a climate model will not produce perfect forecasts of future flood time series. Furthermore, future climate depends on future human decisions regarding emissions of greenhouse gases. No matter how much effort is made, information on future choices made by humans will remain somewhat "unknowable."

2.2.2. Sources of Uncertainty in Flood Reduction Studies

Current Corps of Engineers' procedures recognize the uncertainty inherent in floodplain management. The Corps of Engineers conduct flood damage reduction studies using a risk-based framework. The risk analysis quantifies various sources of uncertainty. In a flood damage reduction study, the sources of risk include hydrologic, hydraulic and economic uncertainty. Sources of hydrologic uncertainty typically include: (1) data availability; (2) data error; (3) accuracy and imprecision of measurement and observation; (4) sampling uncertainty, including the choice of samples and appropriate sample size; (5) selection of an appropriate probability distribution to describe the stochastic events; (6) estimation of the hydrological and statistical parameters in models; (7) low probability flood extrapolation, e.g. tail problems of frequency curves; (8) modeling assumptions; and (9) the characterization of river basin parameters (USACE, 1992a). The hydraulic analysis also typically contains numerous sources of error. Estimates of channel geometry and roughness parameters involve uncertainty. Potentially large sources of error are aggregation errors. When estimating flood profiles or routing floods, areas along the reach are aggregated into segments by using one point to represent the entire segment. Variations along the reach may not be modeled accurately (USACE, 1992a).

The Corps of Engineers calculates the uncertainty in the expected annual damages used in flood damage reduction studies. The Corps uses the method described in Bulletin 17-B to describe hydrologic uncertainty. The procedure calculates a confidence interval for the discharge-frequency function, but ignores uncertainty in the skew. Several methods can be used to estimate the stage-discharge uncertainty. The standard deviation of errors is found for gauged reaches. It is assumed that 95 percent of the error range is contained within two standard deviations of the mean (USACE, 1996). There are also procedures for calculating the uncertainty in stage-damage relationships and in levee performance.

Although there are statistical methods for estimating parameter uncertainty, there are no clear-cut methods to quantify model error, such as a violation of the assumption that the annual floods are independent and identically distributed. Future climate change has the potential to change the frequency of flood events, manifesting itself as a shift in the discharge-frequency curve. Past climatic variability or trends in the flood record will affect the accuracy of the estimate of the discharge-frequency relationship. Persistence or lack of temporal independence may increase the amount of uncertainty in a flood frequency estimate, although the estimate may be unbiased. Land cover changes can also change the frequency-discharge relationship. Channel modifications and land cover changes in the floodplain may change the stage-discharge relationship.

3. Climate Variability and Climate Change

3.1. Future Climate Change

The first IWR study considered how climate variability and climate change might affect the probability of large floods. One aspect of the study examined how climate change associated with global warming may affect future flooding on the Upper Mississippi and Missouri Rivers. The study stated that the results of General Circulation Models used to project future climate are mixed. The report concluded that there was little evidence that flood frequencies will increase as a result of global warming based on the understanding of future climate at that time. The study is discussed more fully in Olsen and Stakhiv (2000) *Flood Hydroclimatology in the Upper Mississippi and Missouri River Basins*.

Since Olsen and Stakhiv (2000) was written, several new studies have been completed evaluating recent advances in climate change science. The Intergovernmental Panel on Climate Change (IPCC) released a new report in 2001 (IPCC, 2001a; IPCC 2001b). The IPCC evaluated and utilized a wide range of General Circulation Models. The study concluded that the Earth's climate is unequivocally changing (IPCC, 2001a). The observed increases in average annual temperatures are consistent with warming caused by increased carbon dioxide in the atmosphere. Increased temperatures are expected to result in a more intense hydrologic cycle. The climate models show that "globally averaged water vapour, evaporation and precipitation are projected to increase" (IPCC, 2001a). On the regional scale, there are both increases and decreases in precipitation. For example, the IPCC report noted that General Circulation Models are inconsistent in projecting future precipitation for Central North America, with some models seeing increases and other models decreases.

A "National Assessment of the Potential Consequences of Climate Variability and Change" was also completed for the United States. The study examined different regions throughout the United States and different sectors, including the water sector. The report states that "scientific evidence is increasingly compelling" that humans are changing climate. The report says there is very high confidence in the following expected climate changes: average U.S. surface temperatures will continue to increase, global precipitation will increase, and regional patterns and timing of precipitation will change (NAST, 2001).

Although there is a very high degree of confidence that annual precipitation will increase on a global basis, there is much less confidence in how the changes will be distributed on a regional basis. According to the U.S. water sector report, "general circulation models poorly reproduce detailed precipitation patterns" (Gleick, 2001). There is low confidence in precipitation projections for specific regions because different models produce different results. Figures A-1 and A-2 in Appendix A show the projected changes in temperature and precipitation given by the two General Circulation Models selected for the U.S. National Assessment, the Canadian and the Hadley models. The Canadian model projects drier conditions in the Upper Mississippi and Missouri basins, while the Hadley model projects wetter conditions. Both GCMs predict warmer conditions, although the Canadian model projections are warmer.

Figures A-3 and A-4 show comparisons of General Circulation Model simulations with observations. Figure A-3 shows that the models reproduce the observed average annual temperatures well. However, Figure A-4 shows that the models do not do as well in reproducing average annual precipitation. Seasonal and extreme values of precipitation have more discrepancies between simulation results and observations.

As would be expected, annual volume of runoff follows changes in precipitation patterns. Wolock and McCabe (1999) estimated mean annual runoff for major river basins using the GCM estimates of precipitation and temperature. They estimated that the Upper Mississippi mean annual runoff from 1990 to 2030 <u>increases</u> 21% using the Hadley model and <u>decreases</u> 22% using the Canadian model. For the same period, the Missouri River basin showed an 18% <u>increase</u> using the Hadley model and a 25% <u>decrease</u> using the Canadian model. The Water Sector report concluded, "regional estimates of future runoff must be considered speculative and uncertain" (Gleick, 2001).

The U.S. National Assessment noted that flood frequencies are likely to change for some regions. The study noted that risk of flooding might increase in parts of the U.S where there are large increases in precipitation. There is however, only medium confidence in this conclusion. The study noted that "impacts on flooding depend not only on average precipitation but on the timing and intensity of precipitation - two characteristics not well modeled at present" (Gleick, 2000, p. 102).

Despite the additional studies completed since Olsen and Stakhiv (2000), there is no new evidence to change the original conclusion. The results of General Circulation Models used to project future climate are still ambiguous. Although flood magnitudes and frequencies may change as a result of global warming, the evidence is not strong enough to project even the direction of change for the Upper Mississippi and Missouri River basins.

3.2. Variability in the Flood Record

Another aspect of the IWR study looked at whether contemporary climate trends are affecting floods on the Upper Mississippi and Missouri Rivers. Several studies reported evidence of historical trends of increasing temperatures and precipitation in the Upper Midwest since 1900 (Lettenmaier *et al*., 1994; Karl *et al*., 1996). Karl et al. (1996) found precipitation trends in the Midwest with many showing increases of 10% to 20%. In addition, the proportion of the U.S. with an above normal number of wet days has significantly increased (Karl et al. 1996). Increasing temperatures and a moister climate could be an indication of a changing climate consistent with global warming.

3.2.1. Precipitation and Streamflow Trends

Karl et al. (1995) found a trend of increasing percentages of total annual precipitation falling as heavy one-day or three-day rainfall events in the United States. Karl and Knight (1998) found that in the Upper Mississippi region, the highest 10th percentile of precipitation events showed an annual increase and increases in the spring, summer, and autumn, but a decrease in the winter. In the Missouri River region, there was a smaller annual increase and increases in the spring and summer and decreases in the autumn and winter. Angel and Huff (1997) also analyzed annual maximum rainfall for the upper Midwestern states and found an approximately 20% increase from 1901 to 1994 in the number of daily precipitation events of 2 inches or more.

Lettenmaier *et al*. (1994) found that average streamflow has tended to increase in the Upper Midwest, particularly in the months of December to April and lagged the increase in precipitation which increased mostly in the autumn. Lins and Slack (1998) evaluated trends for seven different quantiles of streamflow at 395 selected stream gauges in the United States representing relatively undisturbed watersheds. They found that the contiguous United States was becoming wetter but less extreme. There are more statistically significant uptrends than downtrends nationally in the annual minimum daily mean flow and in the lower to middle quantiles of streamflow. The Upper Mississippi and Missouri River basin follows a similar pattern. The area has a number of gauges with significant uptrends in the annual minimum and median flows. However, only a few stations show a significant trend in the annual maximum flow, and the number of uptrends and downtrends are roughly equal.

Groisman et al. (2001) examined the relationship between streamflow and precipitation in more detail. They found a significant relationship between the frequency of heavy precipitation events and high streamflow in the eastern half of the United States. For the Upper Mississippi region, the return period for a daily precipitation above 101.6 millimeters (mm) was 15 years, and the trend in the frequency of the events from 1900 to 1999 was not significant. Groisman et al. did not examine drainage basins larger than 10,000 square miles. For both the Upper Mississippi and Missouri basins, they found a significant relationship between the annual number of days with daily precipitation and streamflow above the 90th percentile, but the correlation was not significant for days with precipitation and streamflows above the 99th percentile. Furthermore, there was no significant correlation between the number of days with precipitation and streamflow in the month with the maximum runoff. In the spring months of maximum runoff, snowmelt contributes a large percentage of runoff.

Matalas and Olsen (2001) examined gauges in the Upper Mississippi and Missouri River basins from the Hydroclimatic Data Network (HCDN) (Slack and

Landwehr 1992; Slack et al. 1993). These gauges are on rivers that are reported to be relatively unaffected by regulation and are shown in Figures 1 and 2. In the investigation, flood sequences were considered as elements of the spectrum of extreme flows, where the spectrum extends from the low to the high flows. Most gauges in the Upper Mississippi basin show significant positive trends in low flows, with larger trends in the more northern part of the basin. There is also a consistent pattern of significant positive trends in the annual mean flows throughout the basin. Longer-duration high flows showed less propensity toward trend and persistence. A few sites in the southern part of the basin showed trends in the 1-day high flow. The significance of the trends for each gauge is shown in Tables 1 and 2. The locations of the trends in the 1-day low, annual average, and 1-day high flows are shown schematically in Figure 3. There are also significant trends in 30-day and 90-day high flows in Iowa, Illinois and Missouri. The results from Matalas and Olsen (2001) are consistent with the findings by Lins and Slack (1998).

3.2.2. Trends in Main Stem Flooding

Analysis of unimpaired flow data constructed by the U.S. Army Corps of Engineers found statistically significant upward trends in many gauge records along the Upper Mississippi and Missouri Rivers. Figure 4 shows the location of trends and their significance on the Mississippi and Missouri Rivers. There is no significant trend on the Missouri River for sites reflecting flood flows from the West, corresponding to Sioux City, Omaha, Nebraska City, and Kansas City. A trend was significant at St. Joseph, but was lost after the Kansas River enters the Missouri River from the west before Kansas City. The trend becomes significant again downstream at Hermann.

In the region dominated by snowmelt floods for the Upper Mississippi River, there are significant trends at St. Paul, Winona, McGregor, and Dubuque. Using the entire 122-year period of record, the trend at Clinton is not significant. The trend at Keokuk is significant at the 6% level for the 117-year period of record. The Hannibal and Alton/Grafton gauges above the confluence of the Missouri River have highly significant trends with $p < 0.1\%$. The Hannibal gauge is not a USGS recording station and some have expressed concern that the rating curve has shifted and was not updated. The three gauges downstream of the confluence of the Missouri and Mississippi, St. Louis, Chester, and Thebes, have significant trends, but are highly correlated ($\rho > 0.975$) and thus represent essentially the same hydrologic experience over the period of record for which the Chester and Thebes gauges have been active (Olsen and Stakhiv, 2000; Olsen et al., 1999).

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 (Olsen and Stakhiv, 2000; Olsen et al., 1999).

One interpretation of the data is that there is not “a great deal of evidence supporting a hypothesis of non-randomness in the Upper Mississippi study region as a whole” (HEC, 1999). If the entire Upper Mississippi and Lower Missouri region is considered as a whole including the large basin gauges along with smaller tributary watersheds, then there is no consistent pattern of non-randomness. However, there are certain areas where the pattern of non-randomness appears to be consistent. The location of the main stem trends corresponds to locations in the basin where there are significant trends in 30-day and 90-day high flows. Our interpretation of the data is 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 (Olsen et al., 1999).

3.2.3. Relationships with Global Climate Patterns

Natural interdecadal climate variation is a potential cause of apparent non-stationarity in the flood process (National Research Council (NRC), 1999). Olsen and Stakhiv (2000) also examined the relationship between global-scale climate patterns and hydrologic variability for the Upper Mississippi and Missouri Rivers. Large floods are often associated with anomalous climate patterns. Many climate patterns are related to ocean temperatures and the associated effects on atmospheric circulation. Some global climate patterns may persist over several years or show oscillations on an interannual to interdecadal time scale. On the other hand, flood frequency analysis generally assumes that the annual floods are independent and identically distributed, and this assumption may be negated if there are persistent climate patterns that change the frequency of floods.

Olsen and Stakhiv (2000; Olsen et al., 1999) used a regression analysis to investigate the relationships of annual maximum Mississippi River floods with climate indices such as the El Niño/Southern Oscillation (ENSO), the Pacific Decadal Oscillation (PDO), and the North Atlantic Oscillation (NAO). The indices could explain only a small percentage of the variability in the annual maximum floods. Patterns, such as tropical Pacific sea surface temperature anomalies associated with El Niño or La Niña events, fluctuate on an interannual frequency and this frequency varies over the historical record. Olsen and Stakhiv concluded that as long as the future intensity and frequency of El Niño events over time resemble the historical values, flood frequency analysis could account for the climate variability associated with these events.

However, there is some speculation that ENSO events may become more frequent and intense as a result of global warming. The 2001 IPCC report states that “current projections show little change or a small increase in amplitude for El Niño events over the next 100 years,” but the study also notes that there are shortcomings in the simulation of El Niño in the current General Circulation Models.

Another recent study found that the occurrence of ENSO events might vary interdecadally. Jain and Lall (2001) examined if the historical record used in flow frequency analysis is representative of the possible time-frequency fluctuations of climate. They noted that the frequency of ENSO events varied over the historical record. Using a simple ENSO model, they showed that sea-surface temperatures in the Pacific were highly non-stationary. Jain and Lall (2001) concluded “it is likely that there will be substantial variations (and potential nonstationarities) over timescales of interest for flood frequency analysis.” El Niño events over time may not resemble the historical values due to nonlinearities of the climate system.

3.2.4. Trends and Persistence

Trend analysis depends on the period of time used in the analysis. Matalas (1999) developed an evolutionary account of trends for the flood sequences of the Upper Mississippi and Missouri basins. The evolutionary account looks at the sequences in two ways: from the beginning of the record forward using different record lengths, and from the present backwards for different record lengths. The analysis showed that trends hold for some segments of the sequences, but not for other segments. In effect, trends “come” and “go”. Matalas suggests that the pattern of “trend-no trend” may be a reflection of oscillatory movements of varying frequency and amplitude. This view of the “trend-no trend” pattern suggests that flood sequences may be viewed as realizations of stationary persistent processes (Matalas, 1999, Olsen, et al, 1999).

Matalas and Olsen (2001) conducted the trend assessment of HCDN gauges in conjunction with an assessment of flow series persistence. Significant persistence was associated with the significant trends in annual low flows and annual mean flows in the Upper Mississippi basin. Matalas (2001) examined the relationship between trend and persistence in more detail. He assumed that the flood sequences could be characterized by trend or persistence, where trend is linear and persistence is Markovian. He showed that de-Markoving the sequences reduced the level of significance of trends in most of the sequences. De-trending the sequences reduced the level of significance of persistence in most of the sequences. Matalas concluded that the results suggest that there is an interaction between trend and persistence in that one partially accounts for the other.

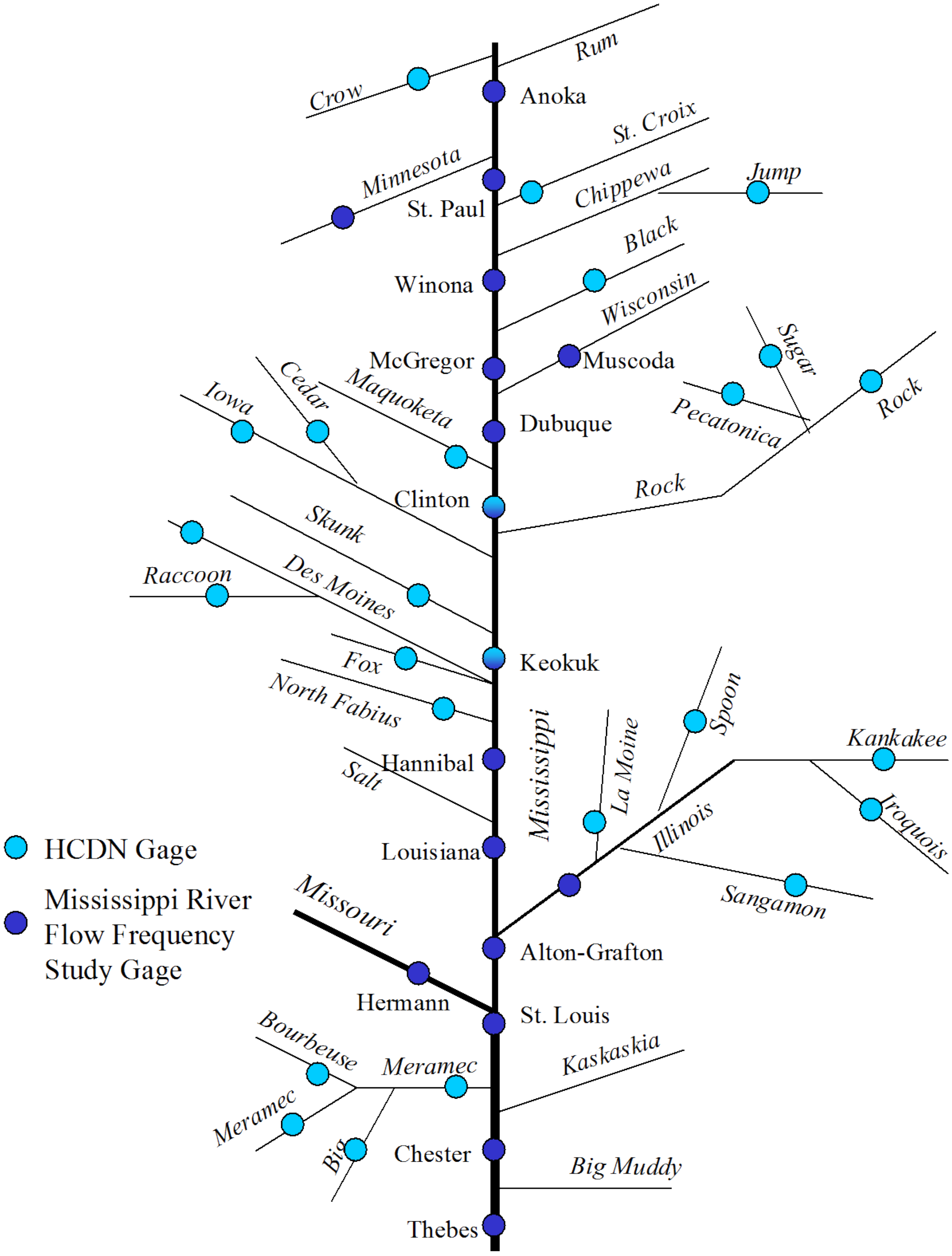

Figure 1: Schematic showing location of Mississippi River basin gauges used in Upper Mississippi River System Flow Frequency Study (UMRFFS) and Hydroclimatic Data Network (HCDN)

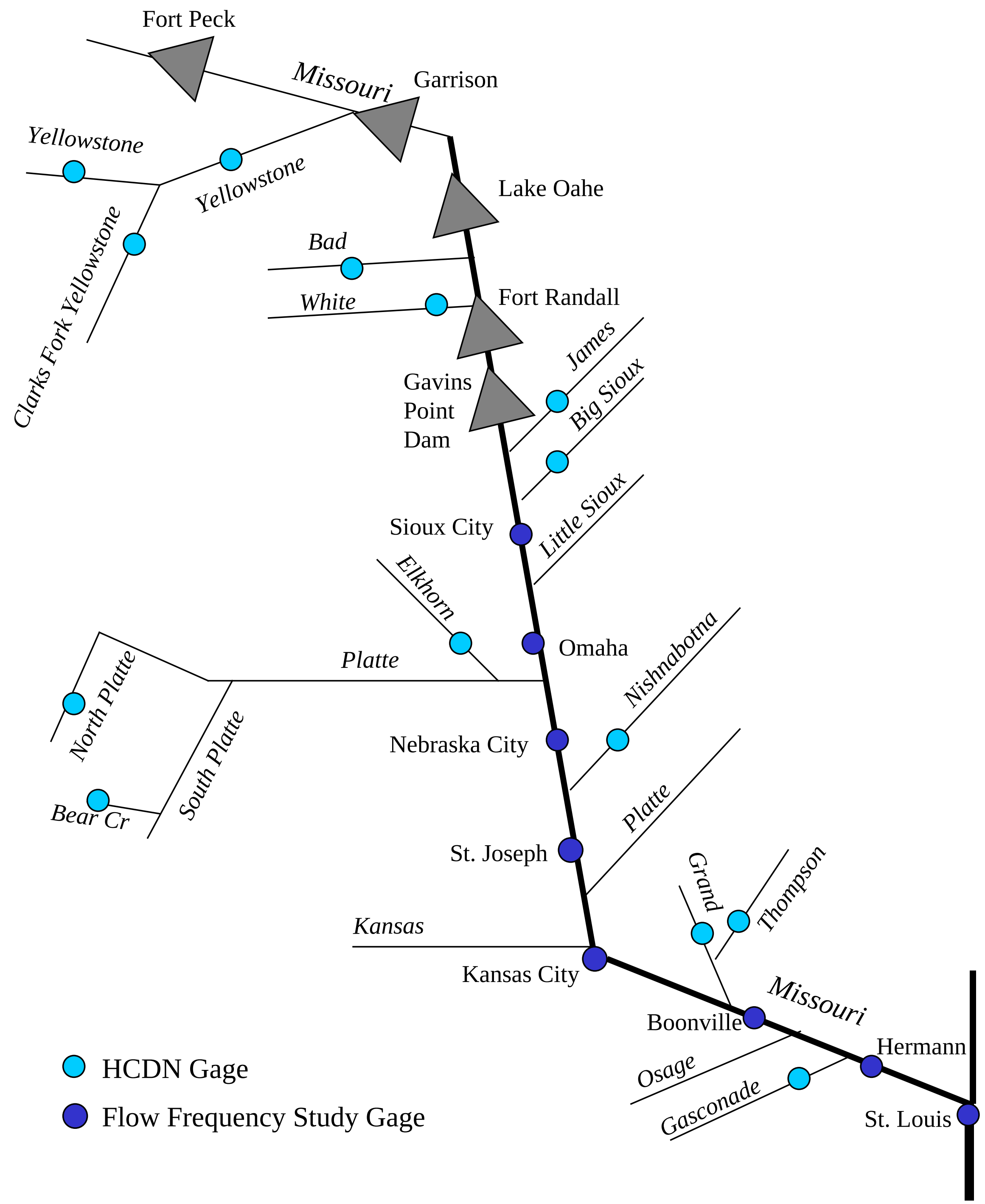

Figure 2: Schematic showing location of Missouri River basin gauges used in UMRFFS and HCDN.

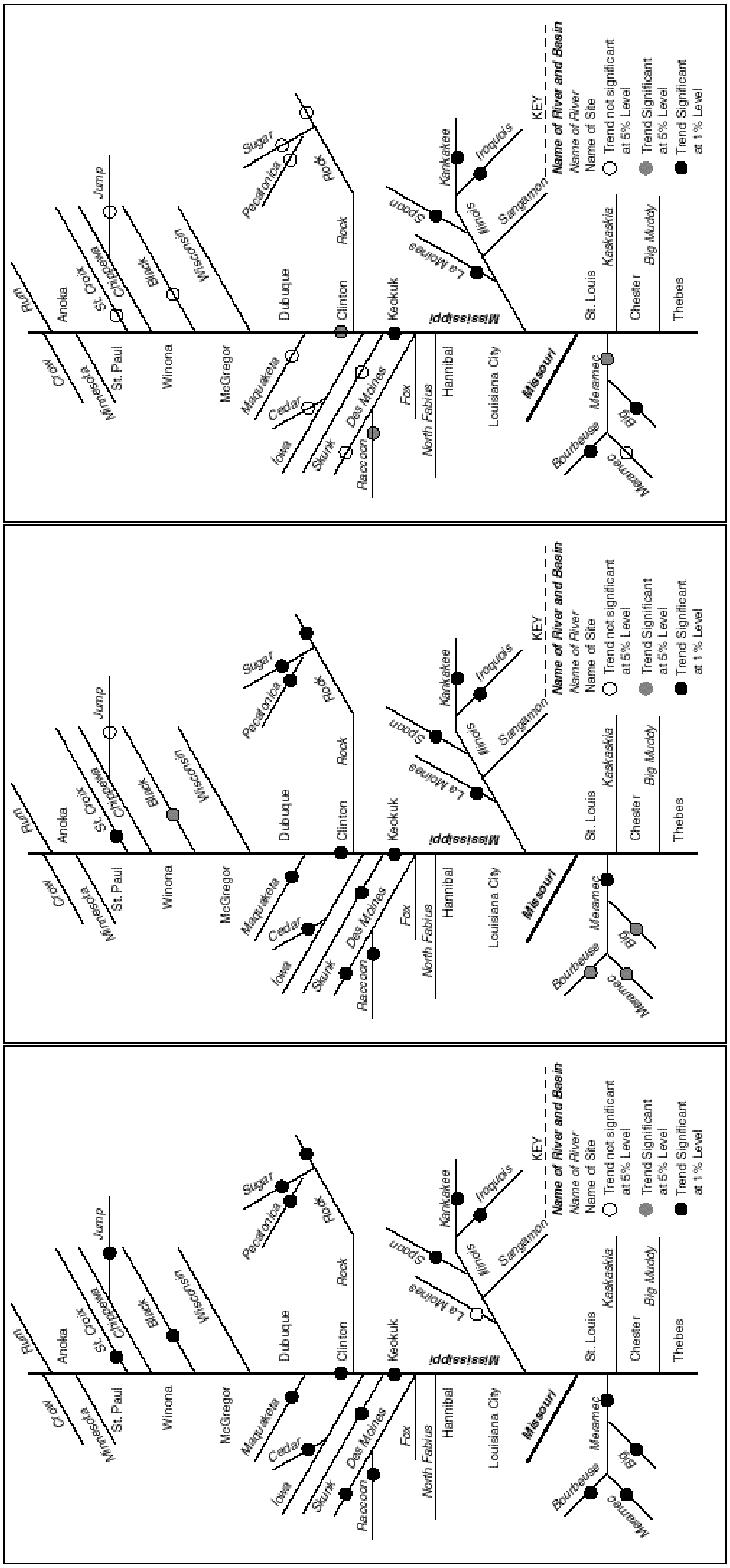

Figure 3: Schematic location of trends in the Upper Mississippi Basin for 1-day low (bottom), annual mean (middle), and 1-day high flows (top).

Table 1: Significance of trends for Upper Mississippi River.

River	**Test**	**1-Day Low**	**30-Day Low**	**90-Day Low**	**Annual Mean**	**90-Day High**	**30-Day High**	**1-Day High**
St. Croix	Pearson	++	++	++	++	0	0	0
	Kendall	++	++	++	++	0	0	0
	Spearman	++	++	++	++	0	0	0
Jump	Pearson	++	++	++	0	0	0	0
	Kendall	++	++	++	0	0	0	0
	Spearman	++	++	++	0	0	0	0
Black	Pearson	++	++	++	+	0	0	0
	Kendall	++	++	++	0	0	0	0
	Spearman	++	++	++	0	0	0	0
Maquoketa	Pearson	++	++	++	++	+	0	0
	Kendall	++	++	++	+	+	0	0
	Spearman	++	++	++	+	+	0	0
Rock	Pearson	++	++	++	++	0	0	0
	Kendall	++	++	++	++	+	0	0
	Spearman	++	++	++	++	+	0	0
Pecatonica	Pearson	++	++	++	++	0	0	0
	Kendall	++	++	++	+	0	0	0
	Spearman	++	++	++	++	0	0	0
Sugar	Pearson	++	++	++	++	0	0	-
	Kendall	++	++	++	++	0	0	0
	Spearman	++	++	++	++	0	0	0
Cedar	Pearson	++	++	++	++	++	+	0
	Kendall	++	++	++	++	++	+	0
	Spearman	++	++	++	++	++	+	0
Skunk	Pearson	++	++	++	++	+	+	0
	Kendall	++	++	+	+	+	+	0
	Spearman	++	++	+	+	+	+	0
Des Moines	Pearson	++	++	++	++	++	++	0
	Kendall	++	++	++	++	++	+	0
	Spearman	++	++	++	++	++	++	0
Raccoon	Pearson	++	++	++	++	++	++	+
	Kendall	++	++	++	++	++	+	0
	Spearman	++	++	++	++	++	+	0

Table 1. (Continued).

River	**Test**	**1-Day Low**	**30-Day Low**	**90-Day Low**	**Annual Mean**	**90-Day High**	**30-Day High**	**1-Day High**
Kankakee	Pearson	++	++	++	++	++	++	++
	Kendall	+	++	++	++	++	++	++
	Spearman	++	++	++	++	++	++	++
Iroquois	Pearson	++	+	++	++	++	++	++
	Kendall	++	++	++	++	++	++	++
	Spearman	++	++	++	++	+	++	++
Spoon	Pearson	++	++	++	++	++	++	++
	Kendall	++	++	+	+	+	+	+
	Spearman	++	++	++	+	+	++	+
La Moine	Pearson	+	+	0	++	+	++	++
	Kendall	0	0	0	+	+	+	++
	Spearman	0	0	0	+	+	+	++
Meremec (Steelville)	Pearson	++	++	0	+	0	0	0
	Kendall	++	++	++	+	0	0	0
	Spearman	++	++	++	+	0	0	0
Bourbeuse	Pearson	++	0	0	+	0	+	++
	Kendall	++	+	0	0	0	+	+
	Spearman	++	++	0	+	0	+	+
Big	Pearson	++	+	0	+	0	++	++
	Kendall	++	++	0	0	0	++	+
	Spearman	++	++	0	0	0	+	+
Meremec (Eureka)	Pearson	++	+	0	++	0	++	+
	Kendall	++	++	+	+	+	++	+
	Spearman	++	++	+	+	+	++	+
Mississippi River (Clinton)	Pearson	++	++	++	++	++	+	+
	Kendall	++	++	++	++	++	+	+
	Spearman	++	++	++	++	++	+	+
Mississippi River (Keokuk)	Pearson	++	++	++	++	++	++	++
	Kendall	++	++	++	++	++	++	++
	Spearman	++	++	++	++	++	++	++

Table 2: Significance of trends for Missouri River.

River	**Test**	**1-Day Low**	**30-Day Low**	**90-Day Low**	**Annual Mean**	**90-Day High**	**30-Day High**	**1-Day High**
Yellowstone (Corwin Springs)	Pearson	0	++	++	++	+	+	+
	Kendall	0	+	+	++	+	+	+
	Spearman	0	+	+	++	+	0	+
Clarks Fork	Pearson	0	0	0	0	0	0	0
	Kendall	0	0	+	0	0	0	0
	Spearman	0	0	0	0	0	0	0
Yellowstone (Billings)	Pearson	0	++	++	++	+	+	0
	Kendall	0	++	++	++	+	0	0
	Spearman	0	++	++	+	+	0	0
Big Sioux	Pearson	++	++	++	++	++	++	0
	Kendall	++	++	++	++	++	0	0
	Spearman	++	++	++	++	+	+	0
North Platte	Pearson	++	++	++	0	0	0	0
	Kendall	++	++	++	0	0	0	0
	Spearman	++	++	++	0	0	0	0
Bear	Pearson	++	++	++	0	0	0	0
	Kendall	++	++	++	0	0	0	0
	Spearman	++	++	++	0	0	0	0
Elkhorn	Pearson	++	++	++	++	++	++	0
	Kendall	++	++	++	++	++	++	++
	Spearman	++	++	++	++	++	++	++
Nishnabotna	Pearson	++	++	++	++	++	++	+
	Kendall	++	++	++	++	++	++	++
	Spearman	++	++	++	++	++	++	+
Grand	Pearson	++	+	+	+	+	+	0
	Kendall	++	++	+	+	+	+	0
	Spearman	++	++	++	+	+	+	0
Thompson	Pearson	++	++	+	+	+	+	0
	Kendall	++	++	+	+	++	+	0
	Spearman	++	++	+	+	+	+	0
Gasconade	Pearson	0	0	0	0	0	0	0
	Kendall	++	++	+	+	0	0	0
	Spearman	++	++	+	+	0	0	0

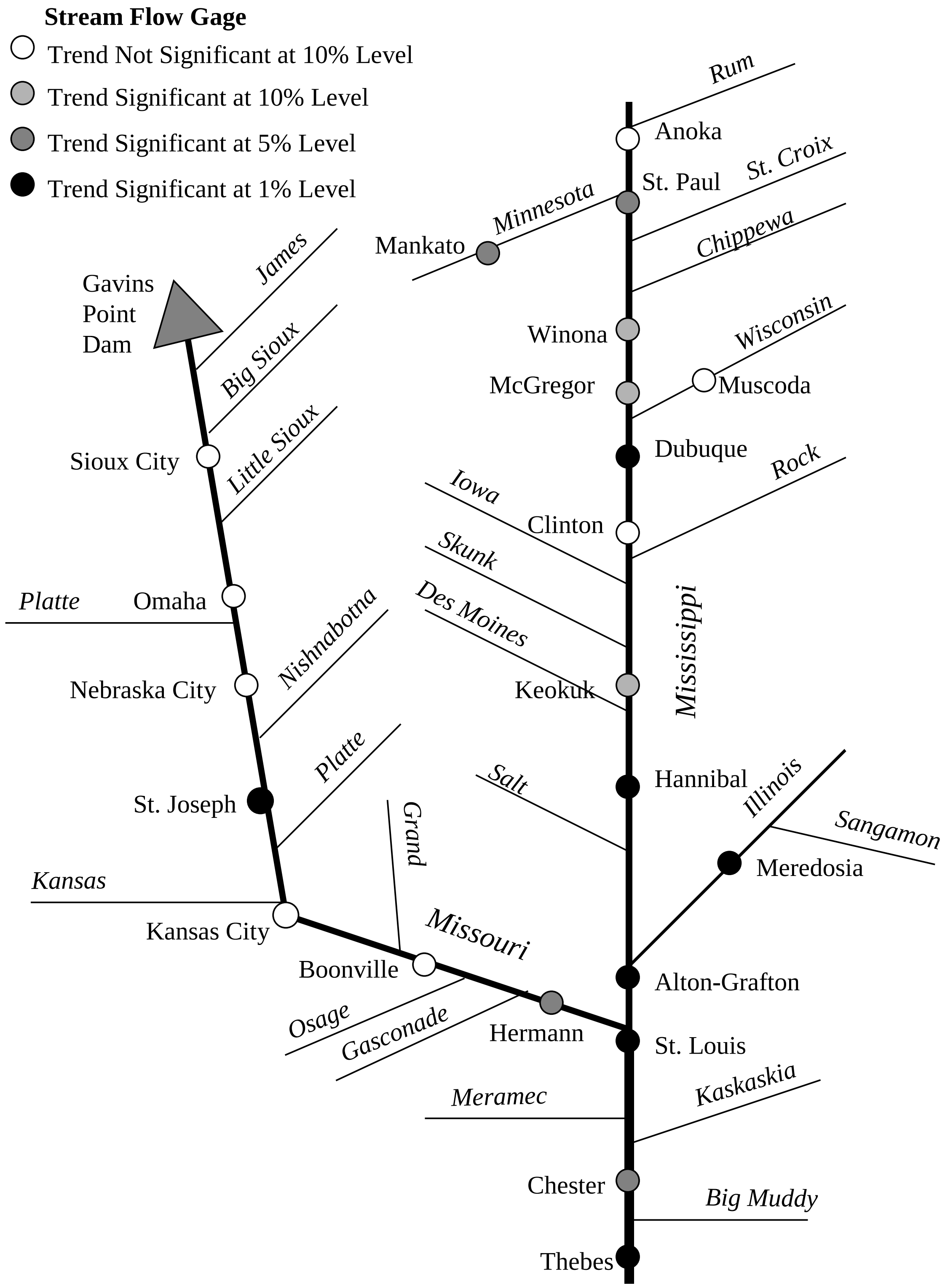

Figure 4: Gauge locations in the UMRFFS showing trends and their significance levels.

3.2.5. Paleoclimate and Interdecadal Climate Variations

Paleoclimatic data can be used to extend the climate record. Lake varves, pollen, sediment and tree rings are examples of proxy data that can be used in paleohydrology (Jarrett, 1991). There are difficulties in using paleoclimatic data directly in flood frequency estimation. Major land cover changes have occurred in the basin. In addition, the correlations between proxy data and floods are imperfect. However, the paleoclimate data can be used to reconstruct long-term hydrologic records that can show low frequency climatic variation and the episodic movement between dry and wet periods.

Tree rings are one type of proxy data. Tree rings represent drought extremes better than wet extremes and tend to underestimate extreme values (Woodhouse and Overpeck, 1998). Cleaveland and Duvick (1992) analyzed tree ring data in Iowa. The driest decades since the 17th century were 1816-1825, 1696-1705, 1664-1673, 1735-1744, and 1931-1940. Therefore, droughts comparable to the 1930s occurred five times in the past four centuries. Cleaveland and Duvick (1992) found the 14 wettest years occurred before 1852, although this result may be due to a decrease in the trees' ability to respond to unusually wet conditions.

Figures 5 and 6 compare Mississippi River flow at Keokuk with a Palmer Drought Severity Index (PDSI) based on tree-ring data. The PDSI data begins in 1696, while the Mississippi River data begins in 1878. The PDSI data are the average of two locations in Iowa (92.5 West, 43.0 North and 92.5 W, 41.0 N) based on drought reconstructions made by Cook et el. (1999). Figure 5 compares the yearly PDSI values and the normalized average annual flow for Keokuk. The correlation between the tree ring PDSI and the annual flow is about 0.7 for the period 1895-1978. Figure 6 shows a comparison of the 10-year moving averages of PDSI and the annual flood at Keokuk. The correlation between PDSI and the flood data is about 0.6 for the period 1895-1978. The 10-year moving averages show a similar pattern of dry periods and wet periods. A trend in flow and PDSI since the dry 1930s is apparent in the graph. A wet period in the late 1880s is also visible. The droughts in 1816-1825 and 1696-1705 can be seen in the PDSI data.

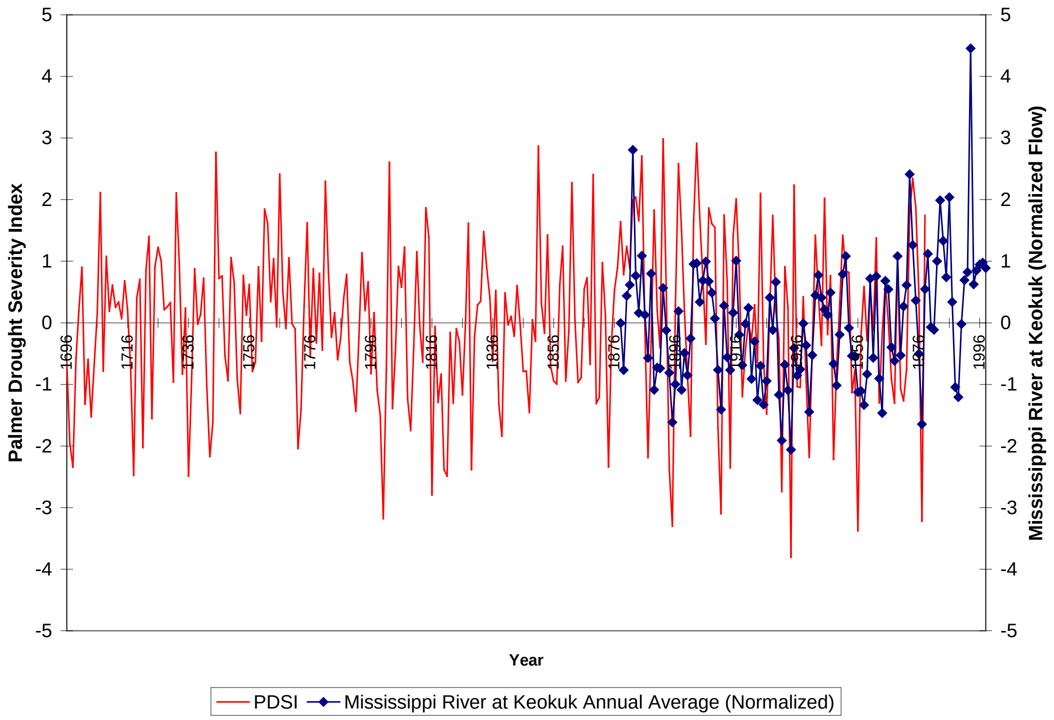

Figure 5: Comparison of the Palmer Drought Severity Index based on tree rings and annual average flow of the Mississippi River at Keokuk, Iowa.

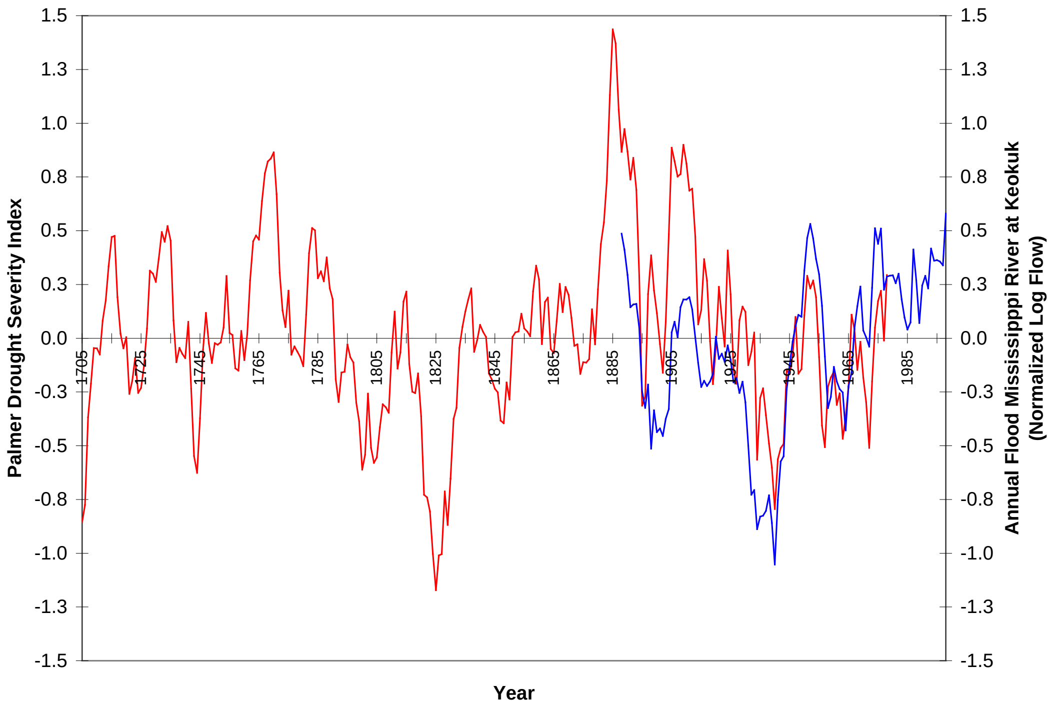

Figure 6: Comparison of 10-year moving averages of the annual flood at Keokuk and the Palmer Drought Severity Index based on tree-ring data.

4. Land Cover Changes and Channel Modifications

Another IWR study reviewed the history of land cover changes in the Upper Mississippi River basin. Major changes in land cover occurred as a result of the westward expansion, particularly in the latter part of the 19th century. One major land cover change was the deforestation of a large area of Minnesota and Wisconsin. Some of the original forested region was converted to farmland, while some of the more northern pine forests became reforested with deciduous trees. Much of the study looked at the effect of this change in land cover on runoff for the major tributaries of the Upper Mississippi in Minnesota and Wisconsin. The study used the University of Washington's Variable Infiltration Capacity model to simulate the effects of land cover on evapotranspiration, infiltration, and runoff. The simulations showed large-scale deforestation reduces evaporation and subsequently increases runoff. The annual mean runoff is higher for the simulated modern land cover compared with presettlement land cover for the lower basin of the Upper Mississippi River at Anoka and the St. Croix River at St. Croix Falls where land cover changed from forest to agriculture.

An objective of the study was to examine how land cover changes and channel modifications affect flood frequencies and magnitudes. The simulations showed that reduced forest in the watersheds and floodplains and other channel modifications tend to increase the magnitude of floods. However, the simulation of modern land cover and channel conditions did not reproduce the observed flood frequency distribution well. Large differences were noted in the variance and skew of the distributions with poor fits in certain flood probability ranges. Therefore, firm conclusions concerning changes in the flood frequency distribution due to land cover changes lack credibility. More details are available in *Land Use Changes, Channel Modifications, and Floods in the Upper Mississippi Basin* (Olsen, 2001).

5. Trend, Persistence, and Flood Risk Assessment

Trends in the flood record challenge the traditional assumption that flood series are independent and identically distributed (i.i.d.) random variables and suggest that flood risk may be changing over time. If nonstationary hydrology manifests itself as positive or negative trends in flood sequences, then flood frequency analysis will need to take into account the "expected" form and duration of the trend given the "expected" time of inception of the trend. 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 (Olsen et al., 1999).

Matalas (1999) suggests that flood sequences may be viewed as realizations of stationary persistent processes. Accepting flood sequences as realizations of stationary persistent processes effectively rejects the i.i.d. assumption underlying flood frequency analysis. The price of acceptance is difficulty in using the Log-Pearson type III distribution. The distribution does not naturally accommodate persistence, even in the form of Markovian persistence. Other distributions, such as the lognormal, may present less difficulty in accommodating stationary persistence than the Log-Pearson distribution. See Matalas (1999) *Flood Frequency Analysis in the Upper Mississippi and Missouri Basins*.

Stedinger and Crainiceanu (2001) evaluated alternative flood risk models that might be adopted using the Hannibal and St. Louis flood records as examples. The first model assumed that the maximum annual floods Q_t are independent and identically distributed random variables where the logarithm of Q_t is normally distributed. This is a traditional model used for flood risk management. Bulletin 17-B recommends a Log-Pearson type III distribution (IACWD, 1982), which for a log-space skew of zero simplifies to a lognormal distribution (Stedinger et al., 1993). A zero skew was adequate in this instance and simplified many of the calculations with this model. The second model assumed that the maximum annual floods have a lognormal distribution around a linear trend. This model represents the non-i.i.d. hypothesis by a trend. The practical problem posed by this model is whether the trend can reasonably be extrapolated beyond the period of record. The third model assumed that the maximum annual floods are generated by a stationary low-order Autoregressive Moving-Average process ARMA(p,q) (Box et al., 1994) for the log-flood series. The ARMA model explains the observed upward trend as variability due to persistence in a stationary time series. This last modeling approach is particularly attractive because it preserves the assumption of stationarity in the long run.

Stedinger and Crainiceanu's (2001) investigation demonstrated that stationary time series models are very flexible and produce a reasonable interpretation of historical records and a corresponding flood risk forecast. Stationary time series allow risk to vary over time but preserve the assumption that hydrology is stationary in the long run. When stationary time series models are used for risk forecasting, the predicted risk returns to the unconditional long-run average as the forecasting horizon increases. Stedinger and Crainiceanu (2001) conclude that the resulting variation in flood risk is likely to affect flood risk management only if decision parameters can be adjusted on a year-to-year basis. In their example, variations in flood risk are likely to have disappeared before major construction projects can be designed, authorized and completed. Because of persistence, the lognormal ARMA model had the largest standard errors of the mean and 100-year flood estimators. The impact on the precision of the estimated mean flood was much greater than on the precision of the 100-year flood estimator. Further details are discussed in *Climate Variability and Flood Risk Assessment* (Stedinger and Crainiceanu, 2001).

6. Climate Uncertainty and Floodplain Management

The Upper Mississippi Flow Frequency Study will update stage-discharge relationships and flood profiles. This information will be used for engineering design in future flood damage reduction studies, the administration of the National Flood Insurance Program, and levee certification. The implications of climate uncertainty on floodplain management are discussed here.

6.1. Flood Damage Reduction Studies

6.1.1. Engineering Design for Flood Control Structures

Flood frequency estimates are used in engineering design for levees, dams and other flood control structures. Economic justification of flood reduction alternatives requires the calculation of expected annual damages given alternative plans. The expected annual damages are calculated from the relationship between flood damages and frequency. Figure 7 shows the mathematical relationships used in developing the flood damage-frequency relationship for use in cost-benefit analysis in flood damage reduction studies. Although the Upper Mississippi River System Flow Frequency Study is not concerned with economic damages, the study is developing discharge-frequency relationships (Figure 7(b)) and stage-discharge relationships (Figure 7(a)) for the basin.

Uncertainty is incorporated into the Corps flood damage reduction studies. Uncertainty in the discharge-probability function is defined as the uncertainty in the mean and standard deviation. Bulletin 17B provides a method to calculate confidence limits based on this parameter uncertainty. Corps procedures (EM 1110-2-1619) also provide procedures for calculating uncertainty in the stage-discharge and stage-damage functions.

As shown in Figure 7, the methods can be combined to estimate the uncertainty in flood damage reduction benefits from a project.

A flood reduction project is evaluated based on whether it contributes positively to national economic development (NED). Projects are analyzed in terms of their expected performance. There is no minimum level of protection required for Corps projects (USACE, 2000). Local sponsors, however, typically want a levee to provide protection for the 1% flood to meet the requirements of the National Flood Insurance Program.

The Corps risk-based analysis method can be interpreted as a method to support an investment strategy in a portfolio of projects. Any one project may not turn out to provide a positive economic return because of the uncertainty in estimating the flood risk over an investment period. However, the portfolio of projects is likely to provide a positive return if the estimate of risk is unbiased (Dave Goldman, 2001, personal communication). The nation as a whole can be considered to be risk neutral. Climatic change has the potential to alter the flood risk over the investment period over parts of the country. Changes in flood frequency may cause the engineering design to be less than optimal in terms of national economic development.

Although the Federal government will on average obtain positive benefits for a flood reduction project assuming the benefit estimates are unbiased, the local sponsor may have less protection than they expect due to uncertainty in the flood frequency estimates. Uncertainty in the stage-frequency relation implies a positive probability that the local community’s residual risk is larger than the exceedance probability of the levee’s level of protection. Larger uncertainty increases the expected residual risk. A risk neutral or risk averse community faced with increased uncertainty due to climate change may want to increase the size of the levee to reduce their residual risk.

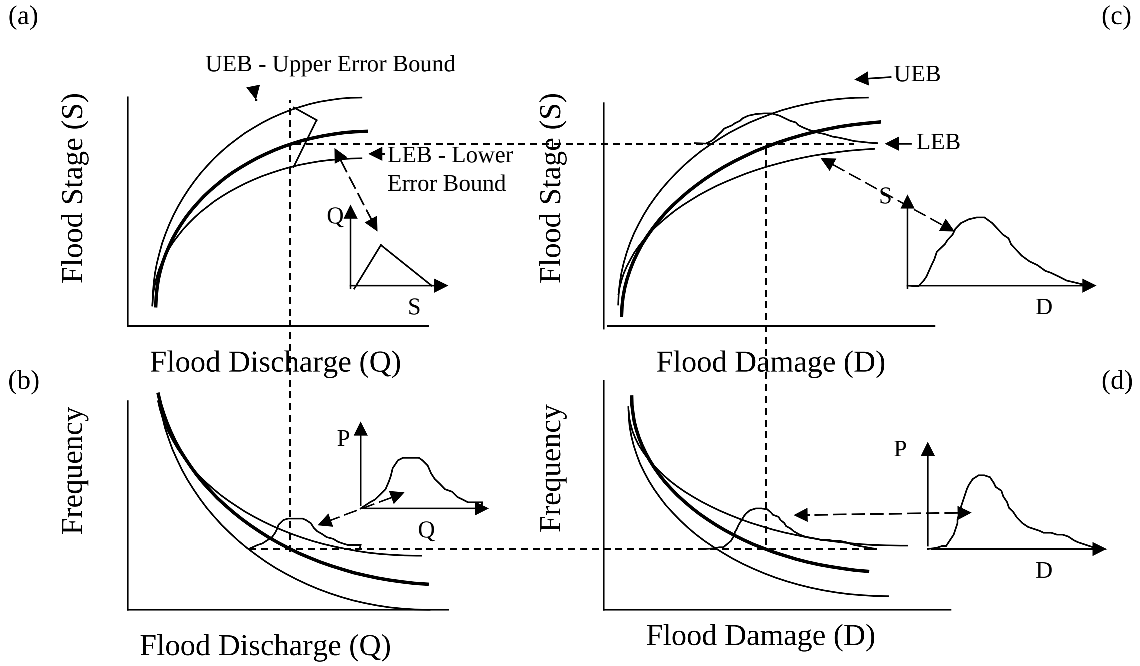

Figure 7: Relationships used in developing the flood damage-frequency relationship for use in cost-benefit analysis for flood damage reduction studies.

6.1.2. Nonstructural Measures for Flood Damage Reduction

Nonstructural floodplain management measures reduce flood damages without changing the extent of flooding. These measures change the uses of the floodplain or adapt existing users to the hazard of flooding. Nonstructural measures include permanent evacuation of the floodplain and relocation/demolition of floodplain structures, regulation of floodplain uses, flood proofing, and flood warning systems.

Benefits for nonstructural flood damage reduction projects are calculated in a similar method to structural projects with some differences. The *Economic and Environmental Principles and Guidelines for Water and Related Land Resources*

Implementation Studies (*P&G,* 1983) define what benefits are claimable for structural and nonstructural measures. In the analysis of permanent relocation/evacuation plans, four benefits are included: (1) value of new use of the vacated land; (2) reduction in damage to public property; (3) reduction in emergency costs; and (4) reduction in disaster relief and administrative costs of the National Flood Insurance Program. Avoided flood damages for relocated or evacuated properties are not included in the calculation of National Economic Development benefits for permanent relocation and evacuation plans (USACE, 2000, p. E-84). The Interagency Floodplain Management Review Committee (1994; commonly called the Galloway Report) noted that although there may be an economic rationale for including only damages prevented to those borne by other than floodplain residents, “the concern still exists that it results in a bias against nonstructural projects.”

6.2. Flood Insurance

The National Flood Insurance Program (NFIP) was established by the National Flood Insurance Act of 1968 (P.L. 90-448). The program identifies flood-prone areas, provides flood insurance to property owners living in areas that join the program, and employs other floodplain management for flood hazard mitigation. The Special Flood Hazard Area (SFHA) is defined as the area of land that would be inundated by a flood having a 1-percent chance of occurring in any given year (also referred to as the base flood or 100-year flood). The Flood Disaster Protection Act of 1973 required mandatory purchase of flood insurance for structures in communities participating in the program if federal loans or grants were used to acquire or build the structures or if the loans were made by lending institutions regulated by the federal government. According to the

Federal Emergency Management Agency (FEMA), flood insurance within the SFHA is required "to protect Federal financial investments and assistance used for acquisition and/or construction purposes within communities participating in the NFIP" (FEMA, 2001). Development can occur in the SFHA, provided minimum floodplain management regulations are met.

The flood insurance program does not recognize uncertainty in the designation of the 1% floodplain, even though a risk analysis would be a useful strategy to ensure a positive return for the flood insurance program. However, the National Flood Insurance Program is not like a private insurance company. The NFIP is not actuarially sound and is not designed to be, since about 30% of the policies are subsidized. Congress authorized subsidized flood insurance rates in policies covering structures built before a community's flood insurance rate map was prepared in order to encourage community participation in the program (GAO, 2001).

A private insurance company may raise premium rates to account for greater uncertainty in their risk estimates. However, raising rates to improve the NFIP's financial health could have an adverse effect on other federal disaster relief costs, such as Small Business Administration loans or FEMA disaster assistance grants (GAO, 2001). Raising flood insurance rates would cause some policyholders to cancel their coverage. There seems to be little chance that the flood insurance program would change policies due to additional uncertainty in floodplain delineation due to climate variability.

6.3. Levee Certification

If floodplain property is protected by a levee certified to provide protection against a 100-year flood, it can avoid being designated as a Special Flood Hazard Area.

The protected community can avoid paying mandatory flood insurance, so levee certification has important economic consequences for a community. The Corps of Engineers has responsibility for levee certification. The historical standard for levee certification, and the standard still employed by FEMA, is the levee height must protect against a 1% flood plus 3 feet of freeboard. The 3 feet of freeboard was an arbitrary standard, so the Corps of Engineers adopted a risk-based approach in the 1990's. The new Corps policy requires a reliability of at least 90% of passing a 1% flood:

> Existing and proposed levees will be certified as capable of passing the FEMA base flood if the levees meet the FEMA criteria of 100-year flood elevation plus three feet of freeboard, with two exceptions, as follows. When the FEMA criteria results in a "Conditional Percent Chance Non-exceedance" (Reliability) of less than 90%, the minimum levee elevation for certification will be that elevation corresponding to a 90% chance of non-exceedance. When the FEMA criteria results in a reliability of greater than 95%, the levee may be certified at the elevation corresponding to a 95% chance of non-exceedance.
> (USACE, 1997)

Uncertainty in the estimate of the 1% flood is based on the same Corps procedures used in flood damage reduction studies (EM 1110-2-1619). Greater uncertainty in the estimate of the 100-year flood will require a higher levee to provide 90% or 95% reliability of passing the base flood. Increased uncertainty due to climate change would lead to higher and more expensive levees in order to protect against a 1% flood with 90% or 95% reliability. However, many decision makers would be hesitant to spend additional funds on an unproven risk.

6.4. Climate Change and Floodplain Management

Although flood risk may have changed over time for some of the stations in the Upper Mississippi basin, there is currently no viable alternative in flood frequency analysis to using the assumption that flood flows are independent and identically distributed random variables. Rates in the National Flood Insurance Program (NFIP) have been set based on methods of Bulletin 17-B, which assume a stationary climate. Uncertainty in the 1% flood is also not recognized by the NFIP. Levee certification for purposes of NFIP recognizes the uncertainty of stage-frequency estimates. However, the method to estimate the 1% stage and its uncertainty again assumes stationary climate. Deviations from the traditional methods of estimating the 1% flood would undoubtedly cause increased litigation. Furthermore, we do not have a good enough understanding of climate to know how long climate trends may continue into the future. Therefore, for the purposes of the Upper Mississippi River System Flow Frequency Study, there is not enough compelling evidence to deviate from application of the Log-Pearson type III distribution estimated by application of the method of moments to log flows.

One proposed method to deal with climate change is “adaptive management” (Stakhiv, 1998). Adaptive management can be applied to floodplain management by planning periodic review of flood frequency estimates. Adaptive management in the design of flood control structures would entail flexible designs that would allow changes based on later information (Olsen, et al., 2000). However, as Arnell and Hulme (2000) point out, “there is presently little economic incentive to invest in flexible structures, as discount rates as currently applied tend to mean that what happens after the first 10 years has little effect on the net present value.”

Arnell and Hulme (2000) and the IPCC (2001b) mention that decision makers typically add a safety factor or “headroom” to account for uncertainty. “Freeboard,” which is equivalent to “headroom,” is an arbitrary amount added to a levee or dam to account for uncertainty. Increased freeboard raises construction costs. Additional freeboard is equivalent to increasing levee size to account for increased uncertainty in order to protect against a 1% flood with 90% or 95% reliability.

One tool for reducing risks is a “demand-management option,” such as changing land-use patterns in the floodplain (Gleick, 2000). Zoning land uses in the floodplain is primarily a function of local governments. Local communities should be aware of the increased uncertainty in flood frequency estimates caused by climate uncertainty. The increased uncertainty should be communicated to floodplain communities, local sponsors of flood control projects, and participants in the National Flood Insurance Program. Local communities should be aware that the 1% flood is an arbitrary criterion and its estimate is uncertain. As Gilbert White noted, “what’s the effect of having a single criterion of 100 years if in doing so a local community is encouraged to regulate any development up to that line and then to say we don’t care what happens above that line?” (Reuss, 1993) Communities should consider the entire range of possible floods in their floodplain management plans. Climate change and variability increase the uncertainty in the estimate of the 1% flood and encourages a broader approach to floodplain regulation.

7. Conclusion

This report examined climate change issues for the Upper Mississippi River System Flow Frequency Study. The General Circulation Models used to project future climate are not consistent in their projections of future climate for the Upper Mississippi and Missouri basins. Therefore, it is uncertain how flood risk may change in the coming decades. However, there is evidence of increased flood risk in recent years in the lower part of the basin. This increased risk cannot now be attributed to anthropogenic climate change. Even without global warming, natural interdecadal climate variability can lead to episodic wet and dry periods in the Upper Mississippi basin.

Our study considered one approach to the episodic changes in flood risk is to treat flood series as a stationary persistent random process. Stationary time series preserves the assumption that flood series are stationary in the long run. Although there are short run changes in flood risk, variations are likely to disappear before structural projects are completed. Another consequence of the stationary persistent flood model is a larger standard error in the estimate of the 100-year flood.

The effect of climate uncertainty on flood risk assessment should be considered in the context of contemporary floodplain management institutions. The flood frequency estimates are to be used in flood damage reduction studies, floodplain mapping for the National Flood Insurance Program (NFIP), and levee certification for purposes of NFIP. For over two decades, the Log-Pearson type III probability distribution under the assumption of stationary climate has been recommended for flood frequency analysis for Federal agencies. Deviations from its use may cause litigation if communities face a larger Special Flood Hazard Area or the loss of levee certification.

Our recommendation for the purposes of the Upper Mississippi River System Flow Frequency Study is that there is not enough compelling evidence to deviate from application of the Log-Pearson type III distribution estimated by application of the method of moments to log flows. Although flood risk may have changed over time for some of the stations in the Upper Mississippi basin, there is currently no viable alternative in flood frequency analysis to using the assumption that flood flows are independent and identically distributed random variables. However, climate change and variability increase the uncertainty in the estimate of the 1% flood and the increased uncertainty should be communicated to the public. In addition, Federal agencies should consider updating Bulletin 17-B with one topic of consideration being how to treat interdecadal climate variability in flood risk assessment.

As others have noted, reducing the vulnerability to floods under current conditions will also reduce vulnerability to floods in a future climate. The Intergovernmental Panel on Climate Change (1997) stated "if we make the water resources sector more resilient to contemporary conditions, this would help in adapting to future changes in climate." Stakhiv (1998) noted "what is considered beneficial for contemporary climate variability will also be useful under future climate uncertainty." After the 1993 floods in the Upper Midwest, the Interagency Floodplain Management Review Committee (1994; Galloway Report) provided several recommendations to reduce vulnerability to flood damages:

> To reduce the vulnerability to flood damages of those in the floodplain, the Administration should:
> Give full consideration to all possible alternatives for vulnerability reduction, including permanent evacuation of floodprone areas, flood warning, floodproofing of structures remaining in the floodplain, creation

of additional natural and artificial storage, and adequately sized and maintained levees and other structures;

Adopt flood damages reduction guidelines based on a revised *Principles and Guidelines* which would give full weight to social, economic, and environmental values and assure that all vulnerability reduction alternatives are given equal consideration; and

Where appropriate, reduce the vulnerability of population centers and critical infrastructure to the standard project flood discharge through use of floodplain management activities and programs.

Implementation of these recommendations would reduce vulnerability under both current conditions and an uncertain future climate.

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10. Appendix A: Color Figures

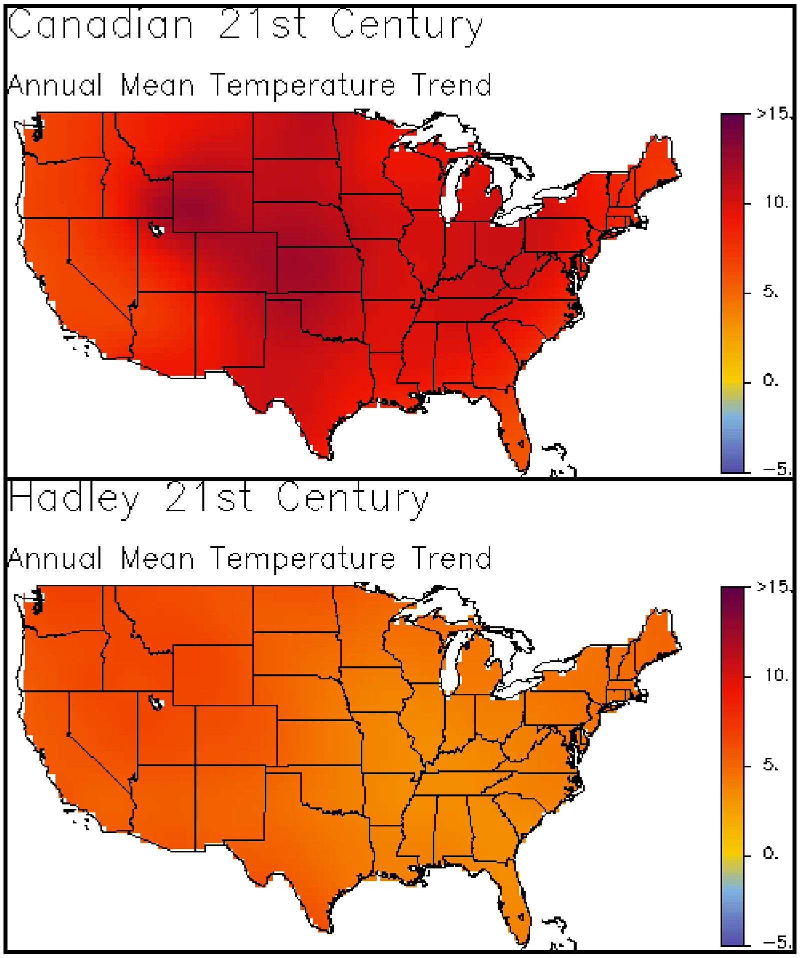
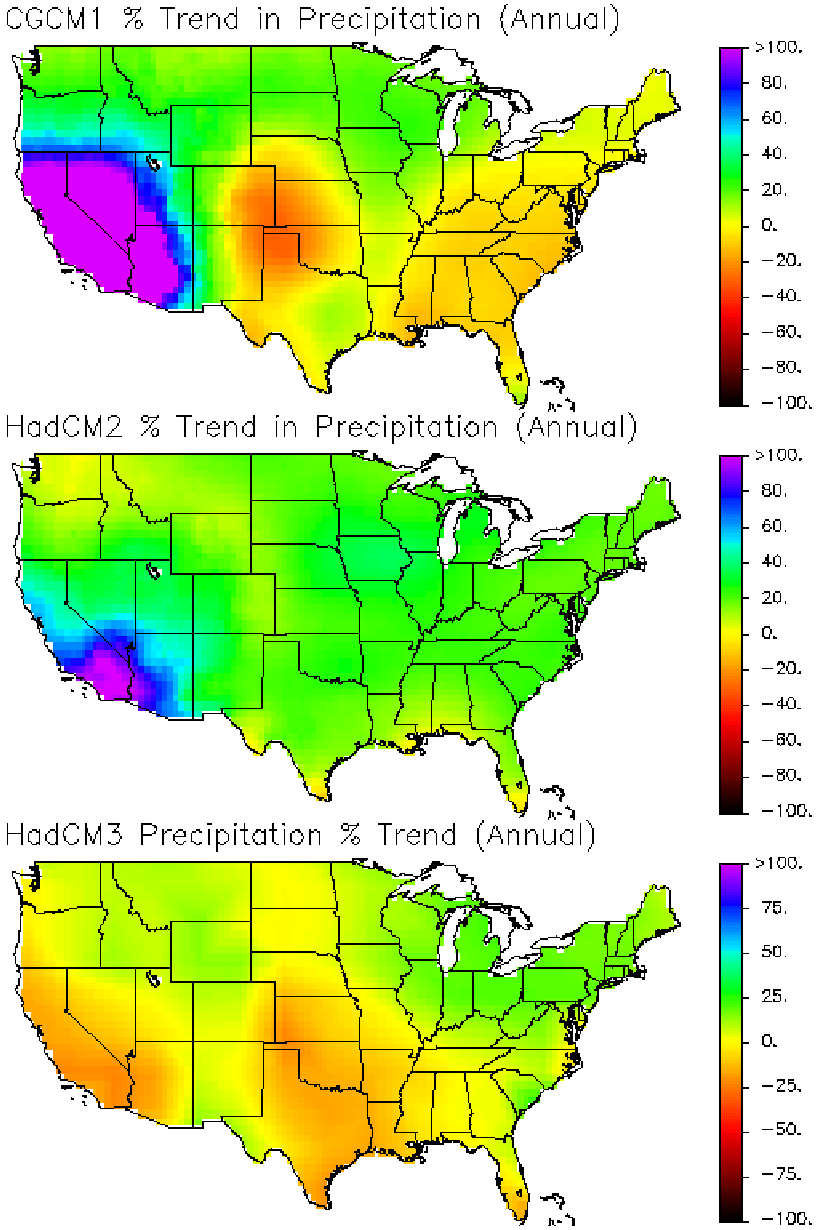


Figure A-1: Projections of future temperature using two different General Circulation Models. The units are in degrees Fahrenheit per century. (NAST, 2001)


CGCM1 % Trend in Precipitation (Annual)

HadCM2 % Trend in Precipitation (Annual)

HadCM3 Precipitation % Trend (Annual)

Figure A-2: Projections of changes in the 21st century in annual average precipitation using two different General Circulation Models. The units are in percentage change per century. The HadCM3 is a revised version of the HADCM2 (Hadley Center Model). (NAST, 2001)

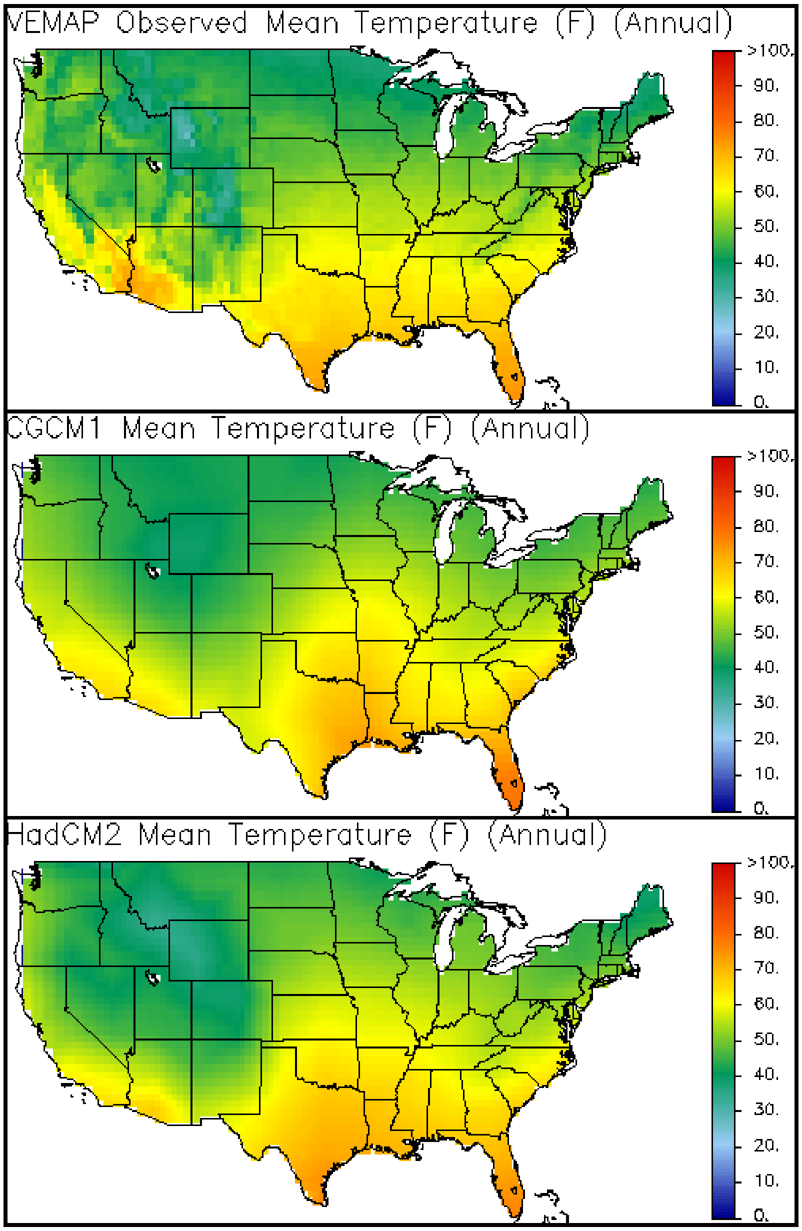


Figure A-3: Comparison of mean annual temperature from two GCMs with observed mean annual temperature for the period 1961-1990 (in degrees Fahrenheit). (NAST, 2001)

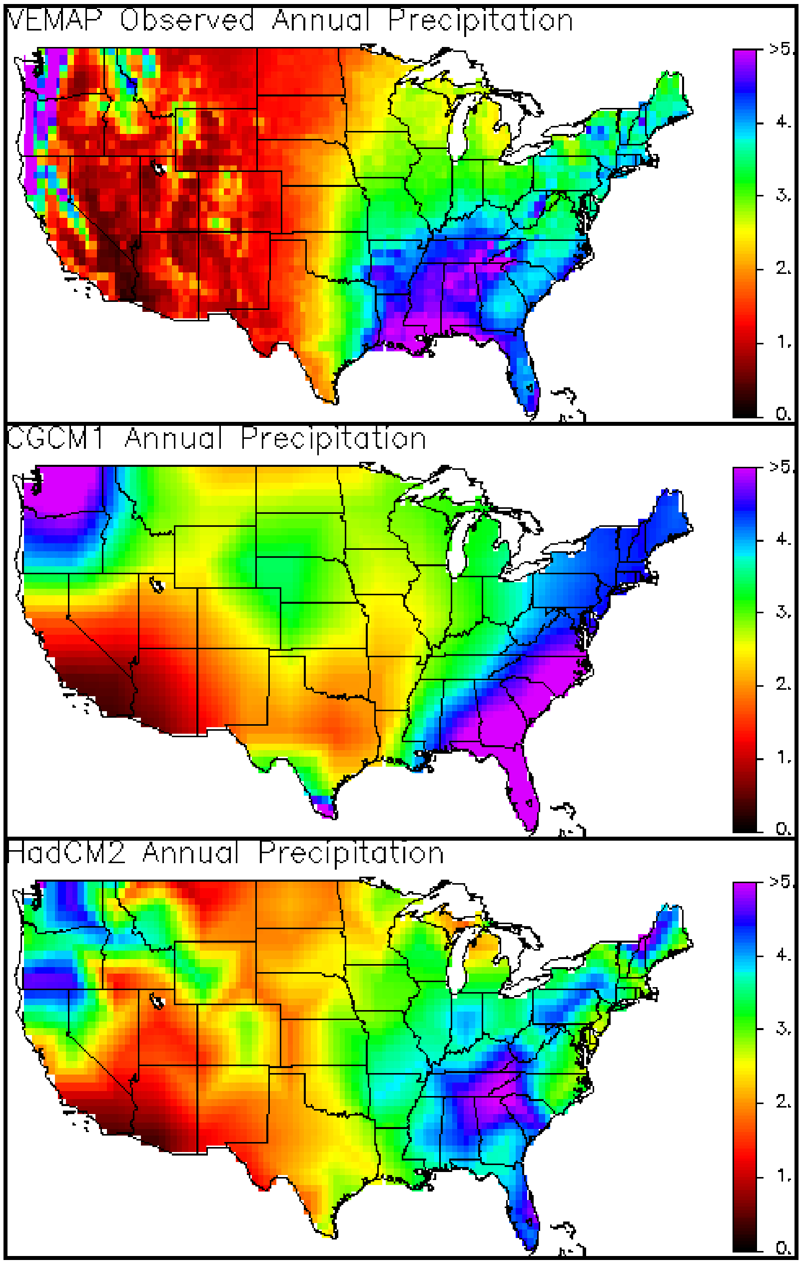


Figure A-4: Comparison of annual precipitation from two GCMs with observed anual precipitation (in inches). (NAST, 2001)