Appendix A-1b
Hydrology

Fargo-Moorhead Metropolitan Area Flood Risk Management

Supplemental Draft Feasibility Report and Environmental Impact Statement

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Expert opinion elicitation on impacts of increasing flood flows on the Fargo, ND-Moorhead, MN flood risk management project

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US Army Corps of Engineers, St. Paul District

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Executive summary

The St. Paul District of the US Army Corps of Engineers (USACE) is studying the feasibility of a number of proposed flood risk reduction measures for the Fargo, ND-Moorhead, MN metropolitan area. These communities are exposed to flooding from the Red River of the North. Data show a trend of increasing magnitude and frequency of flooding in recent decades. A review of pertinent research suggests that this increase in flooding magnitude and frequency is consistent with projections of possible effects of climate change.

Given this, the Corps asked for an expert opinion elicitation (EOE) to serve two purposes: (1) to provide general guidance on how to account for climate change in the hydrologic and hydraulic analyses that support the Fargo-Moorhead feasibility study, and (2) to identify specific actions, if any, that should be taken to account for future probability and uncertainty in flood flows in the quantification of flood risk in the project area.

The topic of climate change was emphasized in the first question posed to the EOE expert panel: "Is it likely that climate change will have a significant impact on the flood flow frequency curve during the life of the proposed flood risk reduction project for Fargo, ND-Moorhead, MN?"

Following the first question, the experts and observers discussed the meaning of the phrase "climate change," particularly in the context of the Fargo-Moorhead flood risk reduction project. There was consensus among the experts that the recent data show a clear trend toward greater magnitudes and frequency of flooding in the Fargo-Moorhead area. It was also generally agreed among the experts and observers that current evidence is insufficient to determine whether or not anthropogenic greenhouse gases are contributing to the trend. However, the experts agreed that it was not necessary to determine the cause of the trend in order to address the Corps' second objective for the EOE (determining how to account for increased uncertainty).

In responding to the subsequent questions posed during the EOE meeting, the experts rather quickly moved away from a discussion of climate change, per se, and focused instead on the apparent lack of stationarity in the flood flow frequency and magnitude data over the period of record (the last 110 years or so).

Taken together, points made during the group discussions and the experts' written responses suggest that the following steps should be taken to adjust the flood frequency curve used in the hydrologic analysis supporting the Fargo-Moorhead feasibility study:

1. Develop, and use as the basis for the frequency analysis, an unregulated time series. Prior to the addition of significant regulation in the system, the series will be the recorded flows. After regulation was added, the recorded flows must be adjusted to "remove" the effects of regulation in the system. This can be done with the reservoir and channel routing models that the District has available.
2. Develop and use a transform function to convert the derived unregulated frequency function to the regulated frequency function that is required for the risk analysis. This transform function can be developed by simulating system behavior without and with regulation for floods from the period of record (POR). As the historical floods may fail to cover adequately the

range of flows needed to define the frequency curve well, historical events can be scaled to simulate larger floods. This is consistent with guidance in EM 1110-2-1415.

3. Analyze the unregulated flow series, and divide the current POR into two portions. Suggestions for identifying the "break" between the wet period and the dry period included:

   - Using qualitative judgment, e.g., define the dry period as 1901-1941 and the wet period as 1942-2009; or define the dry period as 1901-1960 and the wet period as 1961-2009.

   - Use statistical tests for homogeneity to determine where to divide the POR. The expert panel did not agree on the statistical tests, but did note work by Villarini, et al.

4. Fit a log Pearson III distribution separately to the dry components of the split record and the wet component, following generally the guidance in *Bulletin 17B*. Some members of the panel suggested using the total record to estimate the skew coefficient to be used for both components. Others suggested determining the skew coefficients for each portion of the POR separately. If the skew coefficients are close, an appropriately rounded average of the two could be used.

5. Combine the "wet" and "dry" curves, and weight the probabilities for continued wet conditions versus a reemergence of dry conditions. Two schemes emerged from the majority of the experts' responses:

   - Transition from wet to dry over time. For example, begin with p(wet)=1 and p(dry)=0 in year 1 of the project, moving to p(wet)=0.5 and p(dry)=0.5 in year 50, or move p(wet) from 1 to 0 over the life of the project.

   - Do not change the probabilities over time, e.g., p(wet)=0.8 and p(dry)=0.2 over the entire 50-year project life.

6. Account for greater uncertainty. One suggestion was to use an equivalent POR in the Corps Hydrologic Engineering Center's Flood Damage Analysis (HEC-FDA) equal to the number of years of the smaller portion of the POR (either the wet portion or the dry portion).

Overview of Fargo-Moorhead EOE

The Fargo-Moorhead EOE, which was held on September 28-29, 2009, in St. Paul, MN, was planned and implemented according to these three guidance documents:

- *Technical guide for use of expert opinion elicitation for U.S. Army Corps of Engineers risk assessments*, USACE Dam Safety Risk Management Center (2009).
- *A practical guide on conducting expert-opinion elicitation of probabilities and consequences for Corps facilities*, IWR Report 01-R-01 (2001).
- *Methods for expert-opinion elicitation of probabilities and consequences for Corps facilities*, IWR Report 00-R-10 (2000).

The *Technical guide* requires a Level II EOE when the specific information sought is not available from historical records, prediction methods, or literature review. Therefore, the Fargo-Moorhead EOE was a Level II EOE.

Why this EOE was needed

The Fargo, ND-Moorhead, MN metropolitan area has a relatively high risk of flooding from the Red River of the North and relies on emergency responses to ensure safety of the community. Given the high flood risk, the St. Paul District of the US Army Corps of Engineers is completing a feasibility study of alternative measures to reduce flood risk in the Fargo-Moorhead area.

The highest river stages usually occur as a result of spring snowmelt, but summer rainfall events have also caused significant flood damages. In fact, the Red River of the North has exceeded the National Weather Service flood stage of 17 feet in 50 of the past 106 years, and every year from 1993 through 2009.

A review of Red River flow data verifies the increase in flood magnitude and frequency in the relatively recent decades of the period of record (1901-2009). A time series of natural annual maximum mean daily flow for the Red River at Fargo is shown in Figure 1 (Source: David Ford Consulting Engineers, Inc., using USACE data). As can be seen, both the magnitude and variability of the flows have increased since the beginning of record. A review of pertinent research suggests that this increase in flooding magnitude and frequency is consistent with projections of possible effects of climate change.

The Fargo-Moorhead feasibility study follows Corps planning study guidelines, which require that "[r]isk-based analysis… be used to compare plans in terms of the likelihood and variability of their physical performance, economic success and residual risks" (ER 1105-2-100). The annual maximum discharge-probability function (also known as the flood flow frequency curve) at the location of interest is a key input to the risk analysis. For the Fargo-Moorhead project, the Red River frequency was developed following Corps guidelines in EM 1110-2-1415, *Hydrologic frequency analysis,* and EM 1110-2-1417, *Flood-runoff analysis*.

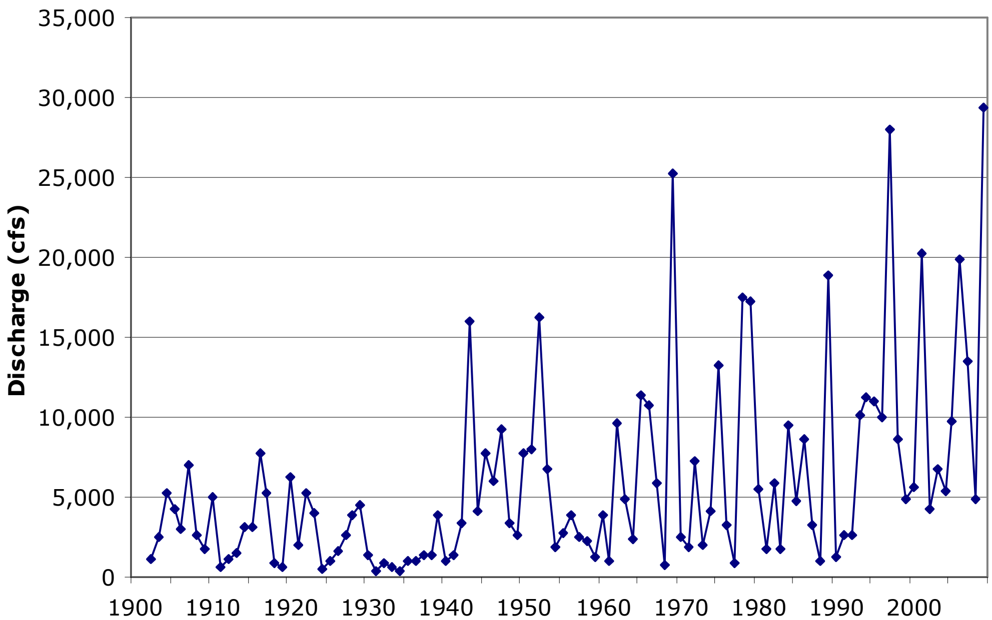

Figure 1. Natural annual maximum mean daily flow - Red River at Fargo

The observed trend in flood flow frequency and magnitude raises the question of whether the current proposed curve accurately represents future conditions for purposes of the feasibility study's risk analysis.

Therefore, to ensure a reliable and robust plan and project design, the Corps Fargo-Moorhead project delivery team (PDT) organized an EOE. The Fargo-Moorhead EOE was held to provide the PDT with specific actions that should be taken, if any, to account for future flood flow magnitude and frequency uncertainty in the quantification of flood risk in the project area.

Fargo-Moorhead EOE participants

Participants in the EOE included six experts chosen by the St. Paul District to serve on the expert panel, five invited observers with specialized knowledge, and staff of the USACE St. Paul District. David Ford, PhD, PE, D.WRE, served as the technical integrator and facilitator (TIF). (David Ford is president of David Ford Consulting Engineers, Inc., the consulting firm selected to organize, prepare for, and facilitate the EOE, and to aggregate and present the EOE results.)

The experts (those who submitted their opinions in writing) are identified in Table 1.

Table 1. Fargo-Moorhead EOE experts

Expert	Affiliation
Michael Deering, PE, D.WRE	Senior Hydraulic Engineer, Water Resource System Division, USACE Hydrologic Engineering Center
Scott Dummer	Hydrologist-in-Charge, National Weather Service North Central River Forecast Center, Chanhassen, MN
Robert Hirsch, PhD	Research Hydrologist, US Geological Survey (USGS) National Research Program
Rolf Olsen, PhD	Water Resources Systems Engineer, USACE Institute for Water Resources
David Raff, PhD, PE	Technical Specialist, Flood Hydrology and Emergency Management Group, Technical Services Center, US Bureau of Reclamation (USBR)
Aldo (Skip) Vecchia, PhD	Research Statistician, USGS

Fargo-Moorhead EOE observers are identified in Table 2.

Table 2. Fargo-Moorhead EOE observers

Observer	Affiliation
Adnan Akyuz, PhD	North Dakota State Climatologist
Ronald Beyer, PE	Hydraulic Engineer, Omaha District, USACE
Greg Hiemenz	Environmental Specialist, Dakotas Area Office, USBR Great Plains Region
David Moser, PhD	Chief Economist, USACE
Richard Pemble, PhD	Retired Professor of Biology, Minnesota State University, Moorhead
Gregg Wiche	Water Science Center Director, USGS North Dakota

Other individuals present for all or part of the proceedings included:

- Michael Knoff, PE, Chief, Hydraulics and Hydrology Branch, St. Paul District, USACE
- Patrick Foley, PE, Chief, Hydraulics Section, St. Paul District, USACE
- Dan Reinartz, PE, Senior Hydraulic Engineer in the Hydraulics and Hydrology Branch, Water Control Section, St. Paul District, USACE
- Mike Lesher, Senior Hydraulic Engineer in the Hydraulics and Hydrology Branch, Hydraulics Section, St. Paul District, USACE
- Craig Evans, Senior Planner, Project Management Branch, St. Paul District, USACE
- Chanel Kass, Civil Engineer, St. Paul District, USACE
- Rhonda Robins, Water Resources Planner, David Ford Consulting Engineers, Inc.

While each of the experts is an employee of an agency involved in flood flow frequency analysis, the opinions they offered were understood to be their personal opinions, and not necessarily the positions of any particular agency. Accordingly, throughout this memo, the opinions and ideas of the experts are reported without attribution. Similarly, comments by the invited observers are reported without attribution.

EOE meeting summary

To prepare for the EOE, expert panel members and observers were sent a read-ahead package following recommendations in the *Technical guide*.

The EOE began with a description of the EOE process and a review of the goals to be accomplished. Then, Ford asked that the experts be mindful of these assumptions:

- The Red River of the North presents a unique hydrologic and hydraulic record, and therefore the results of this EOE do not necessarily set precedent for other regions of the country.
- The time scale of a Corps project is a matter of decades: the life of a project is considered to be 50 years, and the economic analysis often focuses on the first 20-30 years, as this has the greatest impact on the discounted benefits and costs.
- The recommendations that result from this EOE must be implemented within the time, budget, and resource constraints of this project.

Ford also presented an overview of the Corps risk and uncertainty analysis procedures and requirements.

St. Paul District staff presented information about the Corps' flood risk reduction alternatives for the Fargo-Moorhead region, hydrologic and hydraulic analyses related to the Red River of the North and its tributaries, and the apparent climate trend toward an increase in magnitude and frequency of flood events in this region.

After the background information was presented, Ford posed the first question to the experts. The experts wrote their responses on carbonless copy paper. They submitted one copy of each answer to the TIF, and kept the other copy so they could refer to it during the discussion period that followed.

The experts' responses to the first question were shared with the participants and a group discussion followed. Each expert was given an opportunity to explain his answer, and the observers and others were encouraged to ask questions and contribute pertinent information.

Following the group discussion, the experts were asked to respond to the same question again in light of the discussion. As before, they wrote their answers on carbonless copy paper. Each expert kept one copy for future reference and submitted the other copy to the TIF.

When all the experts had turned in their final responses to the first question, the question was closed, and the TIF proceeded with the next question. For the Fargo-Moorhead EOE, a total of four questions were posed.

Experts' opinions

Each question, a summary of the experts' preliminary responses, and a summary of the experts' final responses is provided here.

Question 1

Preliminary: Is it likely that climate change will have a significant impact on the flood flow frequency curve during the life of the proposed flood risk reduction project for Fargo, ND-Moorhead, MN?

The experts were evenly divided in their responses to Question 1: three experts gave a qualified "yes," and three experts gave a qualified "no." Several responses questioned whether the term "climate change" meant an anthropogenic increase in greenhouse gases leading to global warming. Several stated that climate change, which they defined as taking place over a much longer time frame, would not have an effect on flood frequencies over the time period of analysis (20-30 years). All responses acknowledged that natural decadal-scale variability was present in the data. Many responses commented that this variability increases the uncertainty about flood frequency over the next 20-30 years. In sum, the answers seemed to say this: if climate change means global warming over thousands of years, no, it will not impact flood frequency over the life of this project. If climate change means natural variability over a time scale of decades, yes, it probably will impact flood frequency over the life of this project, but we do not know how to predict the impact very well.

During the discussion that followed each expert's preliminary responses to Question 1, there was much talk of what "climate change" means in the context of the Fargo-Moorhead project. There was consensus among the experts that the data show a clear trend toward greater magnitudes and frequency of flooding in the Fargo-Moorhead area. It was also generally agreed among the experts and observers that there is currently insufficient evidence to determine whether or not anthropogenic greenhouse gases are contributing to the trend. Finally, the experts agreed that it was not necessary to determine the cause of the trend in order to examine the question at hand.

Final:

(a) Has historical climate change/variability been accounted for in an appropriate manner in the proposed frequency analysis?

(b) If climate has been addressed appropriately to date, do we need to consider climate change in the flow frequency curve?

To part (a), there were five "no" votes and one "yes" vote. Most responses said that the current analysis (reported in the Corps' feasibility study) does not acknowledge the lack of homogeneity in the flood frequency and flood magnitude data.

To part (b), there were five "yes" votes and one "no" vote. Most responses agreed that project planners need to account for the apparent shifts in and uncertainty in future precipitation and flood flow frequency.

Question 2

Preliminary: How will the frequency curve change?

In answering this question, the experts began to focus on the idea that the POR shows two states, a relatively dry period early in the 20th century and a relatively wet period later in the 20th century. Some experts stated that it was likely the current wet period would persist for some period of time in the future, while others stated that there is no way to know what will happen in the future. A consensus emerged about the need to account for greater uncertainty, whether or not the curve itself is changed.

Final: How will the flow frequency curve for the full range change?

The experts' final responses emphasized these concepts:

- The POR used in the feasibility study's hydrologic analysis, which spans 1901-2009, shows two distinct states: a relatively dry period in the early 20th century and a relatively wet period in the latter decades of the POR.
- To estimate flood risk over the next 50 years, which is what the Corps must do, a prediction must be made about whether and for how long the current wet period will continue.
- Greater uncertainty must be accounted for, whether or not the flood flow frequency curve itself is changed.

Question 3

Preliminary: What are the practicable alternatives for accounting for the impact of the change?

The experts' responses showed that they were thinking of a two-state or mixed-population system, with the POR divided at some point in the mid-20th century between the earlier relatively dry period and the more recent relatively wet period. All the experts' responses included some variation on the theme of dividing the POR into a wet portion and a dry portion. Two experts suggested using only the more recent wet portion of the POR. Two experts suggested developing a wet period curve and a dry period curve, and re-combining them into a single curve using some kind of transition function based on the probabilities of wet and dry conditions occurring in the future. Another suggested using the current curve in the early years of the project, and then "jumping" to a "climate change" curve at some future year of the analysis.

Final (same as initial): What are the practicable alternatives for accounting for the impact of the change?

The two-state or mixed-population approach gained further traction in the experts' final answers to Question 3. They focused on two issues in particular:

- Assuming the POR is divided into two portions, should both portions of the POR be used or just the more recent one?
- If both portions are used and then recombined into a single curve, what should the relative weights of the wet period and the dry period be?

Representative suggestions included:

- Using the two separate portions of the POR, and recombining them using a weighting scheme to transition from wet to dry over time. The relative weights would depend on how likely it is the wet period will persist versus how likely it is that a dry period will occur in the future years of the project life.

- Using only the most recent portion of the POR as way to account for greater uncertainty, with the shorter POR serving to increase the upper confidence curve.
- Doing a scenario analysis for three distributions: the entire POR, a mixed distribution, and a wet period distribution, and keeping them separate for the economic analysis.
- Running HEC-FDA with the current frequency curve, and then running it with a wet period frequency curve. This suggestion included applying year-to-year weightings, and determining a combined expected annual damage (EAD) outside of HEC-FDA.

Question 4

Preliminary: Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo-Moorhead?

The responses to Question 4 acknowledged the time constraints present for the Fargo-Moorhead feasibility study. Further, the experts' responses to Question 4 did not differ substantively from their final responses to Question 3, except that several of the experts added more specificity and detail to their earlier answers. The following are paraphrased from the experts' written answers:

- Make separate HEC-FDA runs using the current frequency curve and a wet period frequency curve. Prepare a spreadsheet that combines weighted EADs incrementally to include combined uncertainties.
- Treat the entire POR as a mixed population, and divide it into a wet period and a dry period using statistical analyses for homogeneity. Develop two separate flow functions, weight them appropriately, then combine them. Weight the probability of continued wet conditions at 0.8, and dry conditions at 0.2.
- Use two frequency curves, one for the period 1960-2009, and the other for the entire POR. Combine the two curves into one curve for each future year using specified probabilities that transition gradually from p=1 for the wet curve and p=0 for the dry curve at the beginning of the analysis period to p=0 for the dry curve and p=1 for the wet curve at the end of the analysis period.
- Ideal approaches to weighting include exploring the use of a Markov chain, using the 600-year rain record, or probability/percentage of dry periods occurring in the next 50 years.
- Use the current curve in the early years of the project, and then "jump" to a "climate change" curve at some future year of the analysis.
- Quick subjective probabilities would be wet p=0.75 and dry p=0.25.
- The final result should be weighted in favor of a continued wet period, with allowance for the occurrence of a dry period not to exceed p=0.5.

- Two frequency curves should be considered from the observed record. The dividing line in the POR can be defined subjectively, or if time allows, using statistical tests for homogeneity.
- Take a mixed population approach as follows:
    - Divide the POR into two portions: 1942-2009 and 1902-1941, based on a paper by Villarini, Serinaldi, Smith, and Krajewski in *Water Resources Research*, Vol. 45, WO8417, 2009. These authors did a change point analysis for change in the mean based on the Pettitt test, and the Fargo record shows a significant step change at 1942.
    - Do LPIII analysis on each period, but to estimate skew, take all the data values (the log discharges) and subtract the group mean, divide by the group standard deviation from the appropriate group and then compute a skewness on all 108 values.
    - Set a subjective estimate of the marginal probabilities of being in the wet (later) population at 0.8 and a probability of the dry (earlier) population at 0.2.
    - For sensitivity analysis, try setting the probability of the dry population at 0.37 (its proportion in the current data set) and also at zero (meaning no return to the dry state).

Final (same as initial): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo-Moorhead?

The group discussions and experts' responses to Question 4 focused on these four related questions:

- How should the current POR be divided into two portions?
- How should the skew coefficient be determined for the two portions?
- How should the two separate curves be combined to arrive at a single curve?
- How should uncertainty be accounted for?

The experts suggested that the POR could be divided using qualitative judgment or statistical homogeneity tests. Several experts suggested that skew coefficients for the two portions of the POR should be calculated independently, and if close, the average of the two could be used.

Most of the experts favored some kind of weighting scheme for combining the wet curve and the dry curve, such as a function that transitions from the current wet period to a dry period in future years. For example, two experts suggested p(wet)=1 and p(dry)=0 in year 1 of the project, moving to p(wet)=0.5 and p(dry)=0.5 in year 50. Another expert had p(wet) moving from 1 to 0 over the life of the project. Alternatively, another expert suggested setting the relative weights as unchanging over time, with p(wet)=0.8 and p(dry)=0.2.

Most experts either suggested or implied that further investigation was needed to determine the best way to account for uncertainty in EAD and project performance. One expert suggested using the number of years in the shorter of the two portions (wet or dry) as the equivalent POR in HEC-FDA to account for the greater uncertainty in future conditions.

Synthesis of experts' opinions: recommendations

Taken together, points made during the group discussions and the experts' written responses suggest that the following steps should be taken to adjust the flood frequency curve used in the hydrologic analysis supporting the Fargo-Moorhead feasibility study:

1. Develop, and use as the basis for the frequency analysis, an unregulated time series. Prior to the addition of significant regulation in the system, the series will be the recorded flows. After regulation was added, the recorded flows must be adjusted to "remove" the effects of regulation in the system. This can be done with the reservoir and channel routing models that the District has available.
2. Develop and use a transform function to convert the derived unregulated frequency function to the regulated frequency function that is required for the risk analysis. This transform function can be developed by simulating system behavior without and with regulation for floods from the POR. As the historical floods may fail to cover adequately the range of flows needed to define the frequency curve well, historical events can be scaled to simulate larger floods. This is consistent with guidance in EM 1110-2-1415.
3. Analyze the unregulated flow series, and divide the current POR into two portions. Suggestions for identifying the "break" between the wet period and the dry period included:
    - Using qualitative judgment, e.g., define the dry period as 1901-1941 and the wet period as 1942-2009; or define the dry period as 1901-1960 and the wet period as 1961-2009.
    - Use statistical tests for homogeneity to determine where to divide the POR. The expert panel did not agree on the statistical tests, but did note work by Villarini, et al.
4. Fit an LPIII distribution separately to the dry components of the split record and the wet component, following generally the guidance in *Bulletin 17B*. Some members of the panel suggested using the total record to estimate the skew coefficient to be used for both components. Others suggested determining the skew coefficients for each portion of the POR separately. If the skew coefficients are close, an appropriately rounded average of the two could be used.
5. Combine the wet and dry curves, and weight the probabilities for continued wet conditions versus a reemergence of dry conditions. Two schemes emerged from the majority of the experts' responses:
    - Transition from wet to dry over time. For example, begin with p(wet)=1 and p(dry)=0 in year 1 of the project, moving to p(wet)=0.5 and p(dry)=0.5 in year 50, or move p(wet) from 1 to 0 over the life of the project.
    - Do not change the probabilities over time, e.g., p(wet)=0.8 and p(dry)=0.2 over the entire 50-year project life.
6. Account for greater uncertainty. One suggestion was to use an equivalent POR in HEC-FDA equal to the number of years of the smaller portion of the POR (either the wet portion or the dry portion).

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Appendix 1. Biographical summaries of EOE participants

Below are brief biographical summaries for the expert panel members; observers; and the technical integrator and facilitator of this expert opinion elicitation.

Expert panel members

Michael Deering, PE, D.WRE. Deering is a Senior Hydraulic Engineer with the Water Resource System Division at the US Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) in Davis, CA, where he specializes in the development and application of flood risk management and system analysis software. His technical expertise includes flood risk management with risk analysis, impact analysis, ecosystem restoration, river hydraulics, stream stability and scour, surface water hydrology, water surface profile modeling, floodplain delineations, and hydraulic structures. Deering holds a BS and MS in civil engineering from the University of California, Davis, and is a registered professional engineer in the State of California. Deering is a Diplomate, Water Resources Engineer (D.WRE), a distinction assigned by the American Academy of Water Resource Engineers.

Scott Dummer. Dummer is the Hydrologist-in-Charge for the National Weather Service (NWS) North Central River Forecast Center located in Chanhassen, MN. Prior to his current position, he was the Deputy Chief of the NWS Hydrology and Climate programs in the Western United States. His operational experiences include the Great Flood of 1993, the Red River of the North floods of 1997 and 2009, the 2006 Taum Sauk Dam Failure in southern Missouri, and a devastating flash flood in Franklin County, MO, in 2000. Dummer is a 1993, 2000, and 2003 US Department of Commerce Bronze Medal recipient, and a 2004 NOAA Administrators Award recipient in recognition for his various operational and developmental contributions to the agency. He holds a BS in atmospheric sciences from the University of North Dakota and an MS in water resources science from the University of Kansas.

Robert Hirsch, PhD. Hirsch is a research hydrologist at the US Geological Survey (USGS) National Research Program in Reston, VA. He is a former Associate Director for Water at the USGS, where he was responsible for the water science programs of that agency. These include water-related research, collection of data on rivers and ground water, and assessments of water quantity and quality. Hirsch has a BA in geology from Earlham College, an MS in geology from the University of Washington, and a PhD in geography and environmental engineering from Johns Hopkins University. He has received numerous honors from the federal government and from non-governmental organizations.

Rolf Olsen, PhD. Olsen is a water resources systems engineer with the Corps' Institute for Water Resources in Alexandria, VA. Olsen is currently managing a new Corps program on adaptations to climate change. He has led many studies involving climate change and water resources, including an analysis of the potential impacts of climate change and variability on flood frequency analysis for the Upper Mississippi River system. He has a PhD in systems engineering from the University of Virginia, an MS from the

Pennsylvania State University, and a bachelor's degree from Columbia University. He was a nuclear submarine officer in the US Navy for eight years.

David Raff, PhD, PE. Raff is the technical specialist for the Flood Hydrology and Emergency Management Group at the Technical Services Center within the US Bureau of Reclamation in Denver, CO. Raff is a registered professional engineer in the State of Colorado. He holds a BS in electrical engineering, an MS in rangeland ecosystem sciences, and a PhD in civil engineering. Raff has been co-technical lead for Reclamation's Research and Development Office climate change activities since 2007 and has been active in the development of the Climate Change and Western Water Group. He has authored articles on varied topics, including landform evolution, geomorphology, remote sensing, water supply forecasting, and climate change impacts on assessments of flood frequencies, as well as broader water resources management issues.

Aldo (Skip) Vecchia, PhD. Vecchia is a research statistician with the USGS in Bismarck, ND. His work focuses on understanding and modeling the complex spatial and temporal variability of climate, streamflow, and water quality. He received his PhD in statistics from Colorado State University and, prior to joining the USGS, held faculty positions at the Colorado School of Mines and the University of Florida. He has authored over 50 journal articles and technical reports relating to stochastic hydrology, time series analysis, and statistical modeling of environmental data. In recent years, he has worked closely with the Corps of Engineers, Bureau of Reclamation, FEMA, Environment Canada, and other federal and state agencies on flooding and water quality issues in the Devils Lake and Red River basins.

Observers

Adnan Akyuz, PhD. As the North Dakota State Climatologist, Akyuz provides the public with weather data, weather data summaries, climate summaries, and climate reports. He also serves as director of the North Dakota Agricultural Weather Network and is an assistant professor of climatology in North Dakota State University's Soil Science Department. Akyuz received his PhD from the University of Missouri-Columbia.

Ronald Beyer, PE. Beyer is a Hydraulic Engineer within the Hydrology section of the Omaha District U.S. Army Corps of Engineers Hydrologic Engineering Branch. Beyer began working for the Corps in November 2000. Beyer is a registered professional engineer in the state of Nebraska. In his current position his duties include hydrologic analysis and modeling for flood risk reduction studies and emergency flood response. He is currently working on a hydrologic deficiency study for Fort Carson near Colorado Springs, CO. Recently he completed work on the Levee Certification Study for the Big Sioux River Phase III Levees in Sioux Falls, SD. Beyer has also been involved in the Omaha District portion of the ongoing Portfolio Risk Assessment for the USACE Dam Safety Program. Beyer aided in the spring 2009 flood fight efforts in Bismarck and Jamestown, North Dakota. He has a bachelor's degree in civil engineering and a minor in biology from North Dakota State University.

Greg Hiemenz. Hiemenz is an Environmental Specialist for the Dakotas Area Office in the US Bureau of Reclamation's Great Plains region. The mission of the Dakotas Area Office is to provide technical assistance and leadership in the responsible development and management of water and related resources to enhance the quality of life in both North Dakota and South Dakota. The Area Office manages six dam and reservoir facilities in South Dakota and three facilities in North Dakota. Hiemenz has a BS in biology and an MS in zoology.

David Moser, PhD. Moser is the Chief Economist for the Corps of Engineers. He is Senior Team Leader—Economics at the Corps' Institute for Water Resources (IWR), and Actions for Change National Team Lead for Risk Informed Decision Making. He has also served as Chief of the Navigation and Water Resources Applications Division at IWR. From 1985 to 2002, he was an economist in the Decision Methodologies Division at IWR. Moser has conducted research in economic methods related to benefit-cost analysis and risk analysis methods applied to water resources, and has led the development of several risk assessment computer models. Moser received his BA in economics from Wittenberg University, an MA in economics from the University of Toledo, and a PhD in economics from the University of Cincinnati.

Richard Pemble, PhD. Pemble retired in the spring of 2008 after 39 years as a professor of biology at Minnesota State University, Moorhead. His research interests have focused on the ecology of the Red River Valley region, especially its native grasslands. In 1996, Pemble was recognized for his research on prairies and his contributions to the preservation of Minnesota's native grasslands when he was awarded the Conservation Award from the Minnesota Chapter of The Nature Conservancy. Pemble earned a PhD in botany at the University of California, Davis, an MS in botany at the University of Montana, and a BS in biology and secondary education at Simpson College.

Gregg Wiche. Wiche is the USGS North Dakota Water Science Center Director. He is a member of the International Joint Commission's International Souris River Board and the International Red River Board. He received a BSc in geography from South Dakota State University and an MSc in geography from the University of Alberta. In addition, he completed course work for a PhD in geography and a minor in civil engineering at Louisiana State University. He began his career as a surface-water hydrologist with the USGS in 1978. He has conducted various hydraulic studies including a 2-dimensional bridge-hydraulics study of the I-10 crossing of the Pearl River near Slidell, LA. From 1984-98 he worked on a series of studies to determine the relations between climate variability and water level fluctuations of Devils Lake and streamflow variability on the Red River of the North. From 1988 to 2003 he served as the Surface-Water Specialist for the North Dakota Water Science Center. He has authored more than 30 USGS reports and journal articles.

Technical integrator and facilitator

David Ford, PhD, PE, D.WRE. David Ford is president of David Ford Consulting Engineers, Inc. He is an internationally recognized expert in hydrologic and environmental engineering and water resources planning and management. Ford has served as a consultant to the Corps of Engineers, National Weather Service, government agencies in India, Portugal, Indonesia, and Romania, the United Nations, World Bank, USAID, state and local governments across the US, and to engineering firms worldwide. Ford ghostwrote the following Corps of Engineers documents: Engineer Manual

(EM) on risk-based analysis for flood-damage reduction studies, EM on hydrologic engineering requirements for flood-damage reduction studies, chapters for the flood-runoff analysis EM, chapter on system theoretic models for the EM on flood forecasting, and technical reference manual and applications guide for HEC-HMS. Ford has a BS in civil engineering, an MS in engineering, and a PhD in water resources systems and hydrologic engineering.

Appendix 2. Protocol for Fargo-Moorhead EOE, Sept. 28-29, 2009

The Fargo-Moorhead EOE was planned and implemented in accordance with these three guidance documents:

- *Technical guide for using expert opinion elicitation in support of USACE risk assessments*, USACE Dam Safety Risk Management Center (2009).
- *A practical guide on conducting expert-opinion elicitation of probabilities and consequences for Corps facilities*, IWR Report 01-R-01 (2001).
- *Methods for expert-opinion elicitation of probabilities and consequences for Corps facilities*, IWR Report 00-R-10 (2000).

The Corps documents describing the EOE process are geared specifically toward Corps risk assessments for civil works infrastructure projects in which the answers sought are generally specific numerical values. In the Fargo-Moorhead EOE, the experts were asked to describe a method for arriving at an answer, rather than the answer itself. Nevertheless, the Fargo-Moorhead EOE conformed closely to the procedures described in the Corps guidance.

The *Technical guide* defines two levels of EOE: Level I is a simplified procedure for preliminary studies, and Level II is a more robust procedure for highly specialized issues or when extensive localized expertise is required. The Fargo-Moorhead EOE was a Level II procedure.

Participants in a Level II EOE include:

- A team of specialized experts who submit their opinions in writing.
- A group of knowledgeable observers who contribute insight and experience to the panel's discussion.
- A technical integrator and facilitator (TIF).
- Additional participants who provide specific information, such as project background information.

The *Technical guide* provides an overview of the EOE process. At the outset of the EOE meeting, the following items are described or clarified:

- The EOE process.
- The goals to be accomplished in the current EOE.
- Definitions and assumptions pertinent to the discussion.
- The questions to be answered.

Once the first question is clearly defined, each expert provides a response to that question without influence of the others.

After the experts turn in their answers, those answers are shared with the EOE participants. A group discussion follows, with experts explaining their answers and others in attendance able to ask questions and offer their perspectives and insight.

Following the group discussion, the experts are asked the same question one more time. Again, they write down their answers and submit them to the TIF.

After the experts turn in their final answers to a question, that question is "closed," and the EOE participants move on to the next question. This pattern of *preliminary question-response-discussion* followed by *final question and response* is repeated for each question until all the questions to be covered in the EOE are completed.

Appendix 3. Agenda of Fargo-Moorhead expert opinion elicitation, Sept. 28-29, 2009

Agenda of Fargo-Moorhead EOE, September 28-29, 2009, St. Paul, MN

Est. time	Activity/topic	Presenter/ participant	Approx. duration
Sept. 28 8:00	Welcome, logistics, overview, introductions	Ford	50 min.
8:50	Break (10 minutes)		
9:00	Describe Fargo-Moorhead project, including discharge frequency curve now used	Corps	50 min.
9:50	Break (10 min)		
10:00	Describe the climate trend	Corps, USBR	30 min.
10:30	Describe Corps R & U procedures	Ford	20 min.
10:50	Break (10 min)		
11:00	Provide overview of EOE process, goals to be accomplished, training example	Ford	30 min.
11:30	Present contextual information for question 1, then pose question 1	Ford	15 min.
11:45	Expert panel members write, submit answers; others break for lunch; Ford collects answers from panel	Expert panel	15 min.
12:00	Lunch; assess need to adjust agenda	Ford, Corps	60 min.
1:30	Present range of answers to question 1	Ford	15 min.
1:45	Expert panel members explain answers to question 1	Expert panel	20 min.
2:05	Discuss question 1	Expert panel + observers	75 min. (breaks TBD)
3:10	Summarize discussion points; expert members submit post-discussion answers; break when finished	Ford	20 min.
3:40	Present contextual information for question 2, then pose question 2	Ford	15 min.
3:55	Expert panel members write, submit answers, take break; Ford collects answers	Expert panel	20 min.
4:15	Present range of answers to question 2	Ford	15 min.
4:30	Expert panel members explain answers to question 2	Expert panel	20 min.
4:50	Begin panel discussion on question 2	Expert panel + observers	40 min.
5:30	Adjourn for day; debrief; adjust day 2 agenda as needed	Ford; Corps	

Agenda of Fargo-Moorhead EOE, September 28-29, 2009, St. Paul, MN

Est. time	Activity/topic	Presenter/ participant	Approx. duration
Sept. 29 8:00 a.m.	Review previous day	Ford	15 min.
8:15	Resume discussion on question 2	Expert panel + observers	35 min.
8:50	Summarize discussion points; expert members provide post-discussion answers, take break (others break until 9:20)	Expert panel	30 min.
9:20	Present contextual information for question 3, then pose question 3	Ford	15 min.
9:35	Expert panel members write and submit answers, take break; Ford collects answers	Expert panel	30 min.
10:05	Present range of answers	Ford	15 min.
10:20	Expert panel members explain answers to question 3	Expert panel	20 min.
10:40	Discuss question 3	Expert panel + observers	75 min.
11:55	Summarize discussion points; experts provide post-discussion answers	Ford	
Noon	Lunch; assess need for agenda adjustment	Corps; Ford	60 min.
1:00	Present contextual information for question 4, then pose question 4.	Ford	15 min.
1:30	Expert panel members write and submit answers; Ford collects answers (others free until 1:45)	Expert panel	30 min.
2:15	Present range of answers	Ford	15 min.
2:30	Expert panel members explain answers to question 4	Expert panel	20 min.
2:50	Discuss question 4	Expert panel + observers	75 min. (break TBD)
4:05	Summarize discussion points; expert members provide post-discussion answers; break if needed	Ford	25 min.
4:30	Wrap up	Corps; Ford	

Appendix 4. Digest of the Fargo-Moorhead EOE

The Fargo-Moorhead expert opinion elicitation (EOE) was held on Sept. 28-29, 2009, in St. Paul, MN.

Per Corps EOE guidance, approximately four weeks prior to the EOE, the experts and observers were sent a read-ahead information packet that contained the following:

- Information about the Fargo-Moorhead feasibility study.
- A description of the apparent trend in increasing Red River flood magnitude and frequency.
- An overview of the EOE process.
- A brief overview of risk and uncertainty analysis in Corps planning studies.
- A CD of relevant research documents provided by St. Paul District staff.
- A list of references.

At the start of the 2-day Fargo-Moorhead EOE meeting, the TIF, David Ford, reminded all the participants of the following points:

- The Red River of the North presents a unique hydrologic and hydraulic record, and therefore the results of this EOE are not necessarily going to set precedent for other regions of the country.
- The time scale of a Corps project is a matter of decades: the life of a project is considered to be 50 years, and the economic analysis often focuses on the first 20-30 years, as this has the greatest impact on the discounted benefits and costs.
- The recommendations that result from this EOE must be implemented within the time, budget, and resource constraints of this project.

Ford also presented information about the EOE process and the Corps' risk and uncertainty procedures and requirements. Ford explained that the Corps' standard of practice for flood risk analysis is described in detail in Engineer Manual (EM) 1110-2-1619, *Risk analysis for flood damage reduction studies*. The procedure described in that manual—and used by District staff for the Fargo/Moorhead study—requires computation of performance indices for proposed risk reduction plans, for current and future conditions, considering the uncertainty about inputs to the computation. The indices computed for each plan are then compared to indices similarly computed for the without-project condition to determine the plan's accomplishments. The economic contributions are evaluated by computing a value of expected annual damage (EAD) over the anticipated life of the project. Changes are accounted for in the computation if hydrologic, hydraulic, and economic conditions change over the span of the project. The flood flow frequency curve at the location of interest is a key input to the risk analysis.

St. Paul District staff presented information about the Corps' flood risk reduction alternatives for the Fargo-Moorhead region, hydrologic and hydraulic analyses related to the Red River of the North and its tributaries, and the apparent climate trend toward an increase in magnitude and frequency of flood events in this region.

After the background information was presented, Ford posed the first question to the experts. The experts wrote their responses on carbonless copy paper. They submitted one copy of each answer to the TIF, and kept the other copy so they could refer to it during the discussion period that followed.

The experts' responses to the first question were shared with the participants and a group discussion followed. Each expert was given an opportunity to explain his answer, and the observers and others were encouraged to ask questions and contribute pertinent information.

Following the group discussion, the experts were asked to respond to the same question again in light of the discussion. As before, they wrote their answers on carbonless carbon paper. Each expert kept one copy for future reference and submitted the other copy to the TIF.

When all the experts had turned in their final responses to the first question, the question was closed, and the TIF proceeded with the next question. For the Fargo-Moorhead EOE, a total of four questions were posed.

Background information presented at the EOE

Background information presented at the Fargo-Moorhead EOE included an overview of the flooding situation in the Fargo-Moorhead metropolitan area and summaries of the hydrologic and hydraulic analyses conducted for the St. Paul District's Phase 2 Fargo-Moorhead flood risk reduction project feasibility study.

Flooding in Fargo-Moorhead

Craig Evans, a Senior Planner with the St. Paul District, provided an overview of the flooding situation in the Fargo-Moorhead metropolitan area and information about the current feasibility study, which began in September 2008. The goal of the study is to develop a regional system to reduce flood risk. The alternatives being evaluated include non-structural measures, flood walls, levees, diversion channels, and flood storage. The final selection of an alternative is scheduled to take place in December 2009, and the feasibility study is scheduled for completion in December 2010.

Evans made these points in his presentation:

- Emergency flood fights have been successful in Fargo and Moorhead, but the area remains vulnerable to flooding.
- Both the 1997 and 2009 flood events came close to overwhelming the emergency levee systems, and many homes and other structures outside the levees were damaged.
- The Red River of the North has exceeded the National Weather Service flood stage in 50 of the past 106 years and in every year from 1993 through 2009.
- A 500-year event would flood nearly the entire city of Fargo and a large portion of the city of Moorhead. (Moorhead sits on relatively higher ground than Fargo.)

- Flooding occurs both from rivers and from local drainage due to large rainfall events that overwhelm storm drainage systems.

Hydrologic analysis

Dan Reinartz, PE, a Senior Hydraulic Engineer with the St. Paul District, summarized the hydrologic analyses that are described in detail in the Hydrology appendix of the feasibility study. Significant points included the following:

- The total drainage area at the USGS streamflow gage for the Red River at Fargo is 6,800 square miles, of which 2,175 square miles are considered noncontributing. Of the remaining 4,625 square miles, 1,405 square miles are controlled by White Rock Dam and Orwell Dam.
- The continuous period of record (POR) dates back to May 1901, with historic flood information available for events occurring in 1882 and 1897.
- The largest observed flow occurred on March 28, 2009, and had an instantaneous peak discharge of 29,400 cfs. This is considered to be approximately a p=0.01 event.
- In the 2009 event, cold temperatures during the rising limb of the flood hydrograph arrested the melt and runoff process and stemmed what would likely have been a p=0.005 event, as occurred upstream in Hickson and Wahpeton.
- The second highest flood of record occurred on April 17, 1997, with an instantaneous peak discharge of 29,000 cfs.
- The annual instantaneous peak discharge frequency relationship for the Red River at Fargo was developed using period of record flows available at the Fargo streamflow gaging station.
- Because of regulation effects from the upstream reservoirs, adjustments in the recorded data set were required to obtain a homogeneous record based on the current regulated condition.
- To develop the natural peak discharge frequency curve:
    - Actual recorded flows were used up to the year 1942.
    - Flows from 1942 to 2009 were adjusted to the natural condition by routing flows from Lake Traverse and Orwell Dam. The gage outflows at these locations were "reverse routed" through the respective reservoirs to arrive at the natural condition inflows.
    - The incremental local flows at the downstream computation points at Wahpeton, Hickson, and Fargo were determined by routing the observed flows and subtraction.
    - The mean daily flows were adjusted to estimate the natural instantaneous annual peak flows. For the period prior to 1942, the actual recorded instantaneous peaks were used. For the period 1942-2009, the adjustment was accomplished by regression of recorded mean daily peaks and instantaneous peaks.
    - The resulting annual peak flows were then input into HEC-FFA for analysis of discharge frequency.

- To develop the regulated peak discharge frequency curve:
  - Recorded annual instantaneous peak flows were adopted for the period 1942-2009.
  - Annual instantaneous peak flows were determined for the period prior to 1942 from a regression analysis of recorded mean daily peak flows versus simulated mean daily flows.
  - Recorded natural mean daily flows for 1902-1942 were read on the simulated mean daily scale to arrive at the regulated mean daily flow.
  - The regression relationship that was used in the natural condition computation was used to adjust the annual mean daily regulated peak flows to annual instantaneous regulated peak flows.
- The POR instantaneous peak flows were plotted with the analytical natural discharge-frequency curve, and a graphical curve was drawn through the points.
- To aid in drawing the upper portion of the curve, synthetic 100-year, 200-year, and 500-year events were routed through the upstream reservoirs and then routed and combined with downstream flows for both the with- and without-reservoirs conditions. The natural condition analytical frequency curve was used to associate a representative frequency and the corresponding regulated flows were plotted at that same frequency.
- For the computation points at Wahpeton and Hickson, the regional skew from the USGS publication for generalized skew coefficients for Minnesota was used. For the computation points at Fargo, Halstad, and Grand Forks, the Grand Forks station skew coefficient with the Grand Forks station mean-square error was used.

Hydraulic analysis

Mike Lesher, Senior Hydraulic Engineer with the St. Paul District, gave an overview of the structural alternatives being considered and summarized the hydraulic analyses done for the Phase 2 feasibility study. Significant points included the following:

- Diversion channels on both the Minnesota and North Dakota sides of the Red River of the North are being considered.
- In the discharge-frequency curve input in HEC-FDA, an equivalent record length of 119 years was used. (This is the average of the systematic record [109 years] and historical period or record [128 years].)
- The discharge-frequency curve input for HEC-FDA was extrapolated to a p=0.0001 event.
- A discharge-frequency transform relationship was developed for the natural and regulated flows at Fargo.

Evidence of nonstationarity in the period of record

Dan Reinartz provided an overview of the data signifying that the frequency and magnitude of flooding has increased in recent decades in the Fargo-Moorhead metropolitan area. Important points included:

- Annual runoff volume, shown in terms of departure from the average, was relatively low during the decades when the Fargo-Moorhead metropolitan area was being developed (roughly the 1930s through the 1960s), and begins to show an increasing trend from at least the mid-1960s to the present.
- For the period 1600-1962, the upper Midwest was a region showing persistent drought, according to Stockton and Boggess (1979).
- The period from 1902 to about 1940 is marked by the relatively rare occurrence of annual peak flows significantly greater than the annual mean flow. On the other hand, the period from about 1940 through 2009 is marked by the relatively frequent occurrence of annual peak flows significantly greater than the annual mean flow.
- The POR appears to be nonhomogeneous, with a period of low annual peak flows in the early decades of the 20th century, and an unmistakable increasing trend in the annual peak flow at Fargo from about 1942 to present.
- Work by St. George, et al. (2001) shows an apparent periodicity in wet and dry periods as measured by the deviation from mean annual precipitation from 1961-1990 for reconstructed annual precipitation at Winnipeg from 1409 to 1998. This pattern would suggest that the current relatively wet period will persist in the future; how long it will last is uncertain, however.
- Trends in peak streamflow for the Red River of the North at Grand Forks, ND, show an overall increasing trend line from 1882-2007. These data also show a possible periodicity, with relatively high peak streamflow values at the turn of the last century, relatively low peak streamflows in the 1930s, and an upward trend from the 1940s to the present. The recent high flows are not unprecedented.

Group discussion following presentation of background information

After the presentation of the background information, a number of experts and observers had questions and comments about what they had seen. In most cases, questions were posed in a rapid-fire manner, as the participants began thinking about some of the issues. Questions and statements of opinion (paraphrased) from this discussion included:

- Were geomorphological changes accounted for in the routing? (They were not.)
- Is overbank storage upstream? (There is.)
- A large amount of uncertainty surrounds the historical flood events of the late 19th century; is more error introduced by including them or omitting them?
- *Bulletin 17B* presumes climatic invariance.
- Is the EOE really discussing climate change or is it discussing nonstationarity? Those are not necessarily the same thing.
- The discharge-frequency curve is strongly negatively skewed, and distributional assumptions may be a source of concern.

- Will the trends in precipitation and streamflow continue into the future, or are the trends seen now manifestations of past changes, with not much more change in the future?
- Freezing/frost plays an important role in flood events: freeze attenuates the flow, for example. In the most recent flood event, the frost let out prior to the first crest, which allowed water to soak into the ground.
- "Something is happening" at Oakport to cause a shift in stages.
- At around the 20-year event (about 20,000 cfs), flood fighting begins.
- Do flood damages in Fargo-Moorhead top out at some point, for example, at the 500-year event?
- Do changes in uncertainty about the discharge frequency curve affect the findings of feasibility of flood risk reduction measures?
- Has uncertainty about the unregulated flow to regulated flow transform function been described?
- The Corps is making the assumption that there is a single curve that is uncertain, but there may be more than one curve, or a single curve that's always changing.
- The Corps' risk analysis is beginning to include other indices besides expected annual damage, such as loss of life.
- How does the length of the period of analysis (20 years? 30 years?) compare to the time scale of climate change?
- The Corps needs to project some climate. Is it the current state, or another state?
- Starting in 1980 or so, it is clear that precipitation increases in this region.
- The record seems to show periods of stability, then periods of variability, repeated over and over.
- Pre-1940, precipitation and evapotranspiration data are quite different than post-1940.
- High floods appear rather stable in the last 50 years, but small floods seem to have disappeared from the record.
- Precipitation right before snow is important. Floods usually occur in the spring. Precipitation is trending faster than evapotranspiration. A significant increase in cool season precipitation is apparent.
- Small changes in precipitation can result in large changes in soil moisture/ accumulated storage.
- What effect does even a small increase in temperature have? Will evapotranspiration increase and balance out the effect of increased precipitation? It would take many years for soil moisture to evaporate.
- Abrupt climate changes have happened at all scales over time. Tree rings and other climate proxies show historical climate change. So, global warming may be contributing to the trends in this region, but it need not be invoked to explain abrupt changes in precipitation and streamflow.

Panel questions, discussions, and responses

Following presentation of the background material and the discussion that followed, the TIF presented the experts with the first question.

Question 1

Is it likely that climate change will have a significant impact on the flood flow frequency curve during the life of the proposed flood risk reduction project for Fargo, ND-Moorhead, MN?

Initial responses to Question 1

The experts were evenly divided in response to Question 1: three experts gave a qualified "yes," and three experts gave a qualified "no." Several responses questioned whether the term "climate change" meant an anthropogenic increase in greenhouse gases leading to global warming. Several stated that climate change, which they defined as taking place over a much longer time frame, would not have an effect on flood frequencies over the time period of analysis (20-30 years). All responses acknowledged that natural decadal-scale variability was present in the data. Many responses commented that this variability increases the uncertainty about flood frequency over the next 20-30 years. In sum, the answers seemed to say this: if climate change means global warming over thousands of years, no, it will not impact flood frequency over the life of this project. If climate change means natural variability over a time scale of decades, yes, it probably will impact flood frequency over the life of this project, but we do not know how to predict the impact very well.

Discussion

The group discussion following the preliminary responses to Question 1 essentially repeated the content of the responses. The experts and observers began to narrow their focus and define relevant terms as they traded ideas. Representative comments included:

- Climate change takes place over thousands of years; state changes take place over tens of years.
- It is more likely that the climate will change than that it will not change.
- We do not understand all the physical factors of climate.
- "Weather" is a sample from the climate probability distribution.
- El Nino and the Southern Oscillation cause "weather," not climate trends.
- The question posed today is not about short-term forecasting; it is about predicting long-term flood probabilities.

At the end of this discussion, the TIF proposed asking Question 1 again, but in two parts:

(a) Has historical climate change/variability been accounted for in an appropriate manner in the proposed frequency analysis?

(b) If climate has been addressed appropriately to date, do we need to consider climate change in the flow frequency curve?

Final responses to Question 1

To part (a), there were five "no" votes and one "yes" vote. Most responses said that the current analysis does not acknowledge the lack of homogeneity in the flood frequency and flood magnitude data.

To part (b), there were five "yes" votes and one "no" vote. Most responses focused on the need to account for the uncertainty in future projections of precipitation and flood flow frequency.

Question 2

How will the frequency curve change?

Initial responses to Question 2

In answering this question, the experts began to focus on the idea that the period of record shows two states, a relatively dry period early in the 20th century and a relatively wet period later in the 20th century. Some experts stated that it was likely the current wet period would persist for some period of time in the future, while others stated that there is no way to know what will happen in the future. A consensus emerged about the need to account for greater uncertainty, whether or not the curve itself is changed.

Discussion

The concept of two states in the POR led to a discussion about transition probabilities. As one participant put it, "drought begets drought, and wet begets wet. But, on the other hand, it could transition into the other state at any time." The group talked about strategies for analyzing the project alternatives under the two states, such as analyzing each alternative under each state separately and comparing the results. There was a suggestion to truncate the POR, thereby increasing the uncertainty in the analysis. The skew factors required by *Bulletin 17B* were discussed, as well. Lastly, Corps staff shared flood discharge versus damage information for the Fargo-Moorhead metropolitan area. The information that was written on a flipchart at the EOE meeting is reproduced in the table below.

Table 3. Flood damage versus discharge for Fargo-Moorhead metro area

Q (cfs)	Old P[1]	Damages
18,000	0.05	$114 M
23,000	0.02	$524 M
31,000	0.01	$1.97 B
45,000	0.004	$4.33 B
57,400	0.002	$5.73 B
--	0.001	$ 6.58 B

1. 1. The computations used to arrive at these values do not include data for 2009.

Final responses to Question 2

Question 2 was re-phrased slightly for the final response: Assuming we have the right frequency curve, how will that change in the next 50 years due to climate change?

All of the experts stayed with their initial answers to Question 2. Some added a bit of clarification or explanation. Several responses reiterated the idea of dividing the entire POR into two periods of record; one suggested using just 1960-2009 for the equivalent POR. Several also reiterated the need to account for greater uncertainty.

Question 3

What are the practicable alternatives for accounting for the impact of the change?

Initial responses to Question 3

All the experts' responses showed that they were thinking of a two-state or mixed-population system, with the POR divided at some point in the mid-20th century between the earlier relatively dry period and the more recent relatively wet period. Alternatives suggested included:

- Truncating the POR and using only the last 30-40 years of observed annual maximum peaks.
- Developing separate "recent/wet" and "past/dry" curves, and estimating transition probabilities for future years.
- Developing a stochastic water-balance model for generating annual flows on the basis of monthly precipitation, evaporation, and basin storage, and using the annual flows to condition the flood frequency curve.
- Using the regulated POR (1942-present) to develop all the frequency curves.
- Using the currently proposed curve for the early years of the project life, and then "switching" or "jumping" to a "climate change" curve at some point in the life of the project.
- Analyzing each alternative flood risk reduction measure under two separate scenarios: (1) the entire POR, and (2) the most recent five decades only, then selecting an alternative that performs reasonably well under both, rather than trying to maximize NED under one or the other.
- Continuing to use the currently proposed curve.
- Dividing the entire POR into two portions at some mid-20th century point to be determined either qualitatively or through statistical tests for homogeneity; using transition probabilities, e.g., from the starting point of the observed record or from the St. George rainfall analysis (≈600 years); and using a Monte Carlo framework to combine the two curves into a simulated flood frequency/damage curve.

Discussion

During this discussion, the experts and observers refined their views of the two-state approach. Representative comments included:

- Using the currently proposed frequency analysis is not responsible because it is obvious something has changed.
- Presenting an analysis using the currently proposed curve is important, and should be discussed in the feasibility report.

- Several statistical tests are available to determine the homogeneity of the POR.
- Using only the most recent portion of the POR is a special case of using both portions of the POR, where one portion has a probability of occurrence = 0 and the other portion has a probability of occurrence = 1.
- Using both portions of the POR is less of a departure from *Bulletin 17B* than using only the most recent portion. If we think of this situation as a mixed population problem, it may be analogous to hurricane vs. no-hurricane years or snowmelt vs. thunderstorm precipitation situations.
- Transition periods present a lot of uncertainty. If the "climate change switch turns on," soil moisture and small depressional lakes would slow down low flows. We do not know how much memory is in the system at wet-to-dry transitions.
- HEC-FDA does handle two frequency curves.
- A key parameter in the economic analysis is the number of years before the climate switch is turned on.
- Maybe a "climate switch" is not the right way to look at it. It is clear that low frequency variability wanders around. Instead of a switch, there is a conditioning ratio. Say, for example, that current floods are two times as high as over the entire POR. There is uncertainty in evaporation, etc. We should generate multiple futures, some going up or down faster than others.
- Where we put the dividing line in the POR is key. We do not want to artificially divide it so that we include only big floods in one set of the data.
- Do the analysis on both sets of data and let the stakeholders decide which outcome they want to use or how to weight them. (The downside is that local stakeholders will probably want the bigger project.)
- We are in a wet period of a climate-variable system, and we should treat it as probable that we will stay wet using the entire 600 years of precipitation record.
- Using a Markov chain is too complex.
- *Bulletin 17B* requires mixed populations that are of equal probability and independent. Once you introduce dependency, it goes beyond Corps guidance.
- Use a marginal approach: what is the probability that it will stay "wet" for the next 20 years?
- Use long-range dependence and autocorrelation to get a reduced POR. But, autocorrelation is an alias or artifact of the trend. We really need to widen the confidence bands.
- We need a function that starts at p=1 for wet and decreases the p over time, drawing from the wet, based on some portion of the historical record.
- Plotting International Panel on Climate Change (IPCC) temperature and precipitation projections may be used as a method to determine the POR

break point and the probability we will remain in the wet period for the study period.

Final responses to Question 3

In their final answers, the experts further refined their preliminary responses to Question 3. Areas of consensus became clear, such as dividing the entire POR. Opinions continued to diverge about what precisely to do with the POR once it was divided. Responses included:

- Experts, not stakeholders, should determine the break point in the full record to determine the two smaller portions of the POR.
- Experts, not stakeholders, should determine the probability of being in each of the two states ("wet" versus "dry").
- Use 1942-2009 as the POR for developing all discharge-frequency curves. The added uncertainty from using a shorter POR is a good outcome of this, especially in that it will increase the upper confidence curve.
- Use a weighting scheme to transition from the "wet" frequency curve to the full-record curve over time.
- Divide the POR into two portions, "wet" and "dry," then re-combine the two frequency functions, with "wet" having greater than or equal weight to "dry." (Suggested weights ranged from 0.8:0.2 to 0.5:0.5 wet to dry.)
- Do a scenario analysis for three distributions: entire POR, mixed distribution, and wet period distribution, and keep them separate for the economic analysis.
- Run HEC-FDA with current conditions and one most likely future condition.
- Run HEC-FDA with the current frequency curve, and then run it with a "wet period" frequency curve. Apply year-to-year weightings, and determine a combined EAD outside of HEC-FDA.

Question 4

Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?

Initial responses to Question 4

Generally, the experts' responses to Question 4 did not differ substantively from their final responses to Question 3. The responses to Question 4 acknowledged the time constraints present for the Fargo-Moorhead feasibility study. Representative responses included:

- Two frequency curves should be considered from the observed record. The dividing line in the POR can be defined subjectively, or if time allows, using statistical tests for homogeneity.
- The two curves can be combined subjectively, although, if time allows, some quantitative basis (e.g., historical precipitation records) for their combination would be preferred.
- The final result should be weighted in favor of a continued wet period, with allowance for the occurrence of a dry period not to exceed p=0.5.

- The final curve should have quantities greater than the current curve has.
- The final curve should have wider confidence intervals than the current curve has.
- Ideal approaches to weighting include exploring the use of a Markov chain, using the 600-year rain record, or probability/percentage of dry periods occurring in next 50 years.
- Quick subjective probabilities would be wet p= 0.75 and dry p= 0.25.
- Use the current distribution based on the entire POR, and include all sources of uncertainty in the economic analysis.
- Do economic analyses for three scenarios: entire POR, mixed population, and wet period only.
- Think beyond the usual maximization of NED as the criteria for selecting an optimum design; account for greater uncertainty in decision-making process.
- Make separate HEC-FDA runs using the current frequency curve and a "wet period" frequency curve. Prepare a spreadsheet that combines weighted EADs incrementally to include combined uncertainties.
- Treat the entire POR as a mixed population, and divide it into a wet period and a dry period using statistical analyses for homogeneity. Develop two separate flow functions, weight them appropriately, then combine them. Weight the probability of continued "wet" conditions at 0.8, and dry conditions at 0.2.
- Use two frequency curves, one for the period 1960-2009, and the other for the entire POR. Combine the two curves into one curve for each future year using specified probabilities that transition gradually from p=1 for the wet curve and p=0 for the dry curve at the beginning of the analysis period to p=0 for the wet curve and p=1 for the dry curve at the end of the analysis period.
- Do a sensitivity analysis using just the wet period for the entire analysis period.
- Take a mixed population approach as follows:
    - Break the POR into two portions: 1942-2009 and 1902-1941, based on a paper by Villarini, Serinaldi, Smith, and Krajewski in Water Resources Research, Vol. 45, WO8417, 2009. These authors did a change point analysis for change in the mean based on the Pettitt test, and the Fargo record shows a significant step change at 1942.
    - Do LPIII analysis on each period, but to estimate skew, take all the data values (the log discharges) and subtract the group mean, divide by the group standard deviation from the appropriate group and then compute a skewness on all 108 values.
    - Set a subjective estimate of the marginal probabilities of being in the wet (later) population at 0.8 and a probability of the dry (earlier) population at 0.2.

- For sensitivity analysis, try setting the probability of the dry population at 0.37 (its proportion in the current data set) and also at zero (meaning no return to the dry state).

Discussion

Following the preliminary responses to Question 4, it became clear that, if the Corps wants to use the strategy emerging from the EOE to develop a new Fargo-Moorhead flow frequency curve, these questions need to be answered:

- How should the current POR be split into two portions?
- How should the skew coefficient be determined for the two portions?
- How should the two separate curves be combined to arrive at a single curve?
- How should uncertainty be accounted for?

The predominant ideas expressed during the group discussion were as follows:

- Split the POR this way: 1902-1941 and 1942-2009, based on Villarini, et al.
- Split the POR this way: 1902-1959 and 1960-2009, based on subjective observation and (unnamed) relevant studies.
- Do statistical tests for homogeneity.
- Use the entire POR (1902-2009) as one population, and use the "wet period" (starting at 1942 or 1960 or some other year to be determined) as another population.
- Skews for each population should be calculated independently, and should account for uncertainty. If the two values are close, the average of the two values could be used.
- Make separate runs in HEC-FDA for each population, then combine/post-process them outside of HEC-FDA.
- Weight "wet" versus "dry" over the life of the project: either weights remain the same each year, or weights change year to year (with "wet" getting relatively more weight in the early years of the project life).
- The equivalent POR is the input for uncertainty in HEC-FDA, so the question is: how do we specify the equivalent POR to account for uncertainty in the two populations? And, is that enough to account for uncertainty in the final curve?

Final responses to Question 4

The experts did not change their preliminary answers, except to comment further on the issue of uncertainty. All reiterated their earlier approaches. The final answers can be summarized as follows:

- Run each curve (wet population and dry population) separately in HEC-FDA for full 50-year economic analysis period. This can be done with either a single weighting of wet and dry or multiple increments with different weightings. Each separate run will account for uncertainty in that particular population. Need to investigate further how to describe uncertainties in the distribution of EAD and project performance.

- Account for uncertainty by selecting the equivalent POR as the number of years in the shorter of the two populations. Run each distribution separately in HEC-FDA, then combine them with the appropriate weighting. Recommend p=0.8 for wet and p=0.2 for dry.
- Use accepted techniques for uncertainty analysis.
- Use a mixed distribution with three weighting alternatives: same as in the POR, an intermediate weight, and a weight that assumes only the most recent (wet) period will continue to occur. Do an economic analysis for each scenario. Compare to the current distribution (which assumes stationarity). Explain to the public and planners the uncertainty inherent in the flow frequency curve, and try to choose an alternative that does well, even if we have mischaracterized the curve.
- Use a mixed population model, with the first being 1942-2009 (wet), and the second being 1901-1941 (dry). Do not include historical floods (of the late 19th century). Start with p=1 for wet in year 1 of the project, then decrease linearly to p=0.5 in year 50 of the project.
- Define break in POR with statistical test of homogeneity or peer-reviewed published value, if available. Consider both populations within LPIII framework. Large historical floods from the 19th century can be included in either population at the discretion of the project engineer. Analysis should be done on natural flows, and re-regulated later. It would be preferable to use a weighting function that begins with p=1 for wet and p=0 for dry in year 1, moving over the course of the project life to p=0.5 for wet and p=0.5 for dry in year 50. Less preferable: 0.75 for wet and 0.25 for dry unchanged over the 50 years. Increase uncertainties upwards before economic analysis; probably will have to be done subjectively, e.g., a 25% increase.

The verbatim text of the experts' preliminary and final responses is included as Attachment 6 to this memorandum.

Attachment 5. Background information: USACE PowerPoint slides

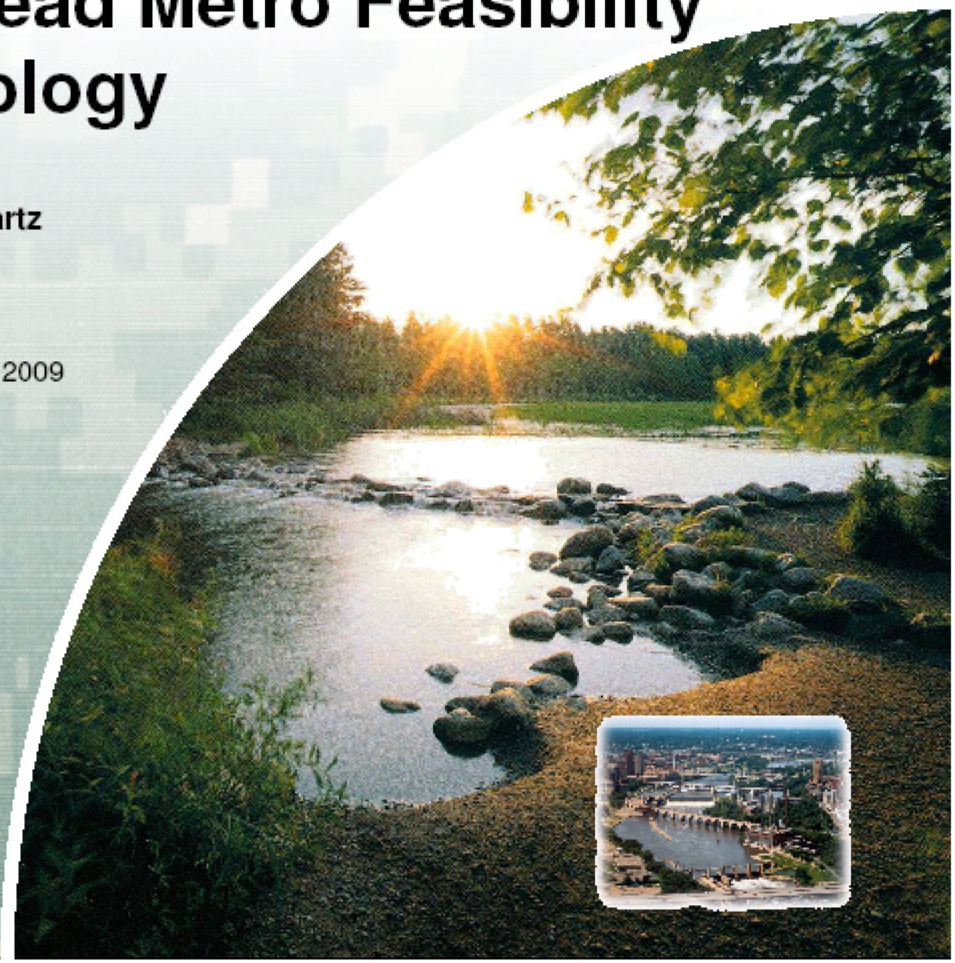
Fargo-Moorhead Metro Feasibility Study - Hydrology

Presenter Name: Daniel Reinartz

Presenter Title: Hydrologic Engineer

Duty Location: St. Paul District

Date of Presentation: 28 September 2009



US Army Corps of Engineers

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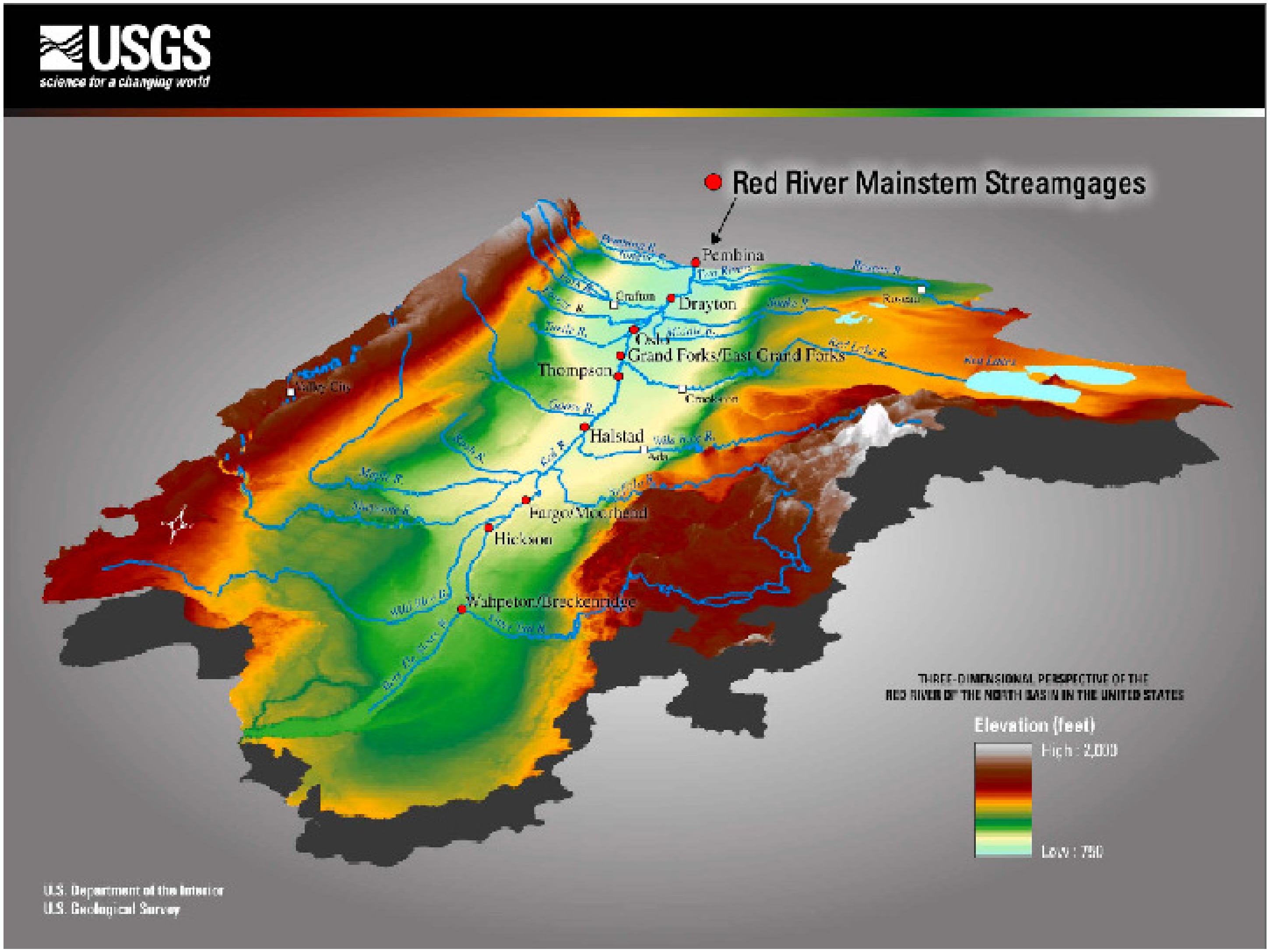
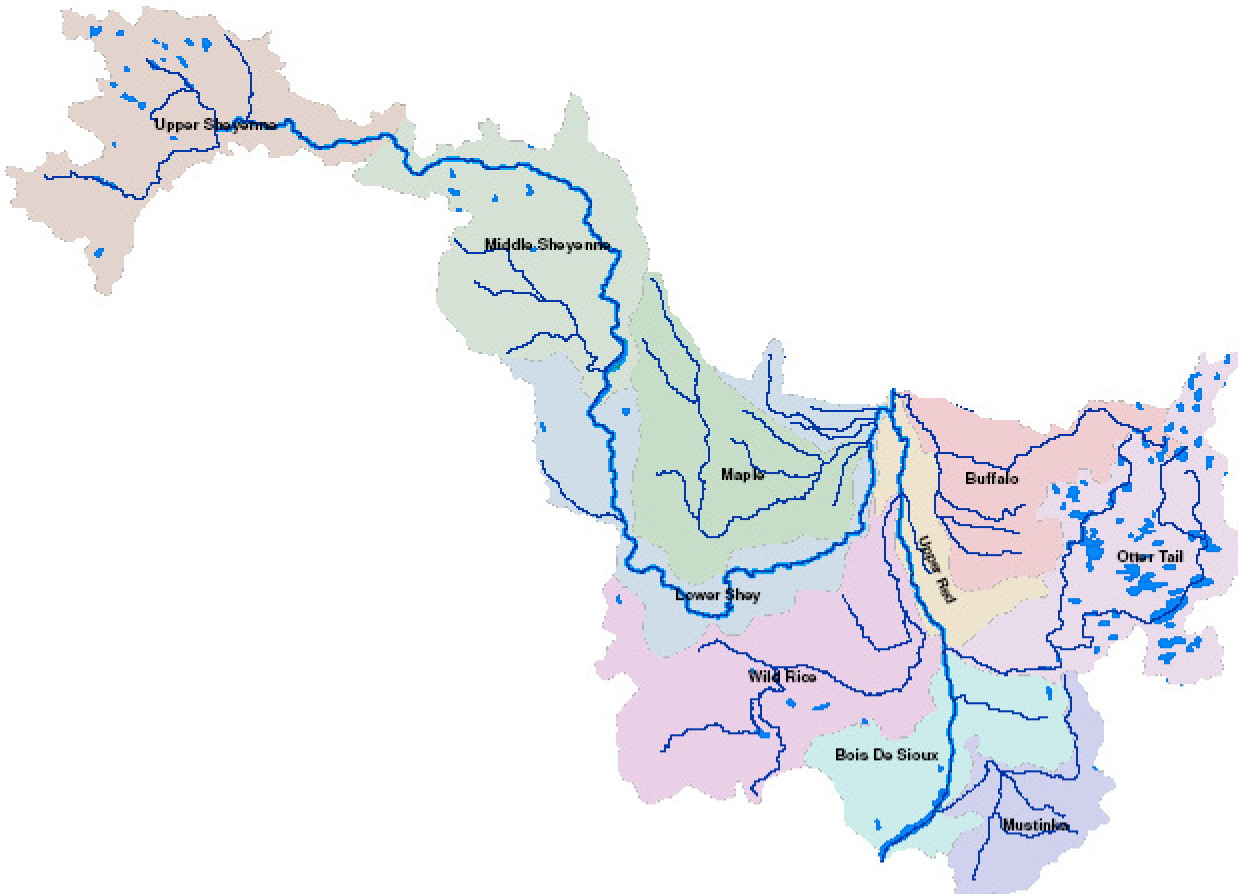
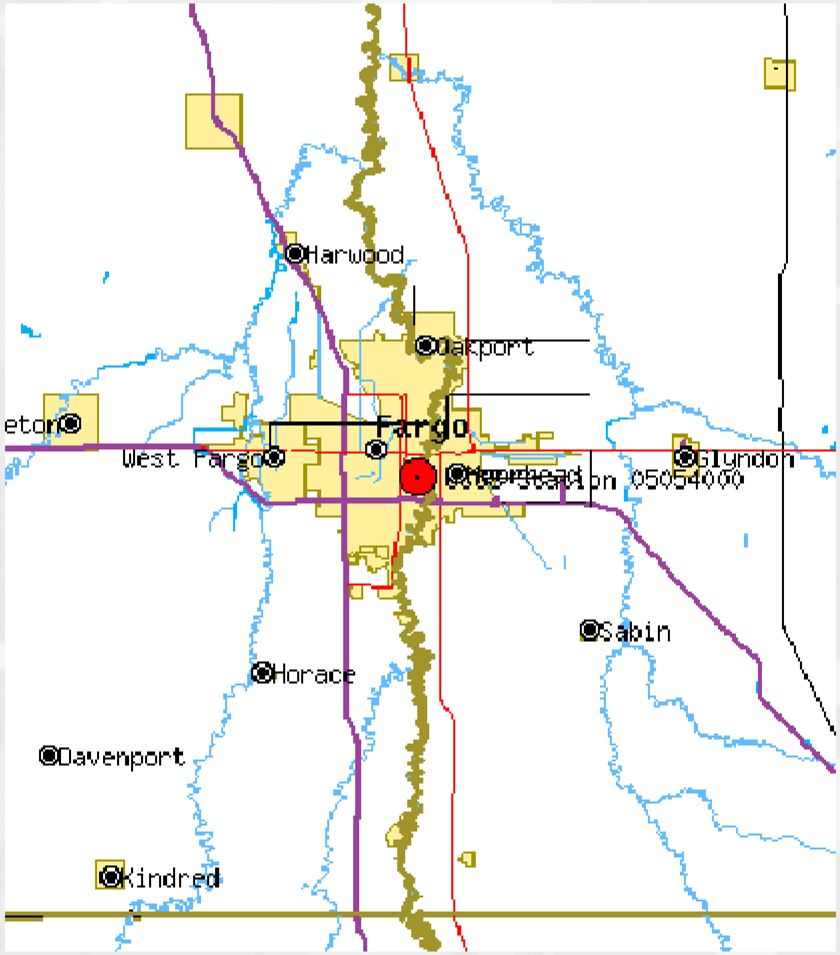

USGS
science for a changing world
Red River Mainstem Streamgages
Pembina
Drayton
Grafton
Oslo
Grand Forks/East Grand Forks
Thompson
Crookston
Halstad
Ada
Valley City
Roseau
Fargo/Moorhead
Hickson
Wahpeton/Breckenridge
THREE-DIMENSIONAL PERSPECTIVE OF THE
RED RIVER OF THE NORTH BASIN IN THE UNITED STATES
Elevation (feet)
High : 2,000
Low : 750
U.S. Department of the Interior
U.S. Geological Survey


Upper Sheyenne
Middle Sheyenne
Maple
Lower Shey
Buffalo
Upper Red
Otter Tail
Wild Rice
Bois De Sioux
Mustinka



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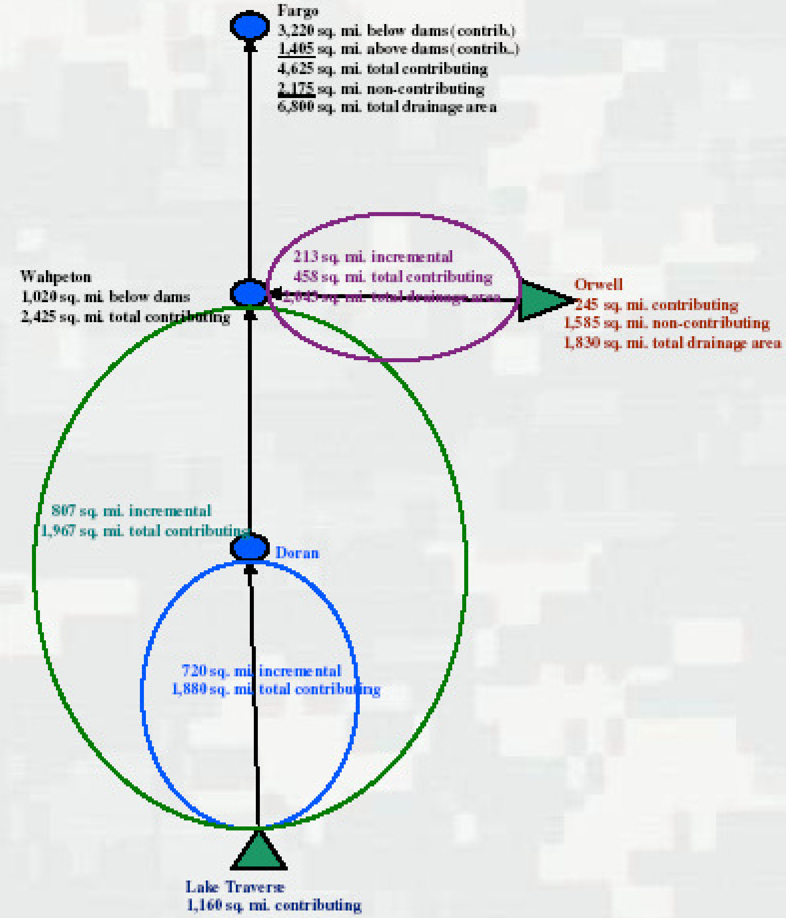

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Upstream Reservoirs

- ORWELL RESERVOIR
  - Built in 1953
  - 13,100 ac.-ft. flood control storage
  - 39 mi. u/s of Wahpeton
  - 135 mi. u/s of Fargo

- Lake Traverse/White Rock Dam
  - Built in 1942
  - Purpose: Flood control & water conservation
  - 137,000 ac.-ft. flood control storage
  - 30 mi. u/s of Wahpeton
  - 125 mi. u/s of Fargo
  - 1997 only event that reservoir releases contributed to peak @ Wahpeton

Period of Record

- POR: 1882, 1897, 1902 – 2009
- Natural Condition:
    - Before Orwell & L. Traverse
    - without Dams Condition
    - 1882-1942
- Regulated Condition = 1942 – 2009
- POR is non-homogeneous
- POR must be adjusted to current homogenous condition

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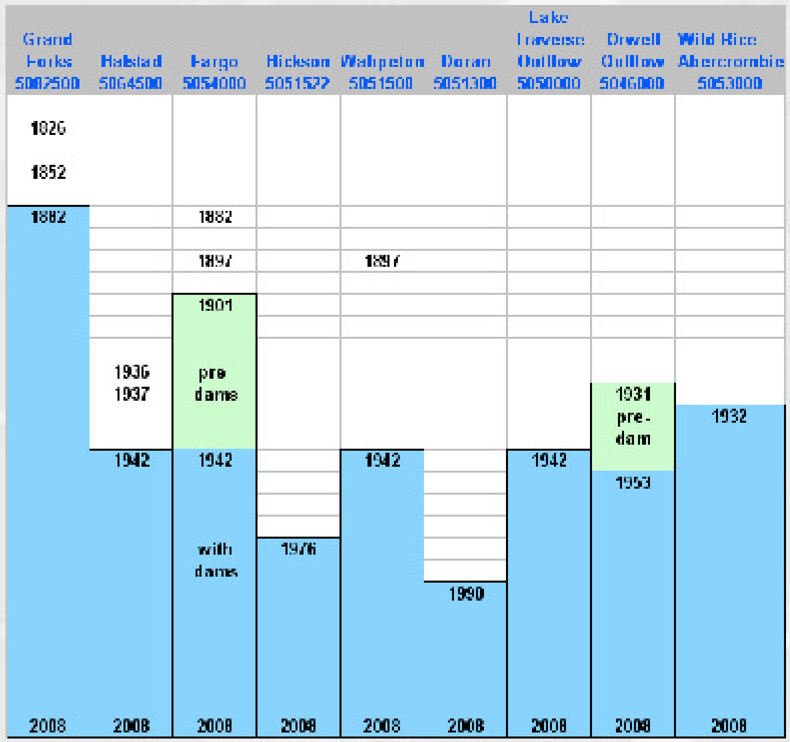
Peak Streamflow Gauge Stations and POR



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Method Overview

- Develop Natural Peak Q-frequency
  - Mean Daily
  - Instantaneous
- Develop REGULATED Peak Q-frequency
  - Mean Daily
  - Instantaneous
- Plot Both Curves Together
  - Plot Natural Analytically LPIII
  - Plot Instantaneous Graphically
  - Use Hickson Peak Q-frequency as guide

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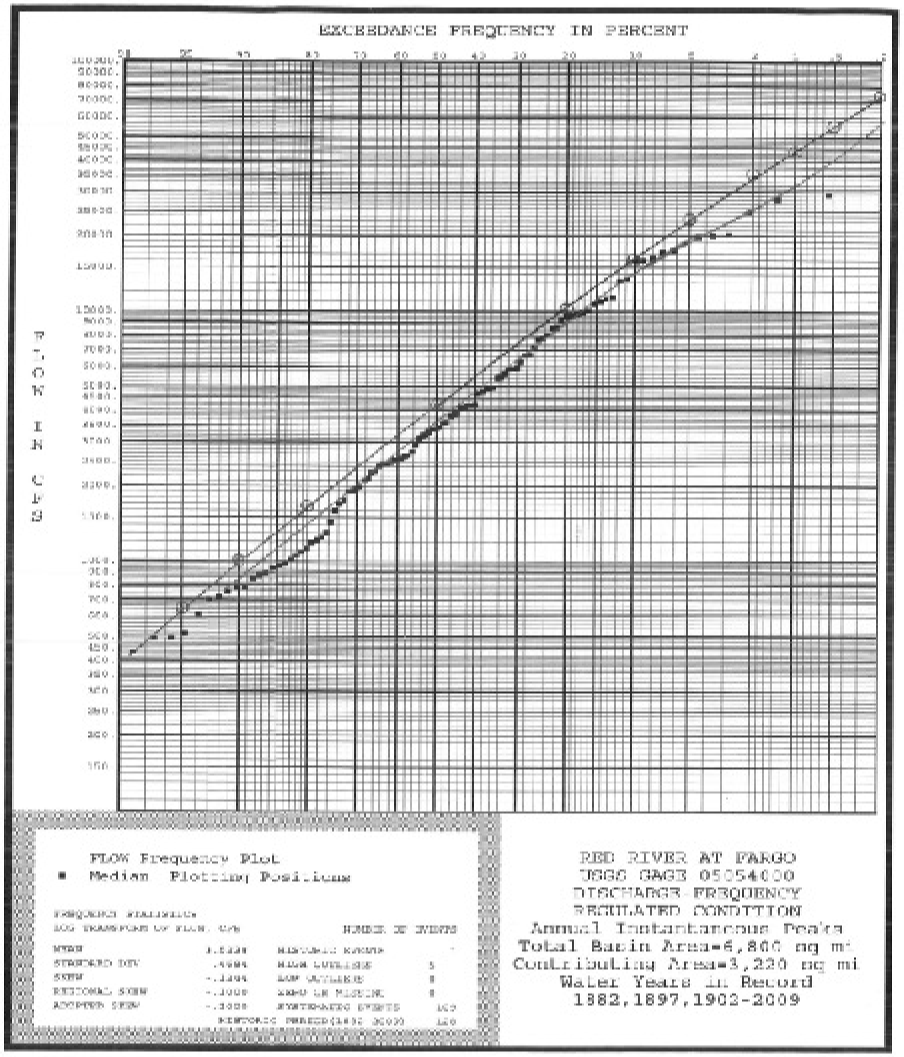

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Develop Natural Peak Q-Frequency

- Use existing record: 1902 to 1942
- Adjust existing regulated pks to natural pks: 1942 to 2009
- Do this using Hec-5 (reservoir simulation model)
- “reverse route” outflows from u/s dams and then route and combine flows d/s to Fargo
- Develop Q-Frequency analytically by LPIII for full record: 1902 to 2009
- Two additional significant events 1882 & 1897
- Systematic record = 109
- Historic record = 128

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Develop Natural Peak Q-Frequency (cont.)

- Use Median Plotting Position
- (m-.3)/(n+1-.3-.3)

- M = order number
- N = number of years

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Develop Natural Peak Q-Frequency (cont.)

- Develop Instantaneous Peaks
- Regress Instant. Pks vs. MD Pks for observed record
- 1942 – 2009
- Apply same relation to simulated MD pks

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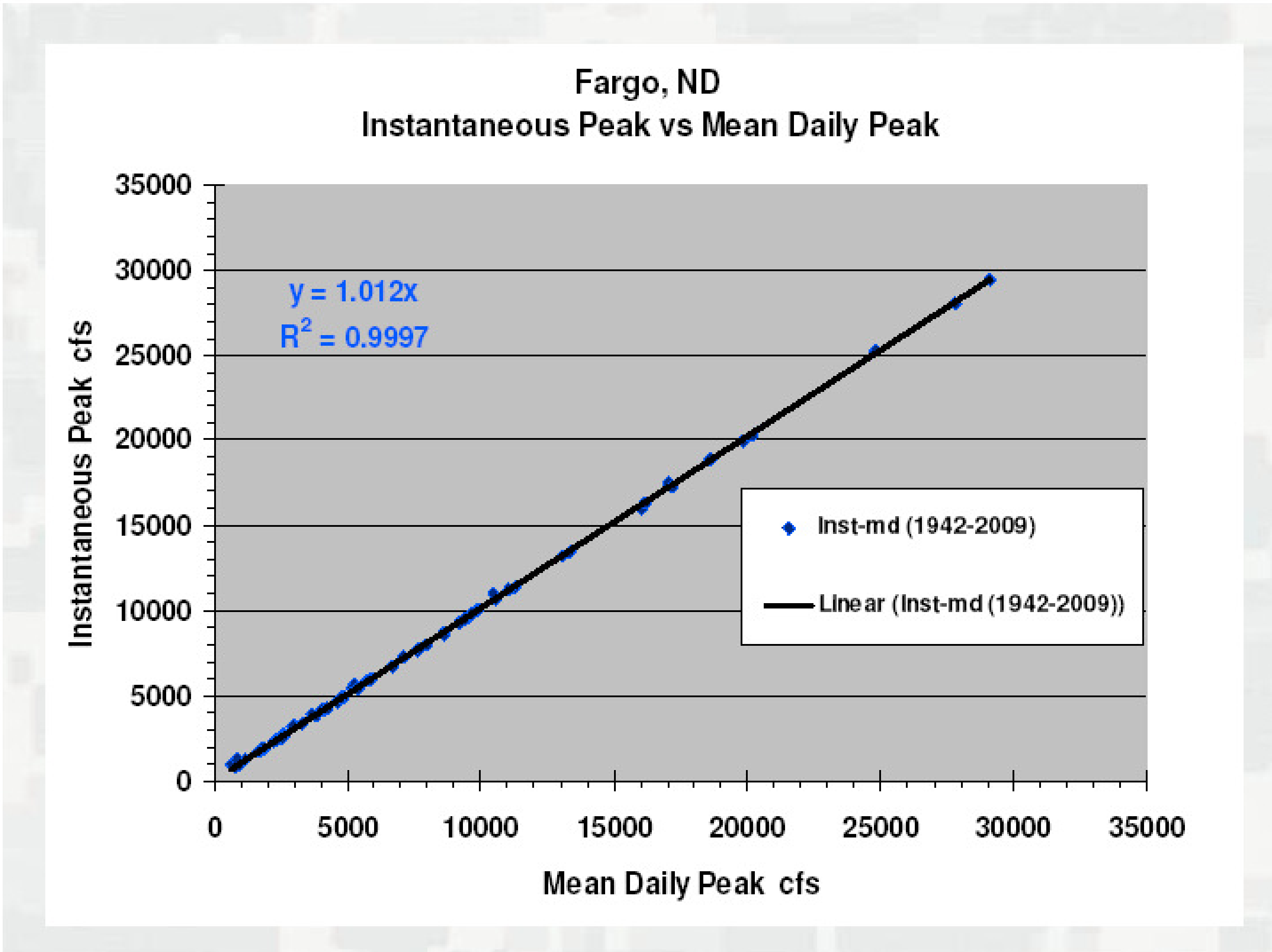
Fargo, ND
Instantaneous Peak vs Mean Daily Peak
y = 1.012x
R^2 = 0.9997
Inst-md (1942-2009)
Linear (Inst-md (1942-2009))
Instantaneous Peak cfs
Mean Daily Peak cfs
0
5000
10000
15000
20000
25000
30000
35000

Develop Natural Peak Q-Frequency (cont.)

- 1 Historic Event = 1897 (largest event since 1882)
- 5 High Outliers

- INSTANTANEOUS PEAK
- ORDERED EVENTS

RANK	WATER YEAR	FLOW CFS	MEDIAN PLOT POS
1	2009	33753.	.55
2	1969	32978.	1.32
3	1997	31768.	2.10
4	2001	28829.	2.88
5	2006	26610.	3.66
6	1897	25000.	4.44
7	1978	22401.	5.29
8	1989	22029.	6.20
9	1952	21585.	7.11
0	1979	21318.	8.03
1	1882	20000.	8.94

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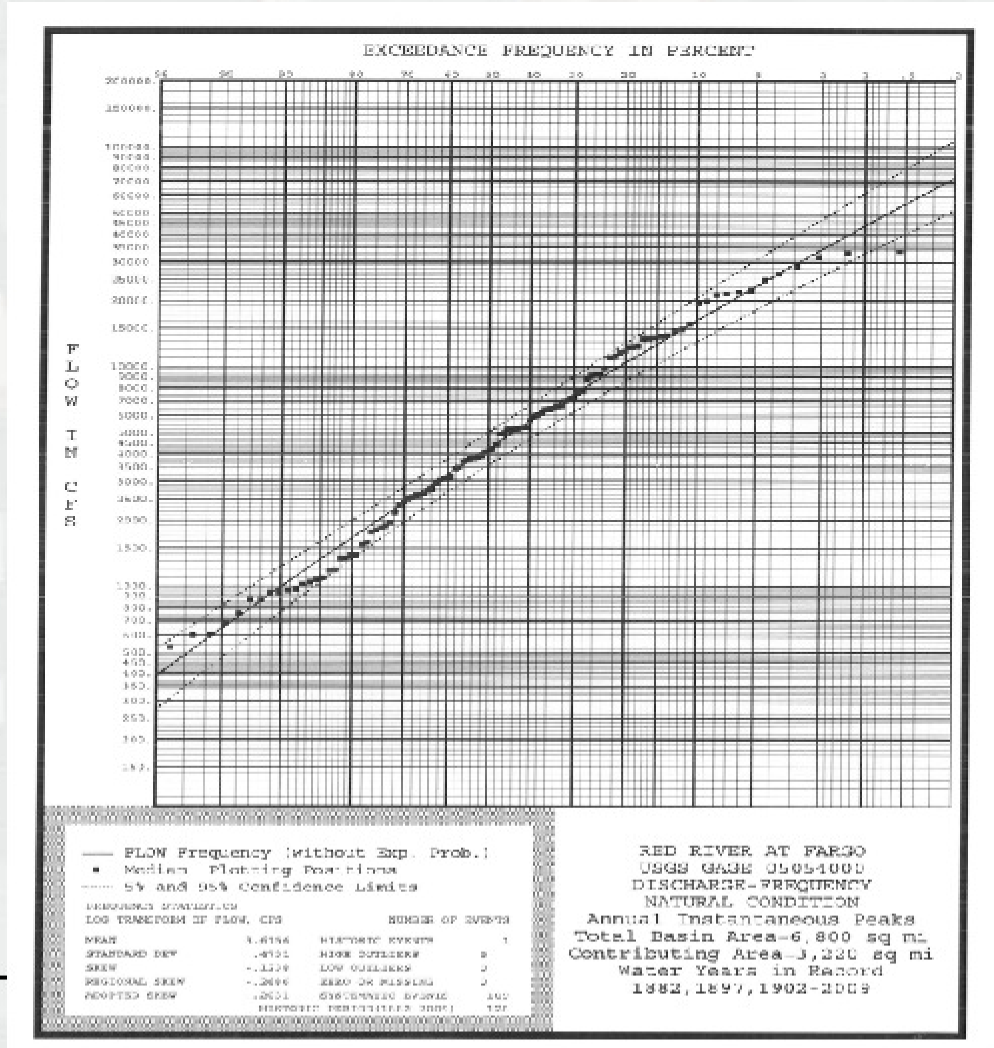

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Method Overview

- Develop Natural Peak Q-frequency
  - Mean Daily
  - Instantaneous
- Develop REGULATED Peak Q-frequency
  - Mean Daily
  - Instantaneous
- Plot Both Curves Together
  - Plot Natural Analytically LPIII
  - Plot Instantaneous Graphically
  - Use Hickson Peak Q-frequency as guide

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Develop Regulated Peak Q-Frequency

- Adjust POR 1902-1942 for regulated condition
- Regress Existing (regulated) MD Pks vs. simulated MD pks
- Develop graphical Q-Frequency for full record
- Plot with Natural conditions curve
- Use Median plotting position

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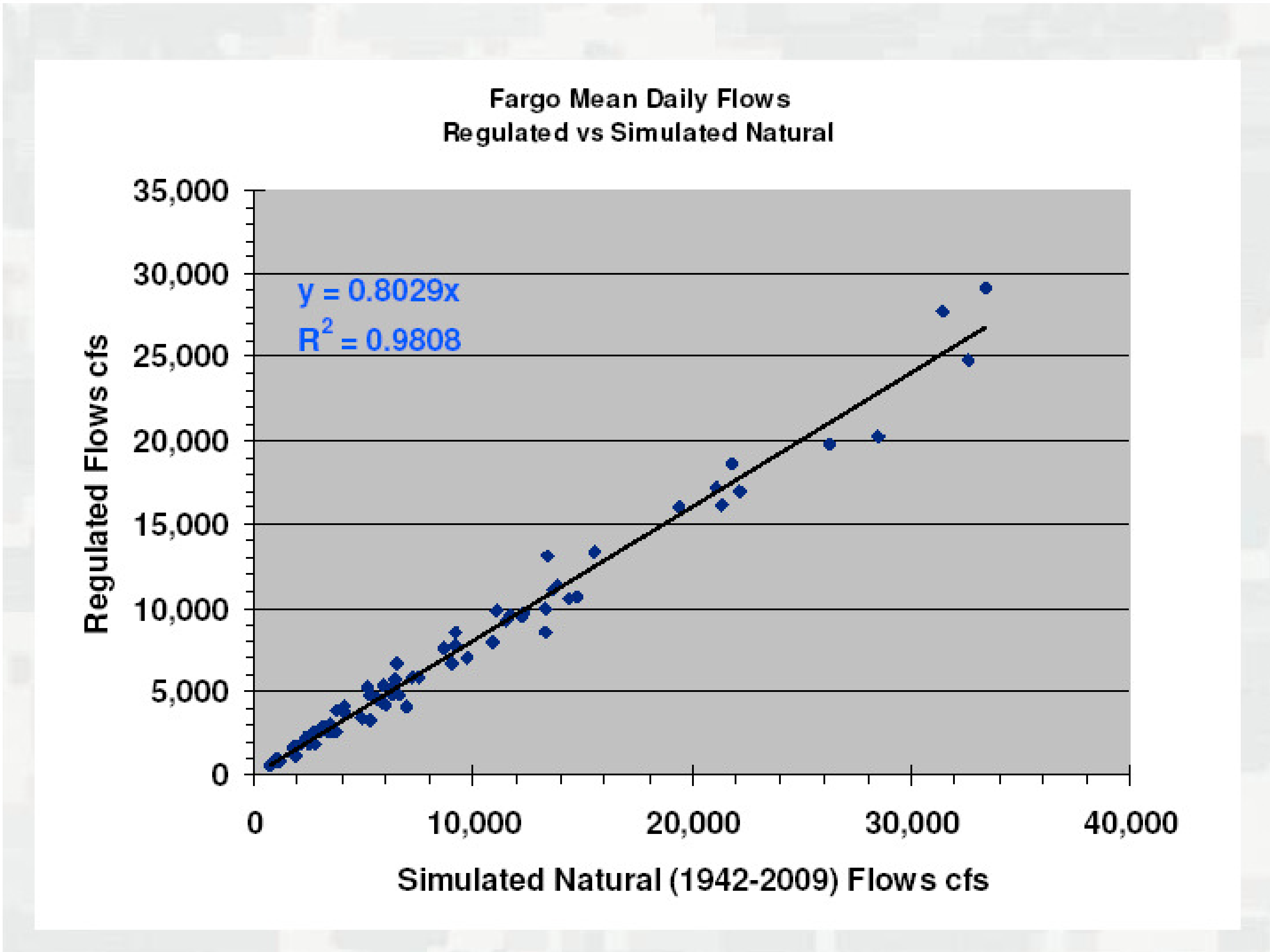
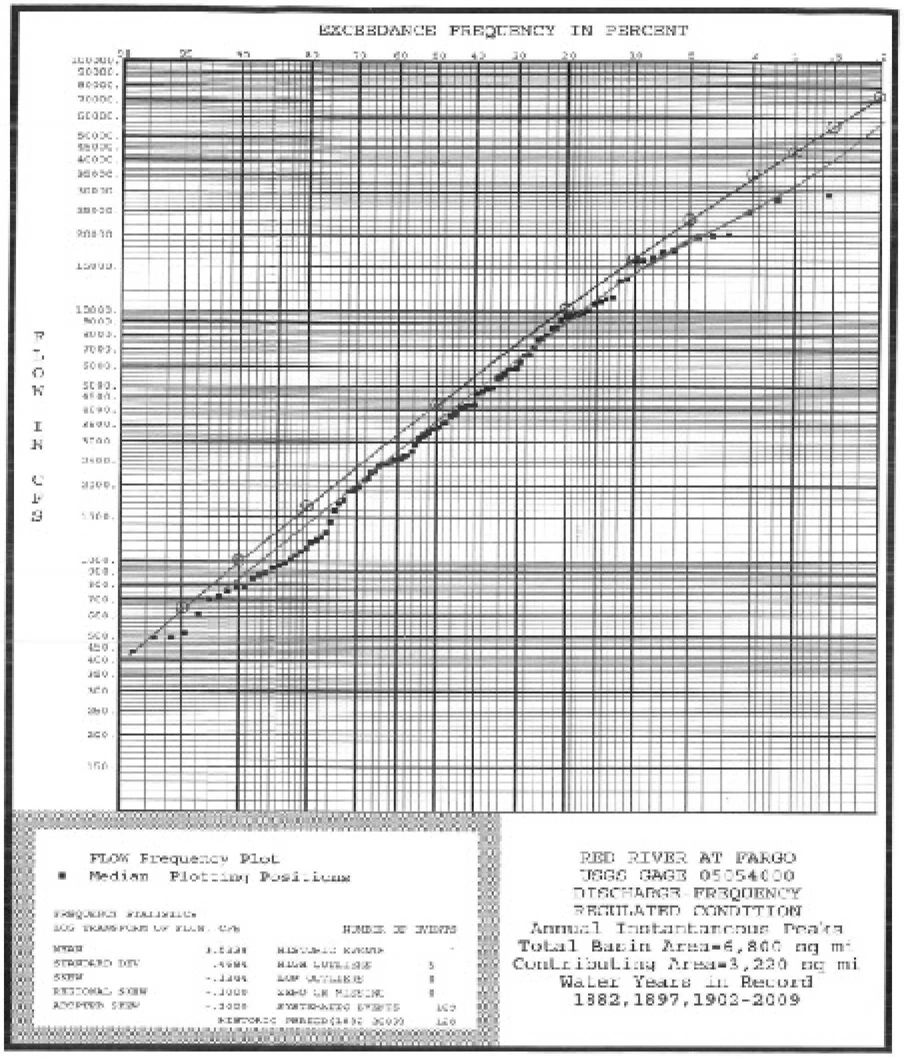

Fargo Mean Daily Flows
Regulated vs Simulated Natural
y = 0.8029x
R^2 = 0.9808
Regulated Flows cfs
35,000
30,000
25,000
20,000
15,000
10,000
5,000
0
0
10,000
20,000
30,000
40,000
Simulated Natural (1942-2009) Flows cfs

Develop Regulated Peak Q-Frequency (cont.)

- 1 Historic Event = 1897 (largest event since 1882)
- 5 High Outliers

ORDERED EVENTS

RANK	WATER YEAR	FLOW CFS	MEDIAN PLOT POS
1	2009	29400.	.55
2	1997	28000.	1.32
3	1969	25000.	2.10
4	2001	20300.	2.88
5	1897	20073.	3.66
6	2006	19900.	4.44
7	1989	18900.	5.29
8	1978	17500.	6.20
9	1979	17300.	7.11
10	1952	16300.	8.03
11	1882	16058.	8.94



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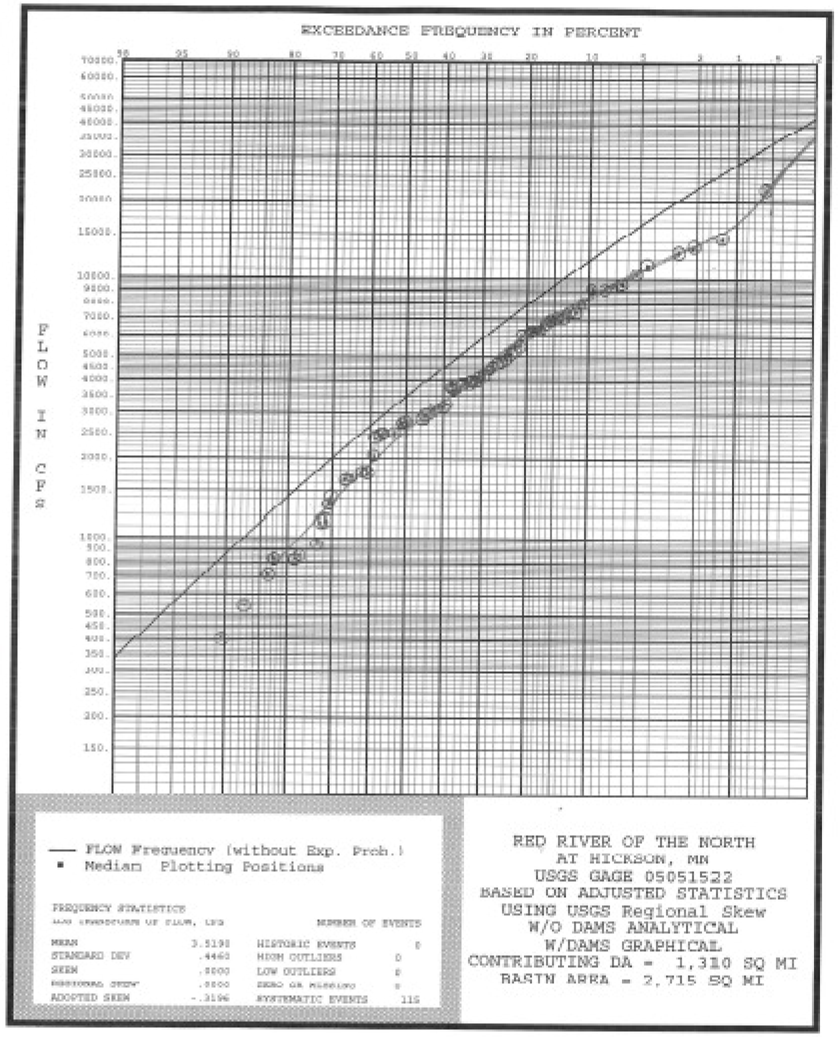
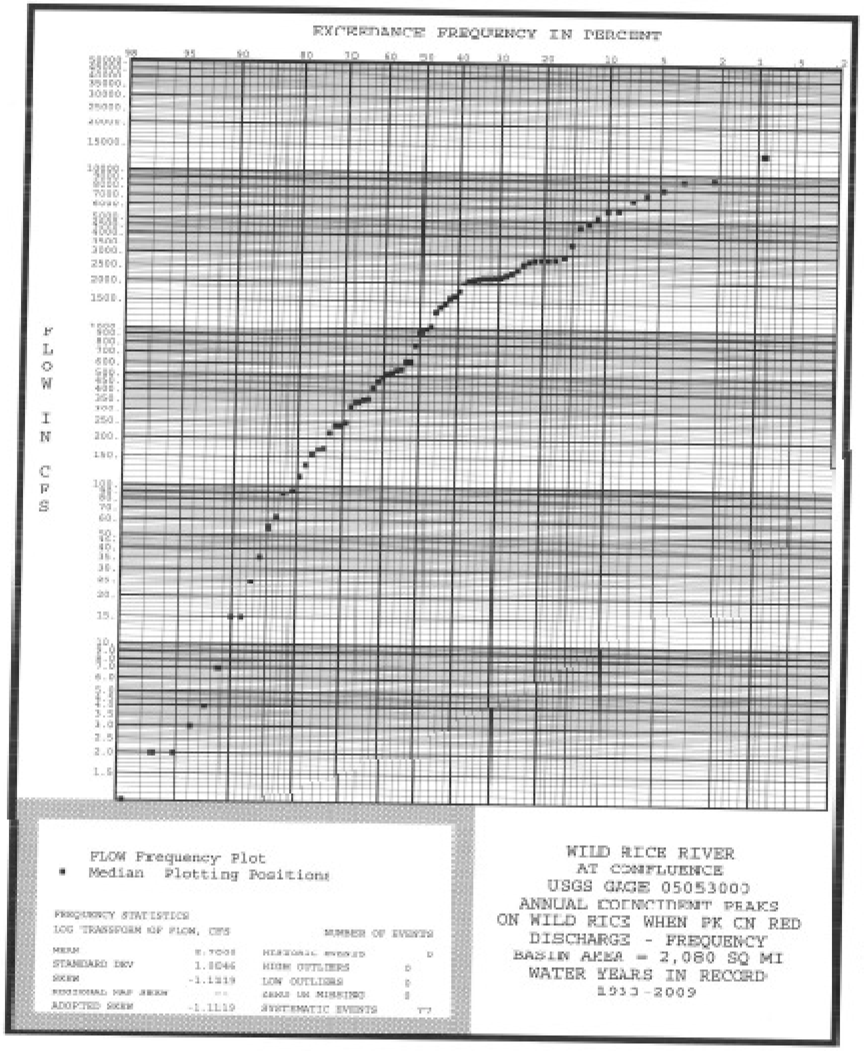

EXCEEDANCE FREQUENCY IN PERCENT
FLOW IN CFS
FLOW Frequency (without Exp. Prob.)
Median Plotting Positions
FREQUENCY STATISTICS
NUMBER OF EVENTS
MEAN 3.5198
STANDARD DEV .4460
SKEW .0000
ADOPTED SKEW -.3196
HISTORIC EVENTS 0
HIGH OUTLIERS 0
LOW OUTLIERS 0
SYSTEMATIC EVENTS 116
RED RIVER OF THE NORTH
AT HICKSON, MN
USGS GAGE 05051522
BASED ON ADJUSTED STATISTICS
USING USGS Regional Skew
W/O DAMS ANALYTICAL
W/DAMS GRAPHICAL
CONTRIBUTING DA = 1,310 SQ MI
BASIN AREA = 2,715 SQ MI



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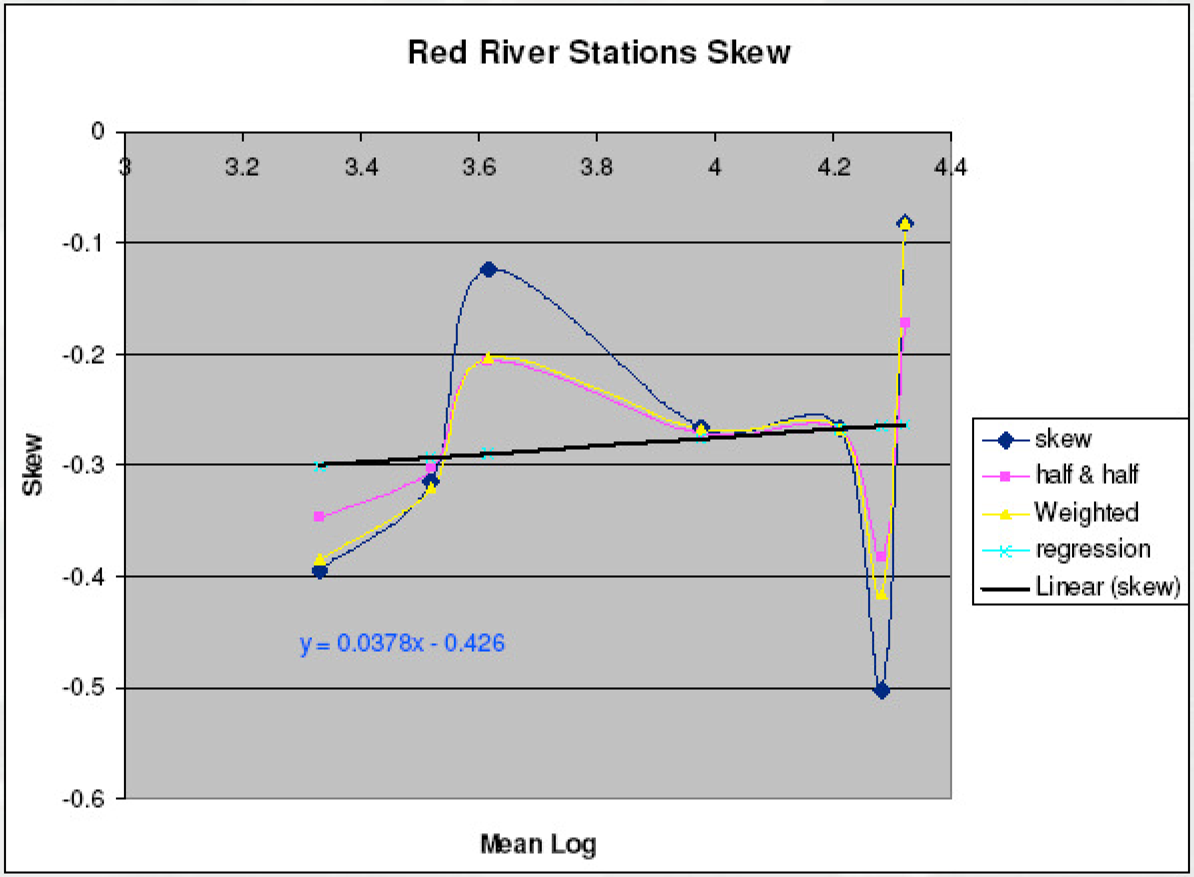
Skew Weight

- Use Regional skew = MN USGS Map
  - Wahpeton
  - Hickson
- Use Grand Forks Station Skew with GF station MSE
  - Fargo
  - Halstad
  - Grand Forks



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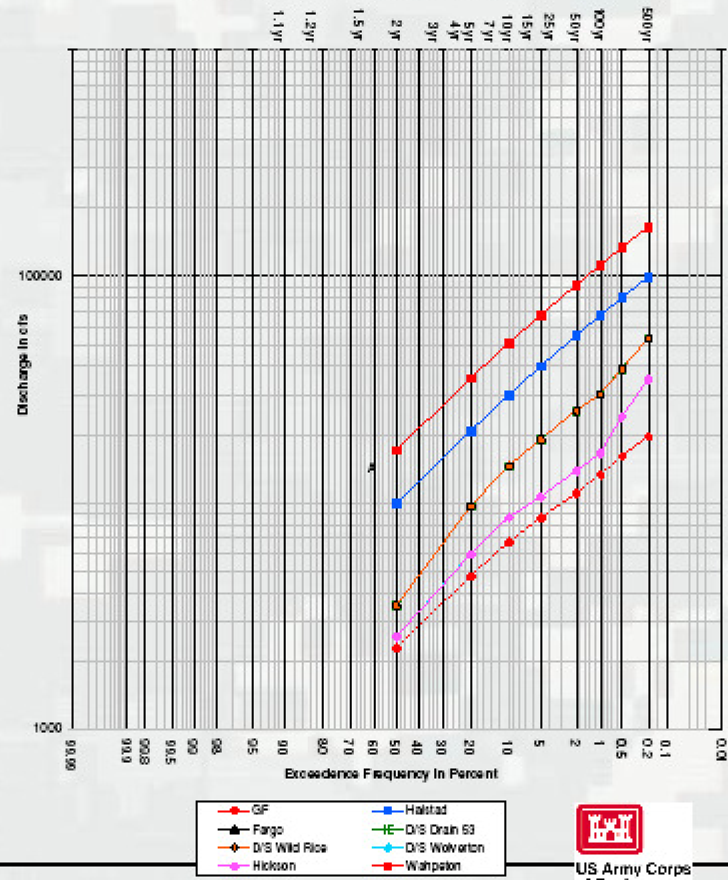
Red River of the North
Discharge-Frequency Curves



US Army Corps of Engineers ®
St. Paul District

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Method Overview

- Develop Natural Peak Q-frequency
  - Mean Daily
  - Instantaneous
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  - Use Hickson Peak Q-frequency as guide

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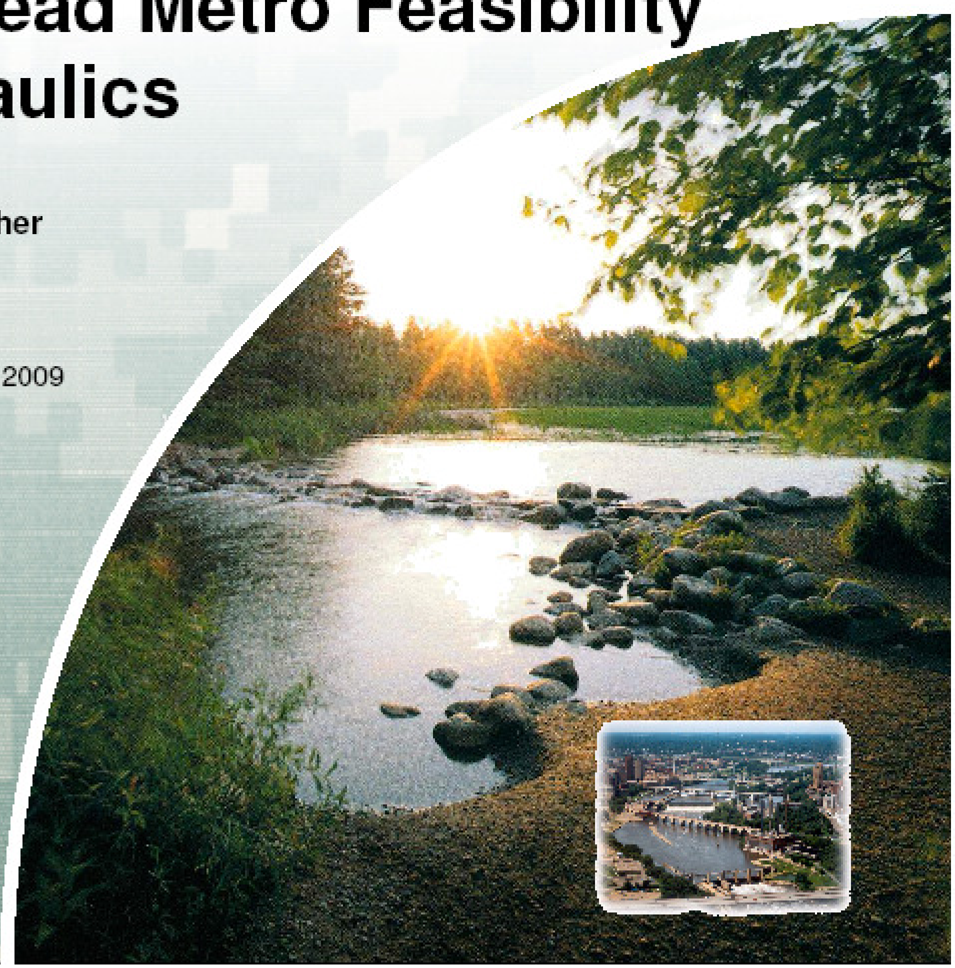
Fargo-Moorhead Metro Feasibility Study - Hydraulics



Presenter Name: Michael Lesher

Presenter Title: Hydraulic Engineer

Duty Location: St. Paul District

Date of Presentation: 28 September 2009

US Army Corps of Engineers

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Fargo-Moorhead Metro Feasibility Study

- Alternatives Overview
- H&H Inputs for Risk & Uncertainty Analysis

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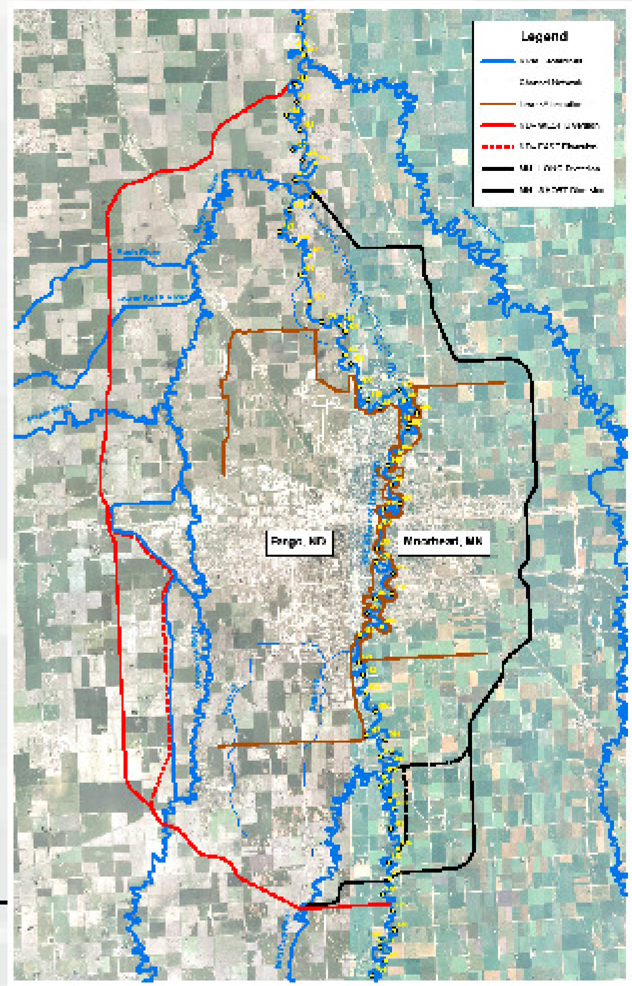
Alternatives Overview



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Diversion Channel Capacities Considered

Minnesota Short & Long

- 25,000 cfs
- 35,000 cfs
- 45,000 cfs

North Dakota West

- 35,000 cfs
- 45,000 cfs

North Dakota East

- 35,000 cfs

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H&H Inputs for Risk & Uncertainty Analysis

- Discharge-Frequency Curve with Transform Relationship
- Elevation-Discharge Curve with Uncertainty

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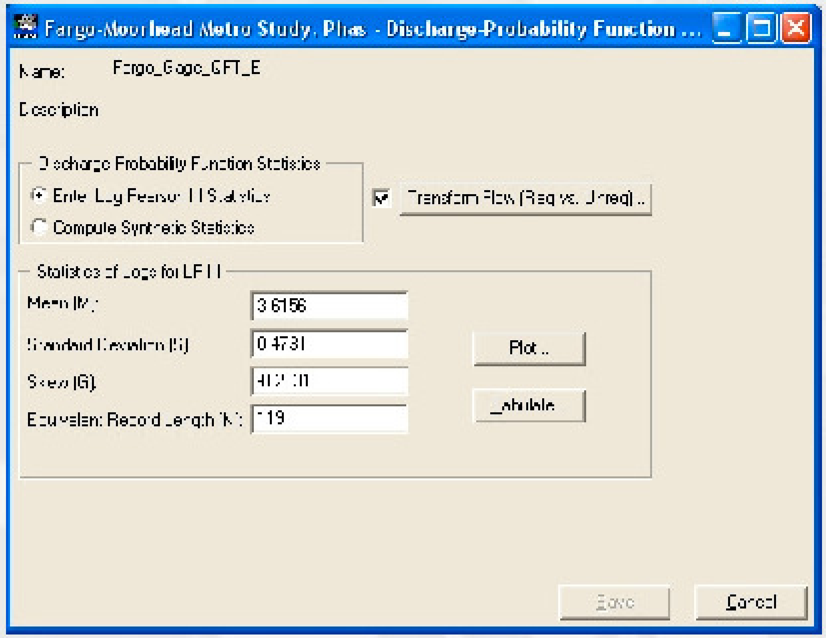
Discharge-Frequency Curve Input for HEC-FDA



N = Average of Systematic Record and Historic Period
= (109 + 128) / 2 = 118.5, Rounded to 119 years

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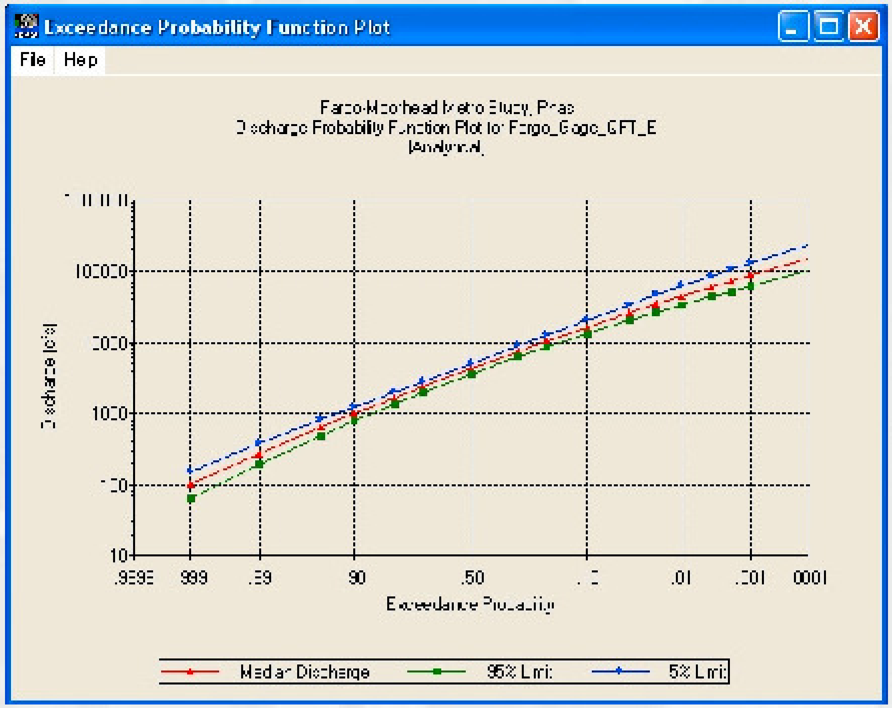
Discharge-Frequency Curve Input for HEC-FDA



Discharge-Frequency Curve
Defined to 0.01%, (10,000-Year) Event

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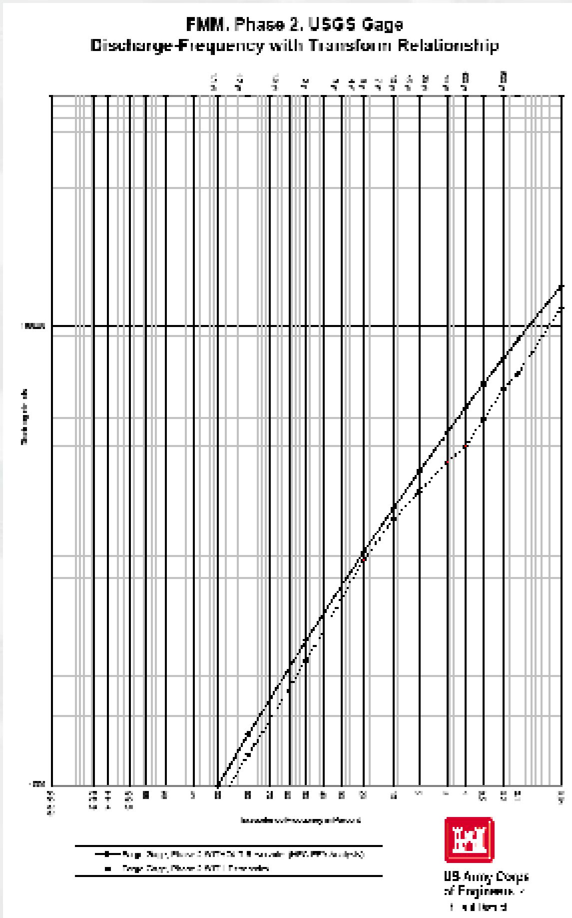
Discharge-Frequency Transform Relationship



FMM, Red River of the North		
DATA Frequency (in percent)	Phase 2 Fargo Natural	Phase 2 Fargo Regulated
0.01	149,000	120,000
0.1	87,500	62,000
0.2	72,600	53,000
0.5	55,400	39,000
1	44,200	30,000
2	34,300	25,500
5	23,200	19,000
10	16,200	14,500
20	10,400	9,800
50	4,280	3,500
80	1,670	1,360
90	1,000	829
95	647	550
99	279	251

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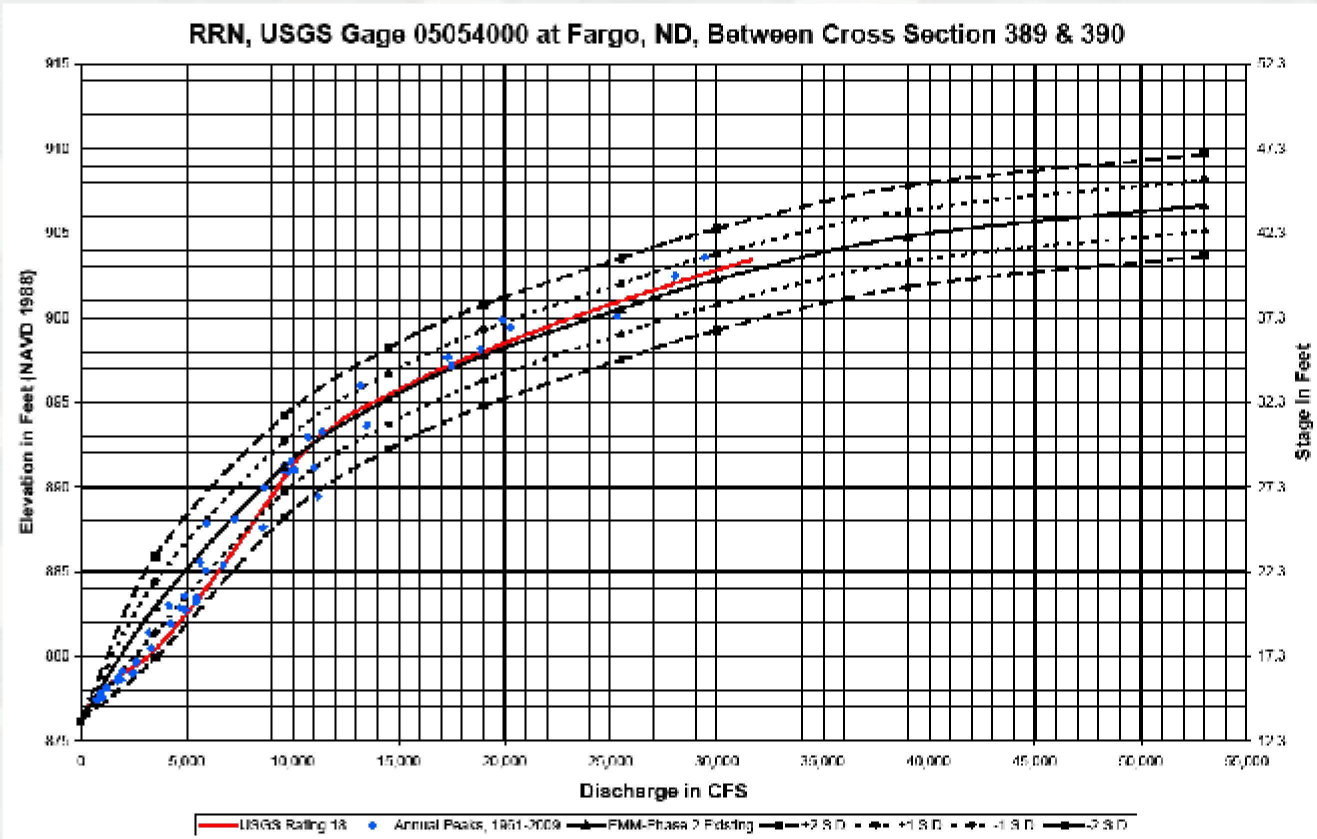
Hydraulic Uncertainty



Hydraulic Uncertainty

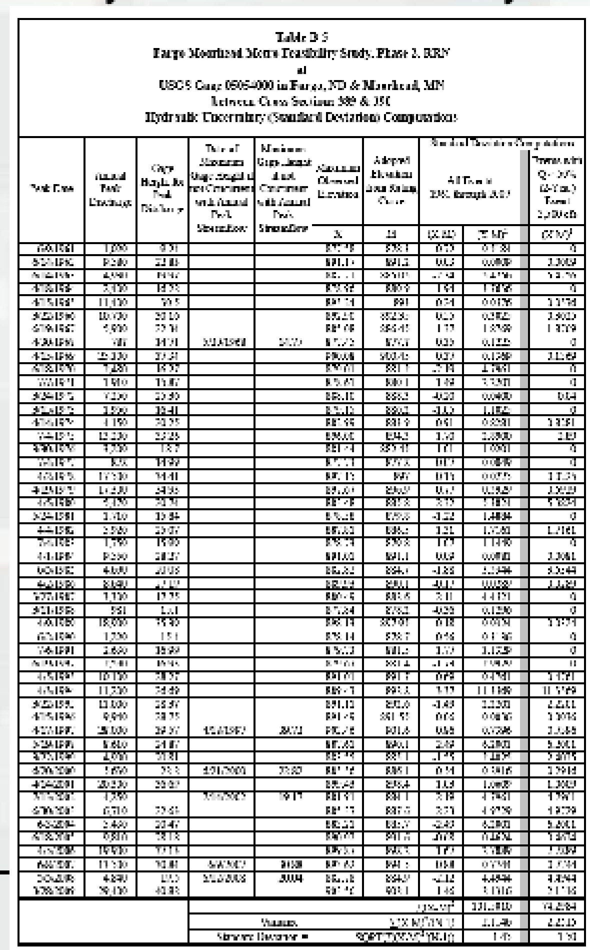


Table D-5
Fargo Moorhead Metro Feasibility Study, Phase 2, RRN
at
USGS Gage 05054000 in Fargo, ND & Moorhead, MN
Between Cross Sections 389 & 350
Hydraulic Uncertainty (Standard Deviation) Computations

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Fargo-Moorhead Metro Feasibility Study

Questions?

Comments?

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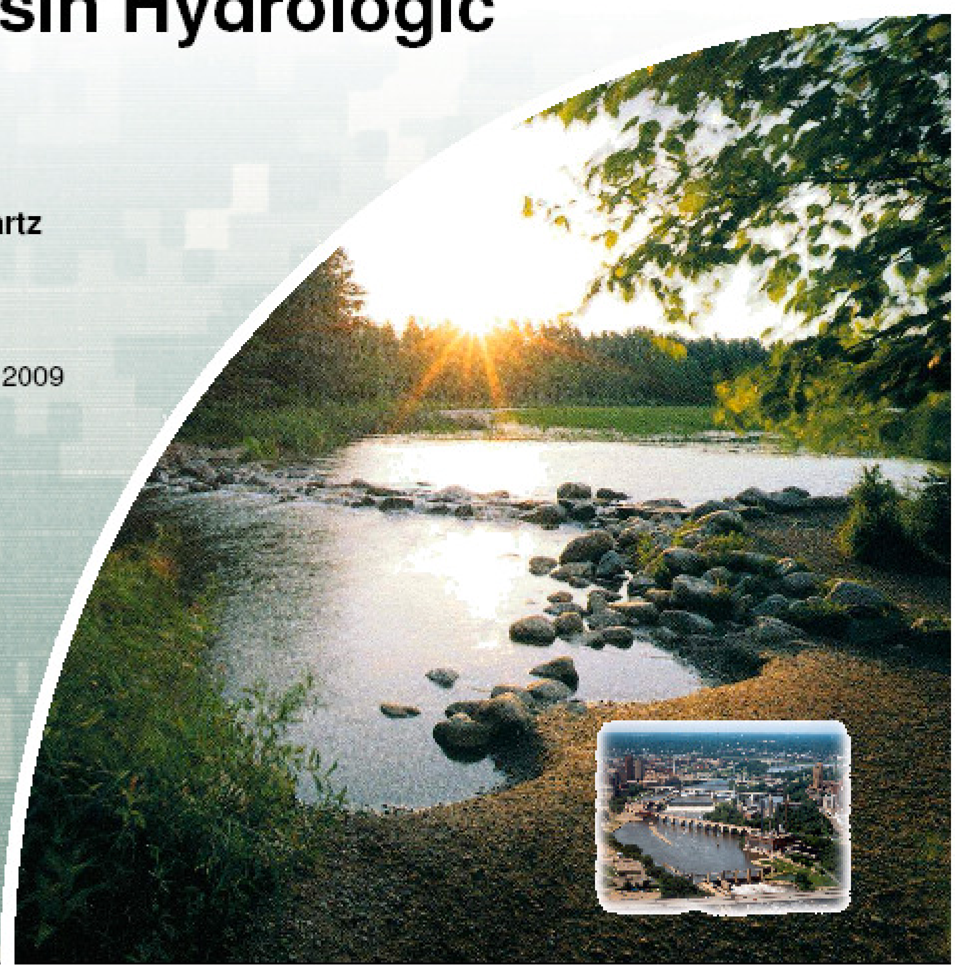
Red River Basin Hydrologic Trends

Presenter Name: Daniel Reinartz

Presenter Title: Hydrologic Engineer

Duty Location: St. Paul District

Date of Presentation: 28 September 2009



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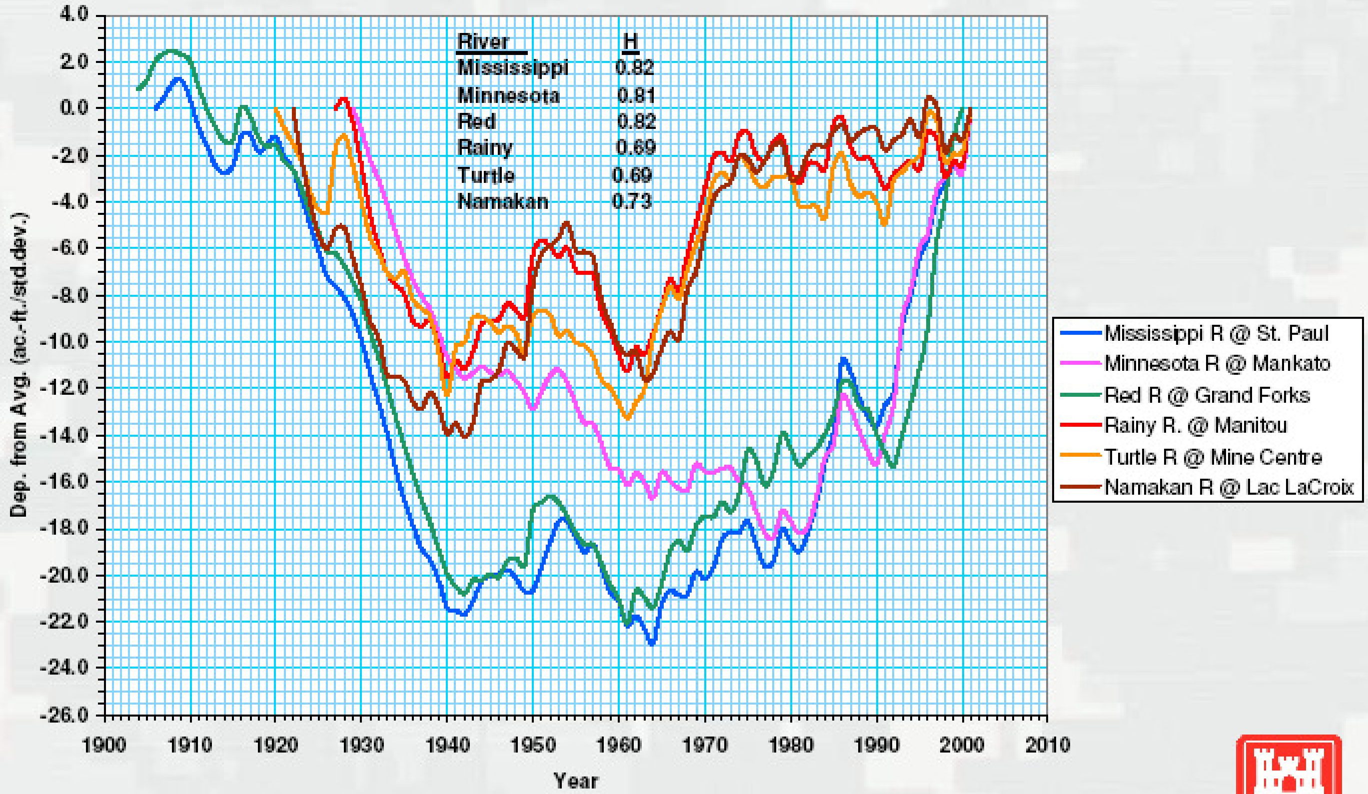
Annual Runoff Volume
Departure From Average



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Hurst Coefficient

$$R / S = (n / 2)^{H}$$

Where:

R = range of cumulative departures from the mean of a time series
S = standard deviation of the series
n = length of record in years
H = the Hurst coefficient

Theoretically, H = 0.5 for a stationary process with finite memory.

For many natural time series H is in fact greater than 0.5.

Averages 0.72 with SD of 0.09

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GEOHYDROLOGICAL IMPLICATIONS OF CLIMATE

CHANGE ON WATER RESOURCE DEVELOPMENT

by

Charles W. Stockton and William R. Boggess
Laboratory of Tree-Ring Research
University of Arizona
Tucson, Arizona 85721

Prepared for

U.S. Army Coastal Engineering Research Center
Kingman Building
Fort Belvoir, Virginia 22060

May 1979

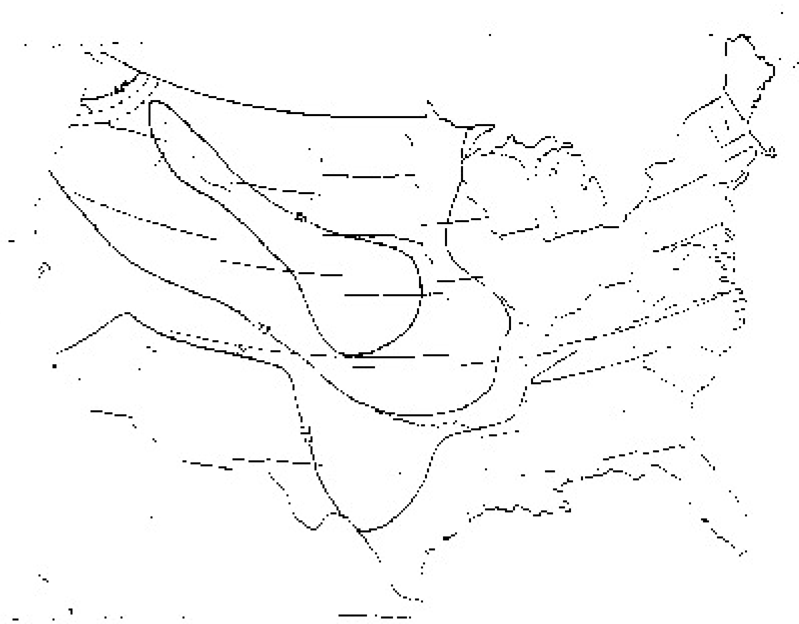
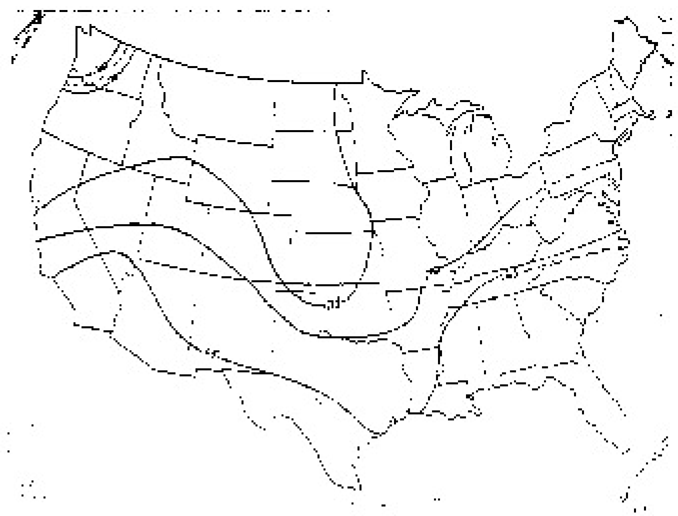
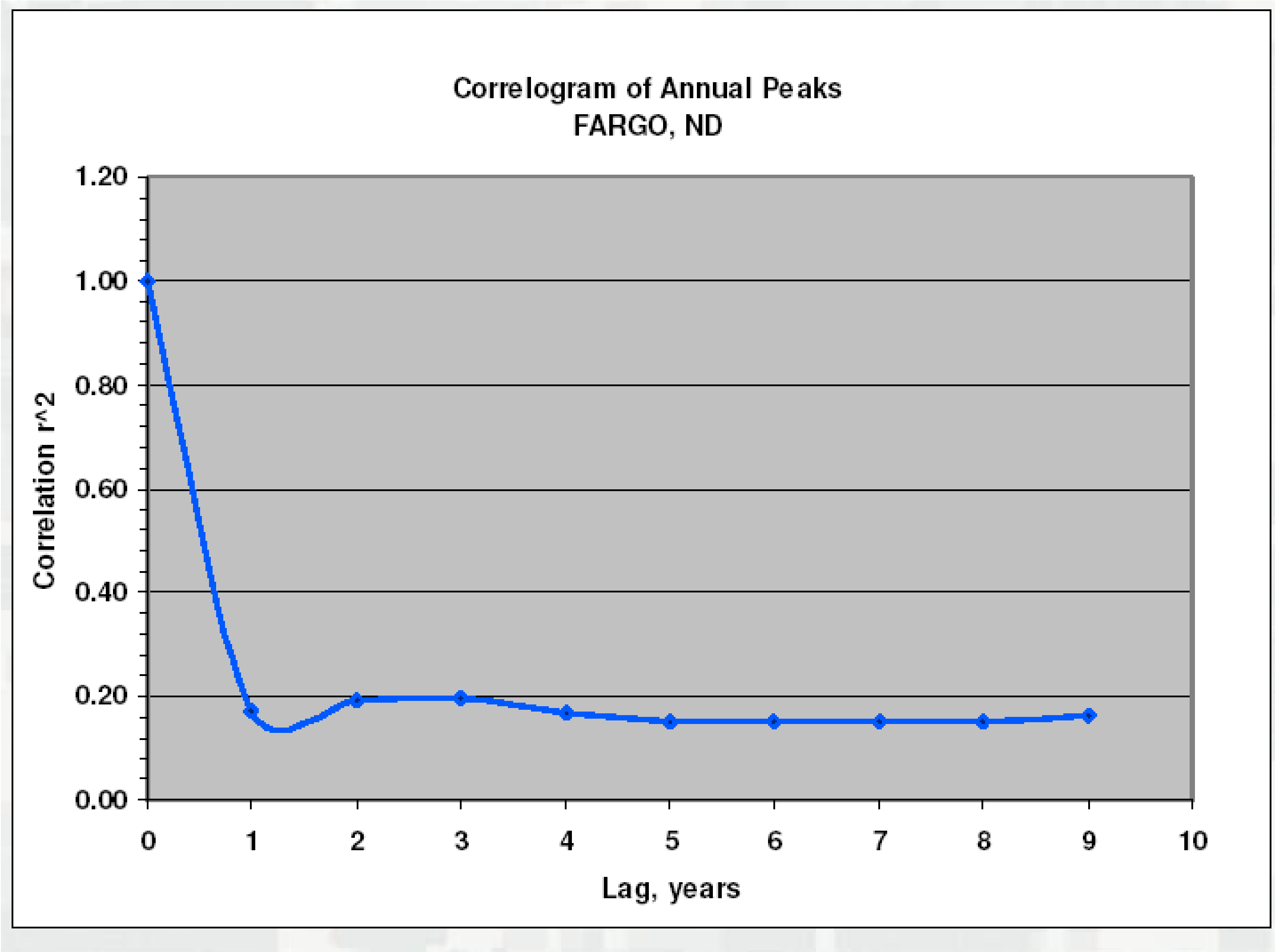


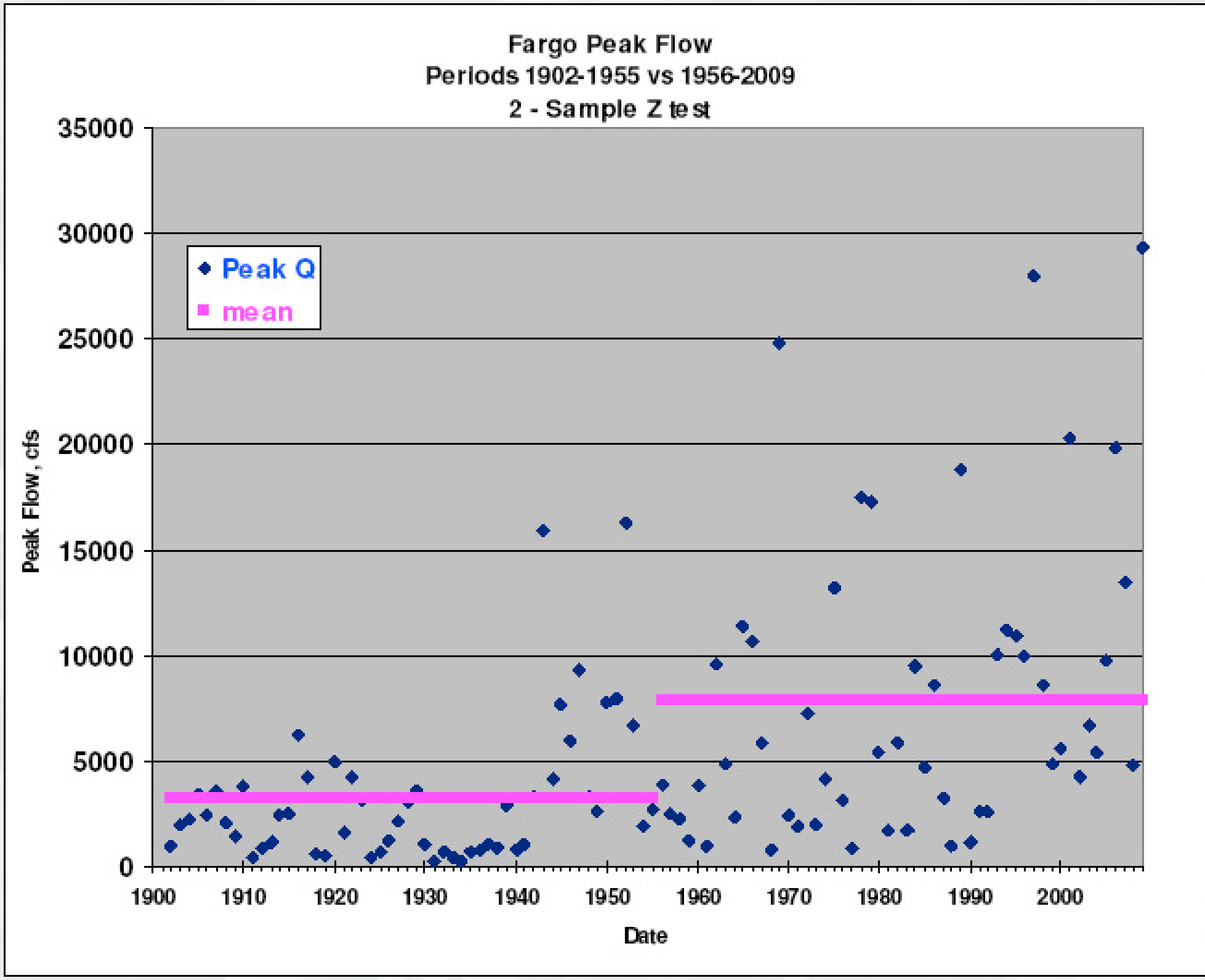
Figure 21. Maps showing regions of most persistent drought occurrences as expressed by Hurst's k. Larger values indicate greater persistence. (a) is based on 50 year increments; (b) is based on 100 year increments; period of record 1630-1962.



(b)

Figure 21. Maps showing regions of most persistent drought occurrences as expressed by Hurst's k. Larger values indicate greater persistence. (a) is based on 50 year increments; (b) is based on 100 year increments; period of record 1600–1962.


Correlogram of Annual Peaks
FARGO, ND
Correlation r^2
1.20
1.00
0.80
0.60
0.40
0.20
0.00
0
1
2
3
4
5
6
7
8
9
10
Lag, years


Fargo Peak Flow
Periods 1902-1955 vs 1956-2009
2 - Sample Z test
Peak Q
mean
Peak Flow, cfs
35000
30000
25000
20000
15000
10000
5000
0
1900
1910
1920
1930
1940
1950
1960
1970
1980
1990
2000
Date

2-Sample z Test of Mean of Peak Flows

$H_o : m_1 = m_2$

$H_a : m_1 \neq m_2$

$z = -4.38 < -1.96$

Therefore : $m_1 \neq m_2$ @ 5% Level of Significance

z-Test: Two Sample for Means		
	1902-1955	1956-2009
Mean	3225.296296	7889.019
Known Variance	11452508	45907998
Observations	54	54
Hypothesized Mean Difference	0	
z	-4.376875721	
P(Z<=z) one-tail	6.01963E-06	
z Critical one-tail	1.644853627	
P(Z<=z) two-tail	1.20393E-05	
z Critical two-tail	1.959963985	

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Variance F-Test

$H_o : s_1^2 = s_2^2$

$H_a : s_1^2 \neq s_2^2$

1.58<< 4.36

Therefore : $s_1^2 \neq s_2^2$ @ 5% Level of Significance

VAR()	11452508	49909998
COUNT()	54	54
F ratio	4.36	
Confidence	95%	
Significance	5%	
FINV()	1.58	

1.58 < 4.36

They are statistically significant at the 5 % level of significance
At 95 % confidence I reject the idea that they might be the same variance
and I accept the idea that one period is different than the other period' variance

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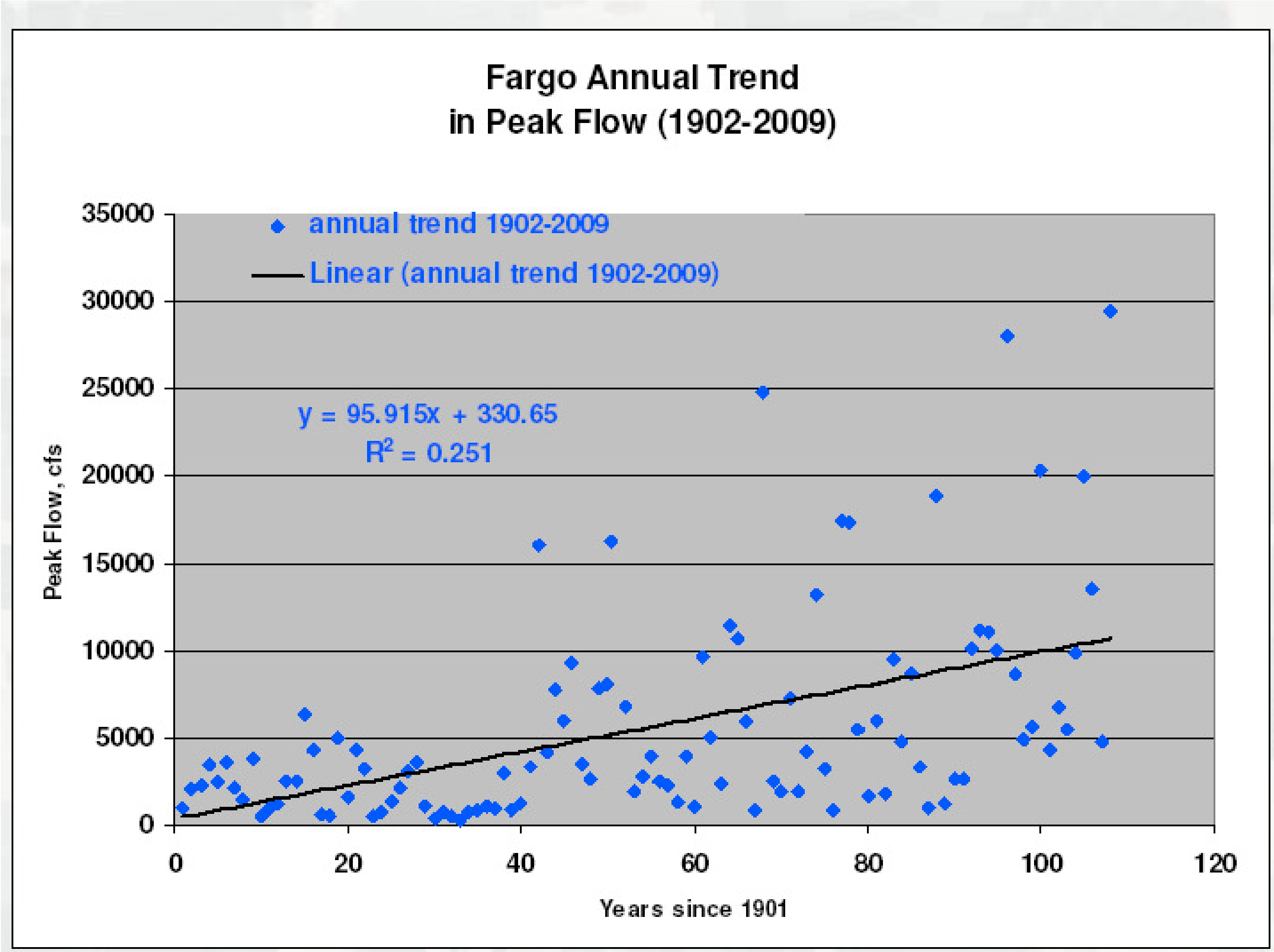
Fargo Annual Trend
in Peak Flow (1902-2009)
annual trend 1902-2009
Linear (annual trend 1902-2009)
y = 95.915x + 330.65
$R^2 = 0.251$
Peak Flow, cfs
Years since 1901
35000
30000
25000
20000
15000
10000
5000
0
0
20
40
60
80
100
120

Test of Regression Slope

- $Q = a + b(t_i)$
- Test slope b @ .05 level of significance
- 2-sided test of the mean
- 5.21 > 1.96
- Therefore: slope is statistically > 0 @ .05

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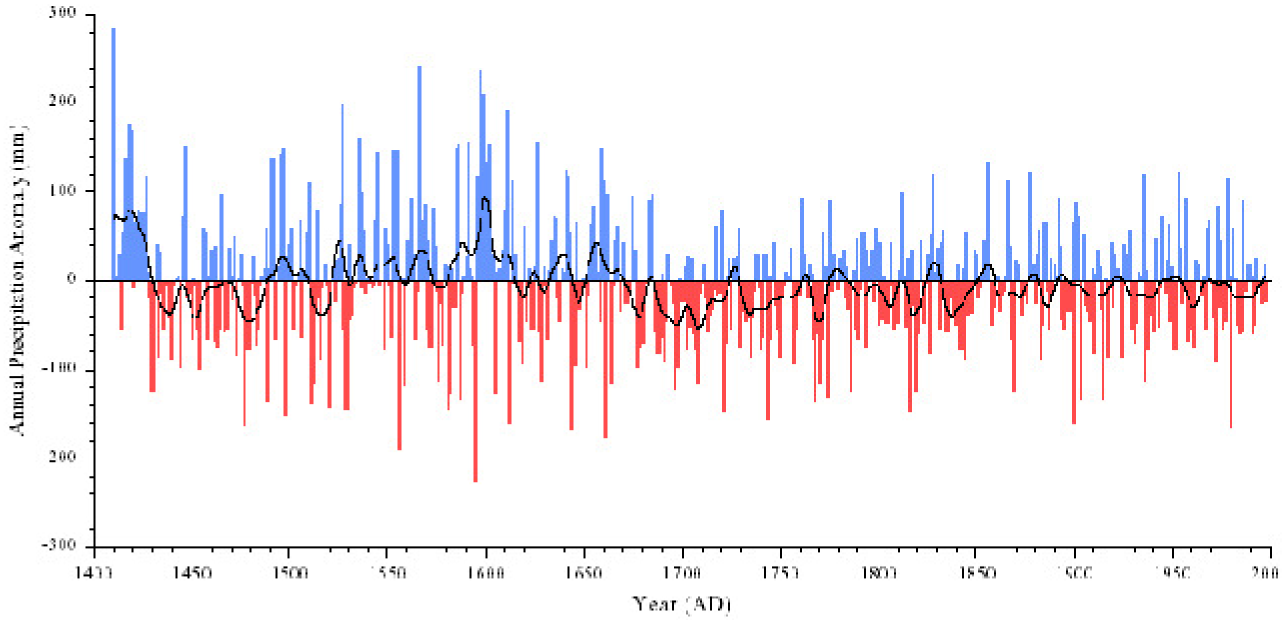

Source: S.St. George, T.W. Anderson, D. Forbes, C.F.M. Lewis, E. Nielsen and L.H. Thorleifson, reference 11.
Reconstructed annual (August-July) precipitation at Winnipeg from AD 1409-1998.
Units are deviations from mean annual precipitation from 1961-1990. Black line represents 15-year Tukey filtered series

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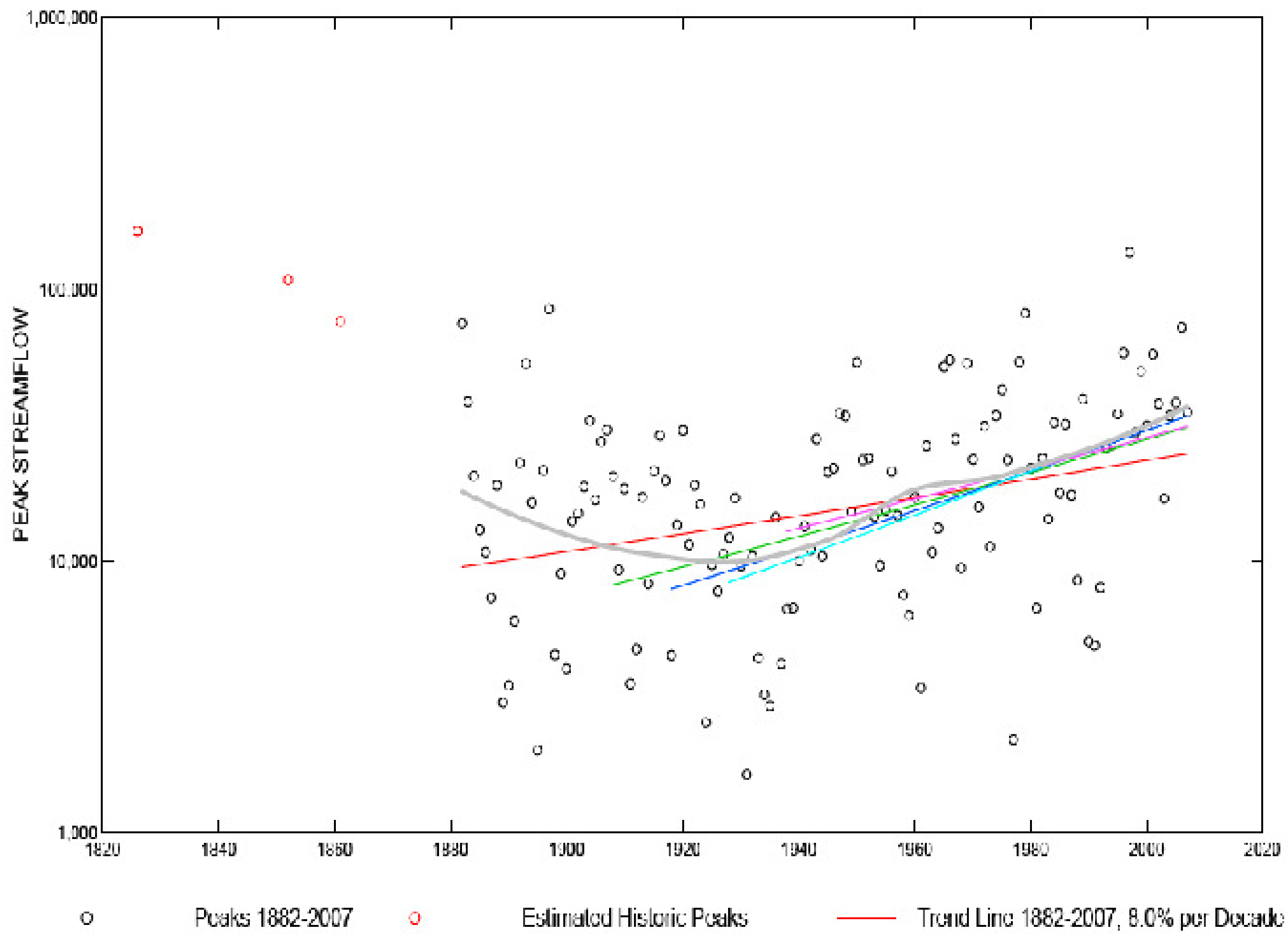


Figure 1. Trends in peak streamflow, Red River of the North at Grand Forks, North Dakota.

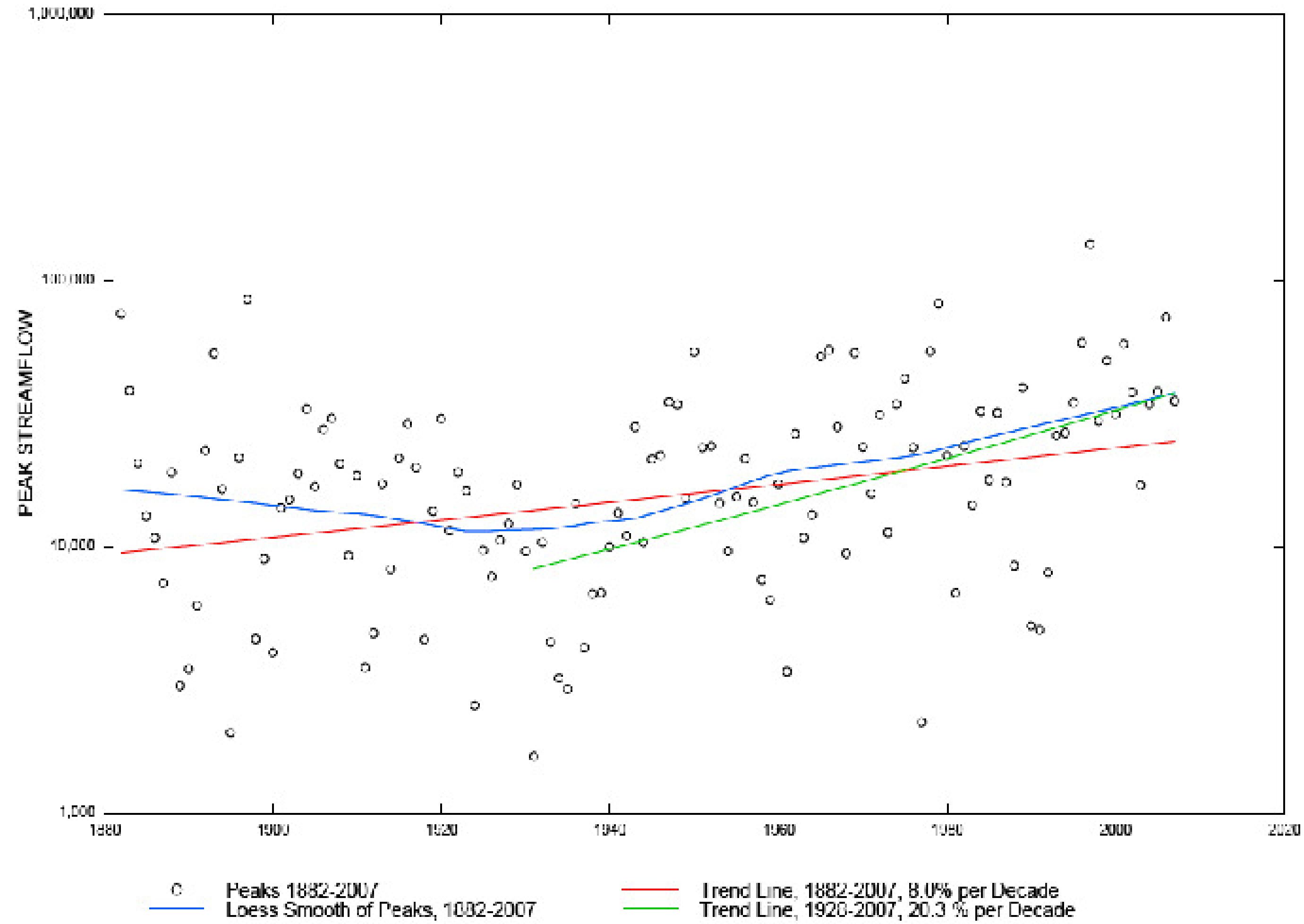


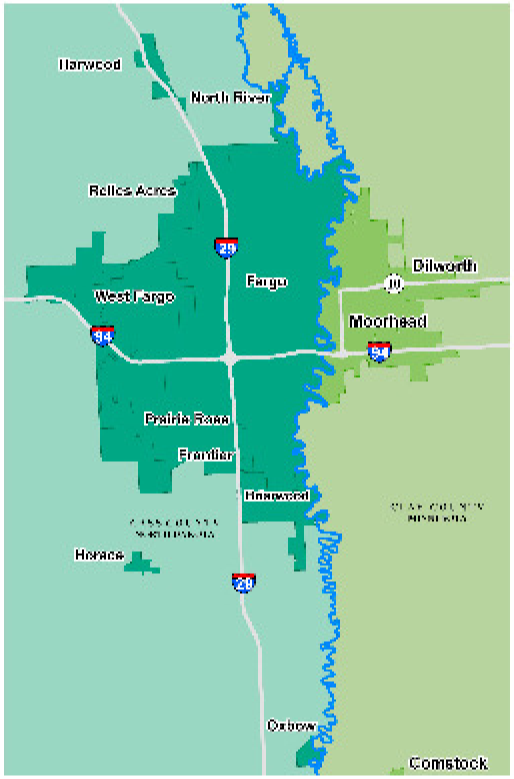
Figure 1. Trends in peak streamflow, Red River of the North at Grand Forks, North Dakota.


Fargo-Moorhead
Metropolitan Feasibility
Study
Presentation
for
Expert Panel
28 September 2009

STUDY AREA

- ✓ Fargo-Moorhead metropolitan & surrounding area

  - ✓ North: Harwood, ND & Kragnes, MN
  - ✓ South: Oxbow, ND
  - ✓ East: Dilworth, MN
  - ✓ West: West Fargo, ND



STUDY GOALS

- ✓ Develop a system to reduce regional flood risk
- ✓ Determine the Federal role in implementation
- ✓ Document findings in a Feasibility Report
- ✓ Recommend a project to Congress

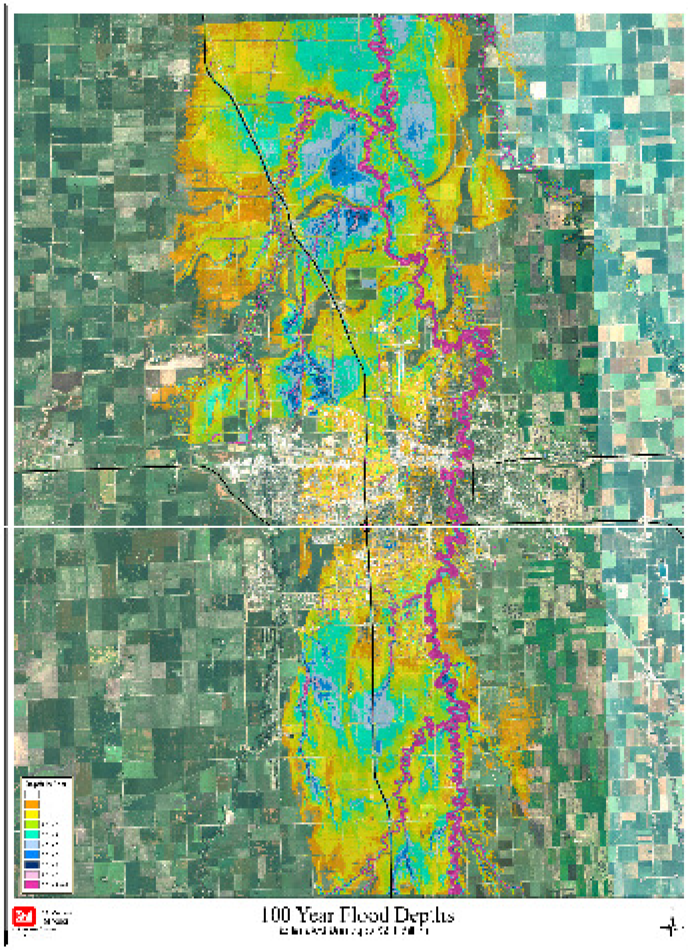
Planning Process

1. Specify problems and opportunities.
2. Inventory and forecast conditions.
3. Formulate alternative plans.
4. Evaluate effects of alternative plans.
5. Compare alternative plans.
6. Select recommended plan.

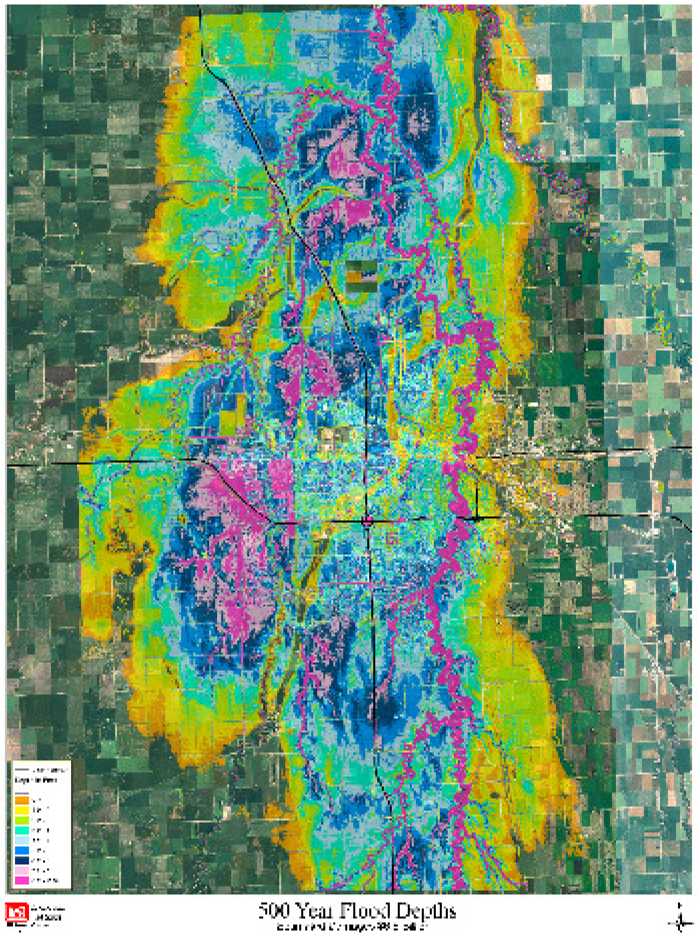
Risk

- ✓ The 2009 flood was approximately a 125 year flood event.
- ✓ Successful flood fights lead to a false sense of security.
- ✓ It would be very difficult to fight floods larger than the 2009 flood.
- ✓ Failure of emergency levees would be catastrophic.

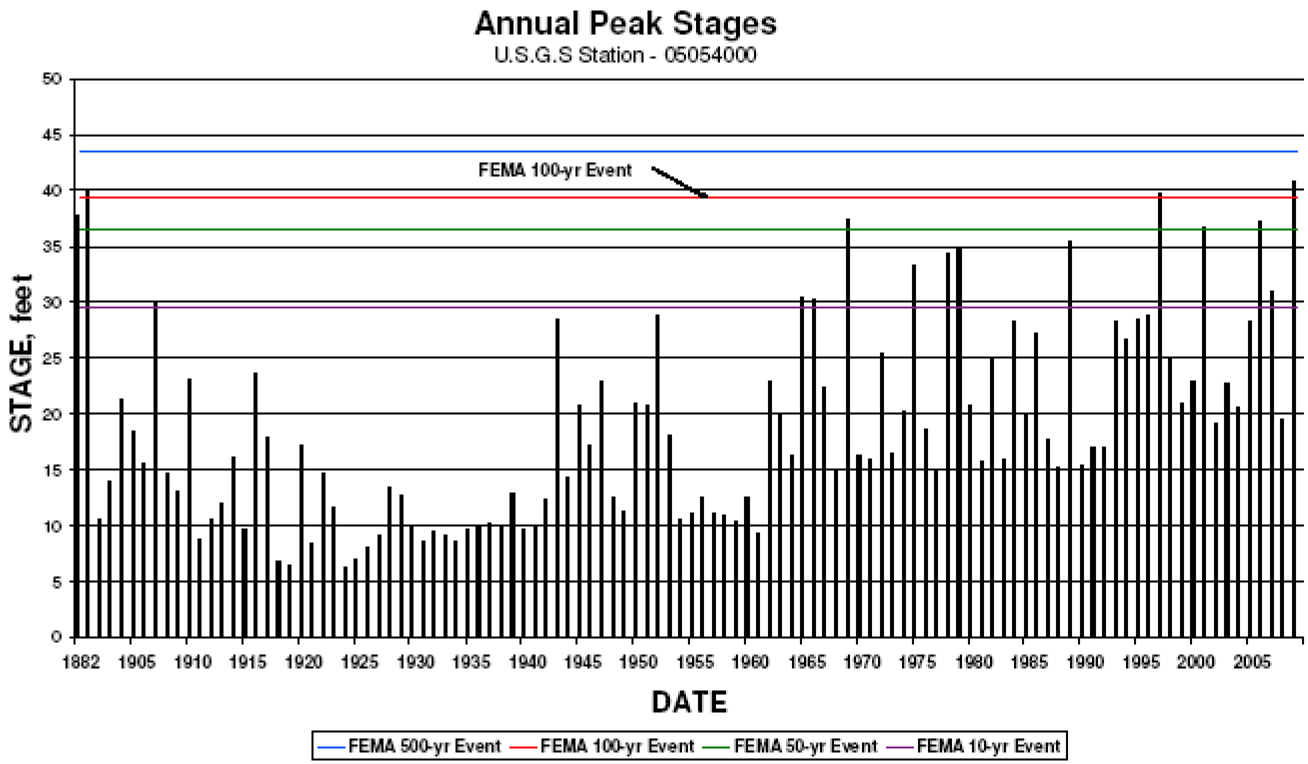
Building of 2nd St. Levee for 2009 Fargo-Moorhead Flood



Potential depths of inundation



Potential Depths of Inundation



✓ 2009 flood in Fargo-Moorhead was approximately a FEMA 125-year (0.8% chance) flood.

Flood Risk

During the life of a 30-year mortgage,
the odds of having a Red River flood
larger than the 2009 flood
are about

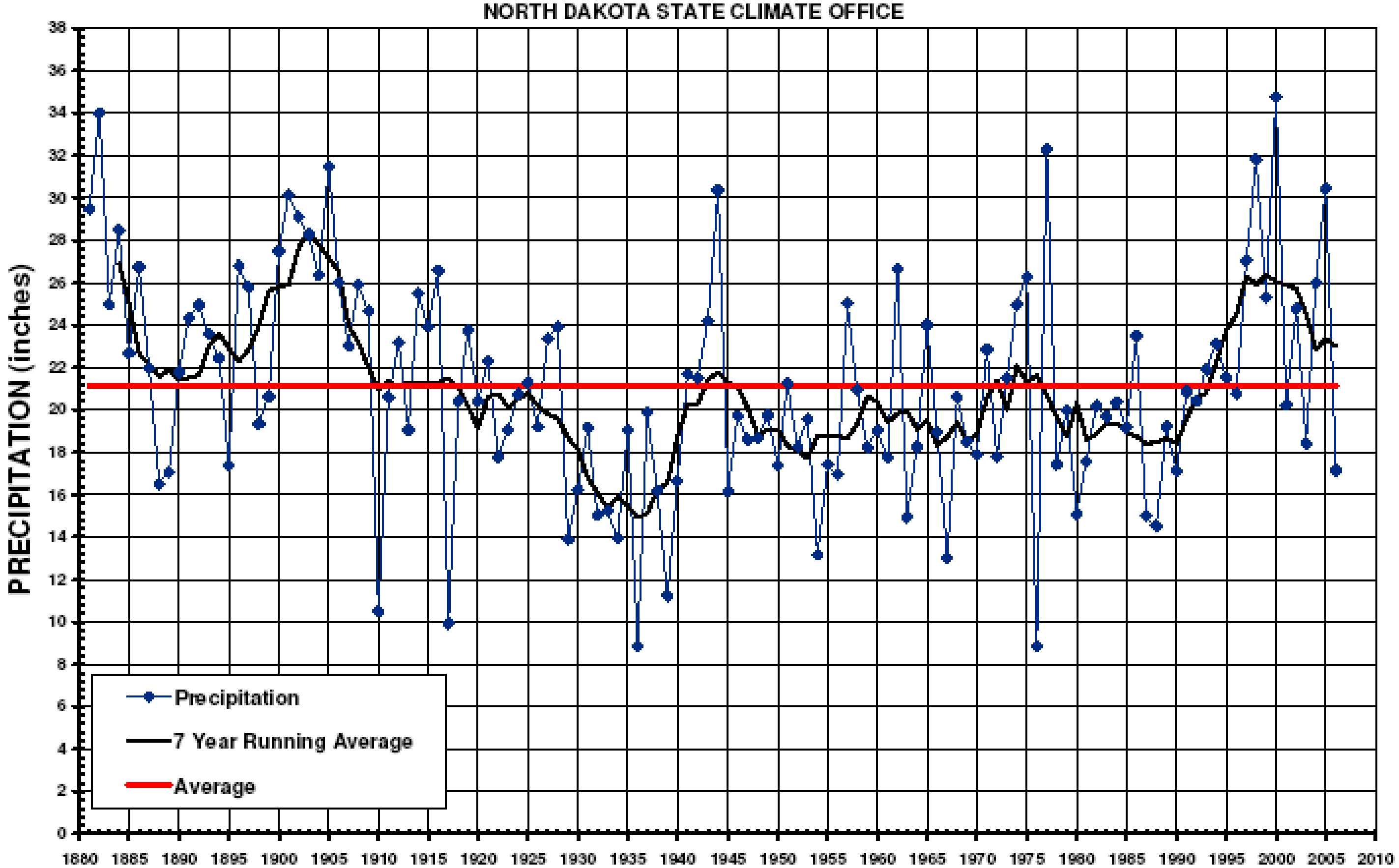
1 in 5.

CITY OF Fargo

CITY OF MOORHEAD MINNESOTA

FARGO ANNUAL PRECIPITATION

NORTH DAKOTA STATE CLIMATE OFFICE



Flood Risk

- Rain events cause flooding, too:
  - 7-inch rain June 20, 2000
  - Flood insurance can help mitigate that risk.

2nd St. North, Fargo

12th Ave. Toll Bridge

ALTERNATIVES

- ✓ Continue Emergency Measures
- ✓ Non-Structural Flood Proofing
- ✓ Flood Barriers
  - ✓ **Levees/Floodwalls**
  - ✓ **Gate Closures**
  - ✓ **Pump Stations**
- ✓ Increase Conveyance
  - ✓ **Diversion Channels**
  - ✓ **Cutoff Channels**
  - ✓ **Replacing Bridges**
- ✓ Flood Storage
  - ✓ **Part of Fargo-Moorhead Upstream Study**

Floodwall at Grand Forks

F-M METRO STUDY TIMELINE

- ✓ Sept 2009: Alternative Screening
- ✓ Jan 2010: Identify tentatively recommended plan
- ✓ Sep 2010: Finalize feasibility report
- ✓ Dec 2010: Transmit recommendation to Congress
- ✓ Jan 2011: Begin Plans and Specifications
- ✓ April 2012: Begin Construction

Attachment 6. Experts' verbatim responses

Each question, the experts' verbatim first responses, and the experts' verbatim final responses are provide here.

The experts are identified here only as A, B, C, D, E, and F.

Question 1

Is it likely that climate change will have a significant impact on the flood flow frequency curve during the life of the proposed flood risk reduction project for Fargo, ND-Moorhead, MN?

Question 1 was re-worded into a two-part question prior to soliciting the experts' final responses: A. Has historical climate change/variability been accounted for in an appropriate manner in the proposed frequency analysis? B. If climate was addressed appropriately to date, do we need to consider climate change [in this project's analysis]?

Question 2

How will the frequency curve change?

Question 2 was re-phrased slightly for the final response: Assuming we have the right frequency curve, how will that change in the next 50 years due to climate change?

Question 3

What are the practicable alternatives for accounting for the impact of the change?

Question 4

Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?

Table 4. Question 1 responses

Expert	Preliminary response	Final response
Question 1 (preliminary): Is it likely that climate change will have an impact on the flood flow frequency curve during the life of the proposed flood risk reduction project for Fargo ND-Moorhead, MN? Question 1 (final—2 parts): A. Has historical climate change/variability been accounted for in an appropriate manner in the proposed frequency analysis? B. If climate was addressed appropriately to date, do we need to consider climate change [in this project's analysis]?		
A	No. If one assumes stationarity and the full period of record. As far as the application, the question of climate change influence on EAD is more to the point. Even if answered yes, when/how you apply the changed condition probably makes even [less of a] change in the economics.	A. Yes, because (assumption) climate change data set "small," however this would need [to be] checked. B. Yes, if one switches and assumes climate change data set.
B	No, climate change and its effect on flood frequency [are] on a longer time scale than the economic benefit (life of project). That being said, we are on an upward trend of having more frequent and severe floods occurring in the Red River Valley the past 30 years as compared to the entire period of record and beyond. Climate change may have a more noticeable effect with regard to flooding on time scales ranging from 50-80 years and beyond.	A. No. Using a long period of record puts too much emphasis on what has happened in the distant past > 50 years. This does not account for anthropogenic effects. B. No, because climate change and its impact has been accounted for in the flood frequency distribution to the best of our ability. Do I believe floods will become more frequent and more severe in the next 50 years? Yes.
C	If "climate change" is defined to mean a change driven by increasing greenhouse gas concentrations, I would say that it is unlikely to have a significant impact on the frequency curve. If "climate change" means a state change (like El Nino, or the Little Ice age) then it is certainly quite possible – but we don't know how to predict it. The most likely condition in the next few decades is construction of the present climate state (because of persistence in this part of the US). One more semantic point – change from the "floodflow frequency curve" does not (for me) mean the one computed over the past 100 or 125 years, but rather a frequency curve computed over the past 4 or 5 decades. I would not use the one from the past 100 or 125 years.	A. No – the analysis has ignored the fact that there has been a huge state-change in climate and flood frequency in this basin and throughout the region. B. Yes – it is likely that climate change will have a significant impact on flood frequency. However, we have no strong basis theoretical or empirical to assert the magnitude or direction of that change. But, our analysis should be done in a way that is cognizant of that uncertainty.

Question 1 (preliminary): Is it likely that climate change will have an impact on the flood flow frequency curve during the life of the proposed flood risk reduction project for Fargo ND-Moorhead, MN?
Question 1 (final—2 parts): A. Has historical climate change/variability been accounted for in an appropriate manner in the proposed frequency analysis? B. If climate was addressed appropriately to date, do we need to consider climate change [in this project's analysis]?

Expert	Preliminary response	Final response
D	Climate variability has had a significant impact on flood frequency in the Fargo-Moorhead region. It is uncertain how future natural variability will affect the flood frequency during the life of [this] project. Climate change due to global warming will likely lead to higher temperatures in the region, but its effect on precipitation is uncertain. Bottom line, yes, climate impacts flow frequency.	A. No. The method assumes there has been no climate change or variability over the record. It appears that the flood frequency curve has been significantly different in different periods. B. Yes. Climate changes over multiple time scales due to multiple reasons. These changes are uncertain. This uncertainty must be taken into account in the analysis. A single flood frequency curve may not be adequate to describe this uncertainty.
E	Alteration of temperature [illegible] mean annually as well as seasonally. Alteration of PET leading to changes in moisture accounting. System is apparently significantly dominated by snowmelt or rain on snowmelt. (Only one major river generated flood (1975)). Can't say for sure whether CC will affect flood flow frequency curve but will change flood magnitudes. Flood magnitudes would also likely change regardless of greenhouse gas forcings. Total answer floods will be influenced by climate direction of shift unknown as function of ΔT, ΔP, and separation from larger time scale climate variability. I think that greenhouse forcings will influence ΔT, ΔP.	A. No. I think there is a clear break in distribution, or at a minimum autocorrelation that affects frequency analysis (FFA). Also I think that uncertainty characterization underestimates true uncertainty. B. Yes, but not necessarily to influence FFA. Simple qualitative sensitivity analysis on projected precip and temp vs. observed. If inside variability envelope in observed record includes projections (which I think it will) then answer = No.
F	Yes, if climate change refers to natural change as a result of decadal-scale variability in ocean temperature and atmosphere pressure anomalies, this change will have a large impact on the frequency curve. If change refers to a gradual change due to greenhouse gases, it's anybody's guess if or how this will affect flood frequencies in the next 20-30 years. There is no way to tell right now how precipitation will change.	A. No, long-term climate variability has not been accounted for. The flood peaks are <u>not</u> part of a homogeneous population as assumed. B. Yes, climate and hence flood-flow frequency will likely change within the life of the project, but not substantially within the first 10-20 years.

Table 5. Question 2 responses

Expert	Preliminary response	Final response
Question 2 (preliminary): How will the frequency curve change? **Question 2 (final): Assuming we have the right frequency curve, how will that change in the next 50 years due to climate change?**		
A	Entire frequency curve will shift upwards especially if you re-establish "new" data set. This is contingent that a decision was made to "accept" climate change is to be "driver" from some point forward.	No change to original answer. However, it seems the "climate change data" apparently has significant influence on the current frequency curve and consideration should be given to separating out data.
B	Severe floods will become more frequent (probable) than they have been in the past. This is based on the currently accepted flow frequency curve. By how much is up for discussion.	The entire probability distribution will be shifted upward. The amount that they would be shifted upward is unknown and up for debate.
C	We have no strong scientific basis for asserting how flood frequencies will change over the coming decades. Warmer air could bring more winter precipitation but warmer air could prevent the build-up of large snowpacks which are required for the generation of large floods. We could see more frequent floods in excess of 25,000 cfs or we could see fewer floods in excess of 25,000 cfs. (I use 25,000 as a rough threshold for floods that are significant producers of economic damage.	I won't change what I said on my first answer to this question – I would add some clarification. I think that in future decades the chance of floods similar to those typical of the 1920s, 1930s, and most decades before about 1960 are relatively small. Flooding behavior more like that which has happened since 1960 is much more likely in the future decades. The very unusual behavior of the Red River should cause us to consider unusual approaches to the problem (like Markov shifts, truncating the record, putting much more uncertainty into our analysis, or selecting other types of flood frequency curves). Assuming that our hundred year (or 125 year) history is a good sample of the likely future or that a stationary model is appropriate would be irresponsible.
D	The change in the flood frequency curve is uncertain. It is likely that more recent climate conditions will persist for a while, so the last fifty years may be more representative of the next decade. However, it is not currently predictable if and when a shift to drier conditions would occur. It is also likely that temperatures will warm. This may impact when and how fast snow melts and could increase evaporation. Rather than rely on a predication of changes for a future flood frequency curve, it is better to accept greater uncertainty in its estimate.	How the flood frequency curve will change in the future is uncertain. It is important to take this uncertainty into account in the decision process. One possible approach is to evaluate how sensitive the decision is to the choice of freq distribution. Two possible distributions to use: 1) Entire period of record. 2) Use data since 1960. It may be better to choose an alternative that does well for both scenarios, rather than try to maximize NED for one or the other distribution.

Question 2 (preliminary): How will the frequency curve change?
Question 2 (final): Assuming we have the right frequency curve, how will that change in the next 50 years due to climate change?

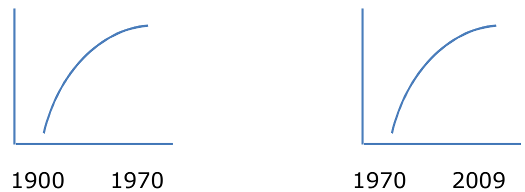
Expert	Preliminary response	Final response
E	(1) I would think you would want to create at a minimum <u>two</u> FFAs for at a minimum <u>two</u> observed climate states. Then you could use a transition probability matrix to consider how to get from one to the other. Most straightforward approach. I do not think that skew should be used to go too negative. For example, [expert drew two images: one showed a curve with x-axis "1900-1970" and the other showed a curve with x-axis "1970-2009."]  Create transition probability matrix from St. George precipitation analysis from 1600-200? Prob: Wet → Wet | Prob: Wet → Dry Prob: Dry → Wet | Prob: Dry → Dry This would fit well within Monte Carlo analysis through time to get at annualized damages. (2) For future climate change if you wanted to consider projection information I think you could use this to influence prob matrix if criteria from answer to 1.B was met. I think that uncertainty bounds on FFA regardless of approach will go up.	Same answer as preliminary answer with the following additions/clarifications. For two FFAS ~1900-1970 – expect FFA ↓ over current ~1970-2009 – expect FFA ↑ over current If all probabilities in matrix are equal then end result is same as now. If wet →wet prob > then wet →dry prob then because we are in a wet period to start overall FFA will also go ↑. Again though uncertainty of new FFA will go up and in my opinion needs to.
F	There will be a much higher frequency of floods in the 20-40 thousand cfs range and a much lower frequency of floods less than 10,000 cfs in the next few decades, compared to the frequencies shown in Dan's [Reinartz] curve. A flood similar to 2009 has a much higher chance than 1% per year of occurring during the next 20 years.	I'll stick with my preliminary answer. It is generally accurate, in my opinion.

Table 6. Question 3 responses

Question 3 (preliminary and final): What are the practicable alternatives for accounting for the impact of the change?		
Expert	**Preliminary response**	**Final response**
A	Alternative 1 – Adopt "mixed population" concept and generate "climate change" frequency curve using last 30 yrs? of data. Determine appropriate out year when that curve should apply e.g., year 15, 20, etc., Use equivalent annual damage analysis in FDA using existing frequency curve at year zero and "climate change" frequency curve at appropriate out year using shortened period of record which results in large uncertainty. Alternative 2 – Using similar concept in Alt 1 only develop composite frequency curve from the two curves and apply composite curve over 50 yr life cycle. Alternative 3 – Assume there will be a 50-year wet period and use 'climate change' curve for plan formulation. Out year determination – Perform sensitivity as to when increase in flows (based on trend) will impact EAD by X%. At that point, apply "climate change" curve.	Alternative 1 – This alternative was offered strictly on the current capability of FDA, i.e., using current conditions and most likely future condition (1 only). Alternative 2 – Can be realized with 2 FDA runs using current frequency curve [and] a "wet period" frequency curve and apply year to year weightings as discussed within the group to determine "combined" EAD outside of FDA.
B	A practicable alternative for accounting for the impact of climate change could be to shorten the period of record and only use the last 30 years of observed annual maximum peaks. This would help place a greater emphasis on the trend that floods in the Red River specifically @ Fargo/Moor. have been increasing in frequency and magnitude. This approach would line up nicely with the way climate statistics are calculated. The question with this approach would be how often would this be re-evaluated and updated? Climate statistics are re-calculated every 10 years. This seems to be a bit too infrequent. An update cycle of 5 years seems to be reasonable. This approach seems logical given the short turn around that is needed with regard to this project. The approach of having two flood frequency curves for wet and dry periods and transitioning between the two seems to be more complex and the benefit or advantage using this approach over shortening the analytical period or record seems unclear.	(1) Shorten the period of record that is analyzed using only the latest portion of the record. The period to use could be to use the "wet" portion of the record, or to use only the latter half, etc. Statistics could be used to determine what should be considered a "wet" period of record. (2) The period of record could be considered a mixed population and could be divided into a wet period and a dry period of record. Statistics could be used to determine this; otherwise the period of record could be divided at the mid point to develop two frequency functions. These two functions could then be combined and be weighted equally or more weight could be assigned to the "wetter" period. Suggested weights that have been proposed are between .2 and .8 for dry and wet to .5 for both wet and dry periods.

Question 3 (preliminary and final): What are the practicable alternatives for accounting for the impact of the change?		
Expert	**Preliminary response**	**Final response**
C	View this as a mixed population of floods. The data are clear, the early decades of the twentieth century are totally unlike the past five or so decades. Fitting a single probability distribution to both samples makes no sense. I would divide the record into two parts 1902-1959 and 1960–2009 and call them the "old" and "new" populations. You can do sensitivity analysis at the dividing line but I'm already pretty sure that it doesn't make too much difference. The dividing line shouldn't be set to "pick up" one particular large flood in the "new" set. Then I would estimate two separate flood frequency distributions. (I'm sure the 100-yr flood in the 'new' will be about 2.5X the 100-yr in the "old.") Then I would construct a mixed population flood frequency from the two distributions. I would run sensitivity analysis, varying the probabilities of the "old" from 0 to 0.537 (0.537 is the fraction of the whole data set in the "old.") I would select a best judgment estimate of this probability somewhere around 0.2. My reasons for this low number are three-fold: 1) persistence of wet conditions in the region based on historical data from tree rings, Grand Forks Q, Winnipeg Q, the research of Knox…2) the potential that greenhouse forcing might favor a tendency to larger floods, 3) engineering judgment calling for high levels of projection against "surprise" in the very vulnerable, very flat, and very hard to understand environment.	A clarification of what I said previously- the expert panel should determine the break point in the record and the subjective probability of being in each of the two states (old and new) explaining the considerations that went into setting it. We were asked to serve as experts on this issue and it is appropriate that we decide and not just "kick the can down the road" for someone else to do it. Given that it is subjective I think it is problematic to have the Corps do it – they asked for our help because credibility and objectivity are important. Having stakeholders do it is a terrible idea/ they will have plenty of opportunity to weigh in on designs and preferred alternatives; this is the technical part of the process and it needs to be handled by the technical experts brought in by the Corps.

Question 3 (preliminary and final): What are the practicable alternatives for accounting for the impact of the change?

Expert	Preliminary response	Final response
D	There is large uncertainty in the flood frequency curve. This uncertainty should be included in the flood damage economic analysis. Uncertainty is more than uncertainty in mean and variance. Include skew uncertainty. Use a smaller effective sample size. Consider doing a scenario analysis with two different probability distributions: 1) Entire period of record. 2) Record since 1960 (or so). Evaluate how choice of probability distribution affects different alternatives. It may be better to choose an alternative that performs reasonably well for both scenarios, rather than maximize NED for one or the other distribution. Both approaches are consistent with current USACE planning guidelines. Uncertainty should be included in economic analysis. P&G says a sensitivity analysis should be done to show effects of uncertainty on decision. The alternative that maximized NED does not have to be the recommended plan.	No major change from preliminary except a mixed distribution could be considered as a third distribution in the scenario analysis. 1) POR distribution 2) Mixed distribution 3) Wet period distribution A long memory process indicated a smaller effective sample size; Hurst coefficient > 0.5.

Question 3 (preliminary and final): What are the practicable alternatives for accounting for the impact of the change?		
Expert	**Preliminary response**	**Final response**
E	Alternatives: [Presented in the text below and the table on the following page.] 1) Account for autocorrelation which will reduce your period of record and increase your uncertainty estimate. Reduction of period of record can be done (a) qualitatively →essentially no time (b) quantitatively →medium effort. 2) Two state system with period of record derived from early 20th century to late 20th century-early 21st century. Definitions of change can be done (a) qualitatively (b) quantitatively → test statistics of homogeneity. Use transition probabilities either (1) from short period of observed record, or (2) from rainfall analysis of St. George et al. Use the Monte Carlo framework to combine into a simulated flood frequency/damage curve. End result of any path will be increase in uncertainty. 3) Truncate record to consider only recent period (don't like this alternative) (a) qualitatively (b) quantitatively 4) Continue with current curve (don't like this). For all cases I think it prudent to spend 1-2 days to look at projections and show that rain / temp projections for next 30 years within envelope of observed variability.	I would like to keep my answer from the preliminary answer sheet. From the discussion period I think that an addition of using two separate analyses in a sensitivity sense through the economics portion (a la [another expert]) is a viable alternative. I think also an outcome from the discussion is that some of the details contained within proposals are important.

Question 3 (preliminary and final): What are the practicable alternatives for accounting for the impact of the change?

Expert	Preliminary response			Final response
	Alt	**Level of effort (1-5)**	**Rating of information (relative to each other)**	
E (cont)	1a –auto corr /qual	2 - requires judgment	3	
	1b –auto corr /quant	3 - some to statistically account for autocorr; could be a little tricky	3+	
	2a1 -2 / qual / obs	3 - easiest of 2 state approach requires judgment and treatment of obs	3+	
	2a2 – 2 / qual / rain	4 - must stat treat rain could be tricky	4	
	2b1 – 2 / quant / obs	4 - quant determine break point	3+	
	2b2 – 2 / quant / rain	5 - quant determine break point must stat treat rain	4 ~ 4+	
	3a – truncate / qual	1 - little	2	
	3b – truncate / quant	2 - little but must do test stat	2	
	4 – cont. with current	1 - no effort	1	

Question 3 (preliminary and final): What are the practicable alternatives for accounting for the impact of the change?

<table>
<tr><th>Expert</th><th>Preliminary response</th><th>Final response</th></tr>
<tr>
<td>F</td>
<td>There are 3 practicable alternatives:

(1) Use the regulated period of record (1942-2009) to develop all the frequency curves. This would somewhat underestimate the most recent (1980-2009) risk and overestimate the prior (1942-79) risk, but on average this may be a good approach for estimating "average" risk over the life of the project.

(2) Develop two frequency curves – one for "wet" conditions and one for "normal" conditions, and estimate transition probabilities (wet→wet, wet→dry, etc.) for future years. There are two problems with this – what to use for future historical "wet" and "normal" periods (1960-2009 (wet) vs. 1901-1959 (normal) is one of the several possibilities) and how to estimate the transition probabilities. If we can decide on answers to these problems, this might be the best approach.

(3) Develop a stochastic water-balance model for generating annual flows on the basis of monthly precipitation, evaporation, and basin storage. Use the annual flows to condition the flood frequency curve (i.e., if annual flows 50% above long-term average then flood flows 50% above average). This may be the hardest to accomplish of the 3 approaches in a short period of time.</td>
<td>I think there are two reasonable alternatives:

1) Use 1942–2009 as the representative time period for developing all discharge-frequency curves. The added uncertainty in using a shorter time period is a good thing, especially in that it will increase the upper confidence curve.

2) Use a weighting scheme to "morph" from the "wet" frequency curve to the full-record curve something like this:
<table>
<tr><th>Year</th><th>Mixed pop probabilities for 1960–2009</th><th>Full record (current curves in Dan's report)</th><td rowspan="8">NOTE: We may want to tweak their probability or do a sensitivity analysis</td></tr>
<tr><td>2010</td><td>1</td><td>0</td></tr>
<tr><td>2011</td><td>.95</td><td>.05</td></tr>
<tr><td>2012</td><td>.90</td><td>.10</td></tr>
<tr><td>2020</td><td>.50</td><td>.50</td></tr>
<tr><td>2021</td><td>.45</td><td>.55</td></tr>
<tr><td>2030</td><td>0</td><td>1</td></tr>
<tr><td>2031</td><td>0</td><td>1</td></tr>
</table>
Develop uncertainty curves for mixed populations using established methods.</td>
</tr>
</table>

Table 7. Question 4 responses

Question 4 (preliminary and final): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?		
Expert	**Preliminary response**	**Final response**
A	Alternative 3 – mixed population by using current frequency curve and a "wet period" frequency curve. Make separate FDA runs. Prepare spreadsheet that combines weighted EADs incrementally (every 1 yr, every 5 yrs, etc.) to include combined uncertainties for generation of distribution about the EAD.	Retain original suggestion. This method allows for evaluation of EAD for full 50-year period using one weighting or multiple increments with different weightings. By running separate FDA runs with each frequency curve, each result will include/retain uncertainty of each population (period of record either actual or equivalent). I would like to discuss with others how the individual uncertainties will play out in developing distribution of EAD and performances. Period of data split—defer to the appropriate test for determining the split.
B	Given the limits imposed by the urgent need to reduce risk in Fargo/Moorhead, the alternative that seems appropriate to use is to treat the entire period of record as a mixed population. The period of record could be divided into a wet period and a dry period. Statistical analysis should be used to determine the break point between the two populations. Once divided, two separate flow frequency functions should be created and weighted appropriately before being combined. Since it is apparent that the Fargo/Moorhead area has been in a wet cycle and future climate projects are calling for this pattern to persist, emphasis should be placed on the "wet" frequency curve with a weight of 0.8 associated with that function. The "dry" frequency function should have a lesser weight of 0.2. This scheme emphasized that the wet years are more appropriate for the foreseeable future, while still hedging that there is still a chance that the climate pattern could become drier the next 30-50 years.	In addition to what was previously written: Assuming skew coefficients are very similar, an average with appropriate rounding of the two should be used. This should be very inconsequential since preliminary analysis shows the skew for both populations were nearly identical. If the skew calculations of the two populations vary significantly, study participants should make the appropriate decision using accepted methods with regard to skew calculations. No recommendation for how uncertainty should be calculated or estimated will be made. However, study participants should consider this problem and make the appropriate decision using accepted techniques with regard to uncertainty analysis.

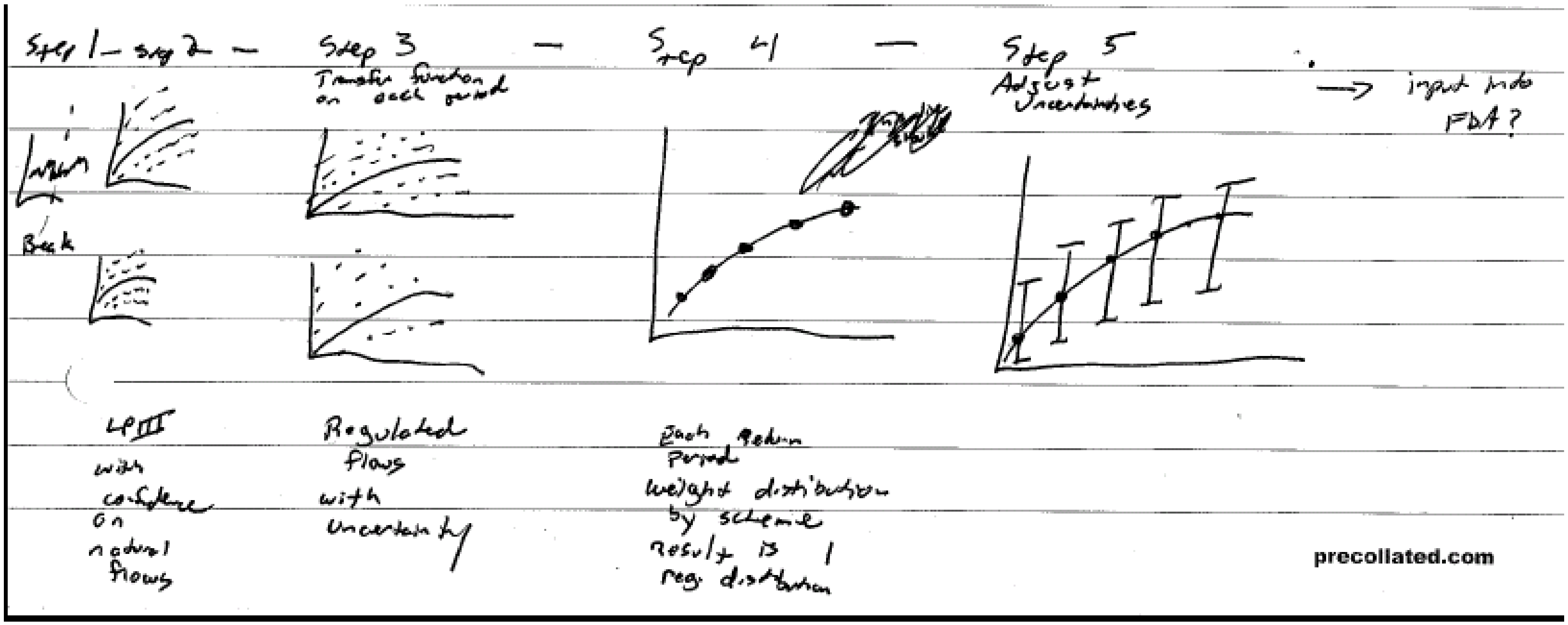
Question 4 (preliminary and final): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?		
Expert	**Preliminary response**	**Final response**
C	I would use approach #3, mixed population. I would break the record into 2 periods 1902-1941 and 1942-2009. I select this break point based on a recent paper by Villarini, Serinaldi, Smith, and Krajewski (Water Resources Research, Vol. 45, W08417, 2009). They did a change point analysis, for change in the mean based on the Pettitt test ($\alpha = 0.05$) and the Fargo record shows a significant step change at 1942. I would do LPIII analysis on each period, but to estimate skew I would take all the data values (the log discharges) and subtract the group mean, divide by the group standard deviation from the appropriate group, and then compute a skewness on all 108 values—I would suggest using this combined skew rather than 2 different ones—they are too small a sample size to do them separately. I would set a subjective estimate of the marginal probabilities of being in the wet (later) population at 0.8 and a probability of the dry (earlier) population at 0.2. However I would, for sensitivity analysis, try setting the probability of the dry population at 0.37 (which is its proportion in the data set) and also at zero (meaning we think we will not be going back to the dry state). I would have the basis for setting the probability at 0.2 be stated (reasons given in my answer to question 3), fully admitting that it is subjective and was set by the expert panel, mindful of the increased hydrologic history of the basin, greenhouse forcing concerns, and engineer's judgment.	The only thing I would add to my previous answer is the way that uncertainty is handled. Given the mixed population model I would be inclined to state the equivalent years of record for both populations as the number of years in the shorter of the two periods—in order to be conservative on this issue. The simulation in FDA should be run twice—once with each distribution and then combined with the appropriate weight based on the probabilities. My choice of weights (probabilities) would be 0.2 for the dry and 0.8 for the wet.

Question 4 (preliminary and final): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?

Expert	Preliminary response	Final response
D	1) Initially, current distribution based on period of record should be used, but the economic analysis should include all sources of uncertainty, including effects of long-memory on effective sample size. 2) Economic damage analysis should be done for other possible probability distributions, including a distribution based on the wet period and a mixed distribution. 3) Planners and designers should think beyond optimizing a design for maximum NED. They must consider the consequences for the design if their assumptions about the flood frequency distribution are wrong. Public safety impacts should be considered in addition to economic analysis. For example, more uncertainty and a wetter distribution would imply a larger design would provide more economic benefits. This would be counter productive if it encourages more development in vulnerable areas. Planner, designers, and the public must know that the flood frequency distribution is uncertain, and what are the potential consequences of their decision under different scenarios.	Recommend using a mixed distribution with three assumptions on weighting wet and dry periods: (1) Using same weights as occurring in period of record (2) Intermediate weight (3) Weighting assuming only the recent wet period will occur Economic damage analysis should be done for each distribution. I would also include the current distribution assuming stationarity be used for comparison. Recommend calculating the skew individually for each part of the mixed distribution. I think the most important action to take is to communicate the uncertainty in the flood frequency distribution to the planners and public, and to try to choose an alternative that does well even if we have mischaracterized the distribution. Then a selected alternative should do reasonably well for each of the three distributions.

Question 4 (preliminary and final): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?

Expert	Preliminary response	Final response
E	My first opinion is that two frequency curves should be considered from the observed record. The definition of these two periods can be done subjectively although if someone is available who has experience with a homogeneity statistic this is preferred. If subjectively I think that care should be given and a couple years considered to see how different the results are. Given the constraints these two curves can be combined subjectively, however I think that at least some attempt should be made to establish a quantitative basis using the historic rain record and potential projections of change. I think that the final result should be more weighted on the wet period but should include some probability for the dry period not to exceed 0.5. Meaning that final curve should have magnitudes greater than what has been presented to date. Further, the end result should have confidence intervals that are wider than those presented. If weighting done quantitatively and not considered research, ideal approach is exploring Markov chain, or 600-yr rain record, or probability percentage of dry period being another 50 years. If looking for a subjective prob., I would propose wet = 0.75 and dry = 0.25, although reasonable response could be anywhere 0.5-0.5.	Two distribution functions. Definition of break should best be determined using statistical test of homogeneity or peer-reviewed published value if available. Both sides should be considered within LPIII framework. Late 1800s floods can be used in either record at discretion of project engineer. This should be performed on "natural flows" and will need to be re-regulated later. Would prefer to see a function of weighting going from 1-wet to 0-dry over the course of the 50-year period if some justification can be determined through exploration of the 600-year rainfall record. If not, a subjective combination can be used, [which] would consider 0.75 wet and 0.25 dry. [Illegible sentence—appears to be something like—a transfer function re regulation is done should be performed on LPIII uncertainties as well as mean estimates.] The result is estimates of flows as well as uncertainties which should be adjusted upwards, i.e., higher uncertainty before entering economic analysis. This most likely will need to be subjective and 25% increase is a reasonable estimate. Step 1: Determine break in period of record. Step 2: LPIII with confidence on natural flows. Step 3: Transfer function on each period→ regulated flows with uncertainty. Step 4: Each return period weight distribution by scheme result is regulated distribution. Step 5: Adjust uncertainties. Input into FDA? Sketches included at the bottom of this expert's final response are presented in the figure below.

Question 4 (preliminary and final): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?		
Expert	**Preliminary response**	**Final response**
E, final response cont.		

Question 4 (preliminary and final): Of the alternatives available, which is best for this particular application, given the limitations imposed by the urgent need to reduce risk in Fargo/Moorhead?

<table>
<tr><th>Expert</th><th>Preliminary response</th><th>Final response</th></tr>
<tr>
<td>F</td>
<td>
Best alternative
1) Use 2 frequency curves for two populations:
curve 1 – 1960 to 2009
curve 2 – whole period of record
2) Compute frequency curve for each future year by mixing these two populations in specified probabilities. These probabilities should start with 1 for curve 1 and 0 for curve 2 and gradually change to 0 for curve 1 and 1 for curve 2. The actual mix might look something like this:
<table>
<tr><th rowspan="2">Year</th><th colspan="2">Probability for</th></tr>
<tr><th>Curve 1</th><th>Curve 2</th></tr>
<tr><td>2010</td><td>1</td><td>0</td></tr>
<tr><td>2011</td><td>1</td><td>0</td></tr>
<tr><td>2012</td><td>1</td><td>0</td></tr>
<tr><td>2013</td><td>.95</td><td>0</td></tr>
<tr><td>2013</td><td>.90</td><td>0</td></tr>
<tr><td>2022</td><td>.5</td><td>.5</td></tr>
<tr><td>2023</td><td>.45</td><td>.55</td></tr>
<tr><td>2032</td><td>0</td><td>1</td></tr>
</table>
3) Do sensitivity analysis using <u>just</u> curve 1 (wet) for the entire future 50 year period. This would acknowledge that the current high flood risk is a consequence of “climate change” and is likely to continue (or get worse) over the next 50 years.
</td>
<td>Use a mixed population model, with one population being 1942-2009 (“wet”) and one population being 1901-1941 (“dry”). Do not include historical floods. Start with a probability = 1 for “wet” in 2010, then decrease linearly to probability = 0.5 in 2060 (end of project). I will need to do some analysis to see how to compute the uncertainty associated with the mixed population model for each future year. I will forward that analysis to you asap. It should be relatively straightforward, but I need to do a little more research.</td>
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