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Red River of the North at Fargo, North Dakota, Pilot Study, Impact of Climate Change on Flood Frequency Curve

Red River 2001 Flood

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Executive Summary

The purpose of this pilot study was to apply and evaluate a rigorous peer-reviewed methodology for computing the impact of climate change on flood frequency curves to the Red River of the North at Fargo, North Dakota. The methodology had been developed and applied by the Bureau of Reclamation. The study used archived statistically downscaled monthly CMIP3 climate data projections and previously developed Corps Water Management System, CWMS, and MVP hydrologic models. The effort required significant modifications to the District's hydrologic model of the Wild Rice watershed, minor modifications to the CWMS models, and generation of daily data from the archived monthly climate values. Flood frequency curves for annual peak flows were computed for four time periods: the base 1950-1999, and future periods 2011-2040, 2041-2070, and 2071-2100. For each time period nine archived climate projections were selected to represent the range of the archived 112 projections, and for each of the selected projections, ten random daily weather generations were developed. The weather generations were developed from daily values of historic months that had temperatures and precipitation values similar to those for the projection months. The hydrologic models were run for these 90 data sets in a continuous simulation mode with a daily time step. The results of the study showed likely increases in the size of all frequency floods, for example up to an average 31-39% increase in the 0.01 annual nonexceedance probability (100-yr) flood from 1950-1999 to 2011-2040; with the 2041-2070 and 2071-2100 having smaller increases from the base 1950-1999. The smaller average increases for the later periods appears to be due to rising temperatures causing a reduction in the accumulated snow water equivalent. The computed results for each future time period had a large range in the computed impacts on the frequency curves across the 9 projections chosen. For all future time periods, on the order of 10% of the climate projections/weather generations showed an actual reduction compared to the median 1950-1999 frequency curve. It is important that stakeholders realize the range in the climate model projections as well as the predicted average impact. The hydrologic modeling was computer resource and data management intensive. The hydrologic models were calibrated to match the frequency curve for the observed annual peak floods and the study results are not considered reliable for precise estimating of the impact of climate change on other variables, such as low flow or seasonality, that were not considered in the calibration.

Background and Problem Statement

Red River of the North floods have been increasing in magnitude and frequency at Fargo and design of a $1.8B Red River diversion channel around the Fargo-Moorhead area is being prepared. 2009, 2010, and 2011 were three of the six largest floods in over 100 years of record, including the flood of record in 2009 that required over 50 miles of emergency levees to prevent catastrophic damages. Figure 1 is a schematic of the basin and Figure 2 shows instantaneous annual flood peaks at Fargo since 1902. An expert opinion elicitation in 2009 concluded that the flood record is non-stationary with a step-change break in the record in 1942. The panel found that over the last several hundred years the flood levels in the Red River have cycled between large-floods periods (like the present) and smaller-flood periods (like the early 1900s). Tree ring studies have shown that the entire Red River Basin has had many earlier wet periods, implying past alternating wet and dry cycles (St. George and Neilsen, 2003). Devils Lake is a closed basin lake in the western part of the Red River Basin and its levels over time document the alternating wet and dry periods. Figure 3, from "Understanding and Explaining Hydro-Climate Variations at Devils Lake", Martin Hoerling, Jon Eischeid, David Easterling, Thomas Peterson, Robert Webb, NOAA, July 2010, illustrates this trend. The expert opinion elicitation panel did not determine the reasons for the non-stationarity or how the frequency of flooding might change in the future due to climate change. The study described in this paper was done to estimate the potential impact of climate change on flood peaks at Fargo through the year 2100 and to evaluate a methodology that uses archived regional climate projections and hydrologic and hydraulic models already available from the District, including a preliminary Corps Water Management System, CWMS, model which was never used by the District, and another District model for the Wild Rice River.

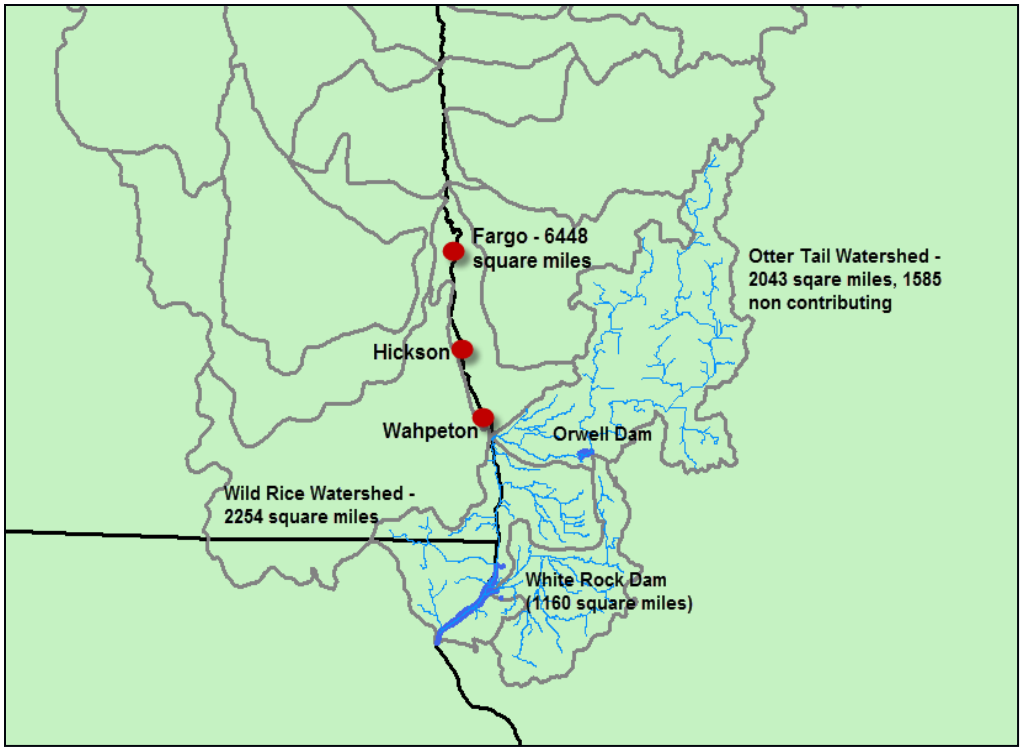

Figure 1. Basin Map for the Red River Climate Pilot Study

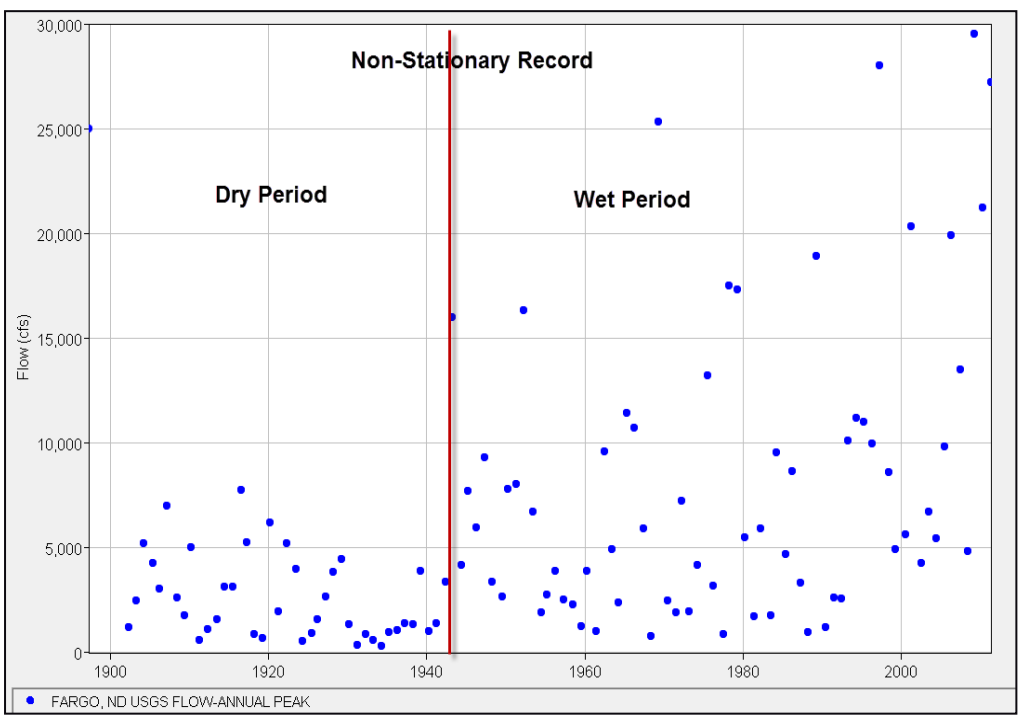

Figure 2. Red River Historic Instantaneous Peaks at Fargo

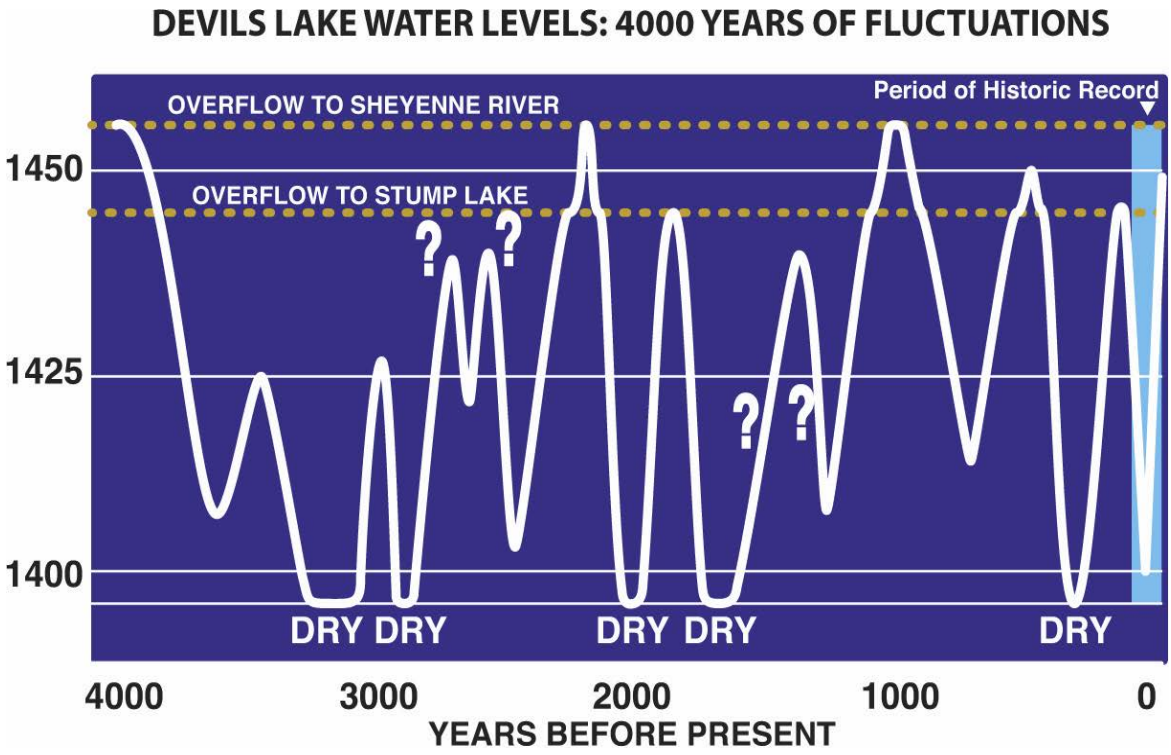

Figure 3. Devils Lake Historic Lake Levels
From "Understanding and Explaining Hydro-Climate Variations at Devils Lake", Martin Hoerling, Jon Eischeid, David Easterling, Thomas Peterson, Robert Webb, NOAA, July 2010:
"*Devils Lake water levels based on paleoecological studies of sediment deposits in the lake bed* (Bluemle, 1991; Murphy et al., 1997). *Low (high) water levels are inferred to correspond to dry (wet) climate conditions. Direct measurements have been taken during the period shown in light blue. The current strong centennial rise in water levels detected by gage measurements is commensurate with historical fluctuations. Graphics Source: North Dakota State Water Commission Fact Sheet, available at http://swc.state.nd.us/4dlink9/4dcgi/GetContentPDF/PB-206/DLFactSheet2010.pdf)"*

The methodology used is based on a study by the Bureau of Reclamation, "A framework for assessing flood frequency based on climate projection information," D.A. Raff, T. Pruitt, L.D. Brekke, that included an assessment of the possible impacts for climate change on the James River at Jamestown, ND, flood peaks (reference 3). The James River basin is adjacent to the western boundary of the Red River basin and Jamestown is only 90 miles from Fargo. The USBR study used CMIP3 data and found that the 1% exceedance probability discharge at Jamestown could increase from a computed present day value of 225 m^3/s (7,950 cfs) to 411 m^3/s (14,500 cfs) based on projected 2071-2099 floods, an 83% increase. While the basins are adjacent, there are significant differences in the watersheds and reservoir capacities and operations, and results from the James River cannot be directly applied to the Red River. However, results for the James River indicate climate change could have a significant impact on flood peaks in the Fargo area. That, plus the identified non-stationarity, made the Red River a good location for a pilot study of the impact of climate change on floods.

Overall Climate Trends

There are numerous papers that include the Red River of the North Basin in their analysis of observed and projected trends for temperature and precipitation. A report entitled: Climate Change and Hydrologic Literature Synthesis for the US Army Corps of Engineers Missions in the United States, Souris, Red, and Rainy Rivers Region 09, is being prepared by CDM Smith and summarizes the findings of many of these studies on the pilot study area. Some of the studies used CMIP3 data and some CMIP5. Regarding observed temperature trends, the draft CDM Smith report concluded: "*A general consensus amongst recent peer-reviewed literature indicates warming trend, especially in the winter and spring seasons. The trend is evidenced by warmer average winter temperatures, warmer average annual temperatures, and earlier spring onset/longer growing season observations. Trends in extreme temperatures have not been observed.*" The draft CDM study found precipitation trends to be less conclusive: "*Though widely studied, there is no consensus on the historic precipitation trends for the Souris-Red-Rainy Region. Studies have found both increases and decreases in total precipitation and extreme events over the past century.*"

The draft CDM report also summarized studies of projected temperature and precipitation trends determined from climate change modeling. For temperatures they conclude: "*Recent climate projection studies concur that warming is predicted for the Souris-Red-Rainy Region. Regional study results are sparse, as they tend to focus on either the Great Plains or Midwest, and the Souris-Red-Rainy Region boundary overlaps just a small portion of each. Warming trends are predicted for both average temperatures and extreme high and low temperatures.*" The report says there was consensus among studies about temperatures increasing in fall, winter, and spring but one study found no increase in summer temperatures while another study did show a summer temperature increase. The draft report concluded for projected precipitations: "*A general consensus amongst recent peer-reviewed literature indicates an increase in projected annual precipitation, recurrence of large rain events, and dry days in Water Resources Region 09. The collection of literature suggests that more precipitation will fall in larger events.*" Studies summarized in the draft CDM report generally found projected increased precipitation for fall, winter, and spring but conflicting impacts on summer precipitation.

Climate Projection Data

A goal of the study was to use readily available regional climate projections. Currently a multi-agency team develops and maintains archived climate data for the U.S. The global models used for this study were the IPCC's fourth assessment's Coupled Model Intercomparison Project phase 3 (CMIP3) that include coupled atmospheric and ocean general circulation models (GCMs). At the time this study was performed the next generation CMIP5 data were not available. The GCMs simulate global response to various greenhouse gas emission paths through the 21th century. However the GCMs grid resolution is on the order of 10^2 km and too coarse for local hydrologic modeling.

The data climate sets used for this study are from "*the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) multi-model dataset*", http://gdodcp.ucllnl.org/downscaled_cmip_projections/dcpInterface.html . The archived CMIP3

dataset includes the results of 112 model runs. The emission scenarios and global climate models used to develop the archived database are show in Figure 4. The archived data set used for this study includes sets of spatially downscaled GCM results that were developed using a statistical downscaling technique called bias-correction spatial disaggregation (BCSD). Bias correcting involves comparing the climate outputs from each of the various GCMs to the observed climate variables from 1950-1999. The bias correction is done to cumulative distribution functions for monthly average temperature and monthly cumulative precipitation. The bias correction developed for the each projection's 1950-1999 period is then applied to that projection's results for the period 2010-2100. It's worth noting that since the bias correcting was with monthly distributions, the results may not match observed individual months or match annual distributions of observed temperature or precipitation.

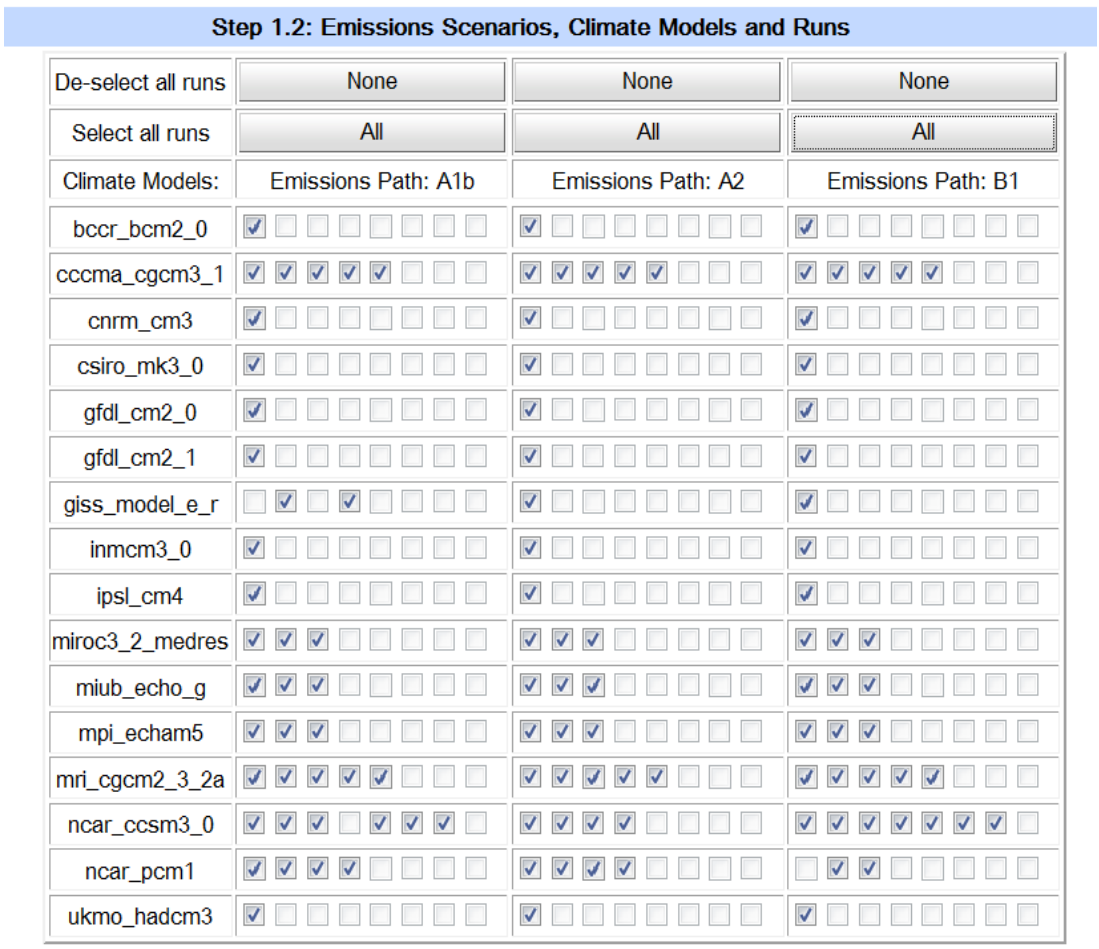

Figure 4. GCMs and Emission Paths for CMIP3 Projection Archive.
Screen shot from the Data Archive. The checked boxes are the 112 projections in the archive and used in this study.

The resolution of the GCMs is generally on the order of a 250-600 km grid. For reference, the State of Minnesota is 650 km from north to south so it could be covered by one or two GCM grids cells. That resolution is too coarse for hydrologic modeling of this basin. The archive data set uses a finer grid size developed using a statistical technique called spatial disaggredation.

The spatial disaggredation of the archived regional climate data used for this study results in a 1/8 degree, about 8X8 mile, grid. The finer grid results were determined by comparing historical observed precipitation and temperature patterns in the GCM cells. For example, if historically 75% of the precipitation in a GCM cell was in the eastern half of the cell, GCM precipitations would be spread so that 75% was in the eastern half. This method is especially appropriate where orographic features, such as a mountain range, divide a GCM cell and observed climate variables have a consistent spatial pattern. The Red River Valley is very flat and the spatial distribution of precipitation is more variable with some randomness, and for areas like this there may be a better disaggredation technique that includes some of that randomness.

Projection selection

The archived regional climate data base had 112 different downscaled climate projections from 1950 to 2100. As mentioned in the Climate Model Projection section, these are monthly data with a 1/8 degree grid resolution. It was not practical to include all 112 projections in the modeling and the method to select climate projections is similar to that proposed in Raff et al. A total of 9 projections that encapsulate the variability of all 112 projections were selected for each of the three future time periods (2011-2040, 2041-2070, and 2071-2099). For each future time period the 9 projections were chosen from a plot of all 112 projections in a tercile grid of future temperature and precipitation ratios, seen in Figures 5 and 6. The projection that was selected represents the shortest geometric distance from each tercile's centroid. Note that some cells contain many more projections than others and the 9 projections were selected to reasonably capture the full range of the 112, but they are not intended to be representative of the average value of all 112. The cells can be thought of ranging from hot, dry in the upper left to warm, wet in the lower right. Different projections are selected for each time period. A reason the selected projections change is that the individual projections can have variability over decadal periods and the tercile location for an individual projection can vary with time. In the plot it can be seen that projection 56 was selected as representative of the upper left hot, dry projection for 2011-2040, but is in the center cell for 2071-2099. Blue and green lines have been placed in the 2041-2070 and 2071-2099 tercile grids to more easily track these selected projections decadal variation over the three future time periods. The blue lines represent the selected projections from the first future time period (2011-2040), and the green lines represent the selected projections from the second future time period (2041-2070).

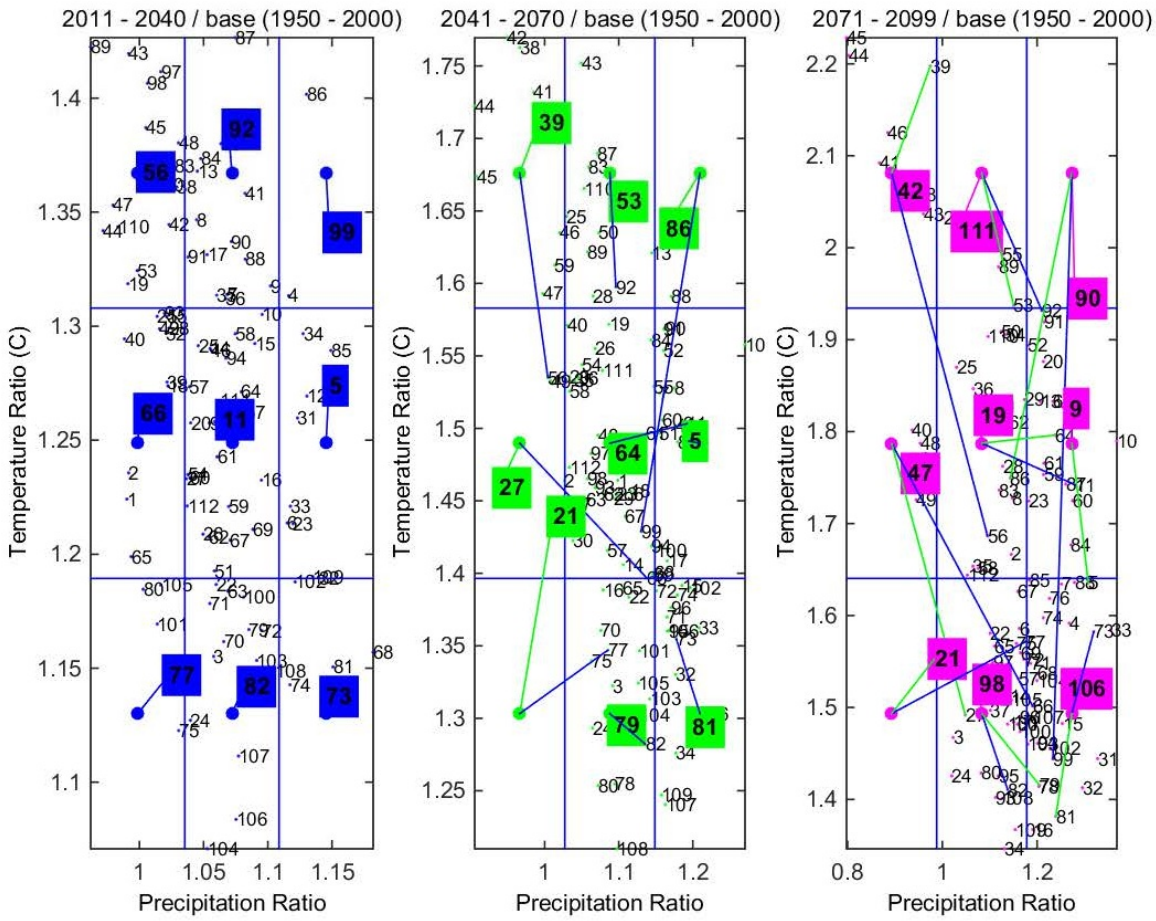

Figure 5. Projection Selection for Future Time Periods Based on 1981-2010 Temperature Ratio F, C, and ratios as follows: Fargo 42.2 (5.67) 1.0, St. Paul 47.05 (8.36) 1.47 Des Moines 50.85 (10.47) 1.85, St. Louis 54.75 (12.64) 2.23.

Figure 5 gives a good illustration of how the 9 projections were chosen, but since it has different scales for the axes it doesn't show how the spread of the projections changes from one period to the next. Figure 6 uses the same scales for the axes. The figure shows how the spread increases and how it moves towards warmer and wetter.

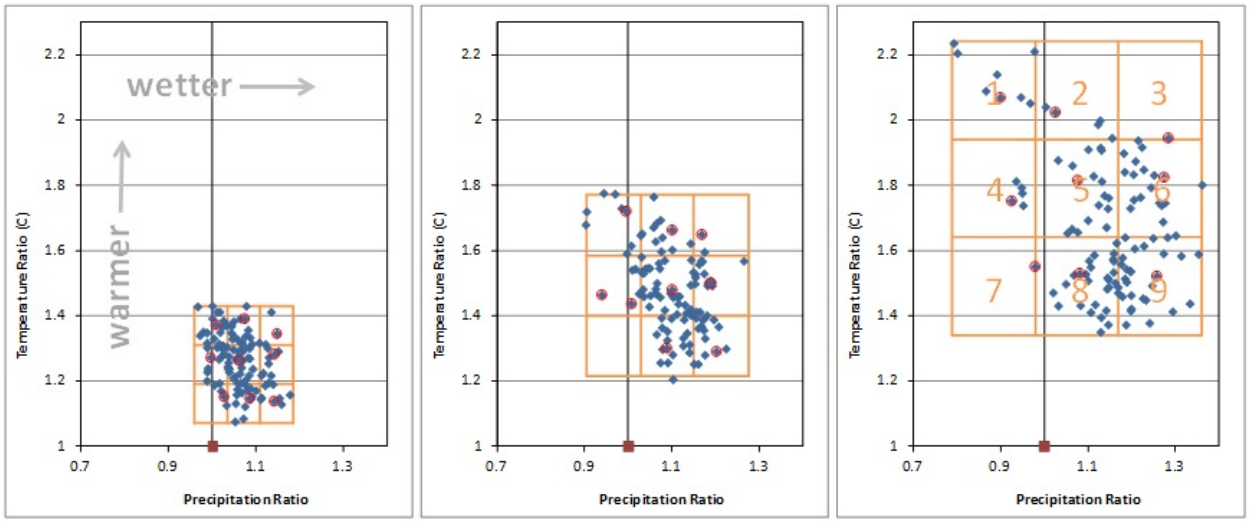

Figure 6. Projection Selection for Future Time Periods, Same Axes Scale

The Red River Valley has shown decadal and longer variations in climate and ideally the climate model variations mentioned above would correspond to the observed variations. However, in correspondence with the study team, Dr. Jeff Arnold said that the CMIP3 models "generally underestimated the decadal and longer variabilities compared to observations." He said that at least some CMIP5 models were designed to address this issue and appear to provide a better match to decadal type variations. The questionable match of decadal variations does not make the CMIP3 simulations un-informative. It is possible the Red River decadal variability sits on top of the climate changes trends and may itself be altered by climate change. For example, future decadal variations could reduce flood peaks on the Red River but climate change increases developed from the CMIP3 data could mean the reductions would not be as large as they were historically. Conversely increases due to decadal variations could be even greater due to climate change.

The precipitation and temperature data from the archive were analyzed using MATLAB. CMIP3 daily precipitation (mm/day) and daily average surface air temperature (˚C) were acquired for the basin using the 1/8 degree, Bias Corrected Statistically Downscaled (BCSD) data. The archived data within subwatersheds for the Red River of the North basin upstream of the Fargo, ND, gage were selected from the data and used in the analysis. MATLAB was used to extract all data and process the archived monthly parameters into annual average temperature and accumulated precipitation values for the 4 periods of interest (1950-2010, 2011-2040, 2041-2070, and 2071-2100). Representative projections for each tercile grid for each period were then selected based on the shortest geometric distance from each tercile grid's centroid. These selected projections were then passed along for hydrologic modeling.

The basin averaged annual temperatures from the 112 projections are shown in Figure 7 and the accumulated annual precipitations for the basin are shown in Figure 8 The solid blue line represents the mean of the data from the 112 down-scaled projections and the lighter blue shows the range of the 112 sets of data. The temperature plot shows that all climate model projections

show an increase in the annual average temperature, with the average annual temperature going from about 40 degrees Fahrenheit in the mid-1950s to about 50 degrees in 2100. The precipitation plot has more variability in future trends. The mean of the annual precipitation increases from about 22 inches per year in the 1950s to about 26 inches per year in 2100. This is a significant increase but it is based on the averages, and many of the model results indicate there could be a decrease in the mean annual precipitation. However, floods are often associated with wet years and the upper bound of the precipitation plot shows the climate models indicate the chance of a very wet year increases over time. In addition, for this watershed it is very important when the precipitation occurs. Changed precipitation in the winter that impacts the snow water equivalent or occurs during the snowmelt period is more significant to flood peaks than summer rainfall.

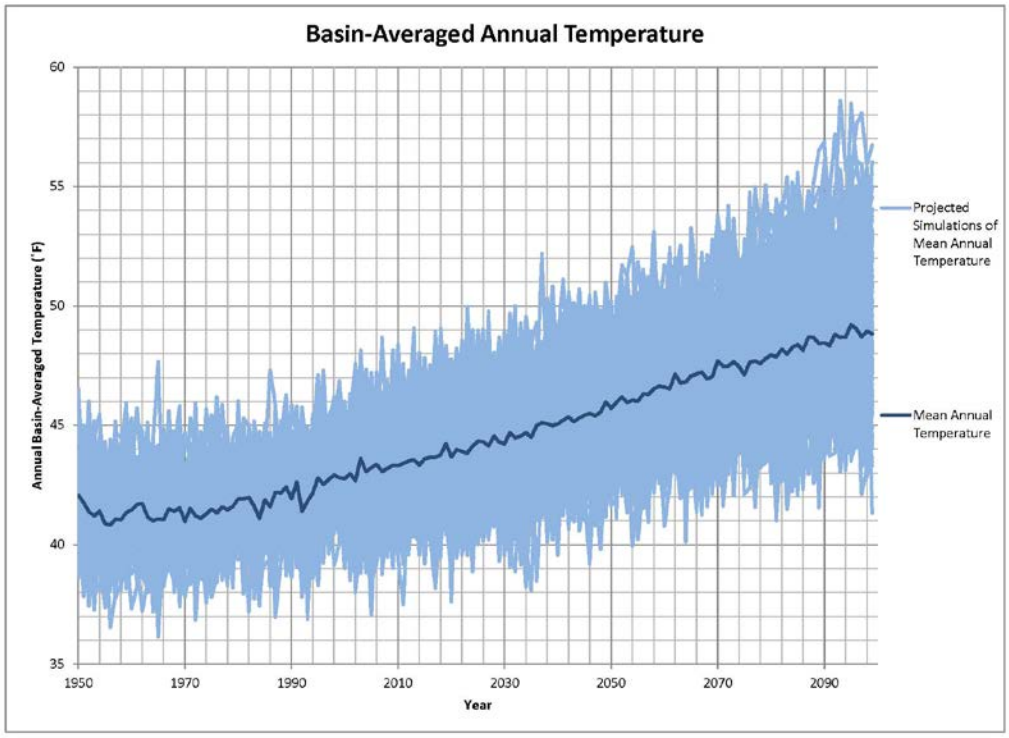

Figure 7. CMIP3 Basin-Averaged Annual Temperature, 1950-2100

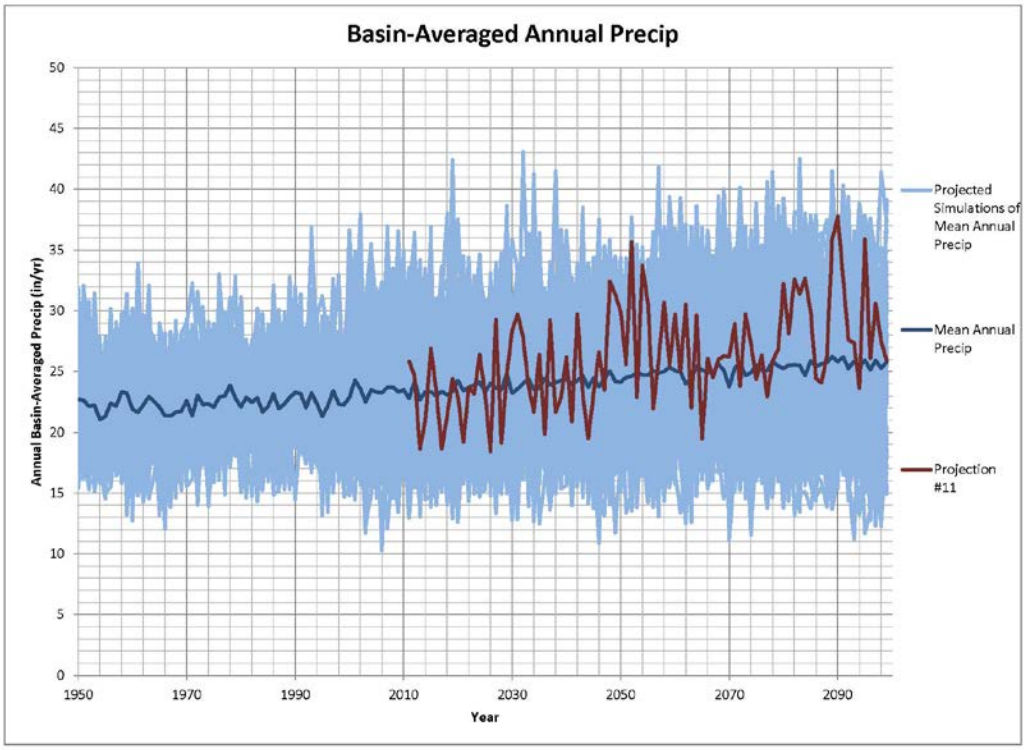

Figure 8. Basin-Averaged Cumulative Annual Precipitation, 1950-2100

A typical projection is highlighted on the precipitation graph (Figure 8). This line is included to emphasize that while the mean of all 112 projection is a fairly smooth line, no single projection shows a smooth precipitation trend over time. All projections show large variations in both temperature and precipitation from year to year. Future observed individual cool years, or a series of them, does not disprove the likelihood of increasing temperatures over the longer term. By the same token, even after a series of observed very wet years, all climate models indicate some of the future years will still be drier than the current average.

CMIP3 data during winter months (November – March) indicates a steady increasing trend in temperature and a small increasing trend in precipitation over the three future climate periods (2011-2040, 2041-2070, and 2071-2099). Although there is scatter in the data on Figures 9 & 10, it is noted that the plots do not show a trend to a future decrease in mean precipitation or temperature for any month or season. It should also be noted that the upper bound of the spread of the precipitation data on Figures 9 & 10 increases at a faster rate than the mean monthly trends, indicating extremes could change faster than the means. Climate model precipitation and temperature trends for November – March from 1950-2099, along with their mean monthly values, are illustrated in Figures 9 & 10, as well as Tables 1 and 2 below.

Table 1: Mean Monthly Temperature (°F)

Year	***November***	***December***	***January***	***February***	***March***
1950	28.8	15.0	8.1	15.3	27.7
2000	29.1	16.1	6.9	14.8	27.8
2010	29.6	15.6	9.3	16.9	28.1
2020	30.1	16.5	10.0	17.0	28.8
2030	30.4	17.1	10.0	17.0	29.1
2040	31.5	18.2	11.0	18.7	29.3
2050	31.6	18.9	11.2	18.7	30.9
2060	32.5	19.3	13.1	20.3	31.3
2070	33.3	21.7	14.2	21.4	32.1
2080	33.2	21.1	14.0	22.2	33.5
2090	34.4	20.7	15.2	22.4	33.7

Table 2: Mean Monthly Precipitation (in)

Year	***November***	***December***	***January***	***February***	***March***
1950	0.48	0.49	0.75	0.78	0.43
2000	0.69	0.50	0.90	0.91	0.39
2010	0.58	0.49	0.94	0.90	0.51
2020	0.68	0.51	1.04	0.87	0.53
2030	0.63	0.53	1.00	0.94	0.53
2040	0.70	0.48	1.14	0.86	0.56
2050	0.70	0.55	0.96	0.83	0.54
2060	0.68	0.51	1.01	0.88	0.58
2070	0.63	0.51	1.02	0.88	0.54
2080	0.72	0.47	1.02	0.96	0.59
2090	0.77	0.58	1.12	0.90	0.58

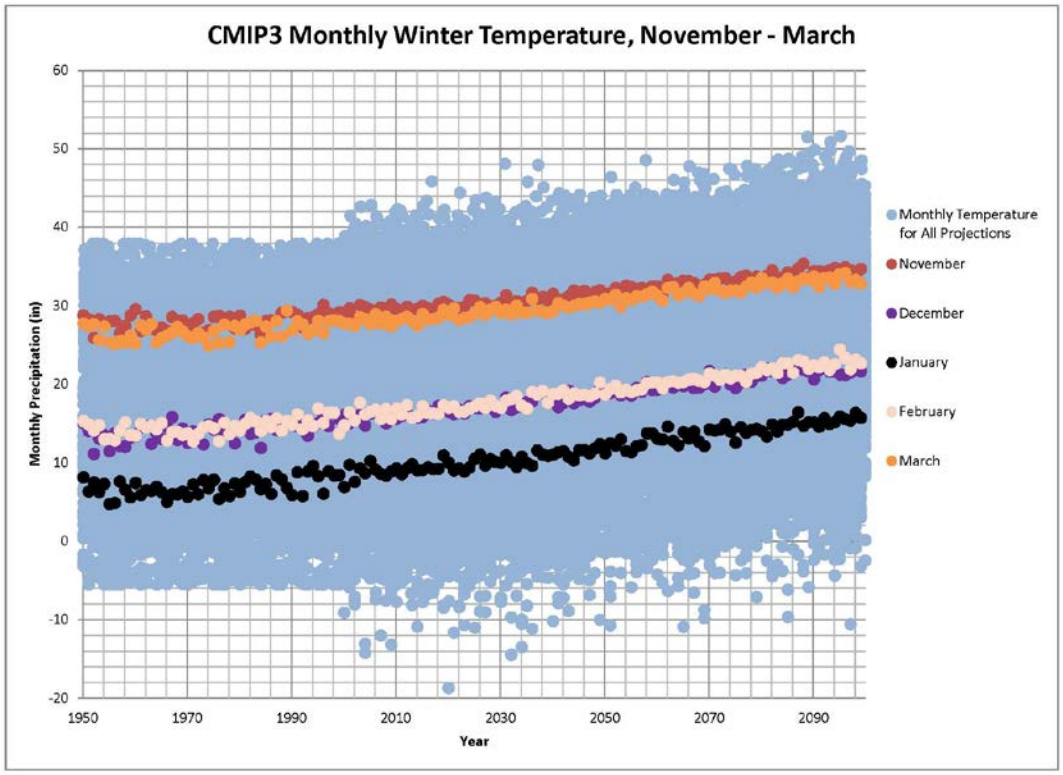

Figure 9: Monthly Winter Temperatures for November – March

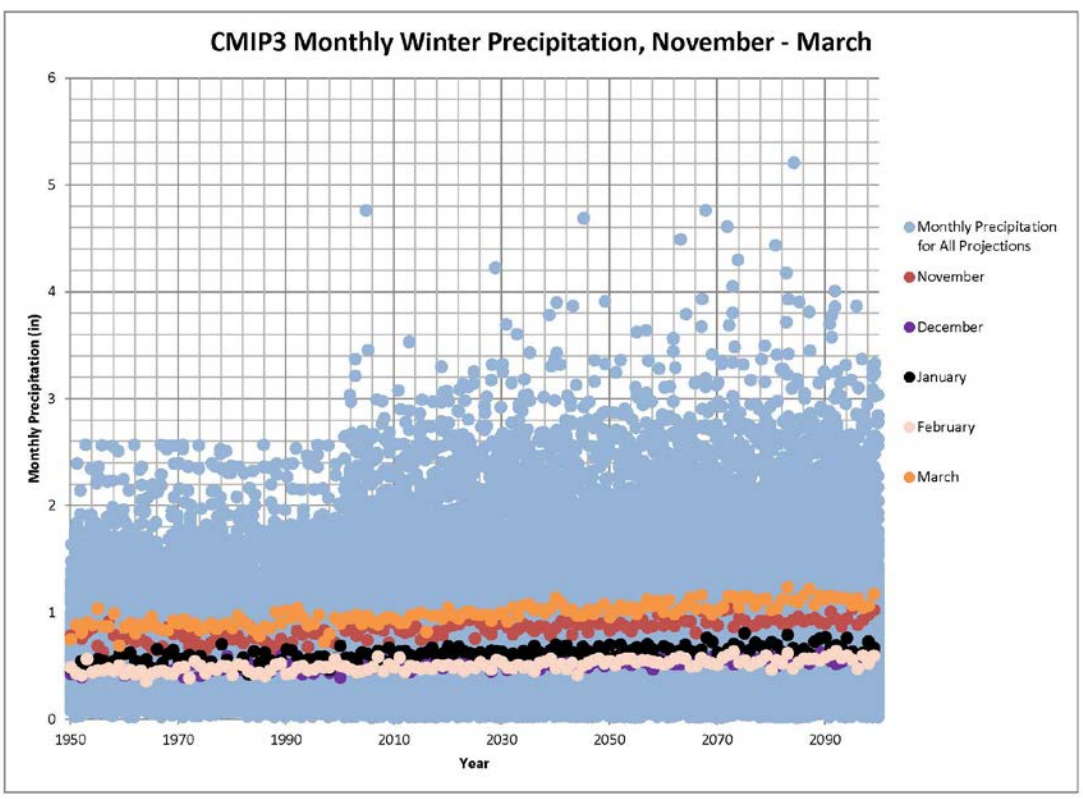

Figure 10: Monthly Winter Precipitation for November - March

The limits of the 1950-2000 scatter for temperature and precipitation in Figures 9 and 10 can be explained by the way the bias correcting was done. The climate models' temperatures and precipitations outputs for 1950-1999 are bias corrected so that the probability distributions of their adjusted average monthly temperature and monthly precipitation accumulation fit the distribution of observed values for that period. This method is applied to each month separately. Since the bias corrected results match the observed distribution, the extreme values from the climate models are capped by the observed values. The bias corrections determined for 1950-1999 are applied to the climate models output for 2000-2100. While this impacts the scatter of future periods, there are no upper and lower caps since the scatter does not need to fit an observed data distribution.

The impact on Red River floods from increasing temperatures and possible increasing precipitation is not obvious, since the largest Red River floods have traditionally been a product of snowmelt, for which climate change has a varying degree of influence. The magnitude of the snowmelt peak flow depends on the accumulated snow water equivalent, precipitation during the melt, and temperature during the melt. Higher future temperatures predicted by the climate models would decrease the snow water equivalent, but could cause a more rapid melt with steeper hydrographs and larger peaks. The timing of precipitation changes during the snow accumulating and snowmelt periods is important and may not be captured in the mean annual and monthly accumulations. Increases in precipitation during the snowmelt period would be especially significant. To determine the impact of climate change on snowmelt flood peaks it is necessary to apply hydrologic models using the forecast climate data.

Weather Generation

The bias corrected spatially downscaled (BCSD) projections in the archive describe series of average monthly temperature and monthly accumulated precipitation. A goal of this study was to use the available District models, including a preliminary Corps Water Management System (CWMS) model, to determine Red River flows at the Fargo, ND, gage. The available CWMS models use an hourly time step. However, as described in the Hydrologic Modeling section, it was determined that it would not be feasible to use hourly time steps due the large number of years to be modeled, thus the existing models were reconfigured and recalibrated to use daily time steps. (Additionally, all boundary condition data was daily as well.) The weather generation portion of this study consisted of developing daily temperatures and precipitations from the archived monthly values. The methodology used was similar to that in Raff, et al. and was done by Dr. Beth Faber at HEC. The work consisted of two steps:

1) Daily data from the historic period (1898 – 1999) was subdivided into 8 categories (temperature was subdivided into hot and cold and precipitation was subdivided into 4 categories). Each category has 12-13 historic patterns. This was done for all months separately. This method is basically the 8-sq method discussed in Raff, et al, without relaxing the criteria to choose the same month.

2) For each month, the climate model output was analyzed to determine which of the 8 categories it falls within. Then a daily time pattern from the category is randomly chosen. The time pattern is scaled based on the monthly total from the climate model. This random choice was made 10 times for each climate model dataset (10 weather generations). Since the daily time pattern selection was random, sometimes the same pattern was used more than once for a single projection month.

For each of the four time periods, 1950-1999, 2011-2040, 2041-2070, and 2071-2100, there were nine different monthly climate projections, each with ten different daily weather generations. This results in 90 datasets for each of the four time periods or 360 continuous simulations for the study.

To determine if the daily weather generations were giving an appropriate representation of possible variation in flood peaks, the hydrologic models was run with 100 weather generations of observed monthly data for the base 1950-1999 base period. Figure 11 shows that the weather variations resulted in a reasonable spread around the peak flows computed from the observed daily meteorological data. These results indicate the HMS/ResSim models were calibrated, given observed daily data at a few gage locations, and that the downscaling of monthly climate data to daily was acceptable. Therefore all results from the weather generations were used in the analysis. The analysis by Raff et al did not have as good a match at the tails of the weather generation vs. observed meteorological data flows and therefore for their evaluation of climate change impacts they did not use computed flows from the upper and lower 5% of the distribution.

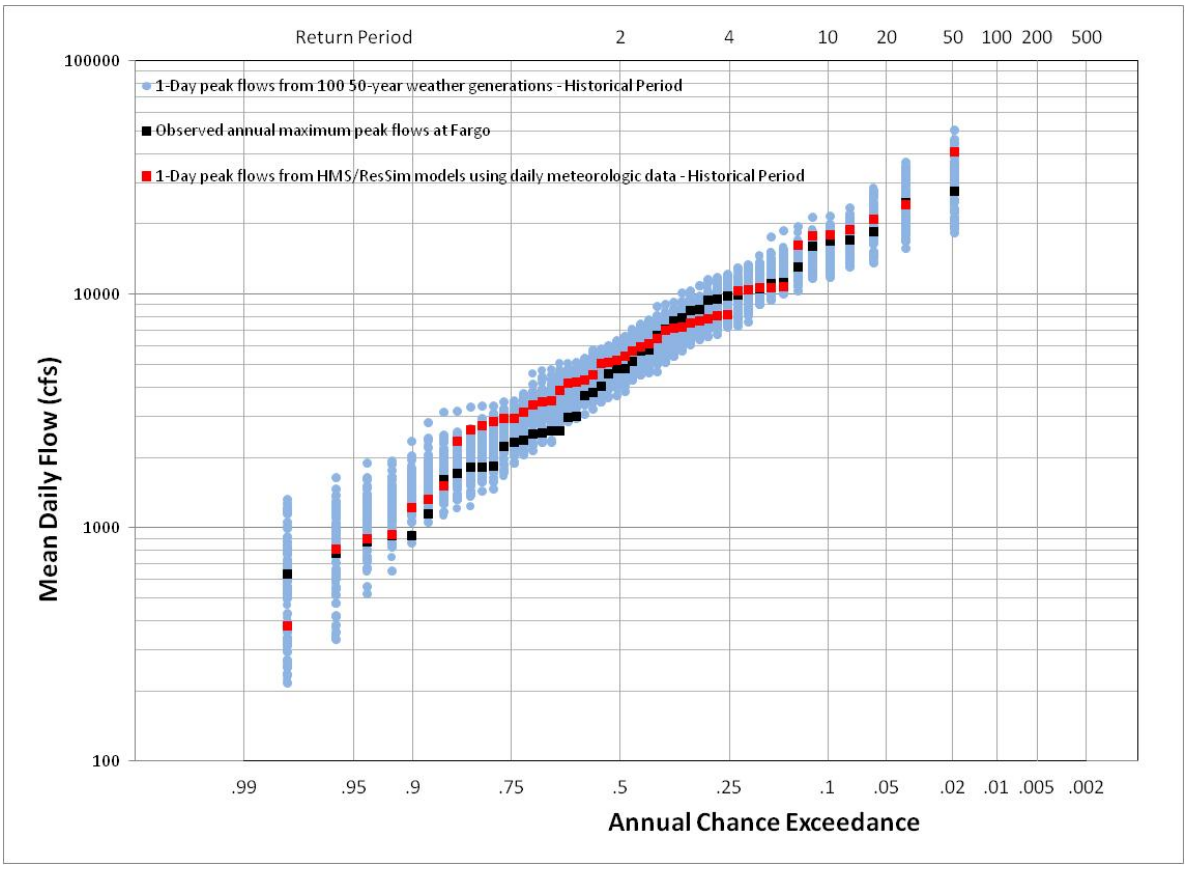

Figure 11. Weather Generation Flows, 1950-1999 Regulated Mean Daily Annual Peaks

Even though this is a 6448 square mile basin with flood durations at Fargo that typically last weeks, the daily variations of climate data during the snow melt had a very large impact on computed flood peaks. For example, for the lowest probability event, the peaks from the 100 weather generations shown on Figure 11 vary from 18,000 to 51,000 cfs. Even for years with the same snow water equivalent, the variation in flood peak from the daily conditions during the snowmelt can have large impacts on the peak flow.

A specific example showing how variations in daily climate data can impact peaks is show in Figure 12, which has computed flood hydrographs from the same projection but different daily weather generations for model year 2011. Since the weather generations use the same monthly climate data, the only differences are the daily variations. The volumes of the hydrographs are approximately the same but one hydrograph has a 50% larger peak than the other. The peak snow water equivalents for the two were similar but the lower peak hydrograph had six days of below freezing temperatures in the middle of the snowmelt. An observed example is 1997 when sharp drop in temperature occurred in the middle of the event. On April 5 and 6th the temperature dropped below 0 degrees F and runoff from fields stopped and water in culverts and drains froze. The peak at Fargo was reduced. Without the drop in temperatures, 1997 could

have been the flood of record at Fargo, larger than the flood of 2009. If changes in future climate impact the daily variations of temperature and precipitation, they could similarly have a large impact on peaks.

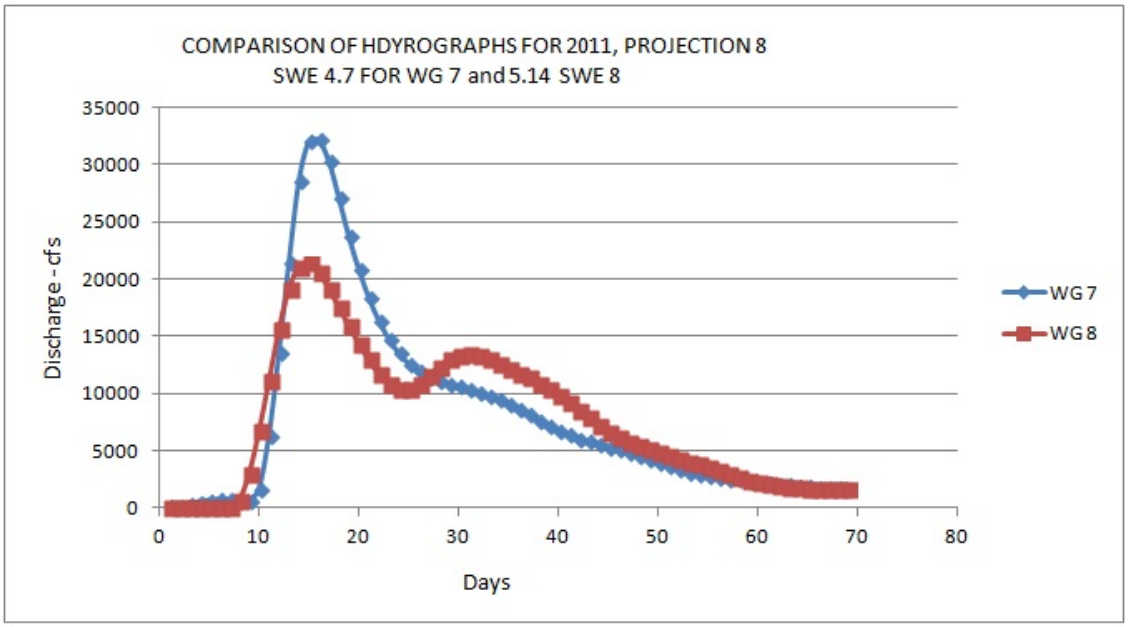

Figure 12. Computed Hydrographs for Two Weather Generations, Same Projection

The goal of this paper is the potential change in flood frequency curves computed from the future climate sets. The reliability of the comparison depends on the reliability of frequency curves computed for each time period. 30 years was selected for length of future time periods in order to minimize the impact of nonstationarity, yet have a long enough period to generate accurate frequency curves. However, a single 30 year period is too short to estimate or evaluate changes to small probability events, like the 1% annual exceedance flood (100-yr return period). A rule-of-thumb is not to use datasets to evaluate return periods more than twice the record length, so if only a single projection and weather generation were used the results should not be used to estimate floods beyond about a 50-yr return period.

The weather generations are based on 102 years of observed climate data and a purpose of randomizing the weather generation, and using this long length, is to increase the variability in the floods and decrease the influence of other errors, like sampling error, on the estimated frequency curve. For this study each 30 year period has 90 datasets: from the 9 projections each with 10 weather generations. For each projection the different weather generation results are not completely independent since they have the same monthly climate values. However, the daily changes in climate add variability and should increase the variability captured and so the accuracy of frequency curves.

A measure of frequency curve accuracy is the equivalent period of record. To estimate the impact of the weather generation on the equivalent period of record for the 50 year base period, Dr. Beth Faber examined the variance of the log10 1% quantile discharge peaks for created samples, and concluded the weather generation procedure provided an equivalent record length equal to approximately N=216 (for the downscaling of one climate model output, nine 30-year datasets), as described below.

If the random daily weather generation added enough information to create independent flood events from the same monthly values, the variability of the log10 1% quantile from random weather generations for the 50 year base period would be that of independent samples of size 50. If it added no information, the process would produce identical flood peaks and the variability of the log10 1% quantile from the weather generations would be zero. The value is expected to be somewhere between these extremes. The experiment compared the variance of the 1% quantile generated from 10,000 independent random samples of size N=50 with the variance generated from 100 weather generations on historical monthly climate data, length N=50. (100 weather generations were used instead of 10 to better estimate the variance added by weather generations.) For the 10,000 random samples the variance of the 1% quantile was 0.0142 and for the 100 weather generations it was 0.0052, showing the weather generation does not provide independent events, but still adds significant variability and so relevant information.

For final results using 10 weather generations, there are 500 peak flows created for each projection of the 50 year period. If these 500 values were truly random, the variance of the 1% quantile would be 0.0142. Because equivalent record length is linearly proportional to the variance, linearly interpolating between a variance of 0 for an equivalent record length of 50 and a variance of 0.0142 for an equivalent record length of 500 random peaks, gives an equivalent record length of 216 for the weather generated variance of 0.0052.

Table 3. Estimate of Equivalent Period of Record Based on Variance of 1% Quantile

Equivalent Record Length	Variance of 1% Quantile log10 flow
50	0
N=216 (interpolated)	0.0052
500 random	0.0142

A further translation would say that each 10 weather generations on a single year of record create the equivalent of 4.3 years. Thus for the 30 year periods the equivalent record length is 30*4.3 = 129 years. By the rule of thumb that the return period should not exceed twice the equivalent

record length, the comparisons in the paper should be good to about the 250-yr return interval event.

The above estimates are for the equivalent record length created from 10 weather generations for each climate projection. The final comparisons in this report use 9 projections for each time period. It is likely the use of 9 climate projections further increases the equivalent period of record. However, that effect was not estimated since the equivalent record length based only on weather generations is adequate for our comparisons.

An unresolved challenge to the above equivalent record length interpretation is whether the weather generations add enough variability, or the right variability, to actually correct the limited (perhaps unrepresentative) 30 year or 50 year sample to a produce a more accurate frequency curve, or whether they simply expand each year's peak flow data points in a mostly uniform way (as any Monte Carlo simulation does), so producing the same unrepresentative frequency curve as from single downscaling of the record.

Appendix A describes the method in more detail and also notes the challenges in estimating the true equivalent period of record. Even given the challenges of accurately determining the equivalent period of record, it is clear that the random selection process and using 102 years of observed climate records to populate the 10 weather generations, and using 9 projections, does add accuracy to the results that would not be obtained using fewer projections, fewer weather generations, or weather generations based on a shorter historical period.

The largest concern with the methodology is that using historic daily variations to develop future daily meteorological data ignores any impact climate change could have on the daily variations. Climate change studies summarized in the Overall Climate Change section states changes in extremes could be significant. The increase in extremes could impact the daily variations of temperature and precipitation. As shown above, daily weather variations have a very large impact on hydrograph peaks and if these daily variations change it could have a large impact on the comparisons of frequency curves. However, at the time this work was done the dataset used only contained monthly data. The archive now includes daily data for CMIP5 and future studies should consider using that for the analysis, or at least using it to estimate the impact of climate change on historic daily variations.

Hydrologic Modeling

An intent of this pilot study was to use available climate data and hydrologic models. As explained in the Weather Generation section the available climate data was monthly and had to be expanded to daily using weather generations. The Corps of Engineers has an on-going multi-year program to develop Corps Watershed Management Study, CWMS, models for all of its reservoirs. The CWMS suite includes hydrologic (HEC-HMS), reservoir operation (HEC-ResSim), hydraulic models (HEC-RAS), and consequence models (HEC-FIA). Portions of the Red River basin had CWMS models developed during the Accelerated CWMS Deployment

effort in 2010 and these were the basis for this study. The accelerated CWMS did not include the Wild Rice River, but the District had an HMS model of that river that was developed for another project. Significant modification to the District's Wild Rice models was necessary as well as modification was made to the existing CWMS HEC-HMS model for application to the climate change study, which are described in detail in Appendix B. Some of the modifications were due to the incomplete and inconsistent status of the models, but many changes were needed to convert to continuous simulation, to shorten the run times to accommodate the huge number of years to be modeled, and to manage the huge amount of data generated and transferred. 90 datasets were run for each of the four time periods. The datasets had 50 continuous years of daily values for the 1950-1999 base period and 30 continuous years for each of the three future periods. The HEC-HMS and HEC-ResSim models were simplified and channel routing was done with HEC-ResSim instead of HEC-RAS. The changes to the models required a recalibration. Even with the simplifications it was necessary to run the models concurrently on the several computers in order to keep the total time for the simulations reasonable. A beta version of HEC-WAT was modified and applied to manage the climate and model combinations, and organize the vast amount of output.

Subsequent to this study, updated basin and updated CWMS models for the Red River were completed in March 2015. It is anticipated that if a study like this was redone using the current CWMS models, some of the work required for this study to make complete and consistent models would be eliminated, but, depending on the models, there could be significant effort to modify the models to run efficiently for the continuous time periods required for this study. The new CWMS models were developed for current conditions and there would also have to be consideration to how basin conditions had changed and will change during the time periods the runs represent, and also how to handle calibration parameters that should change for different flood events. Models within a CWMS project are designed to calibrate in real-time to then-current basin conditions, not for to model long-term historic or future time periods. The current CWMS models would probably have to be revised to represent time period average hydraulic and land use conditions and simplified for an analysis like this.

Calibration. The revised HEC-HMS and HEC-ResSim models were first calibrated to the 1997 and 2006 flood events using a 1-hour simulated time step, and then recalibrated using a daily time steps to match the frequency curve for the observed 1950-1999 flood peaks. Observed precipitation and temperature data were used from a sparse network of gages. Future studies should evaluate use of better datasets for continuous simulation, like the historic PRISM dataset. As shown in Appendix B, the calibration was good for the 2006 event but 1997 was complicated by the sub-freezing blizzard that occurred during the snowmelt. Calibration for all events was also complicated by the limited number of precipitation and temperature gages in the vicinity of the basin (there is only one within the basin). Precipitation data was manually adjusted so that the one day total was never greater than 3 inches. This was a fairly infrequent occurrence, for example in the case of the Wahpeton gage, there were 8 days in the period 1950-1999 with daily

records greater than 3 inches and most of the 8 were not much larger than 3 inches. The gage data represent point measurements. It might have rained more than 3 inches at one of the gages but this high intensity was likely not observed over a large area. Only seven precipitation gages were available to calibrate the model, therefore data at the gage was applied over large areas. Total volume was not lost, any precipitation that was greater than 3 inches was moved to either precede or follow the intense precipitation (this was done when downscaling the monthly data). Future work should explore using other precipitation data sources in areas with limited data.

Figures 13 and 14 show observed and simulated peak flows from the 50 year, 1950-1999, simulation. Figure 13 shows the models both over predict and under predict individual peak flows. The larger inconsistencies in observed and simulated flow can be explained by the problems with the historic daily temperature and precipitation data used by the HMS model. The gage at Wahpeton was the only one in the basin area and was used for most of subbasins downstream of the reservoirs. These subbasins contribute the majority of the flow at Fargo. The amount and timing of precipitation at the Wahpeton gage was sometimes different from other gages and may not provide a good representation of basin wide values. Figure 14 shows the models did provide a better match to the frequency plot for the observed 1950-1999 peak flows. So even though the models were high for some individual floods and low for others, overall it was a reasonable calibration for the frequency curve and the models were considered acceptable for the climate change evaluation.

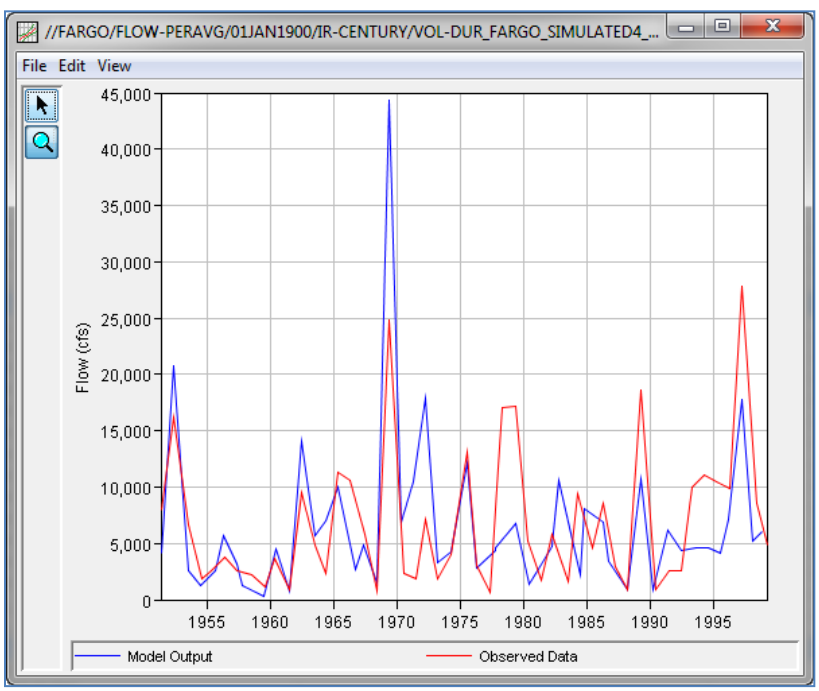

Figure 13. Calibration Results, Individual Floods 1950-1999

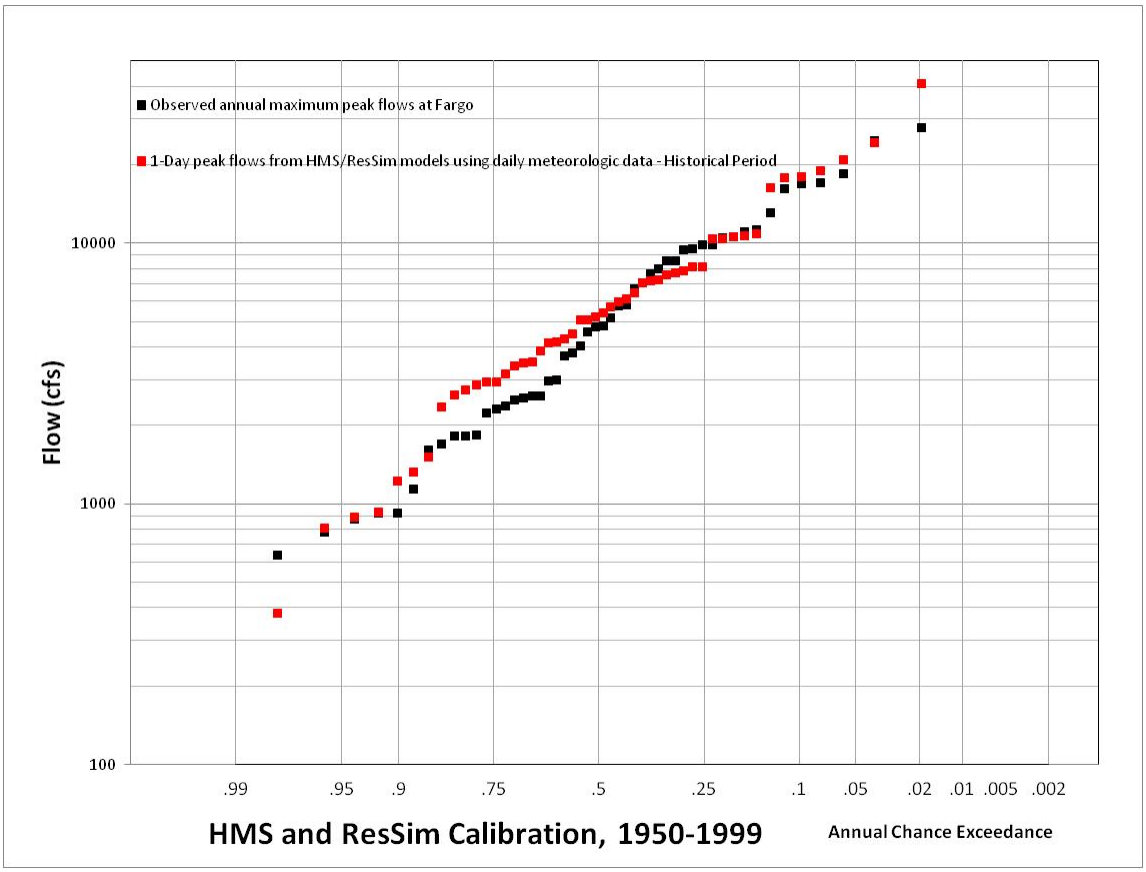

Figure 14. Calibration Results, Frequency Curve, 1950-1999 Regulated Mean Daily Annual Peaks

Results

Two different methods were used to show the computed impact of climate change on the flood frequency curves. The first method was to pool and sort all of the annual peaks for each time period. This method can be applicable for studies where the flow data does not fit a LPIII distribution. The other method involves developing LPIII statistics and flows for each of the 90 data sets in each time period. The median of the 90 LPIII flow data sets are tabulated to show the impact of climate change on the future period frequency curve. This method is somewhat similar to the procedure used in Raff et al. The impacts computed by the two methods are similar.

Median of LPIII Flows Method

1950-1999 Base Period Frequency Curve. The revised and calibrated District HEC-HMS and HEC-ResSim models were run with the daily temperature and precipitation values generated from the downscaled climate model monthly results for the base 50 years, 1950-1999. The nine projections of monthly climate values selected for the 2011-2040 period were used for 1950-

1999 and 10 weather generations were developed for each projection. LPIII frequency curves were developed for each of the 90 sets of regulated annual peak flows at Fargo. Regional skew adjustment was not used and Bulletin 17B guidance was used to remove low outliers. The median flow for each of the frequency curve ordinates was used for the final frequency curve. Though the river is regulated by upstream reservoirs and the traditional Corps of Engineers procedures would use graphical frequency curves, in Appendix A it is noted that the Log-Pearson III is a good fit to the data, plus the use of LP III allowed a consistent and efficient method for comparing results. The resultant median curve is plotted on Figure 15 with the observed and calibration data points. As shown, the median curve is a good fit to the observed and calibrated points. In addition to the medians of the 90 data sets, the 10 and 90% limits of the data are also plotted. The data used for these were the values that had 10% larger and 90% larger for each of the ranked flows, producing an 80% confidence interval. The 1950-1999 median curve was used as the base curve for comparison to future period curves.

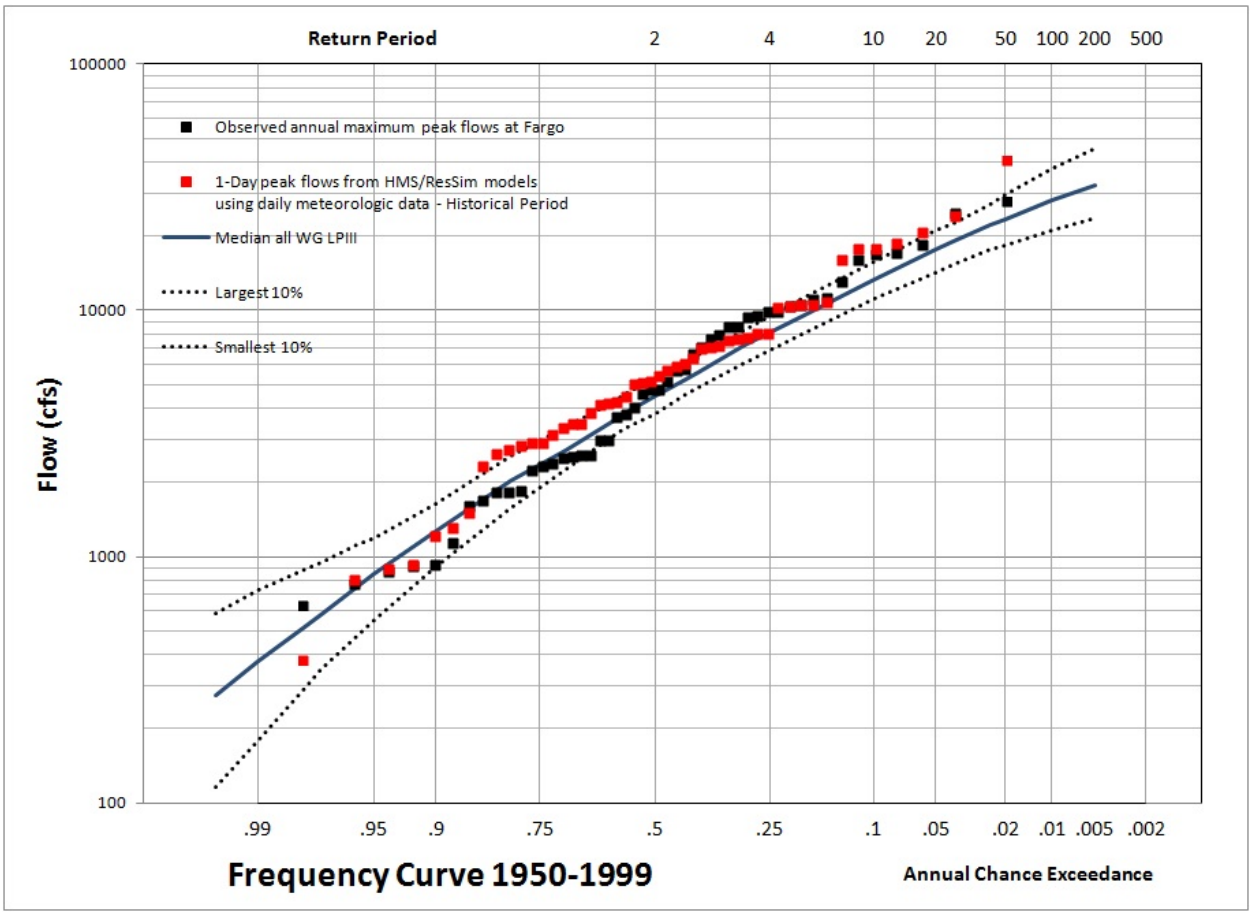

Figure 15. Frequency Curve, 1950-1999 Regulated Mean Daily Annual Peaks Model Results

Raff et al used a similar but somewhat different procedure. In effect, for 1950-1999 they would randomly select 50 points from the 4500 values (minus 10%, since they did not use the top and bottom 5% of the 4500 values, because as explained in the Weather Generation Section, their calibration of the tails of the distribution was not a good match). This was done 100 times and LP III statistics developed for each of the 100 sets. The LP III curves for the median, 10, and 90th quantile 1% exceedance values were displayed in their figures and tables.

Future Period Frequency Curves. Frequency curves for future periods, 2011-2040, 2041-2070, 2071-2100, were computed in the same manner as for the base 1950-1999. LP III statistics were computed from the peaks for each period. As stated in the Projection Selection section, the 9 projections in each time period were selected to represent the range of the 112 model results, not necessarily the average, and it's important to consider the uncertainty in the climate change modeling results. The median, 10%, and 90% curves for each future period are shown on Figures 16 to 18 along with the median 1950-1999 LP III curve. Figure 19 shows the average median curves for all four periods. Tables 4 to 7 compare peak discharges for different return periods.

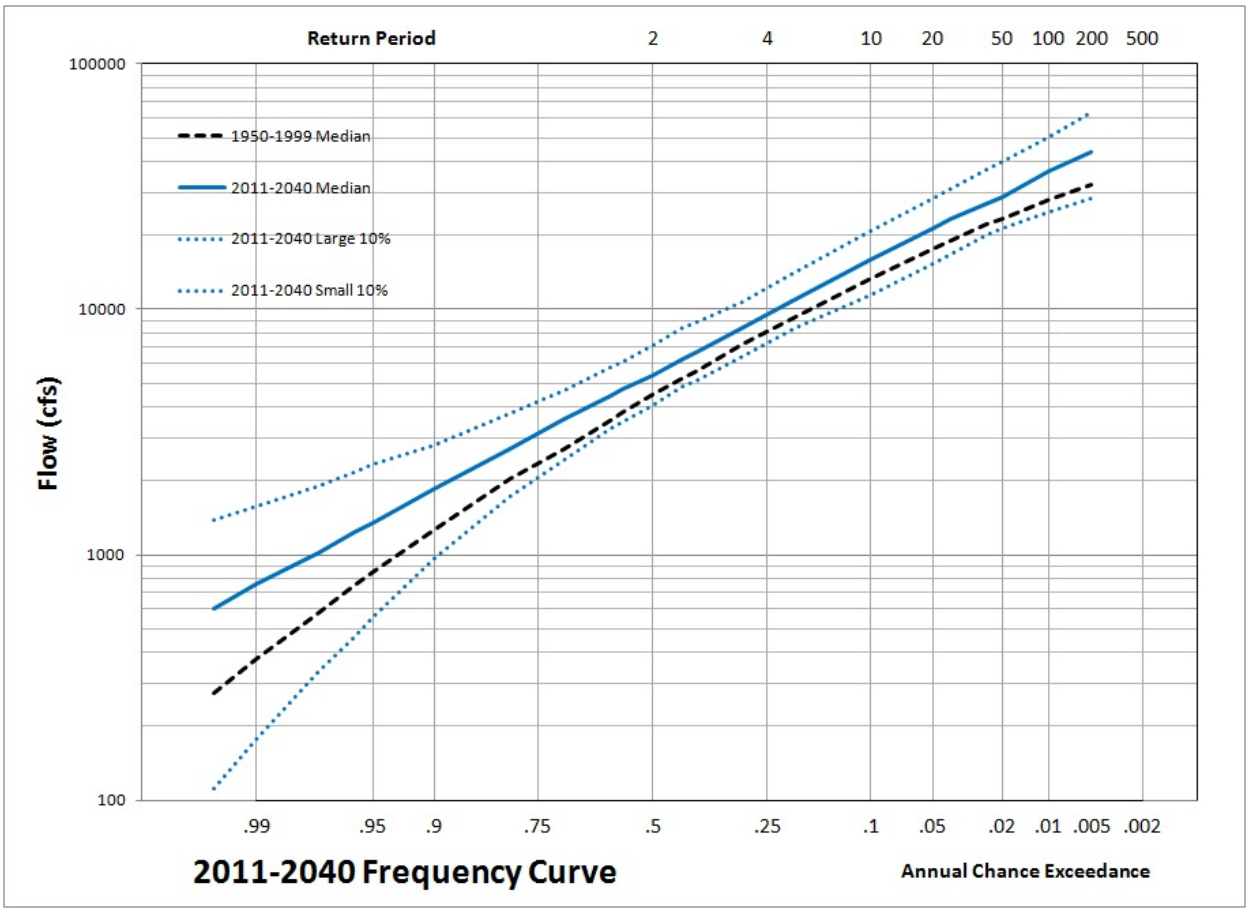

Figure 16. Frequency Curves, Regulated Mean Daily Annual Peaks 2011-2040

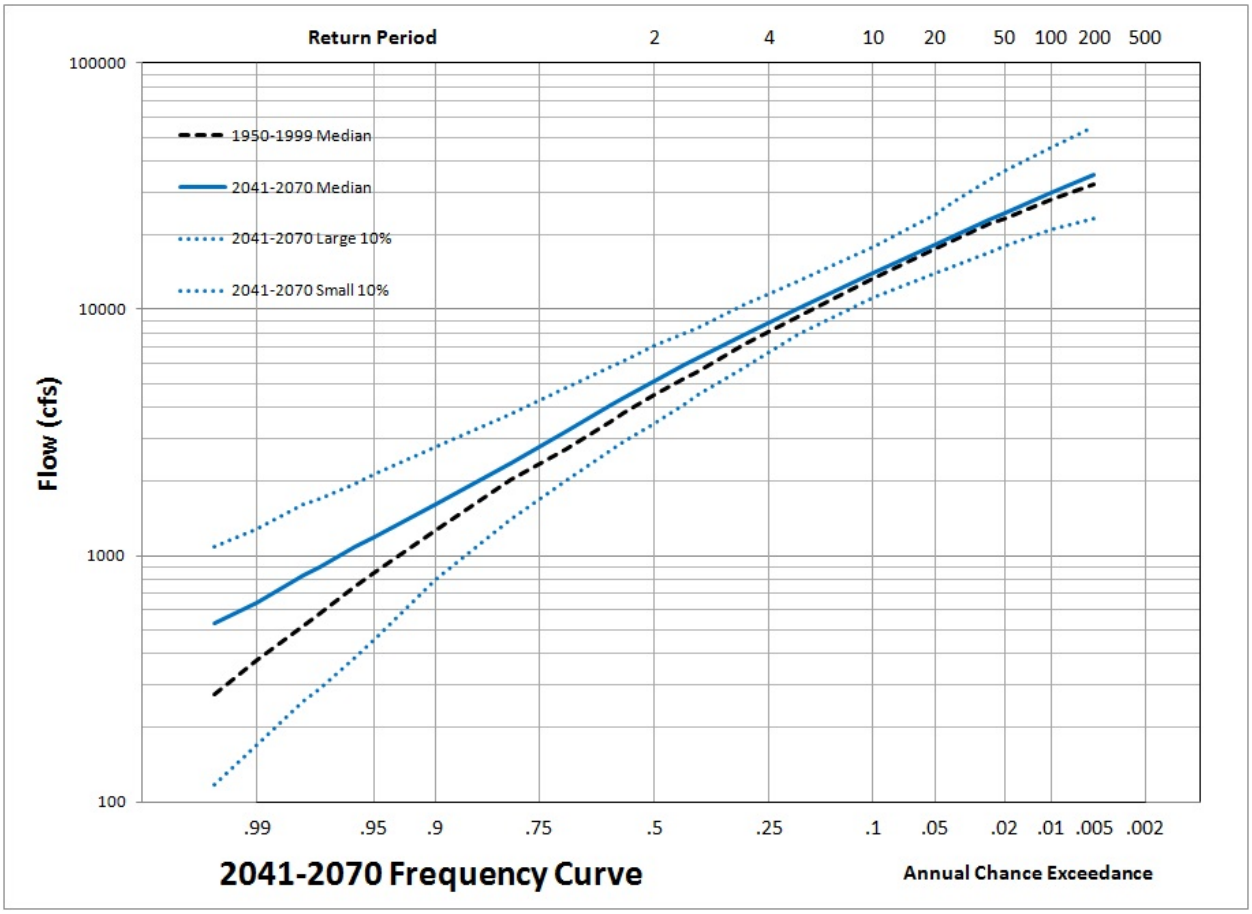

Figure 17. Frequency Curves, Regulated Mean Daily Annual Peaks 2041-2070

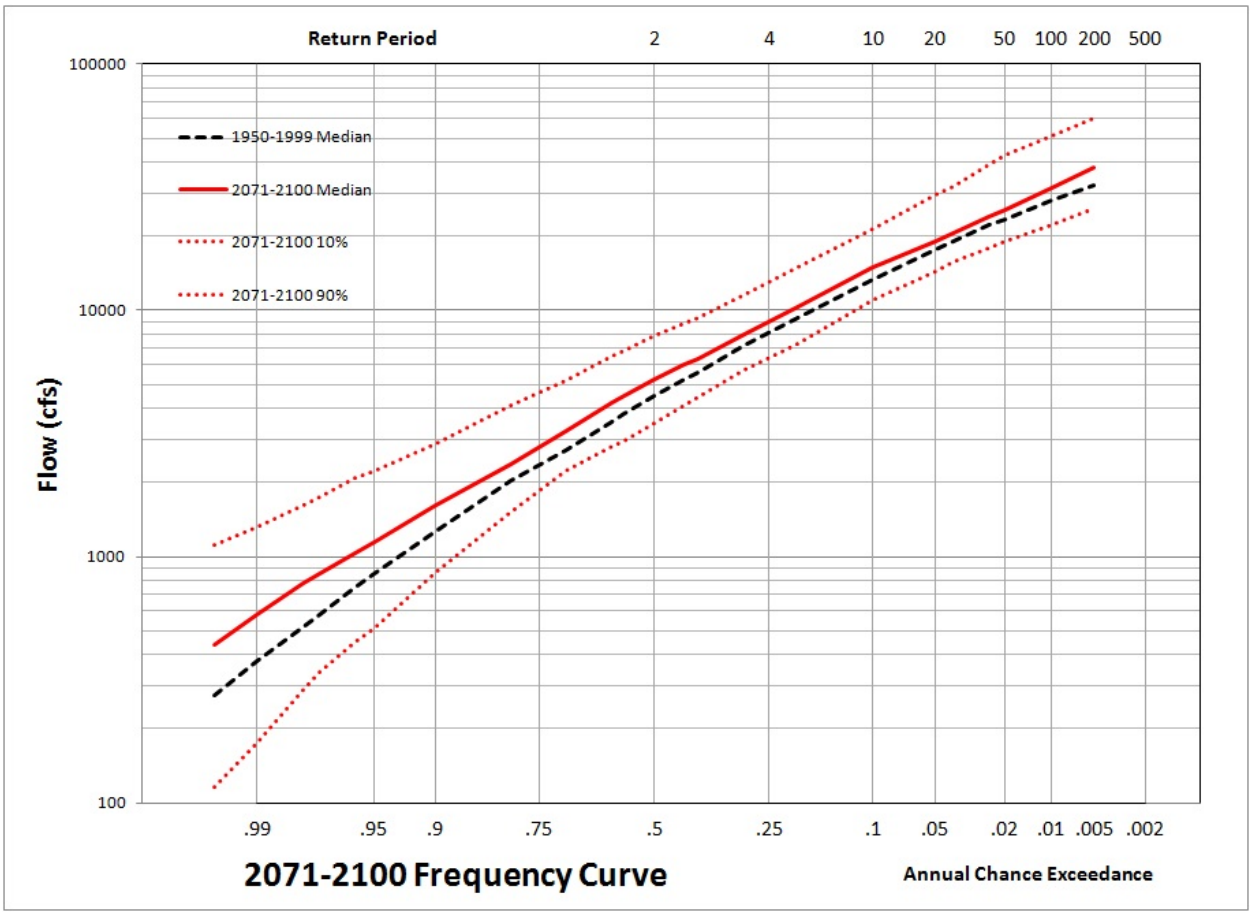

Figure 18. Frequency Curves, Regulated Mean Daily Annual Peaks 2071-2100

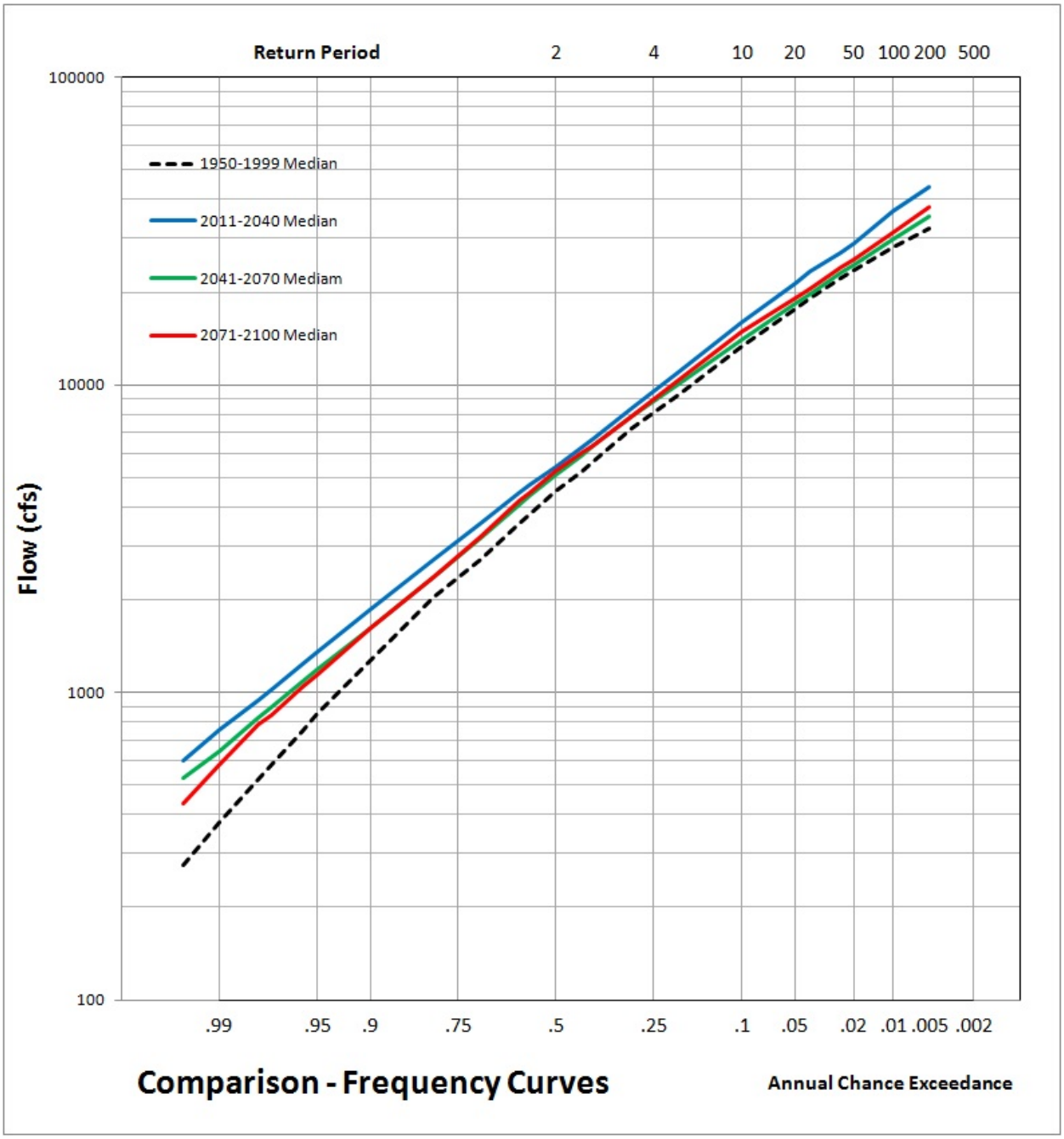

Figure 19. Comparison of Regulated Mean Daily Annual Peaks Frequency Curves for Different Time Periods

Table 4. Climate Change Impact on 2011-2040 Regulated Mean Daily Annual Peaks Frequency Curve

Exceedance Probability	Return Period	1950-1999	2011-2040 Median	2011-2040 90%	2011-2040 10%
0.5	2-yr	4,500	5,400	4,100	7,100
0.1	10-yr	13,300	16,000	11,500	21,000
0.02	50-yr	23,500	28,900	21,300	40,000
0.01	100-yr	28,000	36,800	25,000	50,100
0.005	200-yr	32,400	43,800	28,200	63,500

Table 5. Climate Change Impact on 2041-2070 Regulated Mean Daily Annual Peaks Frequency Curve

Exceedance Probability	Return Period	1950-1999	2041-2070 Median	2041-2070 90%	2041-2070 10%
0.5	2-yr	4,500	5,100	3,500	7,100
0.1	10-yr	13,300	14,000	11,100	18,000
0.02	50-yr	23,500	24,500	18,100	36,700
0.01	100-yr	28,000	29,700	21,200	45,500
0.005	200-yr	32,400	35,400	23,400	55,000

Table 6. Climate Change Impact on 2071-2100 Regulated Mean Daily Annual Peaks Frequency Curve

Exceedance Probability	Return Period	1950-1999	2071-2100 Median	2071-2100 90%	2041-2100 10%
0.5	2-yr	4,500	5,200	3,500	7,900
0.1	10-yr	13,300	14,900	10,900	21,400
0.02	50-yr	23,500	25,600	19,100	42,400
0.01	100-yr	28,000	31,300	22,200	50,800
0.005	200-yr	32,400	37,900	26,100	60,000

Table 7. Summary of Average Climate Change Impact on Future Regulated Mean Daily Annual Peaks Frequency Curves

Probability	Return Period	1950-1999	2011-2040	2041-2070	2071-2100
0.5	2-yr	4,500	5,400	5,100	5,200
Percent Difference			20%	13%	16%
0.1	10-yr	13,300	16,000	14,000	14,900
Percent Difference			20%	5%	12%
0.02	50-yr	23,500	28,900	24,500	25,600
Percent Difference			23%	4%	9%
0.01	100-yr	28,000	36,800	29,700	31,300
Percent Difference			31%	6%	12%
0.005	200-yr	32,400	43,800	35,400	37,900
Percent Difference			35%	9%	17%

All future time periods and frequencies show an increase in the median values. The greatest increase is for 2011-2040 when flood peaks for a given probability were 20 to 35% higher than 1950-1999. For all of the future time periods the 90% values are lower than the mean 1950-1999 curve. In other words, for all future time periods more than 10% of the climate model results show a decrease in the flood frequency curve.

The reduction in the flood peaks after 2011-2040 was somewhat unexpected since both the average annual temperature and cumulative precipitation increase in a fairly even fashion from 1950 to 2100. Red River floods are predominantly snowmelt and the accumulation of snow water equivalent in the snowpack is a primary driver of flood peaks. Figure 20 has frequency plots of the maximum snow water equivalents, SWE, from the hydrologic modeling for the four time periods (the plots were developed by ranking and sorting annual maximum computed SWE values from the historic (4500 values), and future climate periods (2700 values)). The probability of larger SWEs increases from 1950-1999 to 2011-2040 and then falls for 2041-2070 and falls again for 2071-2100. The decrease in SWE after the 2011-2040 time period could explain the decrease in discharge frequency curves. An in-depth analysis was not done to the data, but it appears the increasing temperature reaches a sort of tipping point with respect to SWE and after 2011-2040 reduces the accumulation of snow, even though precipitation continues to increase.

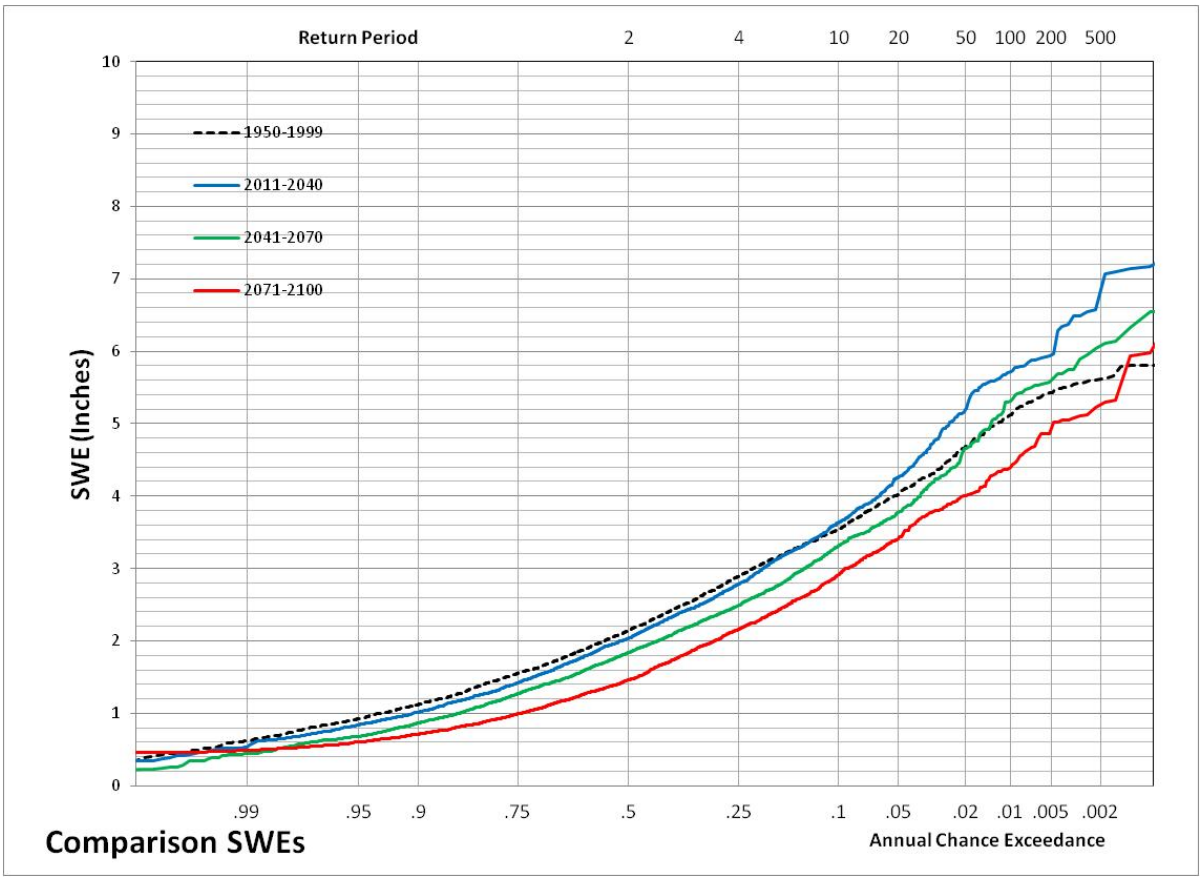

Figure 20. Comparison of Annual Peak Snow Water Equivalents for Different Time Periods

Pooling all Yearly Peaks Method

The other method used to compute the impact of climate change on the frequency curve was pooling all of the projections. For each time period there are nine projections, each with 10 daily weather simulations for a total of 90 simulated projections. For the historical period of 1950-1999, each of the 90 is 50 years long for a total of 4500 simulated years. The future periods are 30 years for a total of 2700 simulated years for each period. For each period all 4500 or 2700 of the simulated annual maximum values were pooled and sorted to create a single best estimate empirical distribution function that combines all projections. Figure 21 shows the empirical distribution function for each of the time periods. These plots include all the annual peaks; no outliers were removed. For all future time periods the plot shows an increase in flood discharges for all probabilities. The increase is especially large for the 2011-2040 lower frequency floods at the far right of the plot. The results are summarized in Table 8.

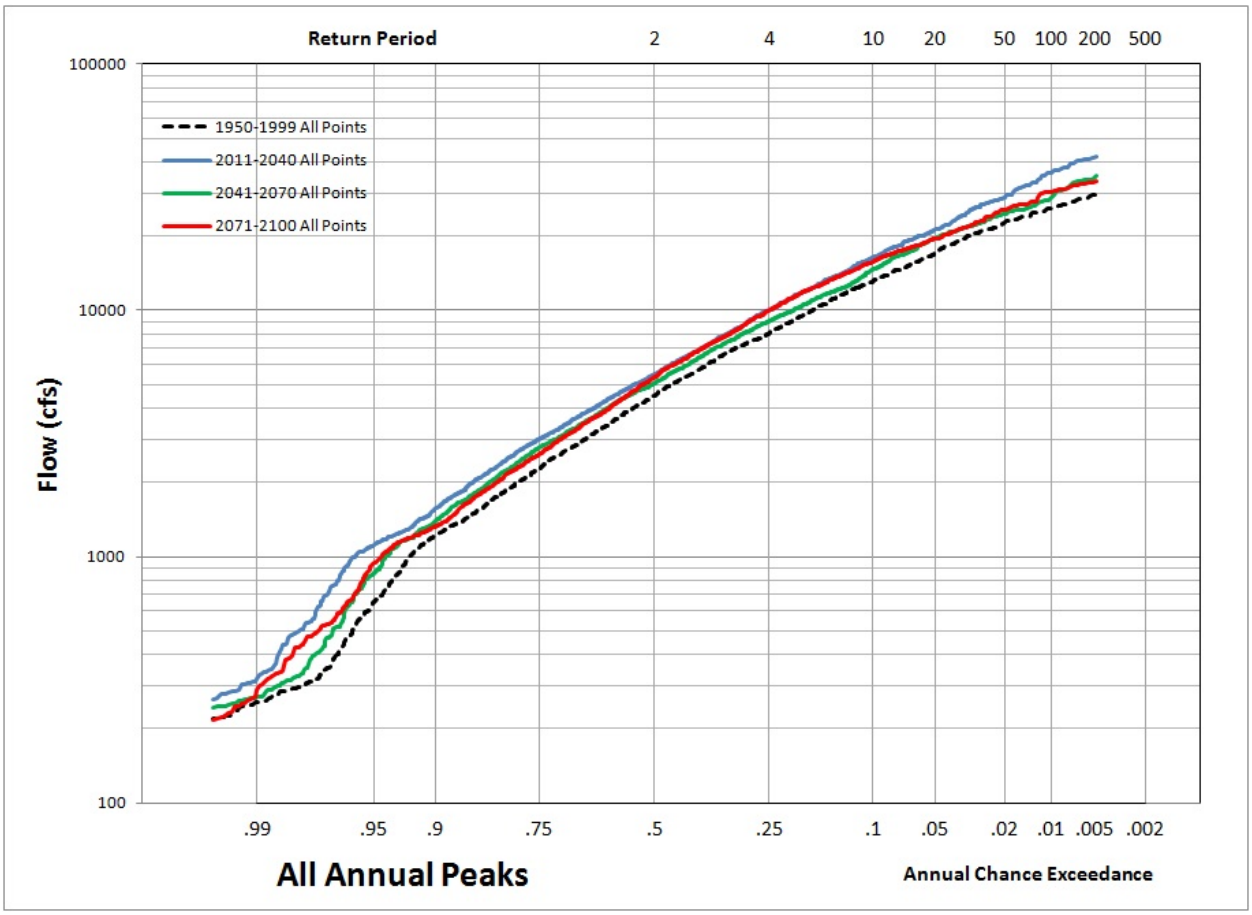

Figure 21. Cumulative Distribution of Regulated Annual Maximum Discharge Based on Ensemble Hydrologic Simulations for the Periods Shown

Table 8. Pooled Method Summary of Climate Change Impact on Future Regulated Mean Daily Annual Peaks Frequency Curves

Probability	Return Period	1950-1999	2011-2040	2041-2070	2071-2100
0.5	2-yr	4,500	5,600	5,200	5,400
Percent Difference			24%	16%	20%
0.1	10-yr	13,300	16,300	14,500	15,300
Percent Difference			23%	9%	15%
0.02	50-yr	22,700	30,300	25,100	27,000
Percent Difference			33%	11%	19%
0.01	100-yr	26,900	37,500	30,500	32,600
Percent Difference			39%	13%	21%
0.005	200-yr	31,100	45,600	35,500	38,600
Percent Difference			47%	14%	24%

The above summary results for the pooled method show an increase in the magnitude of floods for every frequency, however, plots of the individual projections for each time period show that some projections actually have a decrease in future flood levels. Some of the projections show increases greater than the summary results. Figures 22 to 24 are the projection plots for the three future time periods. Confidence limits were not developed for this method but could have been from the data in Figures 22 to 24.

This pooled method has an advantage that it applies even if the flow data does not fit a LPIII or other distributions.

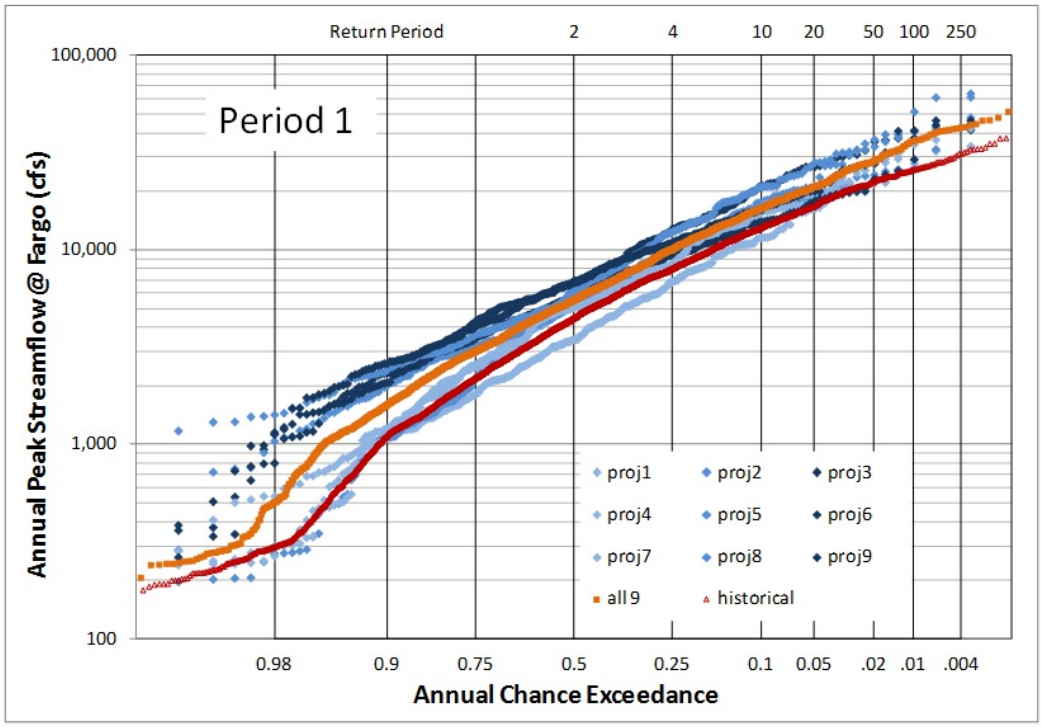

Figure 22. Frequency Curve for 2011-2040, Pooled Weather Generations for the 9 Climate Projections

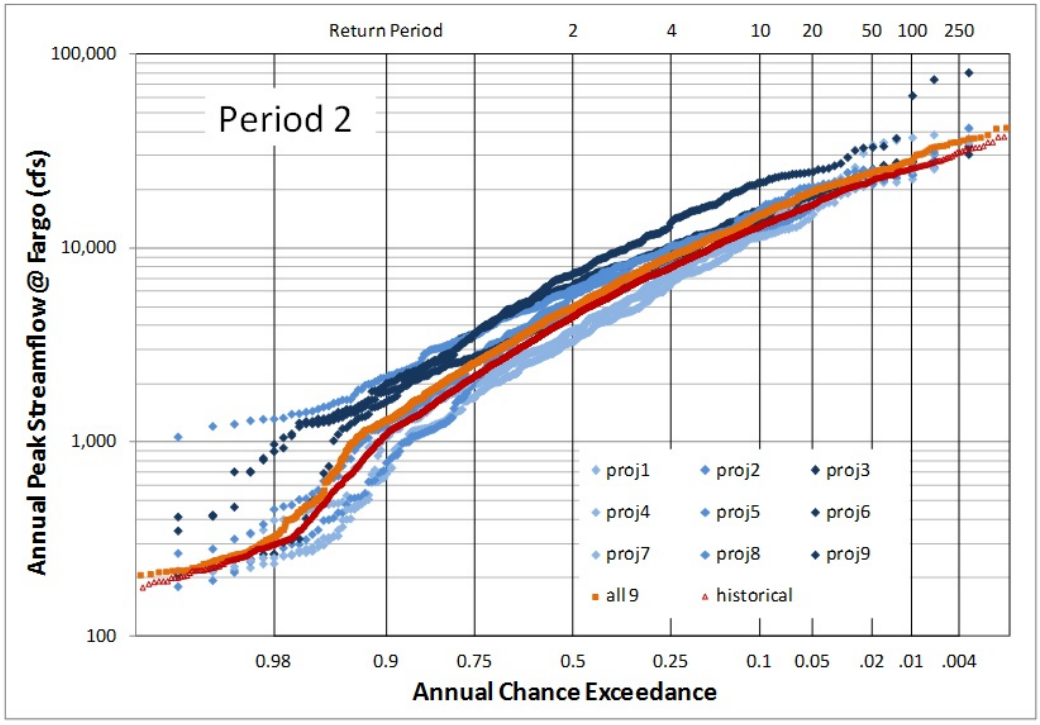

Figure 23. Frequency Curve for 2041-2070, Pooled Weather Generations for the 9 Climate Projections

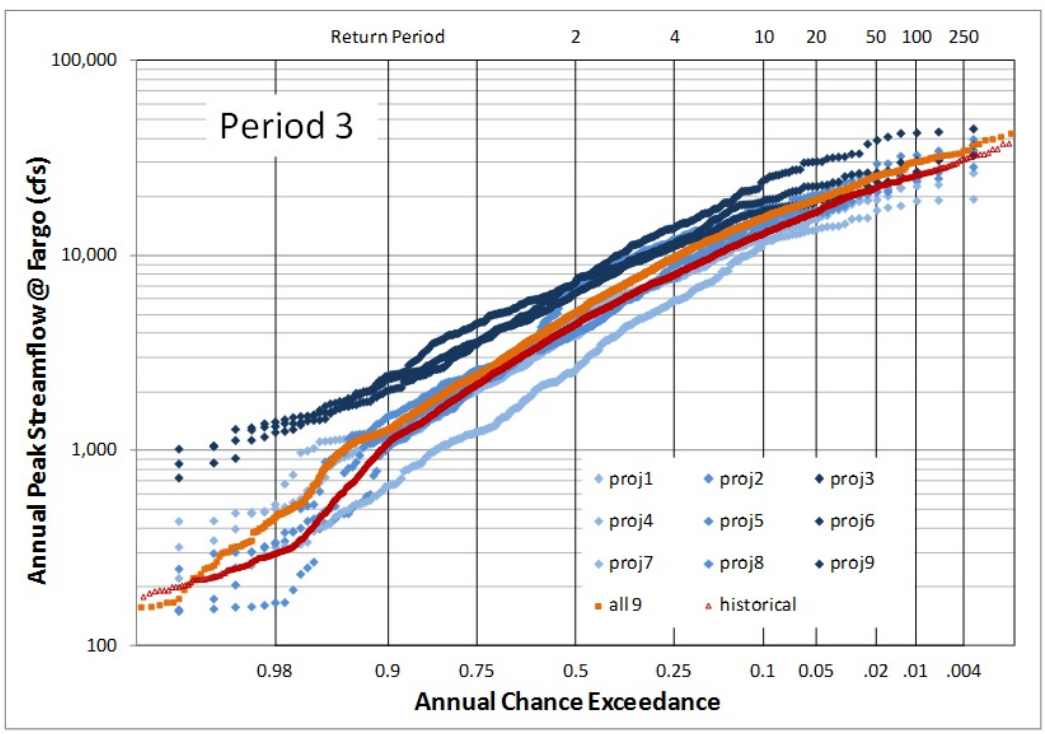

Figure 24. Frequency Curve for 2070-2100, Pooled Weather Generations for the 9 Climate Projections

Comparing tables 7 and 8 it can be seen that the pooled method and the median LPIII method gave very similar results. The similarity in the results can also be seen in Figure 25, which plots the results of the two methods for the 1950-1999 period.

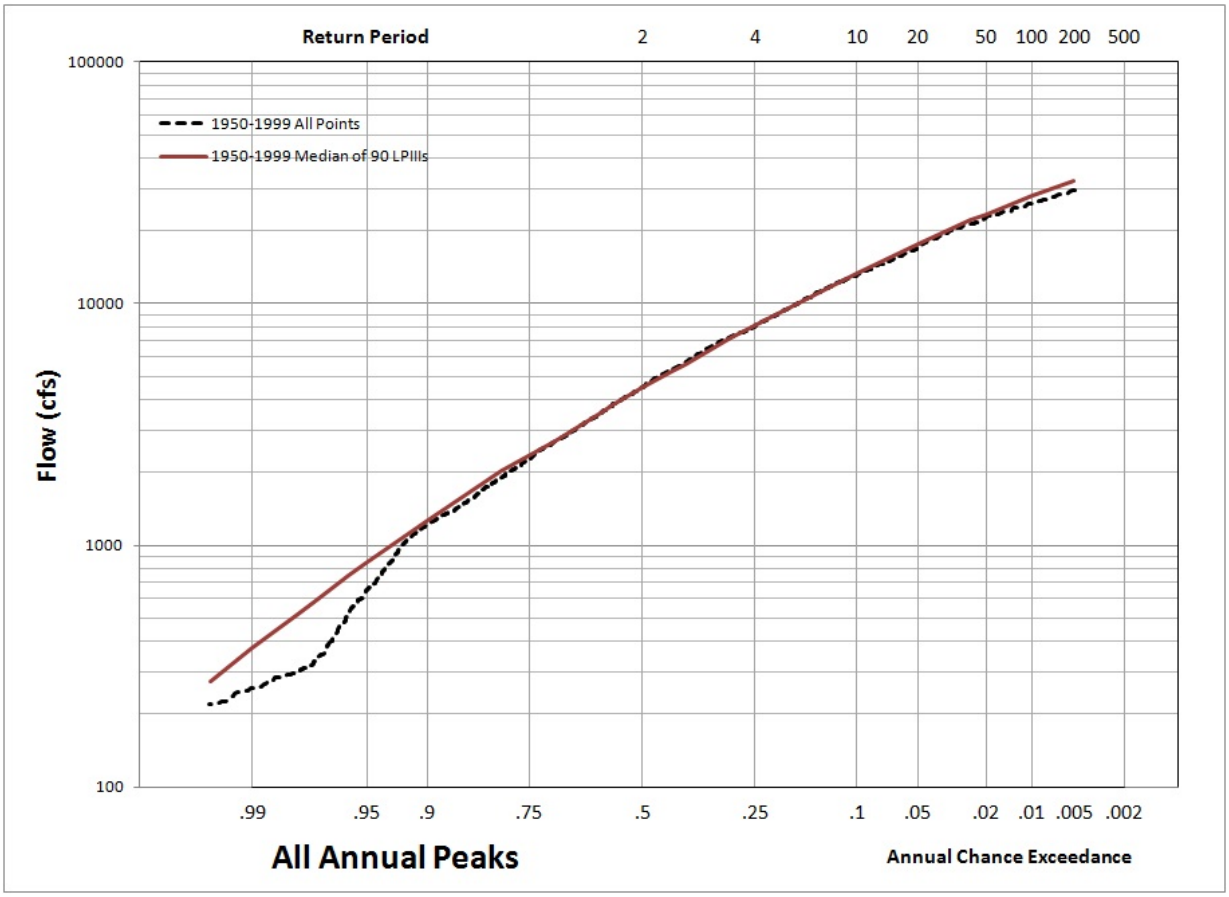

Figure 25. 1950-1999 Model Regulated Mean Daily Annual Frequency Curves

Use of Data for other Comparisons: The hydrologic models were run in a continuous mode and yielded 365 daily flows each year and this could lead some to use the results to evaluate the impact of climate change on something other than the annual flood frequency curve. However, the only charge of this study was climate change impact on the annual flood frequency curve, and the study effort was developed for that purpose. In particular, the HMS and ResSim models were calibrated to match the annual flood frequency curve and not to match low flows or other flow variables. With the limited calibration, care should be taken before using the modeling results for any detailed analysis other than assessing the impacts on annual flood peaks. However, the results do give general trends on the impact of climate change on the seasonality of flood peaks. The results indicate that through 2100 the majority of the flood peaks continue to be in March and April, no large increase was observed in the percentage of annual peaks in any other period. However, it must be remembered that the climate model data used was monthly, and the results may not reflect any large increases in short duration precipitation events that

could occur from climate change. The hydrologic models could be calibrated to match such things as seasonality and low flows, but as explained in the calibration section, the hydrologic model needs to be approximate to run efficiently and it might be difficult to develop a single well calibrated model that would be adequate for annual peaks, seasonality, and low flows.

A brief analysis was done of the data to see if there was a trend for larger fall events. In the past few years there have been some very large fall precipitation events to basins to the south of the project area and there is a question if this trend could continue and spread to the Red River Basin. The modeling results for the future time periods show few fall season floods larger than 20,000 cfs. This is approximately the limit for significant damages in the Fargo area and thus there is not a strong trend for concern. However, the computations did have a limited number of extremely large fall floods. The largest was 40,500 cfs on October 12, 2032, for projection 3. Projection 3 is the warmest/wettest of the projections. This flood was the result of a projected 7.6 inches of rain over the basin in that October, with 6.6 inches in four days. For reference the flood of record at Fargo was 29,500 cfs in 2009. Over 50 miles of emergency measures were built at that time in a successful effort to protect the communities. A 40,500 cfs flood in October would not allow this kind of a flood fight and would be catastrophic. Why such a large flood is possible while the mean of climate trends only shows a gradual increase can be seen by the large increase in the extremes of precipitation on Figures 8 and 10. The climate modeling results show the possibility of extreme events can increase significantly. It should be noted that the 40,500 cfs flood was the largest October value in 8100 (2700 for each of the three future time periods) computed October peaks. The modeling shows it's possible, but not likely.

Project Impacts

The latest frequency curve for the Fargo flood management project is based on the period 1942-2011 and is in, "The use of Synthetic Floods for Defining the Regulated Flow Frequency Curve for the Red River at Fargo", Hydrologic Engineering Center, February 2010 with Appendix A, August 5, 2011. The results of this pilot study give a good indication of the direction and relative magnitude of changes in the project curve due to climate change, but the results of the study do not precisely indicate how climate change could impact the project curve. For example, the results of this study indicate the 1% exceedance flood could, on the average, increase 31-39% from 1950-1999 to 2011-2040, but this does not mean the project curve would be expected to increase exactly 31-39% for the 2011-2040 period. The reasons the study results do not give more exact impacts on the project curve include: the project curve has a different period than the base 1950-1999, synthetic events are used to anchor the upper end of the project curve, observed flows were used for the project curve while model results were used for this report's curves, and instantaneous peaks are used for the project curve and mean daily for the pilot climate study. This study did not include the effort needed to adjust computed frequency curves to be comparable to the project curve. This task could be a fair amount of effort due to all of the differences. It could bias correcting the GCM climate data to 1950-2011 instead of 1950-1999. However, frequency curves for observed 1950-1999 and 1942-2011 flows at the Fargo gage were

compared and found to be very similar, see Figure 26. This was somewhat surprising since five of the seven largest floods in the 1942-2011 period were in the 2000-2011 period, see Figure 2. For the 1942-2011 period the mean log of the peaks increased as expected, from 3.69 to 3.75, but the standard deviation decreased from 0.405 to 0.396, and the station skew got more negative, from -0.10 to -0.15. The net result was little change in the curve. Since the frequency curve for the observed 1942-2011 flows is close to that for 1950-1999 observed, it is assumed that climate change would have approximately the same impact on the project curve as it did for the 1950-1999 curve. In other words, for the 1% and 0.5% exceedance floods (100-yr and 200-yr return period), average computed increases could be in the 30-50% range for 2011-2040 period, about 5-15% for 2041-2070, and 10-25% for 2071-2100. However, there is a wide range of possible impacts that include some chance the curves could actually decrease.

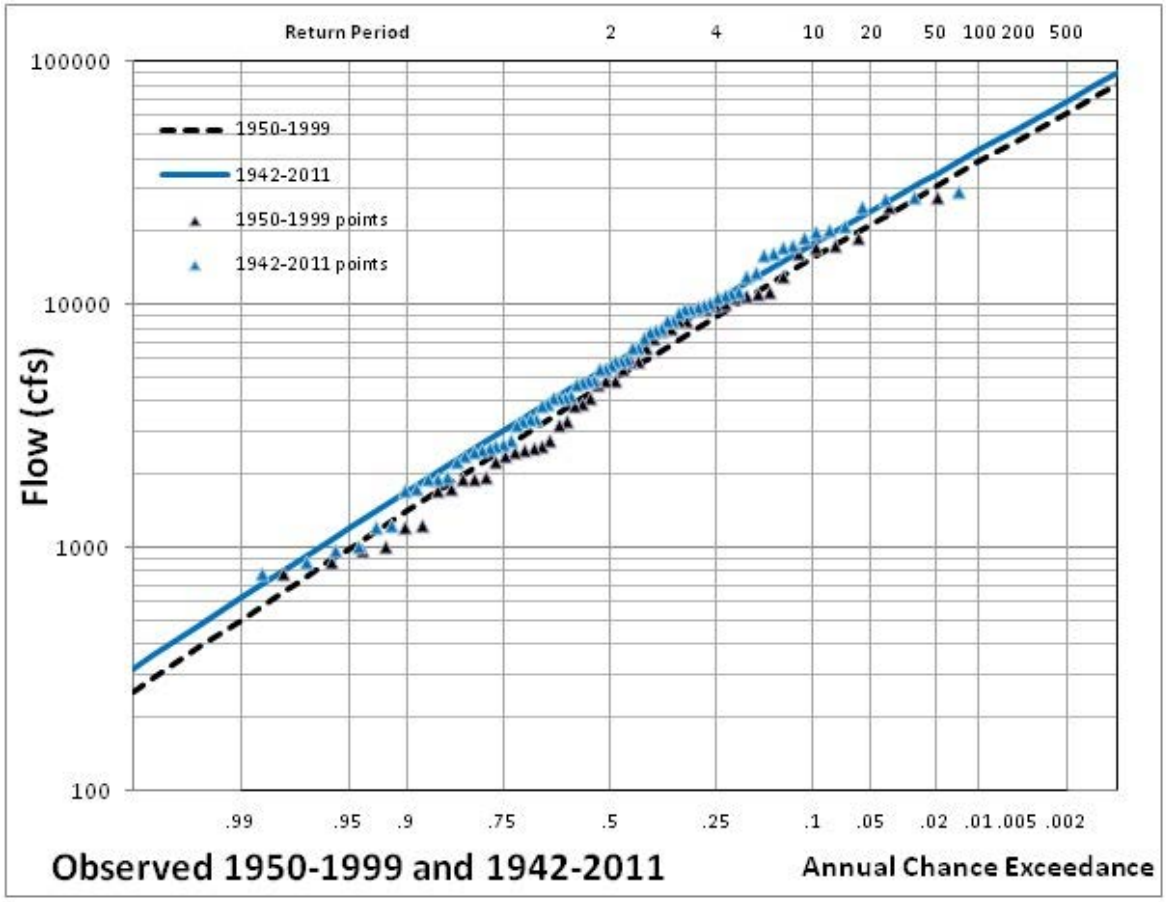

Figure 26. Comparison of Frequency Curves, 1950-1999 and 1942-2011 Observed Instantaneous Annual Peak Flows

Overall Conclusion

The climate model results indicate climate change could have a significant impact on flood frequencies for periods as soon as the current period, 2011-2040. The average of the model results show likely large increases in lower frequency flood flows, but the models also show a wide range in possible impacts, with over 10% indicating that flood sizes could decrease. The results indicate that while the current project frequency curve based on only past events should be accurate for evaluating current flood risk, it could be misleading and underestimate the likely size of future floods

Comparison to CMIP5

When this report was being written in early 2015, CMIP5 average climate data had been summarized for the U.S. portion of the Red River basin but not for the portion of the basin upstream of Fargo. The summarized CMIP5 data was only available for 2015-2100. The basin averaged annual temperature and precipitation for the available CMIP5 data are shown on Figures 27 and 28. Most of the Red River basin is north of Fargo and average temperatures and precipitation are lower for the basin downstream, north, of Fargo, so CMIP3 and CMIP5 values for temperatures and precipitations are hard to compare, however, trends can be compared. The CMIP5 data for the entire U.S. portion of the basin follow the same trends as the CMIP3 for upstream of Fargo; a steady increase in average annual temperature and over time somewhat higher cumulative annual precipitation. No details other than annual averages were compared for this report.

As of May 2015 a collaborative multi-agency team was developing a consistent set of daily flows for larger U.S. basins. These flows are for unregulated conditions and are being developed using about 100 sets of statistically downscaled CMIP5 daily climate data and the VIC hydrologic model. The flows will not be calibrated to observed values. Due to the very approximate nature of the CMIP5/VIC analysis, the results are expected to be appropriate to screen vulnerabilities at a watershed level but not for specific decisions at a project level, especially for basins with significant regulation of flows. While the CMIP5/VIC results will be approximate, the fact that they are based on daily climate data projections may allow insights to the results of this pilot study since the current study was not able to evaluate whether climate change does/does not impact daily climate variability.

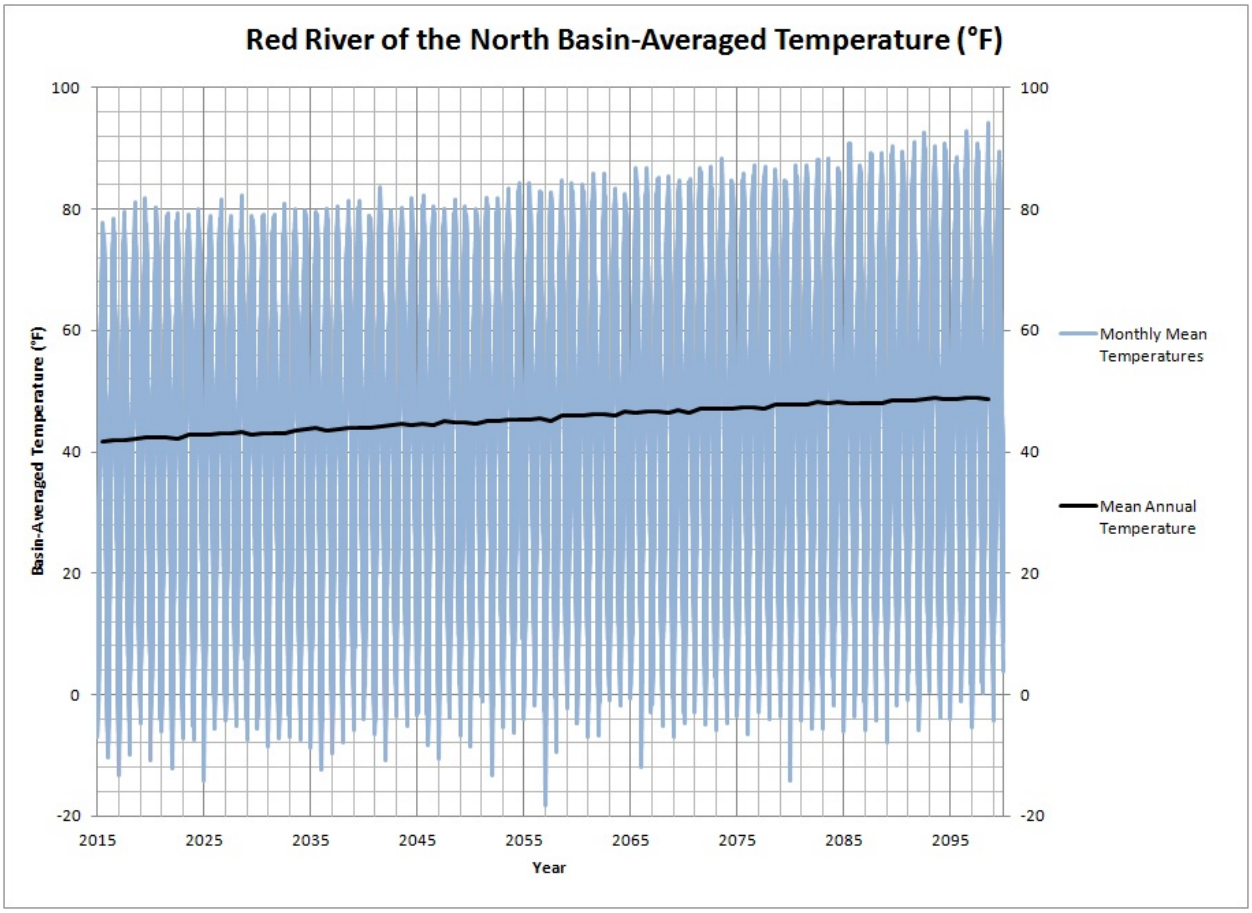

Figure 27. CMIP5 Total U.S. Basin-Averaged Annual Temperature, 2015-2100

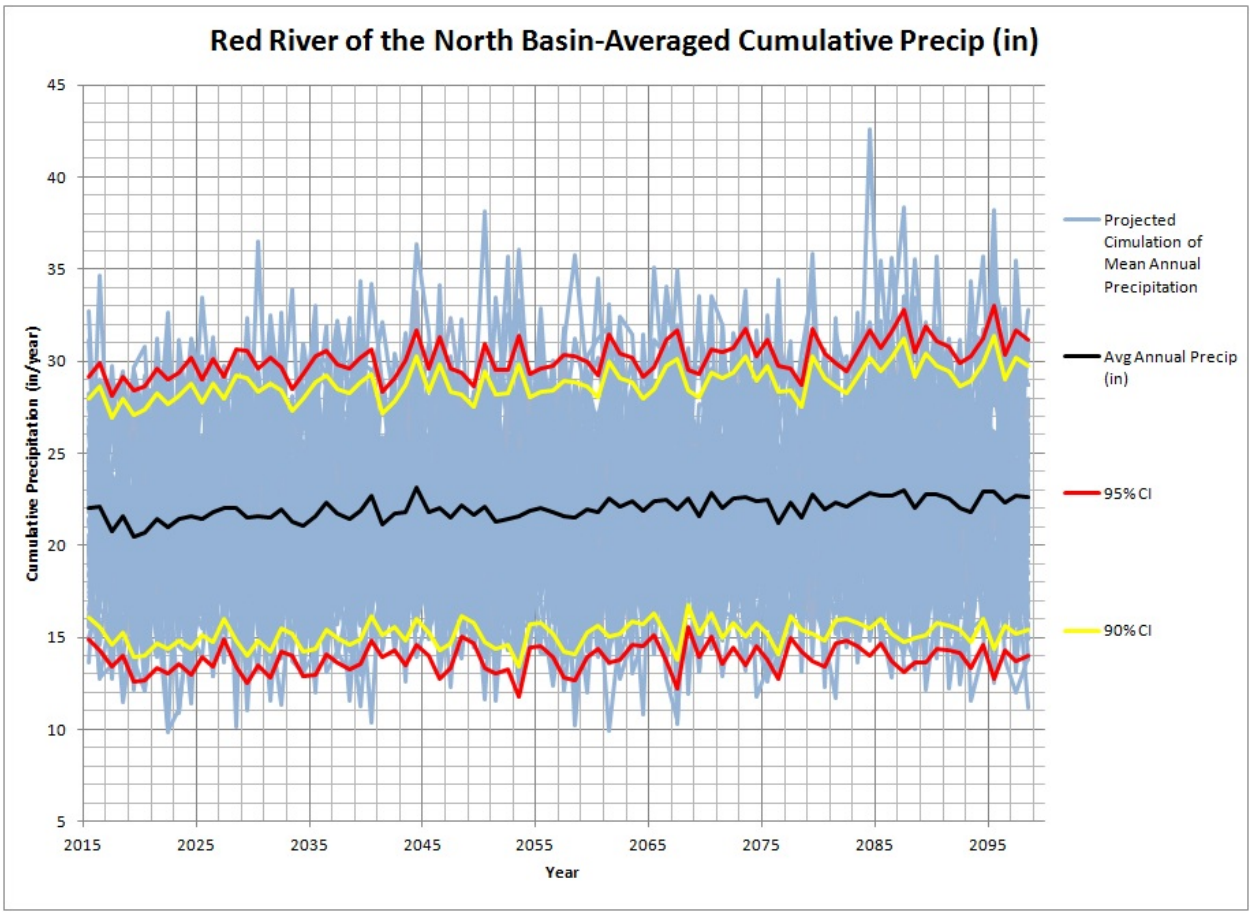

Figure 28. CMIP5 Total U.S. Basin-Averaged Cumulative Annual Precipitation, 2015-2100

Methodology Conclusions and Recommendations

1. Overall. This method gives defendable and quantified results for impacts of climate change on the frequency of flood peaks. The estimated average impact was computed as well as a range of possible impacts. When discussing climate change impacts, decision makers and stakeholders need to be aware of the full range of possible impacts, not just the estimated average change. In addition, detailed modeling captures aspects not included in simpler analysis. For example, inclusion of a reservoir simulation model will incorporate regulation in the watershed and result in a regulated flow frequency curve. A drawback of the method due to limitations of the CMIP3 data is the assumption that historic daily patterns of temperature and precipitation are assumed not impacted by climate change (the CMIP5 data could be used as well and more climate projections selected instead of only 9). The method can be time and resource consuming and could require the climate change expertise of IWR. HEC guidance could be needed if the District was not familiar with WAT and also to generate the daily weather generations

from CMIP3 data, but temporal downscaling should not be needed of CMIP5 data values were used. The use of many years of historic climate data and the random selection of that data very effectively increased the equivalent period of record, but if the daily CMIP5 climate data were used this could eliminate or modify the need to generate the weather generations. The budget for this study was $270,000 but much of that was used to understand and refine the procedure. A redo of the study would be less, given familiarity of the methodology, availability of good hydrologic models, and the use of CMIP5 model output would no longer require downscaling of monthly data.

2. Snowmelt floods. It is very difficult to evaluate the impact of climate change on snowmelt flood peaks without doing hydrologic modeling. The impact of warmer temperatures on snowmelt floods is not obvious and can be paradoxical since warmer temperatures can decrease snow accumulation which would drive down flood peaks but increase the rate of melting which would increase snowmelt peaks. The warmer temperatures also allow the air to hold more moisture which could impact precipitation. Thus warming can affect snowmelt peaks in opposite directions and hydrologic modeling can assist in understanding changing climate impacts on the hydrologic response.
3. Climate data. It is recommended that using the CMIP5 daily data be considered. The results for the weather generations used in this study show that the distribution of daily data can have a very large impact on peak flows. A concern with the method used for this pilot study is that the daily weather generations are based on historic patterns and do not include any impact climate change could have on daily patterns. A point in favor of the pilot study methodology is that the weather generations are based on a much longer period of record than the climate models, and the longer period plus the random selection of the daily variations adds richness to the data and likely more accuracy in the results. The impact of losing this richness if only the CMIP5 daily climate model results are used would need to be considered and perhaps a methodology to combine the benefits of the weather generation used in the pilot study with the knowledge gained from the CMIP5 daily variations could be developed.
4. Hydrologic modeling. For this study the existing models gave a good start but needed modification and simplification to run efficiently for the very large study area and the amount of continuous modeling. Even with the simplifications, the models were resource consuming to run and generated large amounts of data and data management was a priority. Additional model simplification would decrease computing resources and the amount of model output. With a simplified model it may not be not practical to have a "perfect" calibration that matches individual flood peaks, much less to match seasonality and low flow periods. It takes an experienced and confident modeler to know when an imperfect calibration is good enough, especially for the type of analysis being performed. With the goal of understanding how flood peaks might change due to a changing climate, it is not necessary that the hydrologic model reproduce low flow statistics. The current

CWMS program is producing models that are an improvement over the models used for this study and they could require less modification for a study similar to this one.

5. The base 1950-1999 frequency curve developed by this method is based on outputs of hydrologic models that use the climate model results for input. Frequency curves used for existing project studies are usually based on observed annual peak flows. It is not expected that this method's base frequency curve will be an exact match for ones used in project studies. The difference can be seen in Figure 15 where the upper end of the base 1950-1999 model curve is lower than observed and calibration values. Differences between this method's base period curve and curves based on observed data make it hard to provide precise impacts of climate change on project frequency curves. Some things that could reduce the difference between the model base curve and curves based on observed peaks are: a. calibrate the hydrologic models using the climate models' base period gridded precipitation and temperature instead of using observed gage data precipitation and temperature; b. Do a secondary bias correction to the climate model outputs so that the computed based period curve more closely matches the observed; c. "bias correct" the base period frequency curve computed by this method so that it matches the observed period curve. Determining the secondary bias correcting for method b. would be difficult – would you adjust both precipitation and temperature? How much? Which months? Method a. would help reduce the problem and should be considered for future studies, but you'd end up with hydrologic models that might not be calibrated with observed climate data and thus could be of less value for other purposes. Method c solves the problem for the base period but the appropriateness of application of the base period bias correcting to future time periods would have to be evaluated.
6. Besides daily precipitation and temperature, the archive of the newer CMIP5 data will include daily unregulated flows for larger rivers. These flows are being developed using the VIC hydrologic program. The models are not calibrated to observed values and resultant flows may need significant bias correction to match observed. The bias correction manipulation of climate model precipitation and temperature and then hydrologic model flows, makes this method questionable for detailed, project level studies. However, the archive of daily flows offers the potential to determine general trends for large basins.

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Appendices

A. Equivalent Length of Record from RRN "weather generations".
B. Application of HEC-HMS, HEC-ResSim. And HEC-WAT to the Red River of the North Climate Change Pilot Study

Appendix A. Equivalent Length of Record from RRN "weather generations"

There is generally a great deal of uncertainty in the estimate of a probability distribution from a limited sample of data. This uncertainty is referred to as "sampling error," and the variance of the error in probability distribution moments and quantiles is proportional to the sample size N.

This uncertainty is especially relevant in determining if the peak flow frequency curve at Fargo changes through the duration of a single climate projection (or projections in the same wet/dry, warm/cold grouping), because if we create a frequency curve from three successive 30-year periods (2011-2040, 2041-2070 and 2071-2100), there would be too much error (uncertainty) in each of those frequency curves to accurately perceive any change in the curve from one period to the next.

There are multiple ways to address the error in these frequency curves. In this study, we are using the downscale from monthly to daily time-step to introduce a stochastic element that adds more variability to the modeled annual peaks, in the hope that the added variability can be a somewhat accurate way to gain more reliability in the estimated frequency curves, and remove some sampling error. ***However, there is some question whether the added variability just fleshes out the same probability distribution, as any Monte Carlo simulation would do (i.e, adds more points on the same CDF), or actually adds more information to the frequency analysis, reducing sampling error.***

The downscale process is as follows: for each water year in the 30 year period, the monthly temperature and precipitation data of each month is expanded to daily values using the month/day pattern of a randomly chosen historical example of that month, from among those historical months that were similar in temperature and precipitation. This process is called "weather generation" and follows the procedure described in Raff et al. Perhaps the most variability comes from the "down-scale" of monthly total precipitation to daily, as it can range from all precipitation appearing on one day to being spread across the entire month. (Note, this affect is somewhat damped because when a single day's precipitation is greater than an upper threshold – currently 3 inches – it is redistributed to the surrounding days.) The daily temperature and precipitation patterns come from 102 years of record at each of the gage sites.

As stated above, it is important to determine if the variability added by the weather generation technique produces the equivalent of a longer record length and so a more accurate frequency curve (CDF), or just more data on the same CDF. This write-up is intended to describe the process used to estimate an equivalent record length of data (modeled annual peak flows) from the weather generation process, and then to determine the value of that data. To determine the value of the added variability, we created a large number of weather generations from the 50-year historical period, and modeled that data to determine annual peak flows. We then fit an LP3 frequency curve to each 50-year record of peaks in order to assess the variance of the 1% LP3 quantile, and then compared that variance to what would be expected if each 50-year period was actually an independent sample of additional years. The 1% quantile was chosen for this assessment because generally it is of the greatest interest. And although this study considers regulated flows, the LogPearson3 distribution has been found to be a good fit to the data, likely because the regulation is far upstream with a lot of uncontrolled flow below.

<u>First, a discussion of what would be expected.</u> If the weather generation process added no variability to the sample of annual peak flows, each year in the 50-year record would always produce the same peak flow from one weather generation to the next. Each fitted LP3 would be the same, and the variance at the 1% quantile would be zero. Therefore, a variance of 0 would mean that the equivalent record length equals 50. On the other hand, if the weather generation process created in each case the equivalent to an entirely different event, the variance would be that computed for separate independent random samples of size N=50 (computed below). In fact, the results of the weather generations will produce a

variance somewhere between these values. Because the variance of a distribution quantile is proportional to N, we should be able to linearly interpolate the equivalent N from these variances.

Step 1: Find the error variance of the 1% LP3 quantile from frequency curves of independent samples of size N=50. A frequency curve was specified for the 50-year historical period based on model runs of actual daily data, having LP3 statistics ***of mean=3.7, standard.devation=0.4 and skew=-0.31***. 10,000 random samples of size N=50 were generated, and a LP3 curve fit to each sample using Bulletin 17B methods. Figure 1 shows 100 of the 10,000 fitted LP3 curves, along with the sample of modeled flows from the 50-year period and the specified LP3 curve. The variance of the 1% quantile of log10(flow) from these 10,000 estimates was ***variance = 0.014***. (A smaller sample size than N=50 would have generated a larger variance due to greater sampling error, and a larger sample size would have generated a smaller variance , and those variance values would be proportional to sample size N.)

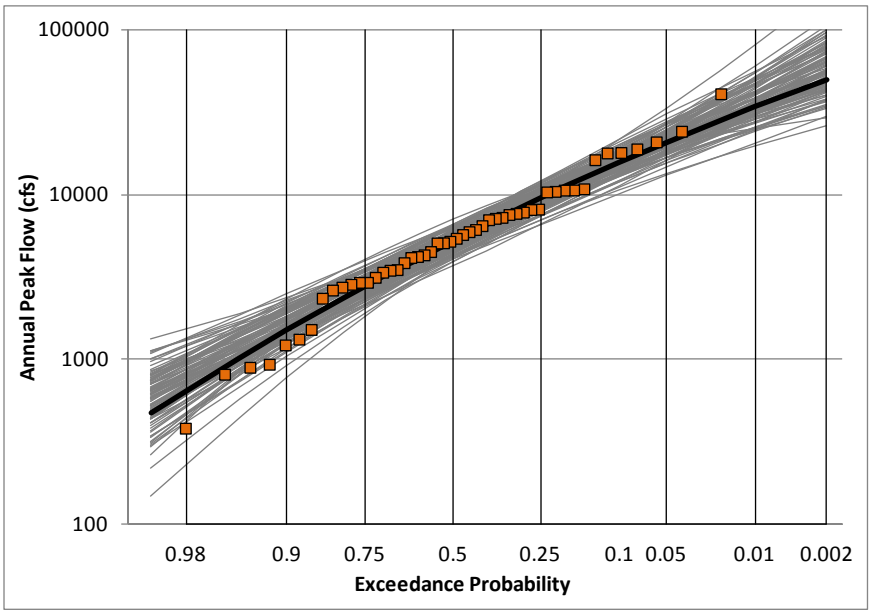


Figure 1. 100 independent random samples of size N=50, from base frequency curve, and modeled peak flows from actual historical daily data

Step 2: Find the variance of 1% LP3 quantile of the weather-generated peak flow records. In the analysis of climate projections, 10 "weather generations" were applied to each period, including the 50-year historical period and each of the three 30-year future periods. However, more than 10 values of the 1% quantile are required to estimate the variance somewhat accurately. Therefore, this analysis used 100 weather generations. So 100 separate daily 50-year records were generated from 100 weather generations on the historical monthly data, and each of those daily 50-year records was run through the models to produce the daily peak flows. Figure 2 shows the 100 annual peaks generated for each year of the historical record, so the variability added by weather generation can be examined. Red squares are observed peaks, and black squares are peaks modeled from daily data. Hollow circles are weather-generated peaks. The first figure has a linear flow axis, and the second has a log-flow axis. Note that for some historical years, all of the variability is above or below the value determined from modeling daily flow, and for some historical years the variability spans above and below.

An LP3 frequency curve was fit to each of the 100 samples of peak flow of size N=50. (As noted above, LP3 tends to be a good fit.) Figure 3, similar to Figure 1, shows the 100 fitted LP3 curves, one from each weather generation and subsequent model run. Note that the LP3 curves cluster more closely around the curve fit to the flows modeled from the actual historical daily data. This lower variability means that

the weather generation process adds less spread (and certainly less information, if any) than having independent random samples of size N, which was expected because the monthly total precipitation and average temperatures are the same. However, the fact that the variance is much greater than 0 means that some variability is being added. In fact, the variance of the 1% quantile of the log10(flow) is ***variance = 0.0053***, which is close to half the variance of the independent samples of size N=50.

The important question at this point is whether the added variability is in some way added information that can improve the limited sample sizes from these short periods of time of 30 and 50 years. If the weather generation results were always evenly spread above and below the peaks modeled from actual daily data, it would not seem that the added variability is actually added information. The proposition, however, is that since the weather-generated peaks sometimes spread asymmetrically around the peaks from the actual daily data, the use of the 102 years of historical monthly/daily patterns might flesh out an unrepresentative 30 or 50 year sample into one that is representative of the flood likelihoods of the period.

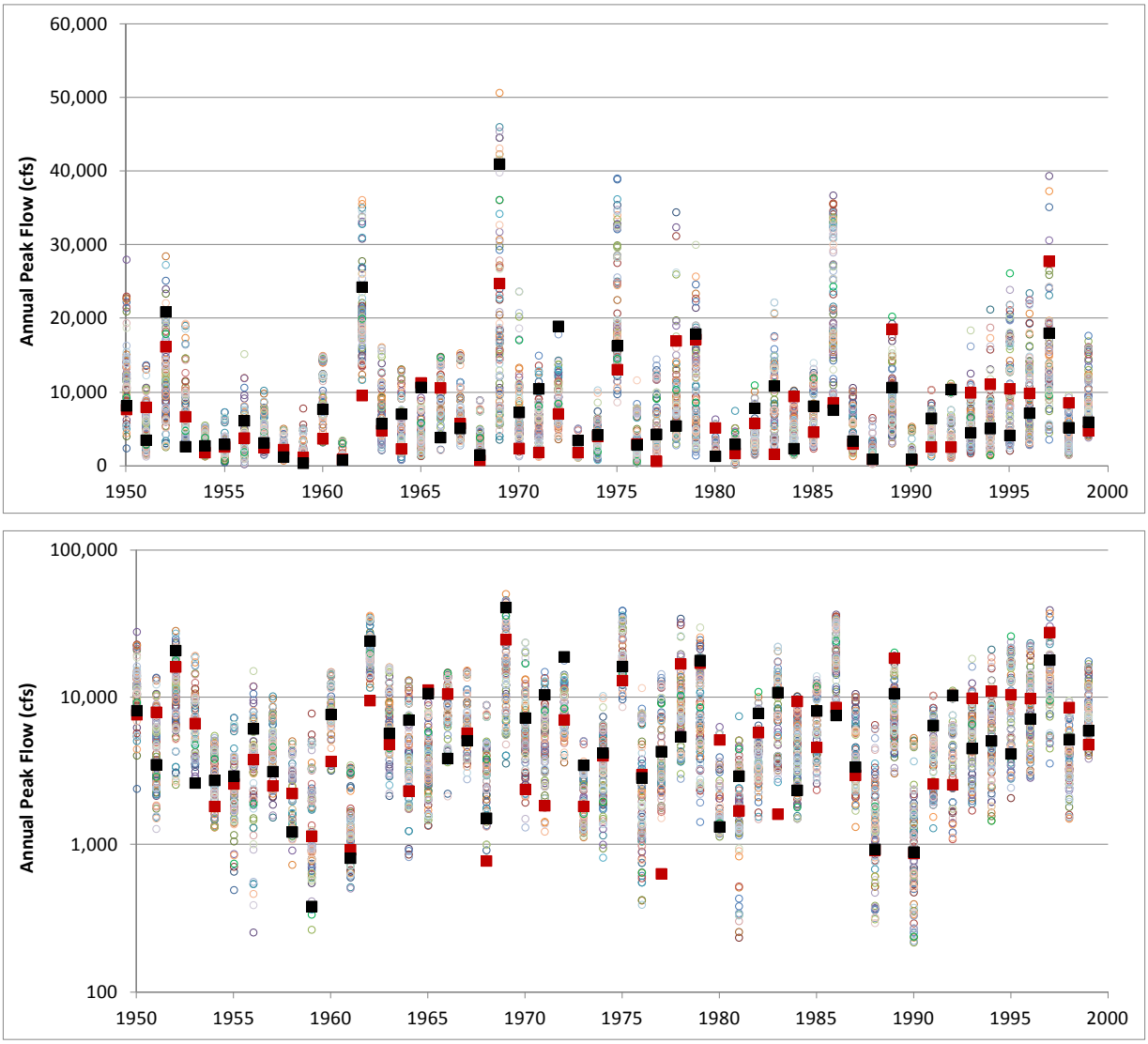


Figure 2. Annual Peak flows resulting from 100 weather generations of 1950-1999. Red squares are observed peaks, and black squares are peaks modeled from daily data. Hollow circles are weather-generated peaks.

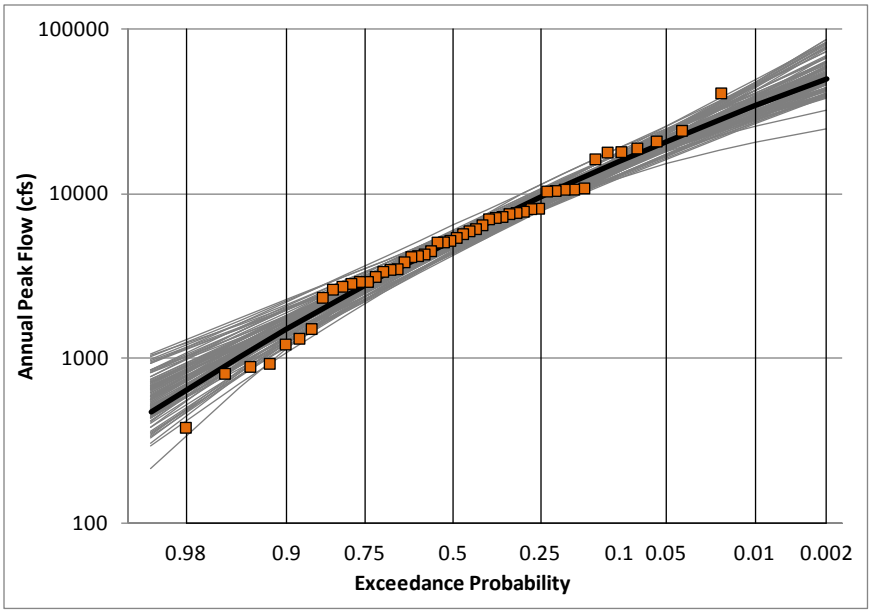


Figure 3. 100 LP3 curves fitted to the results of 100 weather generations on the 50-year historical record, and modeled peak flows from actual historical daily data

<u>Step 3: Determining equivalent record length</u>. Since the sampling error or variance at the 1% quantile is proportional to N, we can estimate an equivalent N by interpolating between the defined values. A variance of 0 would be produced if the weather generation added no variability and so no additional data, meaning the 50-year record is still equivalent to only 50 years. A variance of 0.014 would be produced is each weather generation created the equivalent of a new independent sample of N = 50 years. In this case, 10 weather generations would produce a 500 year record. Because the actual variance of the 1% quantile of the weather generated frequency curves was 0.0052, linearly interpolating between var=0 for N=50 and var=0.014 for N=500, we get var=0.0052 gives N=216. See Table 1 for a clearer view. This means that 10 weather generations on the 50-year historical record gives 500 peak flows that are the equivalent of a sample of size N=215. So when the 500 annual peaks are used to fit a single frequency curve, its equivalent record length is 215 years.

A further translation would say that each 10 weather generations on a single year of record create the equivalent of 4.3 years. So the same procedure performed on each future 30-year period would provide an equivalent record length of 30*4.3 = 129 years when all the annual peaks are used in a single frequency curve.

Table 1. Variance of the 1% quantile of an LP3 curve of log10(flow) of peak annual flow

equivalent record length	variance
50	0
N=216	0.0052
500	0.0142

Implications

There are two implications of this assessment of the equivalent value of 10 weather generations. One is that each sample of N=50 or N=30 years is expanded to a larger sample with more extreme values, making it possible to estimate graphical frequency curves to more extreme events without needing to fit an analytical distribution such as the LogPearson3. The other implication is that we can perhaps produce a more accurate frequency curve from each future 30 year period than would seem possible from having only 30 years. ***We produce a curve worth 129 years, but is it actually 129 years of information, which would correct some of the sampling error, or just the same distribution as from 30 years but with extreme values consistent with a 129 year record?*** If we have actually added more information, we can consider the 3 periods from each projection (or each of the 9 boxes) and perhaps see movement of the frequency curve between the periods.

Note, even if the second implication proves true, in this study we will be combining the results of the 9 projections to produce combined frequency curves for each period that span the range of all projections.

Challenge to the Concept

The challenge to this interpretation is whether the weather generations add enough variability, or the right variability, to actually correct the limited (perhaps unrepresentative) 30-year or 50-year sample to produce a more accurate frequency curve, or whether they simply expand each year's peak flow data points in a mostly uniform way (as any Monte Carlo simulation does), so producing the same unrepresentative frequency curve as from a single downscaling of the record. For example, if a given 30-year period happened to have two 100-year events, the frequency curve would be too high and steep. Would that same frequency curve result from combining the 10 weather generations of that 30-year period? The fact that the 100 weather generations produced frequency curves of the N=50 period that surround the original frequency curve of the actual daily temperature and precipitation values makes me fear that the weather generations will not correct the result of a non-representative sample in any given 30 or 50-year period.

Comment by MattF: I don't see how the weather generations do not add more variability and create a more accurate frequency curve. The use of different 1-day patterns has a huge affect on the flood hydrograph (either spreading the precipitation over three storms vs. 1). I thought the stochastic flood models did this, where different storm patterns were applied to the similar total storm depths. I would think the set of 10 weather generations would at least provide a curve worth 102 years, given the period of record used to sample time-patterns.

Appendix B. Application of HEC-HMS, HEC-ResSim, and HEC-WAT to the Red River of the North Climate Change Pilot Study

Introduction

Existing HEC-HMS and HEC-ResSim models were provided by the St. Paul District (MVP). Two separate HMS models were provided, 1) an HMS model of the Red River at Hickson, which was developed by a contractor for the Accelerated CWMS Deployment effort in 2010 and 2) an HMS model of the Wild Rice River which was develop for a flow frequency analysis by MVP. The ResSim model was also developed by a contractor as part of the Accelerated CWMS Deployment work. Significant modification to the existing models was required for their application to the climate change study, which are described in this report. The Watershed Analysis Tool (HEC-WAT) was used to manage data and simulations for the many model simulations required for this study (360 separate simulations were required). Discussion of the application of HEC-WAT to facilitate the model simulations is included in this report as well.

One of the outputs from the model simulations was regulated flows at Fargo, as generated by the HMS and ResSim models. Annual maximum peak flows were extracted and used to estimate how the regulated flow frequency curve might respond to future meteorologic conditions. The meteorologic data used by the HMS model was obtained from the Coupled Model Intercomparison Project (CMIP), which contains spatially downscaled and bias corrected precipitation and temperature data from numerous climate projections. The climate projection data was obtained by MVP from 1950 - 2099. Specifically, the study was looking at regulated flows for the Red River at Fargo, ND. Figure 1 shows a map of the study area. There are two USACE dams located upstream of Fargo, White Rock Dam on the Bois De Sioux and Orwell Dam on the Otter Tail River. These dams operate to reduce flooding at Hickson. Note the drainage areas in Figure 1: 1160 square miles at White Rock Dam, the Otter Tail watershed is 2043 square miles but 1585 square miles do not contribute to runoff (only 245 square miles upstream of Orwell Dam contribute to runoff), the Wild Rice Watershed is 2254 square miles, and the total drainage area at Fargo is 6448 square miles.

Modifications of Existing HEC-HMS and HEC-ResSim Models for the Climate Change Study

Regulated flows at Fargo were modeled using calibrated HMS and ResSim models. HMS was used to model the precipitation-runoff process (including snow accumulation and melt). Runoff hydrographs from HMS were input as boundary conditions for the ResSim model which modeled operation of White Rock and Orwell dams. The ResSim model also routed regulated flow to Fargo while combining unregulated flow from the Wild Rice watershed (computed by the HMS model).

The calibration process involved merging the separate Wild Rice and Red River HMS models into one model and then making major modification to the models so that they were able to reproduce observed flow for the 1997 and 2006 events as well as a continuous period-of-record simulation, 1950 - 1999.

Figure 2 shows a schematic of the HMS model. The subbasin icons, , represent subbasins within the model where hydrologic processes are modeled to generate a runoff hydrograph. These hydrographs are routed downstream and combined with other hydrographs. Notice the level of detail in the Wild

Rice and Red River models is different, the Wild Rice model has many more subbasin elements where the drainage are per subbasin is much smaller. One important consideration when developing a model is its application. The Red River HMS model was developed to be applied as a forecast model. The Wild Rice model was developed for a flow frequency application. These are two different applications that require different levels of detail. A forecasting application requires a model that is easy to modify and quick to simulate in order to provide timely forecasts, while a flow frequency analysis might need the ability to define flows at multiple points in the watershed for floodplain mapping. For the climate change study, the HMS model was used to simulate long time periods, 50 years. A detailed model, like the Wild Rice model, is not the best candidate for continuous simulation due to the amount of data generated and excessive simulation run times. The level of detail of the Red River HMS model was adequate for a continuous simulation model.

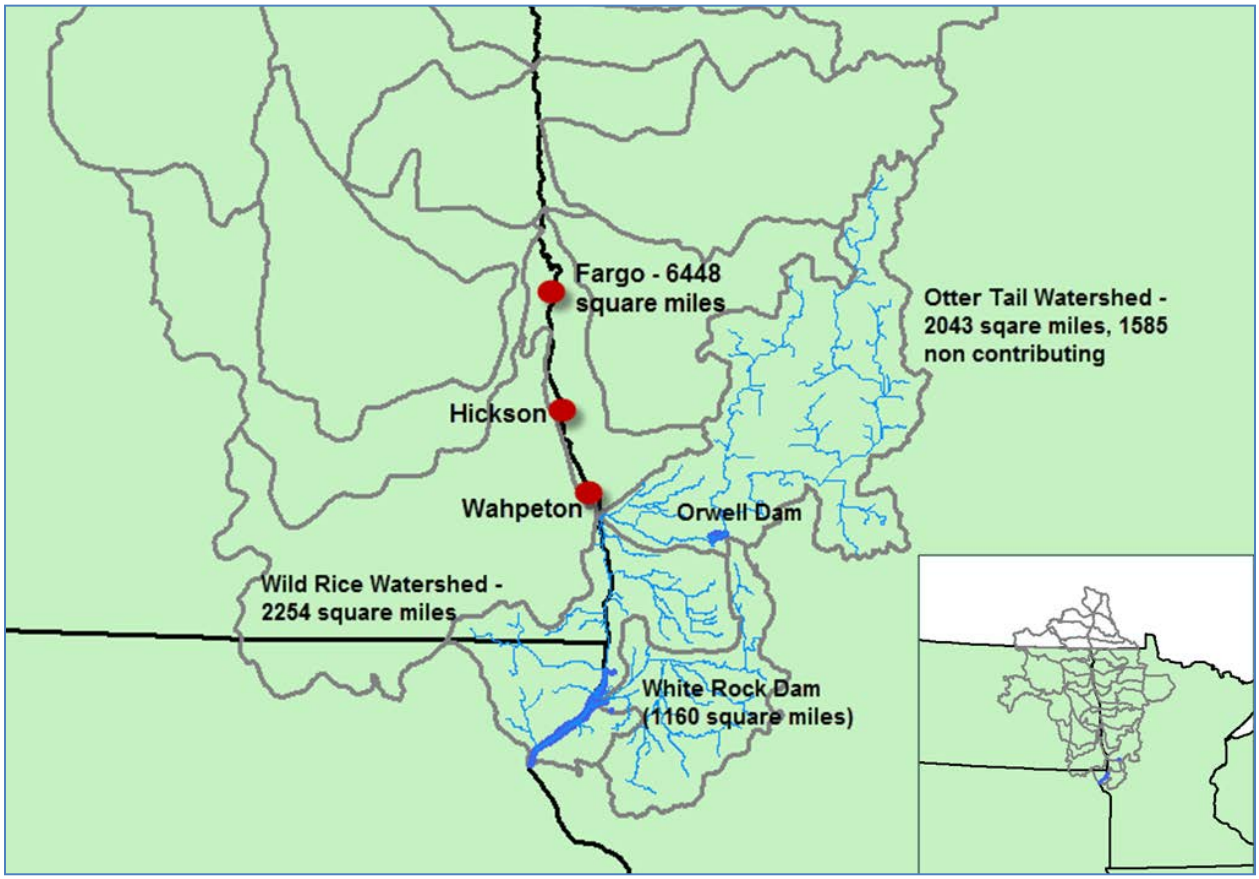


Figure 1. Study Area for the Red River Pilot Climate Change Study.

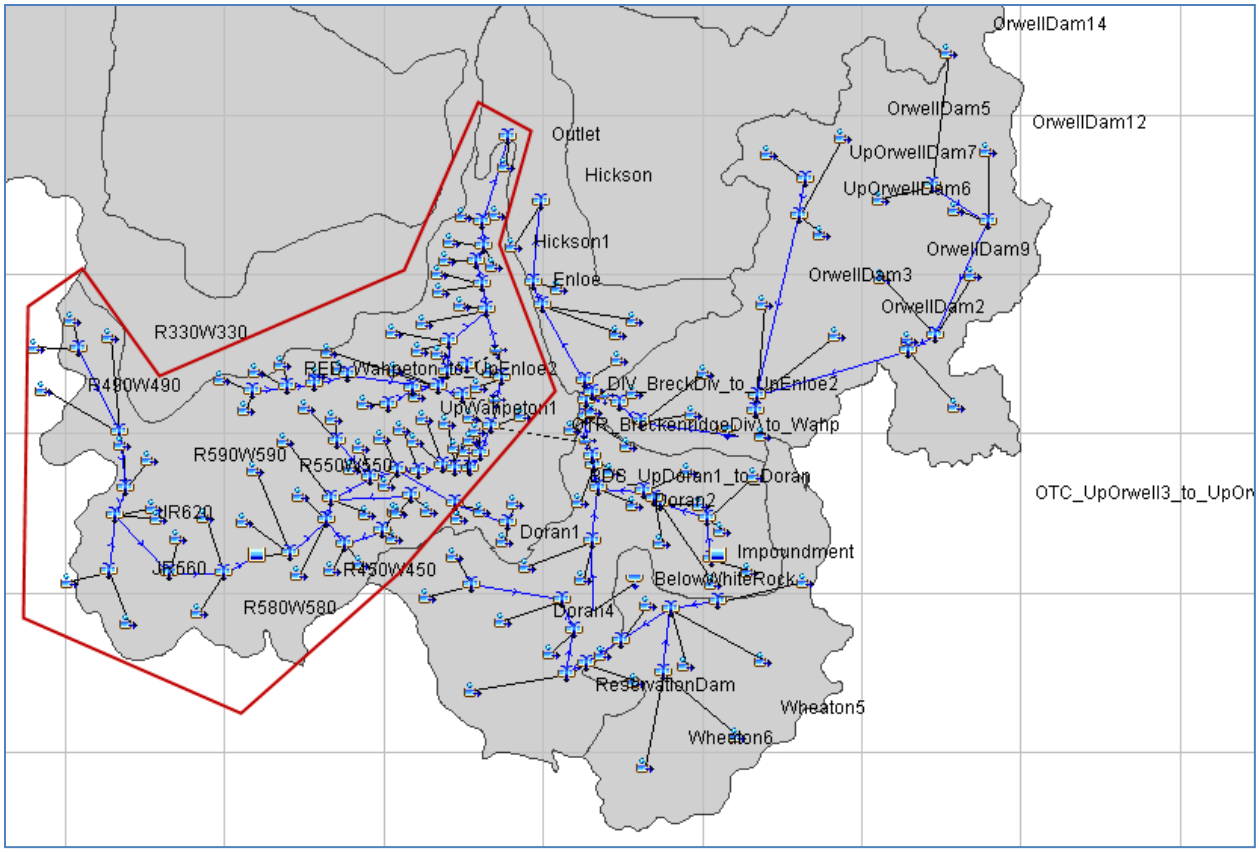


Figure 2. Schematic of HEC-HMS Model.

The combined Wild Rice and Red River HMS models were calibrated for 2 large historic flood events before calibrating the model to a continuous period, 1950 – 1999. Hourly precipitation data (downloaded from the National Climatic Data Center (NCDC)) was used to calibrate the model. The hourly precipitation data was only available at two gages in the basin, Fargo and New Oaks. In addition to the hourly NCDC data, the gridded precipitation data in the CWMS model in the 2010 study was also used; a precipitation gage was created by taking the average of all grid cells. It's not clear from the 2010 CWMS report how the gridded precipitation was developed for the 1997 event, but for the 2006 event, the gridded precipitation was radar data from the National Weather Service. The hourly precipitation data originally used to calibrate the Wild Rice model was not used in this analysis; this data did not match observed data gathered from the NCDC.

The biggest changes made to the HMS models for the initial calibration simulations were modifications to the snowmelt method and modification to the transform method (the complete list of changes is contained below). Both the Red River and Wild Rice HMS models were developed using different snow accumulation and melt parameters; because the models were combined, one set of parameter was required. In addition, the Red River HMs model was converted from gridded to subbasin average because 1) the Wild Rice model was not gridded and it would have taken significant effort to modify it for gridded simulations and 2) simulation time and output generation would be prohibitive for multiple 50 year and 30 year gridded simulation periods. Issue 2 should improve as enhancements are added to HMS to speed up gridded simulations and limit storage of simulation results.

Figure 3 and Figure 4 show a comparison of simulated and observed flow at Fargo for the 2006 and 1997 flood events. There is good agreement in simulated and observed flows for the 2006 event but the simulated peak flow is about 13 percent lower than the observed flow for the 1997 flood event. Evaluation of flow and precipitation data show a majority of this difference at Fargo is due to simulated flows on the Wild Rice for the second flood wave (Apr 15 – 20). There is no precipitation measured at the New Oakes gage for this period. The temperature did drop below freezing on April 6th. This could have slowed the snowmelt until temperatures warmed again (daytime temperatures at the Fargo gage did not go above 40 degrees F until April 12th). A more exhaustive search for precipitation and temperature data is needed to improve results for the 1997 flood, the use of two gages is not adequate.

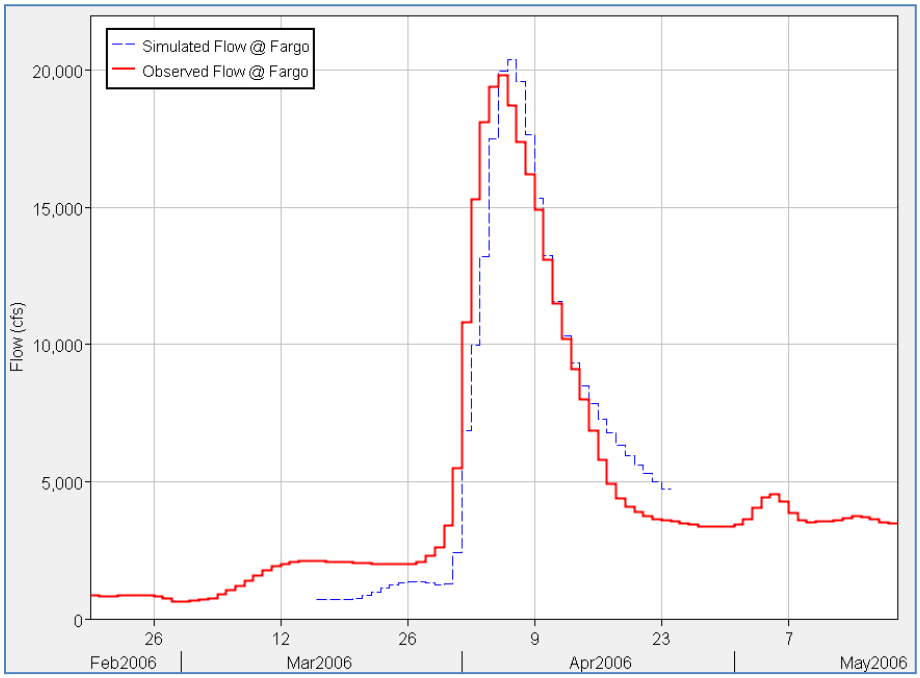


Figure 3. Simulated and Observed Flow for the 2006 Flood.

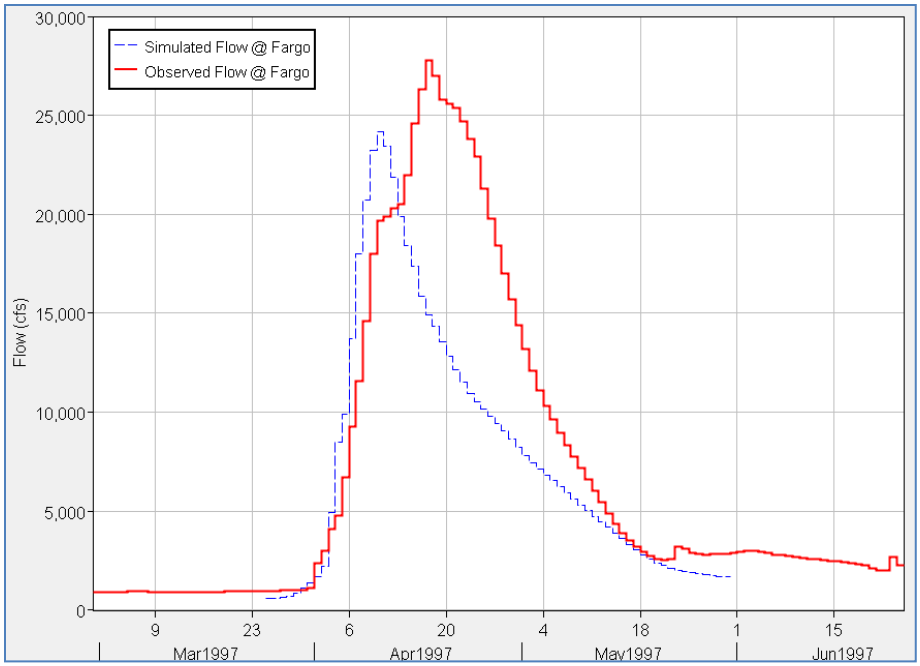


Figure 4. Simulated and Observed Flow for the 1997 Flood.

Due to long simulation times and the amount of output generated when using a 1-hour simulated time step, it was decided to run the HMS model at a daily simulation time-step. Daily precipitation and temperature data were gathered from the U.S. Historical Climatology Network (USHCN) for a number of gages in the basin. Figure 5 shows the location of the daily gages. (Note, there are not very many gages for this study area and really only one gage within in watershed.) The ResSim model was also simplified to reduce the simulation time. Operation rules that had no or little impact on flood flows at Hickson were removed from the model.

Simulation of the different climate model projections required continuous simulation, which includes evaporation/transpiration. The HMS models provided by MVP were only developed for single events. The loss method was changed to deficit and constant in order to model evapotranspiration removing water from the soil layer. The user specified evapotranspiration method was selected within the meteorologic model and requires the user to create a time-series of potential evaporation. The Hargreaves method was used to calculate the evapotranspiration time-series given temperature and latitude. An additional assumption was made that all evapotranspiration was basically 0 inches during colder months. The Hargreaves method was also used to compute potential evapotranspiration using temperature data from the climate projections.

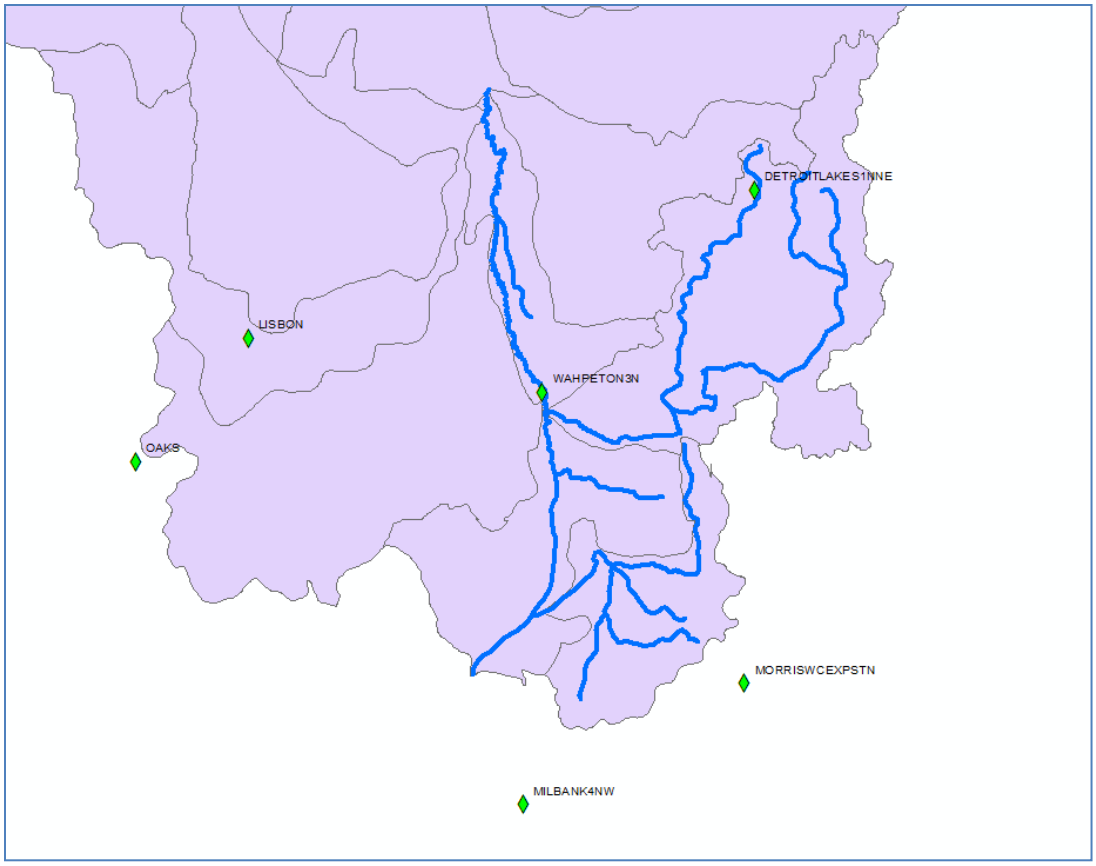


Figure 5. Location of Precipitation and Temperature Gages used to Calibrate the Model.

Below is a list of modifications made to the HMS and ResSim models in preparation for continuous simulation using climate projections.

1) The models were imported and run with HMS version 4.0 beta.
2) The Wild Rice HMS model was imported into the Red River HMS project.
    a. Since the Wild Rive model was developed in a different coordinate system, the element icons were manually located to their appropriate location adjacent to the icons representing the Red River elements (Figure 2).
    b. For subbasin elements in the Wild Rice basin, the subbasin loss method was changed to deficit constant (for continuous simulation).
    c. During calibration to the 1997 and 2006 events, unit hydrograph parameters were modified in the Wild Rice subbasin elements.
    d. For Subbasin elements in the Wild Rice, the baseflow parameters were modified to be consistent with the Red River elements.
3) The models originally contained many basin models and meteorologic models. Only the 1997 and 2006 event models were kept since the combined model was calibrated to these events.
4) The conversion of the CWMS model to non-gridded involved:
    a. Changing unit hydrograph parameters from Mod Clark to Clark

b. A meteorologic model was created to work with precipitation gages as well as the temperature index snowmelt method. Only one elevation band is used per subbasin (assuming that temperature is consistent throughout the subbasin).
c. The meteorologic model incorporated subbasins in both the Wild Rice and Red River basins. Evapotranspiration was added for the subbasin elements in the Wild Rice model.

5) The meteorologic models from the Wild Rice and Red River models were very different, the snowmelt parameters were not consistent with snowmelt parameters in the Red River model. There were aspects of the Wild Rice snowmelt model that were not correct; mainly the melt rate used when rain on snow occurred (it was lower than the dry melt rate). Therefore, an effort was made to develop a snowmelt model that worked for subbasin elements in both the Wild Rice and Red River models (these models were combined so only one meteorologic model is required). This involved calibrating the snowmelt model to both the 1997 and 2006 events. Note, the Wild Rice model did not use snowmelt for the 2006 event and it used daily precipitation. An effort was made to incorporate snowmelt and hourly precipitation for the 2006 event for the subbasin elements in the Wild Rice portion of the combined model.
6) The precipitation and temperature gages used by the Wild Rice model are not consistent with published data. The Wild Rice portion of the combined model was calibrated as much as possible given the readily available precipitation and temperature data. Additional data will improve results for the 1997 flood shown in Figure 4.
7) Loss rates and unit hydrograph parameters were adjusted when calibrating the model. Adjustments were made when calibrating the model to the single events and when calibrating the model to a continuous period of record.
8) Only the Network named **Synthetic Event_Regulated** was saved in the ResSim model (ResSim version 3.2, build 1170). All other networks, alternatives, and simulations were deleted.
9) The model was extended to Fargo. The Coefficient Routing method was used to rout flows from Wahpeton to Fargo. Model parameters were calibrated to the 1997 and 2006 events.
10) The ResSim model was linked to output from the HMS model.
11) A period of record (1950 – 1999) simulation was created in the ResSim model. The ResSim model was slightly modified for continuous simulation and to decrease compute times from 45 minutes to 15 minutes for one 50 year simulation.
    a) Rate of change rules were removed from the reservoirs. These had little effect on flows at Fargo.
    b) Evaporation was added to the reservoirs.
    c) The backwater and Breckenridge diversions were removed from the model. These have little effect on flows at Fargo.
12) After the HMS model was calibrated to the two historic events, the 1950 – 1999 simulation was created. This simulation was set up to use daily precipitation and temperature data from the USHCN dataset, gage locations are shown in Figure 5. Gages were assigned to the closest subbasins; this was done visually since no GIS layer of subbasin boundaries was provided. Below are changes to the model/data for the 50 year simulation.
    a) A time-series of potential evapotranspiration was computed using the average temperature at Wahpeton. The Hargreaves method was used to compute this dataset.

b) The simulation time-step was increased to 1-day. The HMS model takes about 8 minutes to run a 50 year simulation and 700 mb of data is generated.
c) Because the simulation time-step changed and because the model is now using daily data, the model was re-calibrated to observed flow data at Fargo. Loss rates and maximum deficits were adjusted as well as snowmelt modeling parameters.
d) A few modifications were made to the historic data. 1) Precipitation data was manually adjusted so that the 1-day total was never greater than 3 inches. The gage data represents point measurements. It might have rained more than 3 inches at one of the gage, but this high intensity was likely not observed over a large area. The HMS model was overestimating runoff without this change to the observed precipitation data. 2) The average temperature time-series for the 1997 flood was modified. Initially, no runoff was generated for the 1997 flood. The reason was the average temperature for Apr 6, 1997 was below 32 degrees and the Wahpeton gage recorded a majority of the precipitation for this event on April 6th. This is different than the hourly data at Fargo and other gages in the basin that show a majority of the precipitation on the 5th (when it would be all liquid). It's possible the 1-day precipitation from the USHCN dataset represents the precipitation measured from 1200 on one day to 1200 on the next, not the total precipitation for the 24 hour day. Figure 6 shows a comparison of observed daily precipitation at Wahpeton and hourly precipitation at Fargo for the 1997 flood.
e) A number of routing reaches were removed from the HMS model. This was due to the fact that ResSim is being used to route and combine flows to Fargo. This helped speed up the simulation time for the HMS model.
f) As mentioned in the 2010 CWMS report, the area upstream of Orwell and White Rock dams was never "calibrated" in the HMS model. The model was originally set up so that all subbasins upstream of Orwell Dam contributed to runoff even though a significant portion of this area does not generate runoff. Subbasins upstream of the dams were modified to improve simulation results downstream of the reservoirs.

Figure 7 and Figure 8 show observed and simulated peak flows from the 50 year simulation (output from the ResSim model). Figure 7 shows the models both over predict and under predict peak flows. Figure 8 shows similar regulated flow frequency curves would be fit to the observed and simulated data. The larger inconsistencies in observed and simulated flow in Figure 7 can be explained when looking at daily precipitation and temperature data used by the HMS model. As mentioned in bullet 12-d above, the precipitation data at the Wahpeton gage was not consistent with data from other gages for the 1997 event. Since this gage is used by a majority of the subbasins downstream of the reservoirs, it has a large impact on simulated flows. The April 1969 event is another example where the temporal scale and spatial resolution of the observed precipitation and temperature data is probably not adequate for modeling this flood. For this event, the HMS and ResSim models simulate approximately 44,500 cfs while the observed flow is around 25,000 cfs. The precipitation gages are reporting about 2 – 3 inches of precipitation on April 8th and 9th and the daily average temperature is around 40 degrees for this period. The HMS model is treating this event as a rain on snow event, so most of the snowpack is melting in addition to the 2 – 3 inches of rainfall. However daily minimum temperatures for this event

show values close to freezing. A more detailed analysis of the precipitation and temperature data is needed to improve simulation results for this event. It's possible that modeling this event at a 1-day time-step is not appropriate given its complexity.

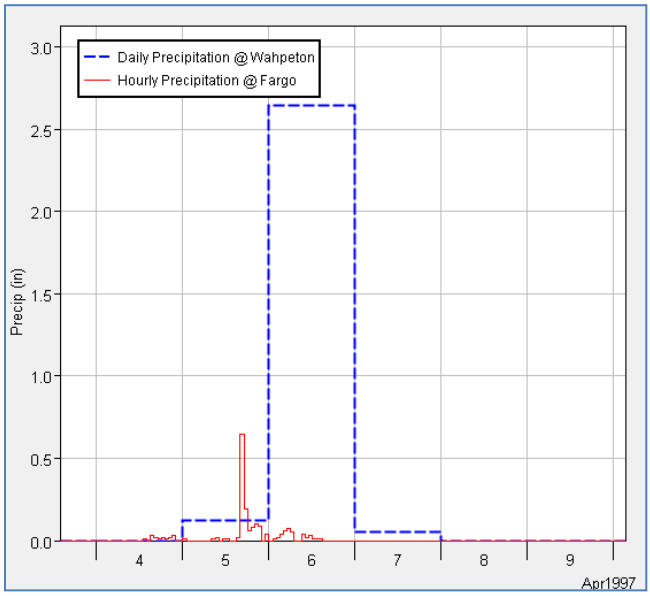


Figure 6. Comparison of Observed Hourly Precipitation at Fargo and Daily Precipitation at Wahpeton for the 1997 Flood.

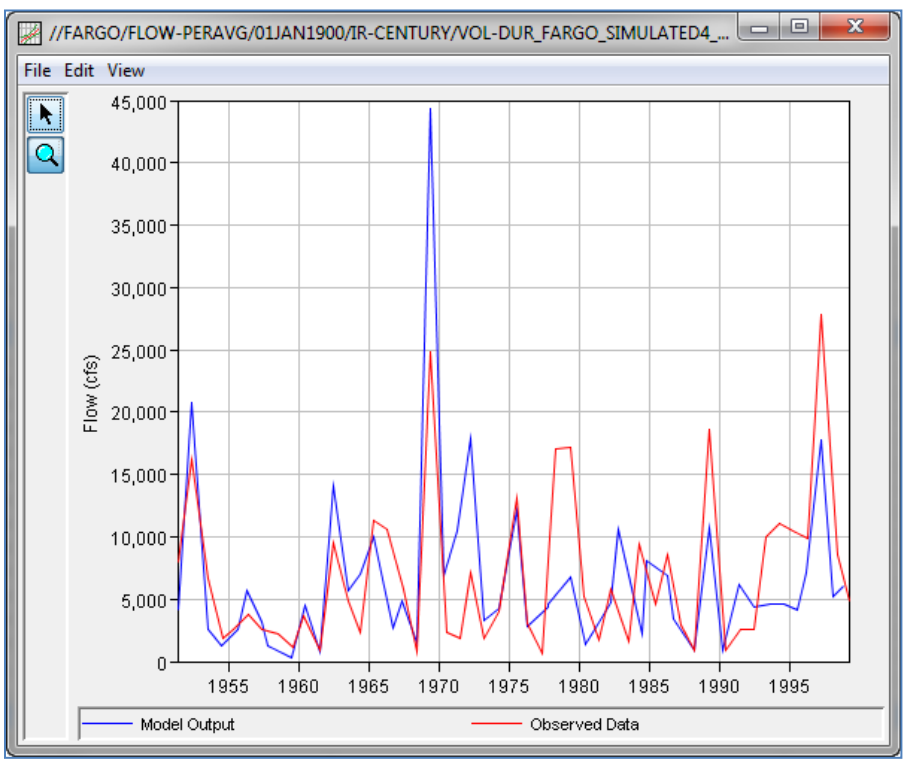


Figure 7. Comparison of Simulated and Observed Annual Maximum Flow at Fargo for 1950 - 1999.

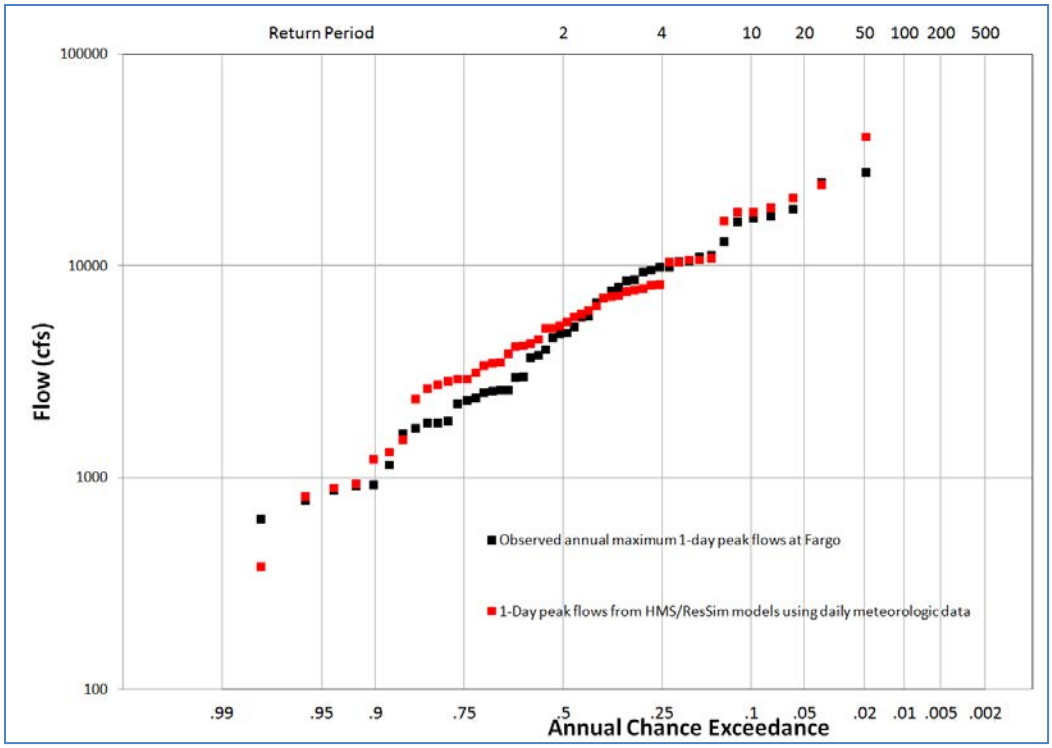


Figure 8. Observed and simulated 1-day flow at Fargo.

Use of HEC-WAT for Running Numerous Climate Model Projections

After calibrating the models to observed data, they were applied to numerous simulations using meteorologic data from the climate projections. Nine different climate projections were chosen for the four simulation periods; a historic period, 1950 – 1999, and the three future periods, 2010 – 2040, 2041 – 2070, and 2071 – 2100. A statistical downscaling technique was used to take the monthly data from the climate projections and downscale it to a 1-day time-step. For each climate projection, 10 sets (precipitation, temperature, and evapotranspiration) of 1-day data were generated. Each set of 1-day data is referred to as a weather generation. Therefore, there are 9 (climate projections) * 10 (weather generations per climate projection) = 90 datasets for each of the 4 periods. This results in 360 different continuous simulations using the weather generation datasets.

HEC-WAT was used to manage input and output data and to facilitate the numerous simulations required. HEC-WAT is currently under development and its application will likely change as improvements are made to both WAT and how HMS functions within the WAT environment. Both the HMS and ResSim models were imported into a HEC-WAT project. Before the HMS model was imported, modifications were made to improve its application, below is the list of changes.

1) Only one basin model was kept in the HMS project. The final basin model, “CalibratedBasin” contains the final parameters from the 50 year period-of-record simulation.
2) The HMS model was set up to run 10 simulations only. All weather generation from one climate projection were included in the HMS project. Figure 9 shows part of the HMS model. Notice there are separate meteorologic models and precipitation gages for each weather generation.

Since there are 10 weather generations and 6 gages being used (Figure 5), there are a total of 60 precipitation, 60 temperature, and 60 evapotranspiration gages in the HMS model. The gages point to an external DSS file in the HMS project directory. The meteorologic model and gages only had to be set up one time. The WAT project directory (which includes the HMS and ResSim model files) were simply copied and the base folder was renamed for each of the climate projections. For example, the folder named RedRiver_ClimateStudy_20112040_proj1 would be used for simulation of the 10 weather generations for climate model 1, during the period 2011 through 2040. This approach resulted in 36 different WAT projects with the same structure. The only major difference in the 36 WAT projects is that the data in the DSS file containing precipitation, temperature, and evapotranspiration data (for example, \RedRiver_ClimateStudy_20112040_proj1\hms\data\1stperiod10.dss) is different. This data DSS file was renamed for each of the simulation periods, HistoricTest10.dss for the historic period, 1stperiod10.dss for 2011 – 2040, 2ndperiod10.dss for 2041 – 2070, and 3rdperiod10.dss for 2071 – 2099. The HMS model was modified to look for the correct DSS file based on the simulation period.

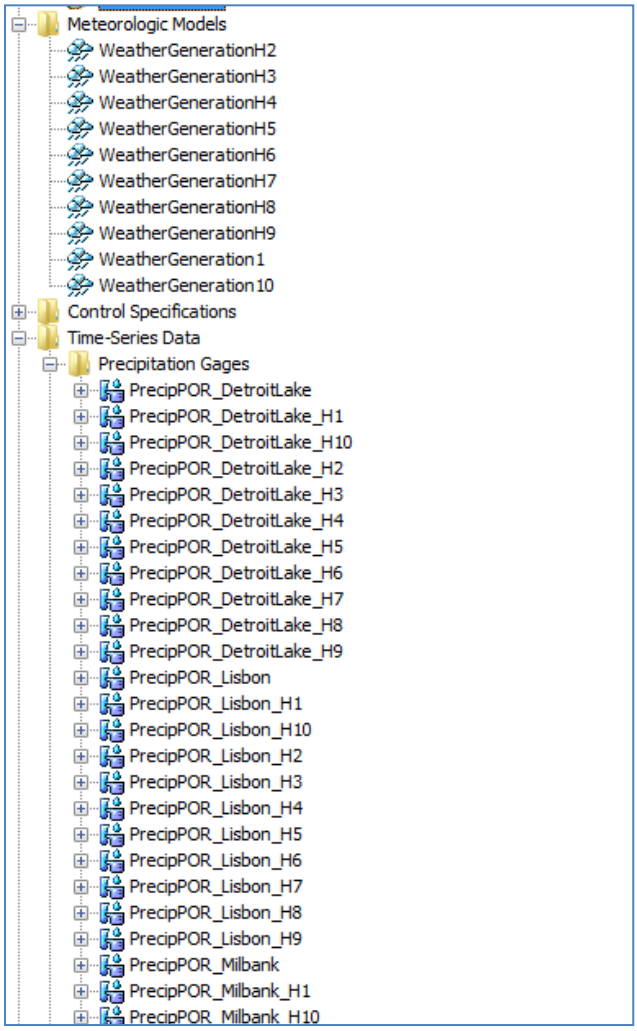
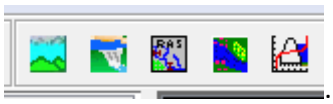


Figure 9. Snapshot of the HMS Model Imported into the WAT Model.

When the HMS and ResSim models were imported into the WAT project, a copy of the HMS and ResSim project files were automatically placed in the WAT project directory. Figure 10 shows the file structure for one of the 36 WAT projects. The ResSim model files were saved to the “rss” folder and the HMS model files were saved to the “hms” folder. Figure 11 shows part of the Red River WAT model. Through the WAT interface, you can access the HMS and ResSim models; click the HMS or ResSim icons to open these programs  . Notice in Figure 11 that the HMS “Model” is selected in the WAT tree and the panel in the lower left shows the 10 simulations created in the HMS project (there is a separate simulation per weather generation). Only one ResSim alternative was required for this study.

Name	Date modified	Type	Size
autorss	5/7/2013 7:58 AM	File folder	
fia	6/6/2013 10:38 AM	File folder	
hms	5/7/2013 7:59 AM	File folder	
layouts	5/7/2013 7:59 AM	File folder	
maps	5/7/2013 7:59 AM	File folder	
rss	5/7/2013 7:59 AM	File folder	
runs	1/8/2013 9:10 AM	File folder	
shared	5/7/2013 7:59 AM	File folder	
study	5/7/2013 7:59 AM	File folder	
supplemental	5/7/2013 7:59 AM	File folder	
w2	5/7/2013 7:59 AM	File folder	
wat	5/7/2013 7:59 AM	File folder	
contacts.xml	11/30/2012 10:25 AM	XML Document	1 KB
Default.ag	11/16/2012 1:38 PM	AG File	1 KB
HistoricPeriod.sch	11/25/2012 2:26 PM	SCH File	1 KB
modelAltInfo.xml	11/30/2012 10:25 AM	XML Document	1 KB
programOrder.xml	11/19/2012 1:50 PM	XML Document	3 KB
RedRiver_ClimateStudy.log	6/6/2013 10:38 AM	Text Document	26 KB
RedRiver_ClimateStudy.log.bak	12/27/2012 10:25 AM	BAK File	26 KB
RedRiver_ClimateStudy.sty	12/27/2012 10:25 AM	STY File	14 KB
RedRiver_ClimateStudy.sty.bak	12/27/2012 10:22 AM	BAK File	14 KB
RedRiver_ClimateStudy.wksp	12/27/2012 10:25 AM	WKSP File	3 KB
RedRiver_ClimateStudy.wksp.bak	12/27/2012 10:25 AM	BAK File	3 KB
stream.align	12/27/2012 10:25 AM	ALIGN File	43 KB
stream.align.bak	12/27/2012 10:22 AM	BAK File	43 KB

Figure 10. WAT Project Directory for one of the Climate Projections.

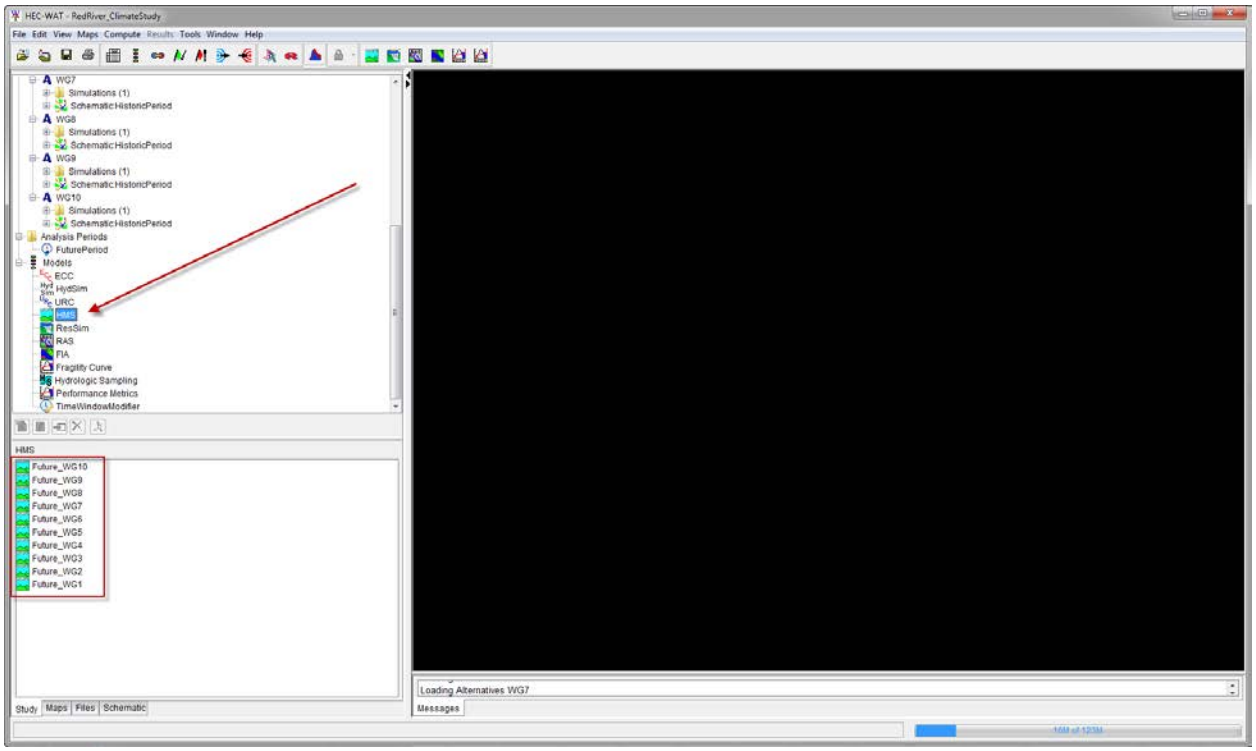


Figure 11. HEC-WAT Model of the Red River.

The following is a brief description of the components used to configure simulations within the WAT model.

- The WAT requires an analysis period; this is the time window for the simulation. The WAT passes the analysis period to the individual models, HMS and ResSim, when telling those models to run a simulation within the WAT compute.
- An alternative is used within WAT to configure a simulation. For this application, a separate WAT alternative was set up for each weather generation (for one climate projection).
- The WAT requires a program order be defined. This program order is used to set the order that the individual models are simulated in the compute sequence. For the Red River application, the program order is HMS and then ResSim.

Once a program order, alternative, and analysis period are defined, simulations can be created. Figure 12 shows the 10 alternatives and corresponding simulations for one climate projection. Notice the same ResSim model is used for all 10 weather generations, but a different HMS model is used for each simulation.

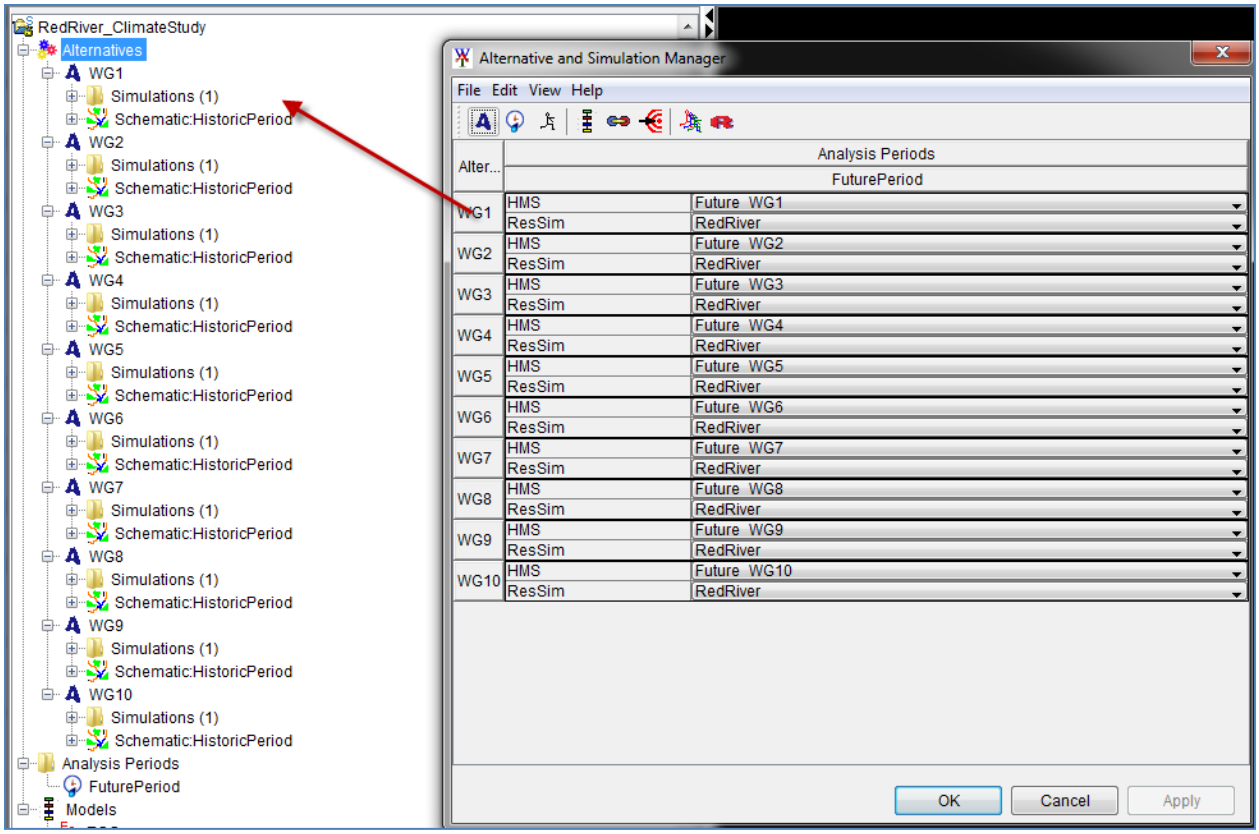


Figure 12. Alternatives and Simulations Defined in Red River WAT Model.

The models were linked together from the WAT using the model linking editor. Figure 13 shows the linking editor for 1 alternative. Notice that output from the HMS model simulation (Future_WG1) is being linked to the ResSim alternative (RedRiver). Currently, it is not possible to link the HMS model, all linking was taken care of through the HMS interface; precipitation, temperature, and evapotranspiration gages were linked to the external DSS file mentioned above.

The WAT Compute Manager was used to run all 10 simulations (10 different weather generations for 1 climate projection) in the WAT project. Figure 14 shows the compute manager for the Red River project. All 10 simulations can be run in a batch mode by checking the box and clicking the compute button, this is ideal for the Red River model. It takes about 8 hours for all 10 simulations to run. Using the batch simulation tool allowed for all 10 simulations to be run overnight. Because the 360 simulations were broken up into 36 different WAT models, multiple computers were used to complete all simulation. The HEC classroom computers were utilized to finish all 360 simulations in about a 5 day period.

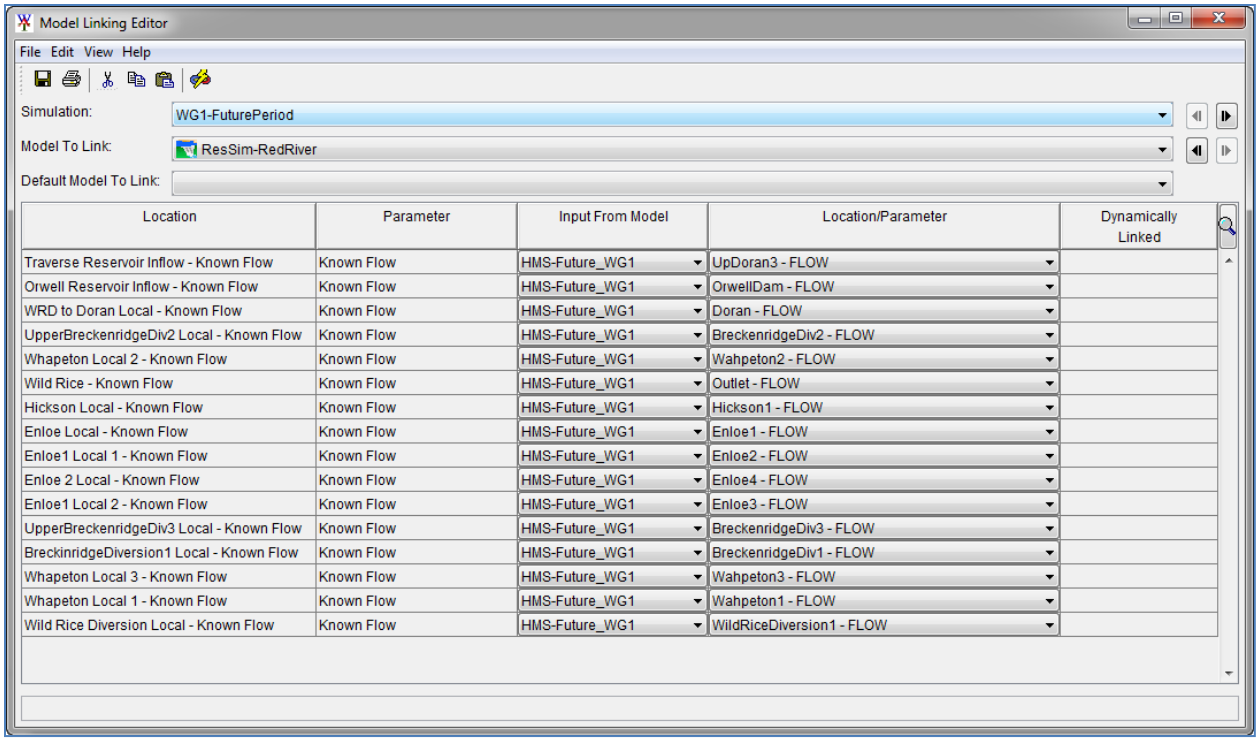


Figure 13. WAT Linking Editor for One Simulation.

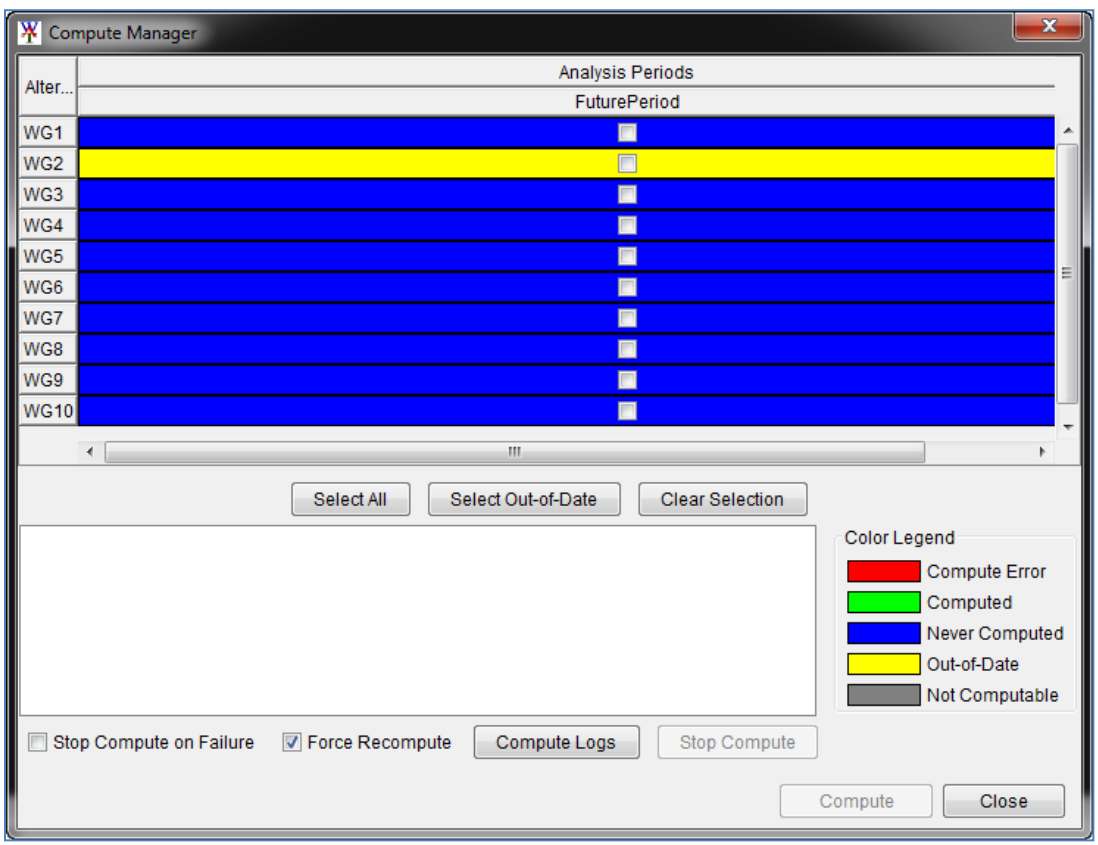


Figure 14. WAT Compute Manager.

Output from a WAT simulation is saved to the "runs" directory. Within the "runs" folder, a new directory is created using the name of the alternative and analysis period. For example: the directory RedRiver_ClimateStudy_8square_**20112040_proj1**\runs**WG1**\FuturePeriod\ contains output from weather generation 1, climate projection 1, period 2011 – 2040. Within this directory, output from HMS and ResSim are saved to the WG1-FuturePeriod.dss file. One thing to note with the current version of the software, HMS saves data for all simulation runs to the root HMS folder within the WAT project. This is duplication of the data in the WAT runs directory. Periodically, the output DSS file in the "hms" folder should be deleted. Application of HMS by WAT has been improved after the completion of this study. HMS will no longer save output to the root "hms". Instead, HMS will copy model files to the runs directory and run the simulation from that location; this is how the other applications function within a WAT compute.

The output extracted from the simulation DSS files included the flow time-series at Fargo computed by the ResSim model, Figure 15. There is a separate DSS file per simulation and there are a total of 360 simulations. The regulated flows at Fargo were extracted from all 360 simulations for further analysis. This was done manually using HEC-DSSVue, but a script could be used to automate this process (a script was used to extract precipitation and temperature data from the simulations).

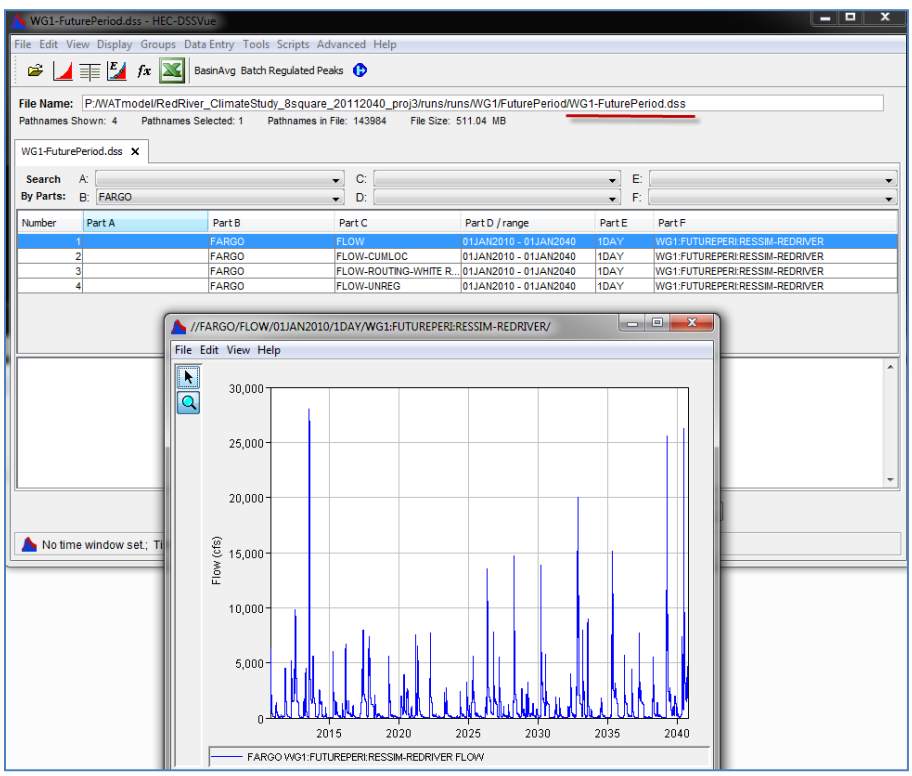
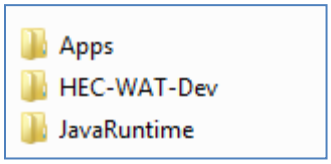


Figure 15. Regulated Flow Time-Series at Fargo from the Combine HMS and ResSim Models.

Installation of HEC Software

The WAT, HMS, and ResSim software used for this study has been provided to MVP. Currently, there is not an official install package for HEC-WAT. However, there is a portable version of software that can be copied to the C:\Programs directory on a computer. Currently the software is contained in a folder named HEC-WAT (place this folder in the C:\Programs directory). Within the HEC-WAT folder there are a number of directories, Apps, HEC-WAT-Dev, and JavaRuntime. The Apps folder contains the HMS and ResSim software. The HEC-WAT-Dev folder contains the WAT software and the JavaRuntime folder contains the version of Java the WAT uses.

To start the WAT, double click the wat.exe file in the HEC-WAT-Dev directory. To make sure both HMS and ResSim open when the WAT opens, select the Tool→Option… menu option. On the Plug-ins tab, make sure HmsPluginClient and ResSimPluginClient are checked. If they were not checked, then you will need to close and restart the WAT.



WAT Models

All 36 WAT models used for the 360 simulations can be provided. If additional simulations are desired then a handoff of the "base" models is straight forward. There is a base model for each simulation period, 1950-1999, 2011-2040, 2041-2070, and 2071-2099. For example, the base model for the historic period is in a folder named "RedRiver_ClimateStudy_HistoricPeriod". This WAT model has already been configured to run between October 1949 and September 1999. The other base models have been configured to run within their respective periods. The only modification needed to these projects would be to append additional text to the folder name to identify what climate projection it was used for and to edit the input DSS file used by the HMS model; located in the **…\hms\data** directory.