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Hydrologic Modeling of Climate Scenarios for Two Illinois Watersheds

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Abstract

Watershed modeling applications for the Fox and Iroquois River watersheds in Illinois were used to evaluate the response in simulated streamflow to various climate scenarios. The climate scenarios applied to both watersheds are based on simulations from two global climate models, the Japan and Hadley models, which respectively represent comparatively “dry” and “wet” scenarios of future climatic conditions. The “Dry” climate scenarios result in a considerable reduction in the simulated flows for both modeling applications, although the specific amount of reduction varies considerably between the two applications. The “Wet” climate scenarios cause relatively small amounts of change in simulated streamflow amounts. For the Fox River watershed, changes in most flow parameters for the “Wet” scenario are less than 10 percent; whereas for the Iroquois River watershed, the changes are generally less than 15 percent. In particular, results indicate that increases in precipitation values may not necessarily translate into increased flooding conditions if also accompanied by warmer temperatures. The two watershed applications use different hydrologic simulation models, which is useful since the “true” hydrologic response to variations in climate is unknown and using different models can present a range of credible simulated hydrologic responses. However, more work is needed to identify and separate the varying responses related to different model algorithms versus the varying responses related to the physical characteristics of the individual watersheds being modeled.

Introduction

One of the basic uncertainties concerning the assessment of future water resource availability and water supply is the issue of potential climate change and/or future variability in the climate. One commonly-accepted approach to estimate the effects of climate variability on water resources is through the use of watershed or hydrologic simulation models. Although there are no strict guidelines as to what types of models can be used for this purpose, it is generally accepted that such models should have both explicit accounting of soil moisture in the watershed and estimates of plant growth and evapotranspiration that are responsive to soil moisture and changes in basic climate elements such as temperature. Two available watershed modeling applications at the Illinois State Water Survey (ISWS) meet these basic requirements, these being: 1) the Fox River Forecast Model developed for the Upper Fox River watershed in northeastern Illinois and southeastern Wisconsin and 2) the SWAT model application to the Iroquois River watershed in east-central Illinois and northwestern Indiana. These models were used as is, that is there was no additional modification of these models in preparation for their use in the present analysis.

The purpose of the present work is to examine the response in simulated streamflow to various climate scenarios as simulated by global climate change models (GCMs). There is considerable difference in the climate simulations produced by the various GCMs and this difference is reflected in both the selected climate scenarios and the range of streamflow conditions simulated by the hydrologic simulation models. In the same sense that it is useful to compare the range simulations from various GCMs, it is also useful to compare hydrologic simulation from various models, since various watershed models have basic differences in the way each mathematically represents a hydrologic process.

Description of the Watershed Model Applications Used in this Analysis

Upper Fox River – Fox River Forecast Model

The Fox River watershed is located in northeastern Illinois and southeastern Wisconsin. Only the upstream, northern portion of the Fox River watershed is modeled; that being the portion that is located upstream of Stratton Dam near McHenry, IL. The drainage area at this location is 1250 square miles and most of the watershed is located in Wisconsin. The watershed was modeled using the Fox River Forecast Model (FRFM)(Knapp et al., 1991), which is a hybrid of the PACE watershed model (Durgunoglu et al., 1987) and a separate Muskingum-Cunge flow routing component developed especially for the upper Fox River. The model was originally calibrated using flow data for 1974-1987 from two streamgages: the Fox River near New Munster (USGS Gage #05545750) and Nippersink Creek near Spring Grove (USGS Gage

#05548280). Selected model parameters have been adjusted since the original calibration was performed. Continuous streamflow records for the New Munster and Spring Grove gages date back to 1939 and 1966, respectively.

Precipitation and temperature data from 9 gaging stations for the period 1901-2000 were used as input to the model. Not all nine stations had records dating to 1901, and prior to 1940 there were generally no more than 5 active gages at any one time. Incomplete records were treated the same as other missing values, which were filled in using available data from nearby stations. Monthly climatic averages were used as input for all other meteorological variables, which include relative humidity, wind speed, and percent sunshine.

Comparison of Model Simulations to Observed Streamflow Data. The characteristics of simulated flow from the model were compared to the 60-year streamflow record from the Fox River gage near New Munster. The comparison of flow duration curves (magnitude of flow versus frequency of exceedence) for the simulated and observed flows is shown in Figure 1. There is a very good match between the flow exceedence characteristics for all flows. The most noticeable difference in flow exceedence is for low flows (exceedence probabilities of 90 percent or more), where the magnitude of simulated flows is on average 25 percent higher than that for the observed flows.

Figure 2 presents a scatter plot comparing the simulated and observed daily flows for the Fox River near New Munster for the period 1970-2000. The amount of scatter shown in this figure is typical of most continuous simulation modeling. Figure 3 presents a time series comparing simulated and observed monthly flows for the 10-year period from 1991-2000, and Figure 4 presents a scatter plot comparing the simulated and observed monthly flows.

The Nash-Sutcliffe Efficiency (NSE, Nash and Sutcliffe, 1970), which measures the relative magnitude of the residual variance (‘noise’) to the variance of the flows (‘information’), was used as a performance measure to evaluate the goodness of fit of the simulated monthly flows. The NSE indicates how well the plot of observed versus simulated data fits the 1:1 line. The optimal value of NSE is 1.0, and values should be larger than 0.0 to indicate ‘minimally acceptable’ performance - a value equal to 0.0 indicates that the mean observed flow is a better predictor than the model. NSE is given by the following equation:

$$NSE = 1 - \sum_{i=1}^{n}(P_i - O_i)^2 / \sum_{i=1}^{n}(O_i - \overline{O})^2$$

where, O_i and P_i are the observed and model simulated values for *i*th event or flow value, respectively, $\overline{O}$ is mean observed value, and n is the number of events.

The NSE value for the simulated monthly flows for the Fox River near New Munster was computed to be 0.886. Based on a literature review of continuous simulation models, Duncker and Melching (1998) suggest that model accuracy can be considered satisfactory if the NSE value for monthly flows is greater than 0.80.

Iroquois River – SWAT Model

The Iroquois River watershed is located in east-central Illinois and northwestern Indiana, with a drainage area of 2119 square miles. The watershed was modeled by Singh et al. (2003) using the SWAT hydrologic model (Arnold et al., 1998). Streamflow data from the Iroquois River near Chebanse (USGS Gage #05526000) for the period 1987-1995 was used to calibrate the model. The entire daily flow record for this gage runs from 1923 to the present.

The model uses daily precipitation and temperature data for the period 1970-1995 from 6 gages located in and near the watershed. The data for all gaging stations is complete, as missing data for all gages was filled in as needed using precipitation values from other nearby gages. Average annual precipitation of the Iroquois River Basin for the 1970-1975 period is 39 inches.

Comparison of Model Simulations to Observed Streamflow Data. The characteristics of simulated flow from the model were compared to the 25-year streamflow record from the Iroquois River gage near Chebanse. The comparison of flow duration curves for the simulated and observed flows is shown in Figure 5. There is an excellent match between the flow exceedence characteristics for medium and high flows. However, there is a considerable deviation between simulated and observed flows for low flow conditions below 100 cfs. Singh (2003) noted difficulty in calibrating to low flow conditions on the Iroquois River watershed with two different hydrologic models (SWAT and HSPF). For this reason, the model simulations performed using the Iroquois River SWAT model may be useful in identifying the relative magnitude of streamflow changes associated with the selected climate scenarios, but should not be used either for predicting the absolute magnitude of potential flow conditions or for water resource planning purposes. Additional calibration effort with the Iroquois River model can likely improve the simulated values of low flow.

Figure 6 presents a time series comparing simulated and observed monthly flows for the 10-year period from 1985-1994. The match between simulated and observed monthly flows is good, although there are more differences than that shown earlier in Figure 3 for the Fox River. The NSE value for the simulated monthly flows for the Iroquois River near Chebanse was computed to be 0.850.

Selected Climate Scenarios

The watershed models were used to simulate flows for historical climate conditions as well as four additional climate scenarios, described as follows:

Climate scenario	Change in precipitation and temperature
Wet2050	All historical precipitation values were increased by 5 percent; all historical temperature values were increased by 2 degrees Fahrenheit.
Wet2100	All historical precipitation values were increased by 11 percent; all historical temperature values were increased by 4 degrees Fahrenheit.
Dry2050	All historical precipitation values were decreased by 3 percent; all historical temperature values were increased by 6 degrees Fahrenheit.
Dry2100	All historical precipitation values were decreased by 10 percent; all historical temperature values were increased by 14 degrees Fahrenheit.

The Wet2050 and Wet2100 scenarios are associated with simulations from the Hadley global climate model (GCM) (UK Meteorologic Office's Hadley Center Climate Model Version 2) for years 2050 and 2100, respectively. The Dry2050 and Dry2100 scenarios are associated with simulations from the Japan GCM (Japan Center for Climate System Research Global Climate Model), also for years 2050 and 2100.

Effects of Climate Scenarios on Simulated Flows

The precipitation and temperature data for both watershed models were modified to reflect the climate scenarios defined in the previous section. All other basic climate inputs to the models (relative humidity, wind speed, and cloud cover or solar radiation) were unchanged. The estimates of potential daily evapotranspiration, which are dependent on changes in temperature, were recalculated. Each model contains explicit accounting of soil moisture, and actual daily evapotranspiration were computed for each scenario based on available soil moisture. The average annual precipitation and actual evapotranspiration associated with each climate scenario are shown in Tables 1 and 2.

Upper Fox River – Fox River Forecast Model

Comparisons of the streamflow values for the present condition and the four climate scenarios are given in Figures 7 and 8 and Table 1. Figure 7 compares the monthly simulated flows for the Fox River near New Munster for the time period 1991-2000; Figure 8 compares the flow duration curves for the complete simulation period, 1901-2000; and Table 1 provides a summary of statistics, including the mean annual flow, maximum and minimum flows, and selected low flow statistics for the complete simulation period.

Table 1 indicates that many of the flow parameters simulated for the Wet2050 and Wet2100 scenarios are of similar magnitude to simulated flows for the present condition. Average flows for the Wet2050 and Wet2100 conditions would be 3 and 10 percent higher, respectively, than the present condition. Although it is estimated that the 6-month and 18-month flows during drought periods would be decreased by 5 to 30 percent, the 7-day 10-year low flow would be increased by 25-30 percent, and the minimum daily flow is essentially unchanged. Interestingly, the maximum daily flow is reduced. This probably occurs because the highest flow events for the Fox River occur as a result of snowmelt, and the frequency and magnitude of snowfall and snowmelt would be noticeably changed by the warmer temperatures associated with these climate scenarios. The plot of monthly flows (Figure 9) also shows that high flows associated with the Wet2100 scenario are neither consistently higher nor consistently lower than the simulated present condition.

In contrast, the Dry2050 and Dry2100 scenarios represent considerable departures from the present condition. The Fox River (FRFM) model estimates that average flows would be reduced by 35 and 80 percent, respectively, for the Dry2050 and Dry2100 scenarios, and that maximum daily flows would be reduced by 34 and 55 percent, respectively. The most severe reductions would potentially be associated with low flows. In the Dry2100 scenario, it is estimated that the river would experience zero flow during low flow and drought periods, with zero flow occurring for as much as 6 consecutive months during a 25-year drought.

Iroquois River – SWAT Model

Comparisons of the streamflow values for the present condition and the four climate scenarios are given in Figures 9 and 10 and Table 2. Figure 9 compares the monthly simulated flows for the Iroquois River near Chebanse for the time period 1985-1994; Figure 10 compares the flow duration curves for the complete simulation period, 1970-1995; and Table 2 provides a summary of statistics.

Simulated average flows for the Wet2050 and Wet2100 scenarios are 8 and 15 percent higher, respectively, than the present condition (see Table 2), and simulated maximum daily flows are also 8 and 15 percent higher, respectively. Estimated low flows for the Wet2050 and Wet2100 scenarios are also moderately higher than those for the present condition. The 7-day 10-year low flow is 77 and 50 percent higher for the Wet2050 and Wet2100 scenarios, respectively, although the absolute change in magnitude is no more than 2 cfs; the 3-month drought flow is unchanged for the Wet2050 scenario and 8 percent higher for the Wet2100 scenario; and the 18-month drought flows are 9 and 14 percent higher for the Wet2050 and Wet2100 scenarios, respectively.

Simulated average flows for the Dry2050 and Dry2100 scenarios are 21 and 52 percent lower, respectively, than that for the present condition. The maximum daily flows for the Dry2050 and Dry2100 scenarios are 8 and 14 percent lower than that for the present condition. The simulated7-day 10-year low flows from the SWAT model are reduced from the present condition of 2.6 cfs to zero flow for both of the dry scenarios. The 3-month 25-year flow for the Dry2050 and Dry2100 scenarios are 38 and 75 percent lower than the present condition, respectively; and the 18-month 25-year low flows are 24 and 62 percent lower, respectively.

Discussion of Results

Two basic conclusions can be reached from the modeling results:

- The “Dry” scenarios cause a considerable reduction in the simulated flows in both modeling applications, although the specific amount of reduction varies considerably between the two applications.
- The “Wet” scenarios cause relatively small amounts of change in simulated streamflow amounts. For the Fox River watershed, changes in most flow parameters are less than 10

percent; whereas for the Iroquois River watershed, the changes are generally less than 15 percent.

Some of the differences in estimates between the two modeling applications may be associated with variations in the physical characteristics (hydrologic and climatic) of the watersheds being modeled, whereas other differences in the estimates may be related to dissimilarities in the structure and algorithms of the FRFM and SWAT models. It should be expected that both the FRFM and SWAT models may display considerable uncertainty when applied to extrapolated conditions that are noticeably different than those for which the model was developed and tested. In this respect, the differences in watershed modeling results may be analogous to the differences shown by the various global climate models. Although the two watershed models have many similar processes, the formulation of each model is slightly different and the sensitivity of each model to variations in climatic input will also be different. To more directly compare the different results between the two models, it would also be necessary to apply both models to the same watershed.

Increases in precipitation values may not necessarily translate into increased flooding conditions if also accompanied by warmer temperatures, as noted with the two “wet” scenarios Wet2050 and Wet2100 for the Fox River watershed. Although the soil moisture values in the watershed models were not analyzed, it is believed that lower soil moisture brought about by warmer temperatures and increased evapotranspiration could reduce the chance of high runoff, and thereby offset the effects of increases in precipitation. Although these findings are not conclusive, we note that they are contrary to some climate change studies (for example; Kling et al., 2003) that suggest that increased precipitation associated with climate change may cause increased flooding.

In terms of average precipitation and temperature, the “Dry2100” scenario produces climatic conditions that are more typical of southwestern Oklahoma and the “Dry2050” scenario produces climatic conditions that are typical of northwestern Kansas. In this respect, it does not seem unusual that there would be considerable differences in the streamflow conditions with the scenarios. In contrast, the “Wet2050” and “Wet2100” scenarios for the Fox River watershed produce climate conditions that are more typical of Will County and Champaign County, Illinois, respectively. Thus, it does not seem unusual that the streamflow conditions for these two scenarios would not be drastically different than the present condition.

Clearly, there will be substantial impacts on streamflows and likely a water supply crisis in Illinois if the “Dry” climate scenario occurs in the future; but there will also be broader impacts to agriculture, land use, and ecosystems that will substantially change the expectations related to water resource management. In contrast, if the “Wet” climate scenarios occur in the future, streamflow amounts may be only slightly modified, and water resources management may be more likely driven by other societal changes such as those associated with population growth. Thus, the overall impacts to future water resources will become clearer as our ability to identify climate change and climate variability improves.

Recommendations for Future Analysis

Because there is considerable variability between the results of the two modeling applications, it would be very useful to examine the source of this variability and determine if it comes from differences in the physical characteristics of the two watersheds being analyzed or structural differences in the two models being used. To examine differences between models, it would be necessary to apply both models to the same watershed, such as could be accomplished by developing a SWAT model application for the upper Fox River watershed.

Future interpretation of model results should not only center around changes in streamflow, but also include analysis of soil moisture and evapotranspiration, which are central elements in each model’s water budget. Additional modeling efforts might also investigate more detailed descriptions of possible changes in other climate parameters that may affect the water budget, such as changes in relative humidity and cloud cover, and the magnitude and frequency of heavy rainfall.

The two modeling applications were not modified for use in the present analysis. Additional model calibration to better match observed low flow conditions, particularly for the Iroquois River watershed application, may be desirable if the results are to be used for water resource and water supply planning purposes. The climatic database used for the Iroquois River (or other watersheds examined in the future), if possible, should also be expanded to a longer period such as the 100-year climatic record used for the Fox River model application.

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Table 1. Comparison of Parameters for the Simulated Water Budget and Streamflow, Fox River Watershed

	Present	*Wet2050*	*Wet2100*	*Dry2050*	*Dry2100*
Average annual precipitation (inches)	33.0	34.5	36.6	32.0	29.7
Average annual evapotranspiration (inches)	24.7	26.0	27.5	26.6	28.0
Average annual flow (inches)	8.3	8.5	9.1	5.4	1.7
Average flow (cfs)	531	547	582	343	107
Maximum daily flow (cfs)	6825	6307	6551	4498	3051
Minimum daily flow (cfs)	10	9	10	0	0
7-day 10-year low flow (cfs)	71	89	92	11	0
3-month 25-year low flow (cfs)	61	57	61	7	0
18-month 25-year low flow (cfs)	303	260	284	126	16

Table 2. Comparison of Parameters for the Simulated Water Budget and Streamflow, Iroquois River Watershed

	Present	*Wet2050*	*Wet2100*	*Dry2050*	*Dry2100*
Average annual precipitation (inches)	39.0	41.0	43.3	37.8	35.1
Average annual evapotranspiration (inches)	24.7	25.6	26.8	26.5	28.2
Average annual flow (inches)	14.3	15.4	16.5	11.3	6.9
Average flow (cfs)	2200	2375	2531	1734	1059
Maximum daily flow (cfs)	27569	28452	29758	25345	21639
Minimum daily flow (cfs)	0	0	0	0	0
7-day 10-year low flow (cfs)	2.6	4.6	3.9	0	0
3-month 25-year low flow (cfs)	24	24	26	15	6
18-month 25-year low flow (cfs)	1081	1175	1234	819	412

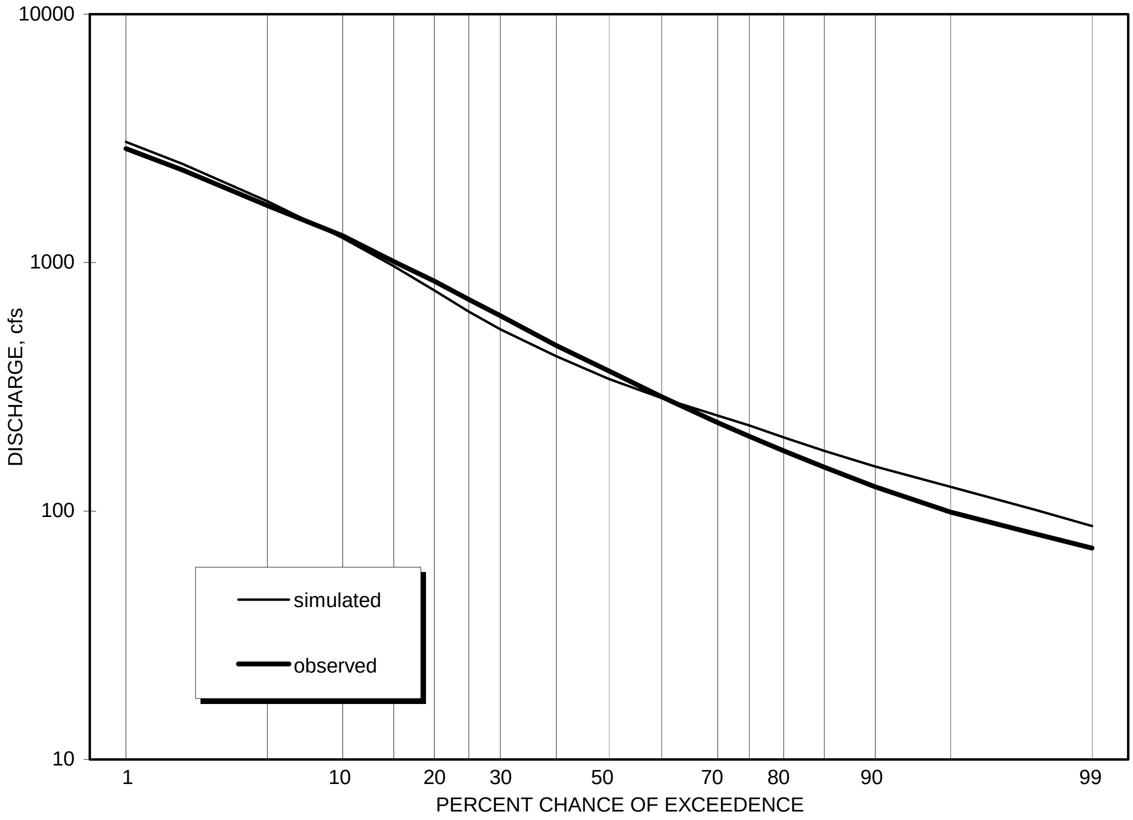

Figure 1. Comparison of the frequency characteristics of simulated and observed daily streamflow, Fox River near New Munster, 1940-2000

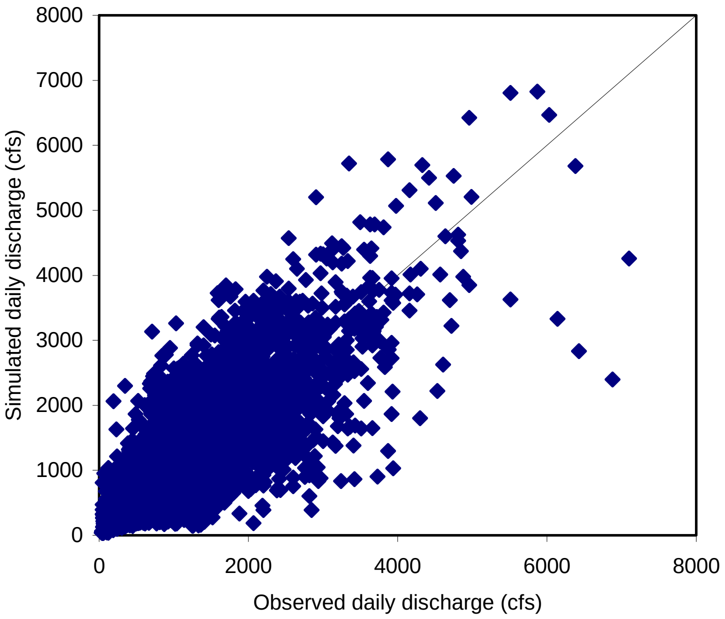

Figure 2. Scatter plot comparing simulated and observed daily streamflow, Fox River near New Munster, 1970-2000

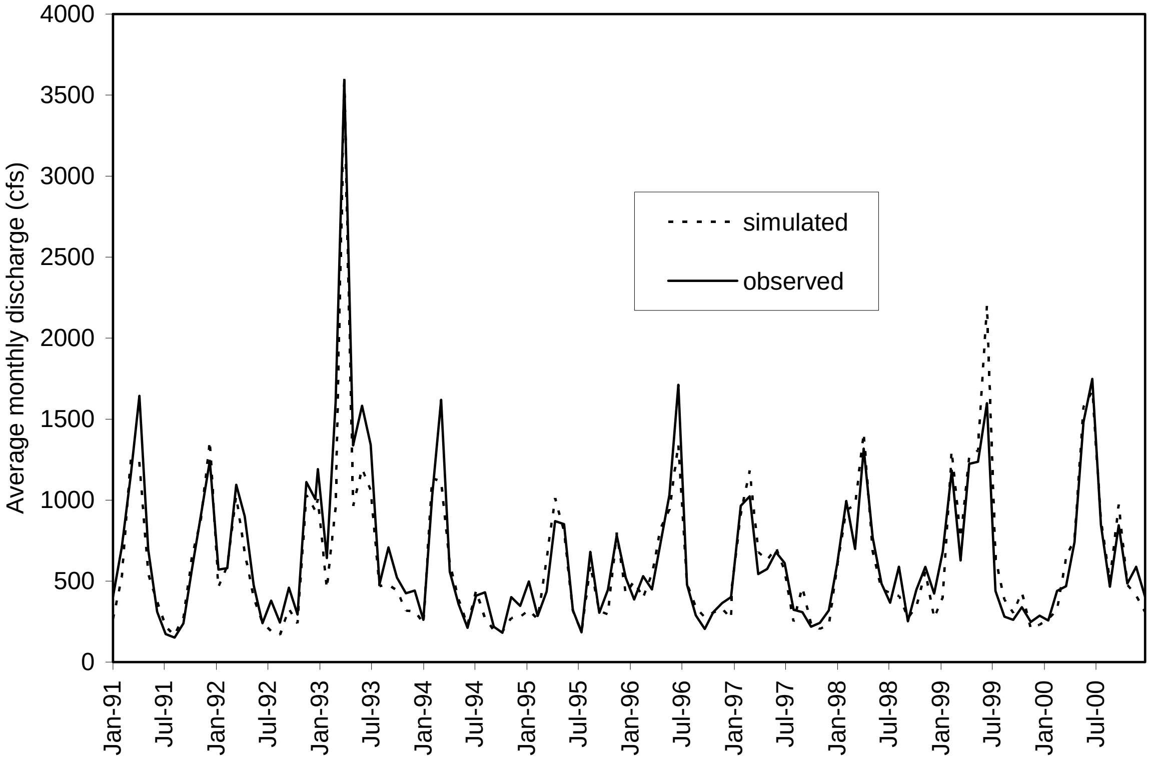

Figure 3. Time series comparing simulated and observed monthly flow for the Fox River near New Munster

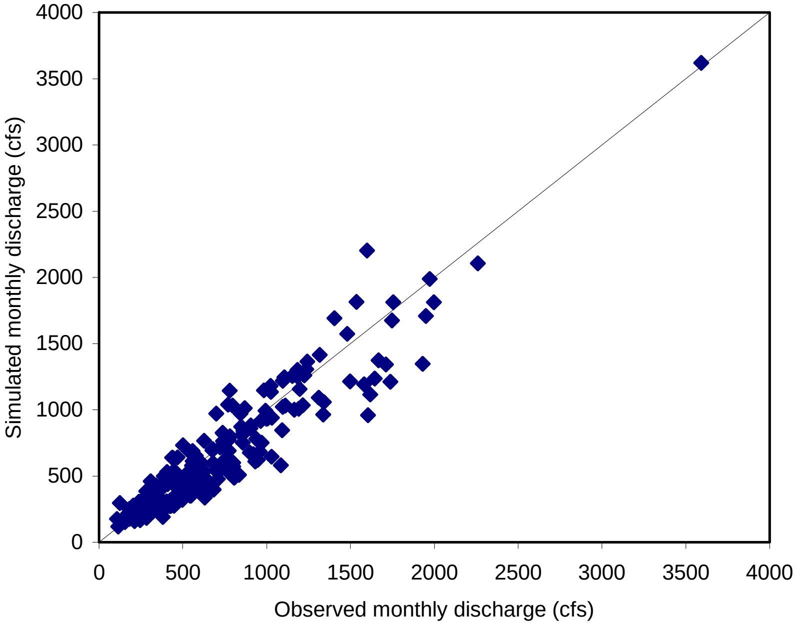

Figure 4. Scatter plot comparing simulated and observed monthly streamflow, Fox River near New Munster, 1970-2000

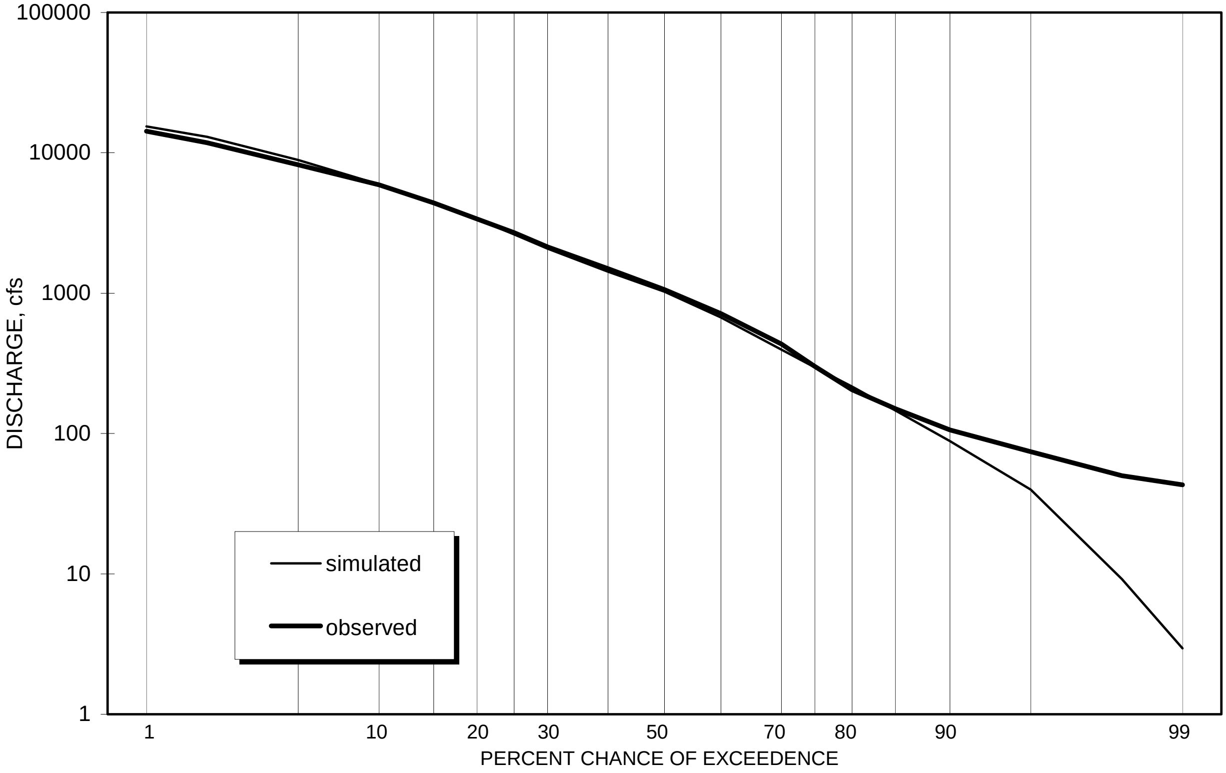

Figure 5. Comparison of the frequency characteristics of simulated and observed daily streamflow, Iroquois River near Chebanse, 1970-1995

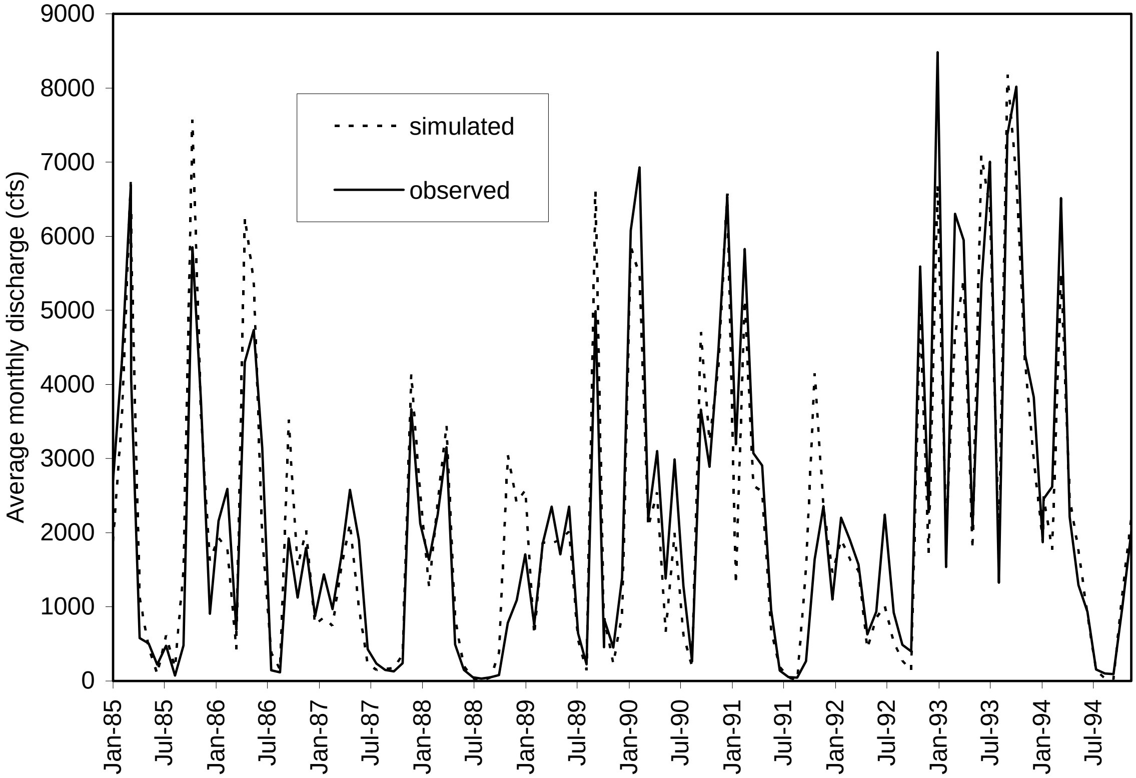

Figure 6. Time series comparing simulated and observed monthly flow for the Iroquois River near Chebanse

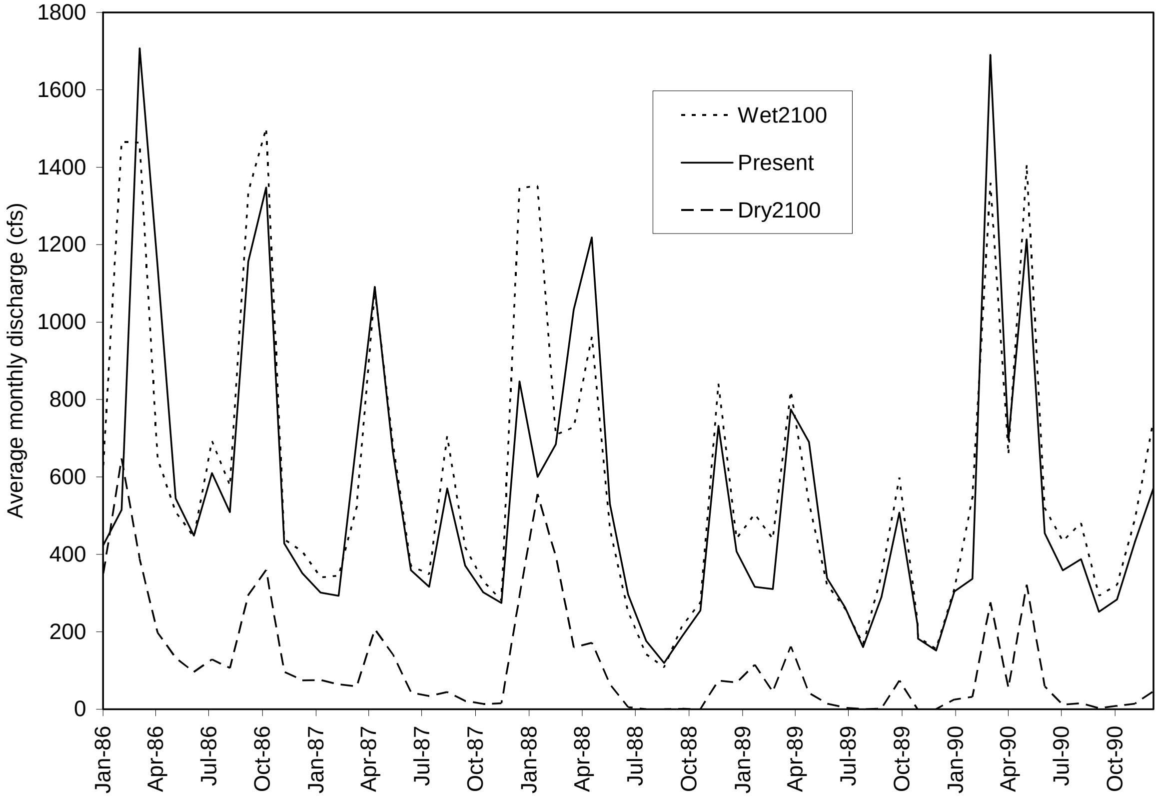

Figure 9. Time series comparing simulated monthly flow for the Fox River near New Munster, 1986-1990, for present flow conditions and the Wet2100 and Dry2100 climate scenarios

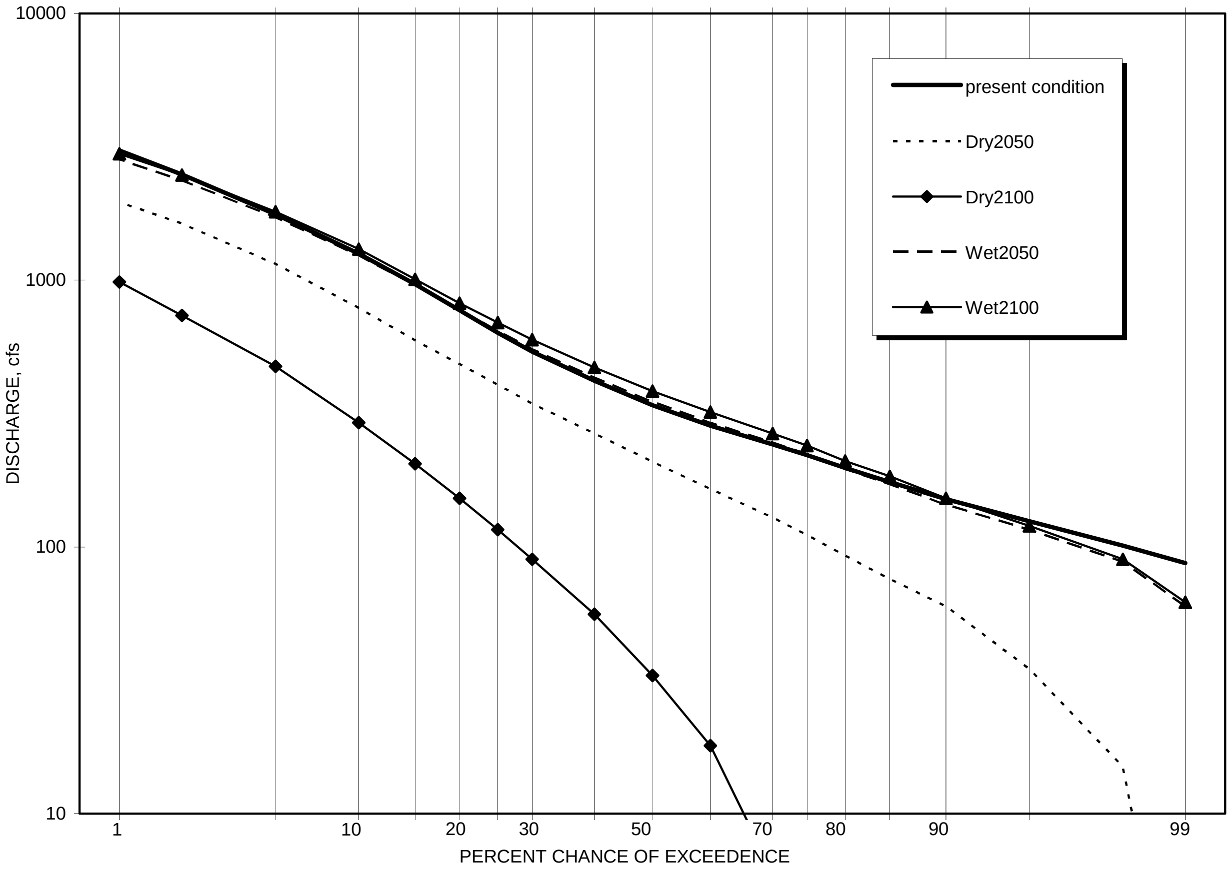

Figure 8. Comparison of the frequency characteristics of simulated flows for the present condition and four climate scenarios, Fox River near New Munster 1901-2000

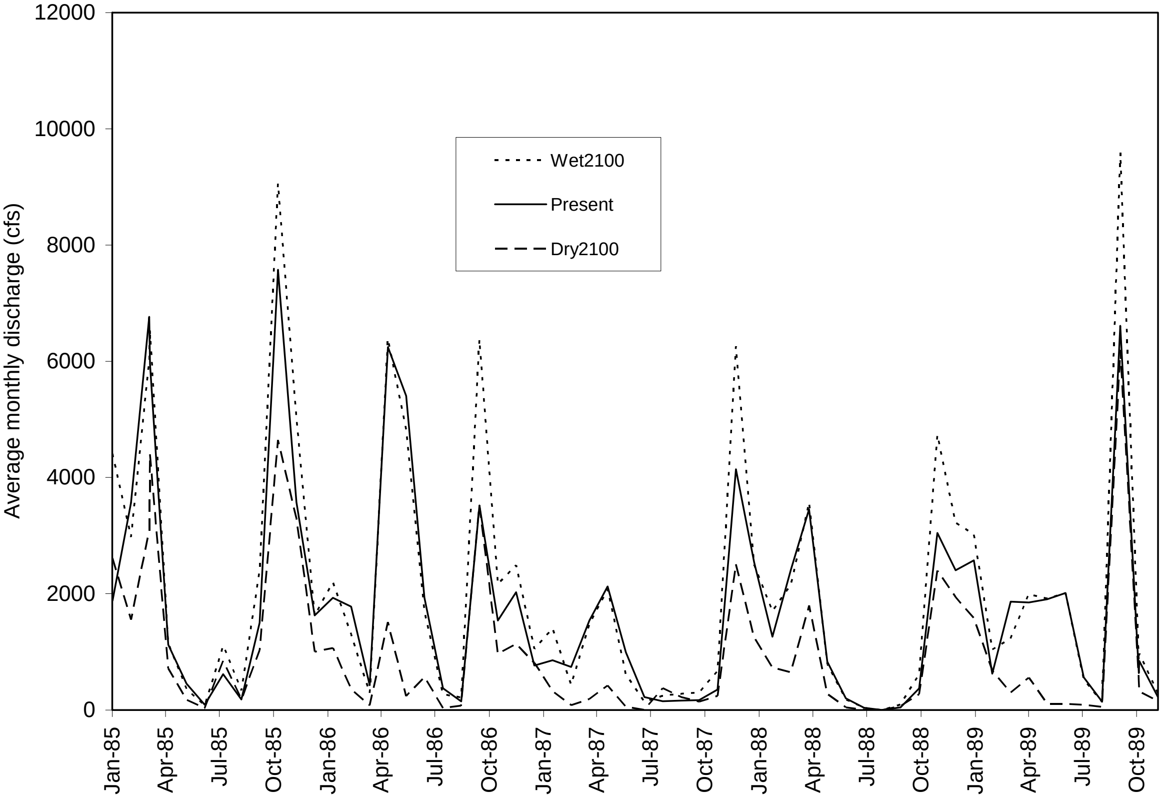

Figure 9. Time series comparing simulated monthly flow for the Iroquois River near Chebanse, 1985-1989, for present flow conditions and the Wet2100 and Dry2100 climate scenarios

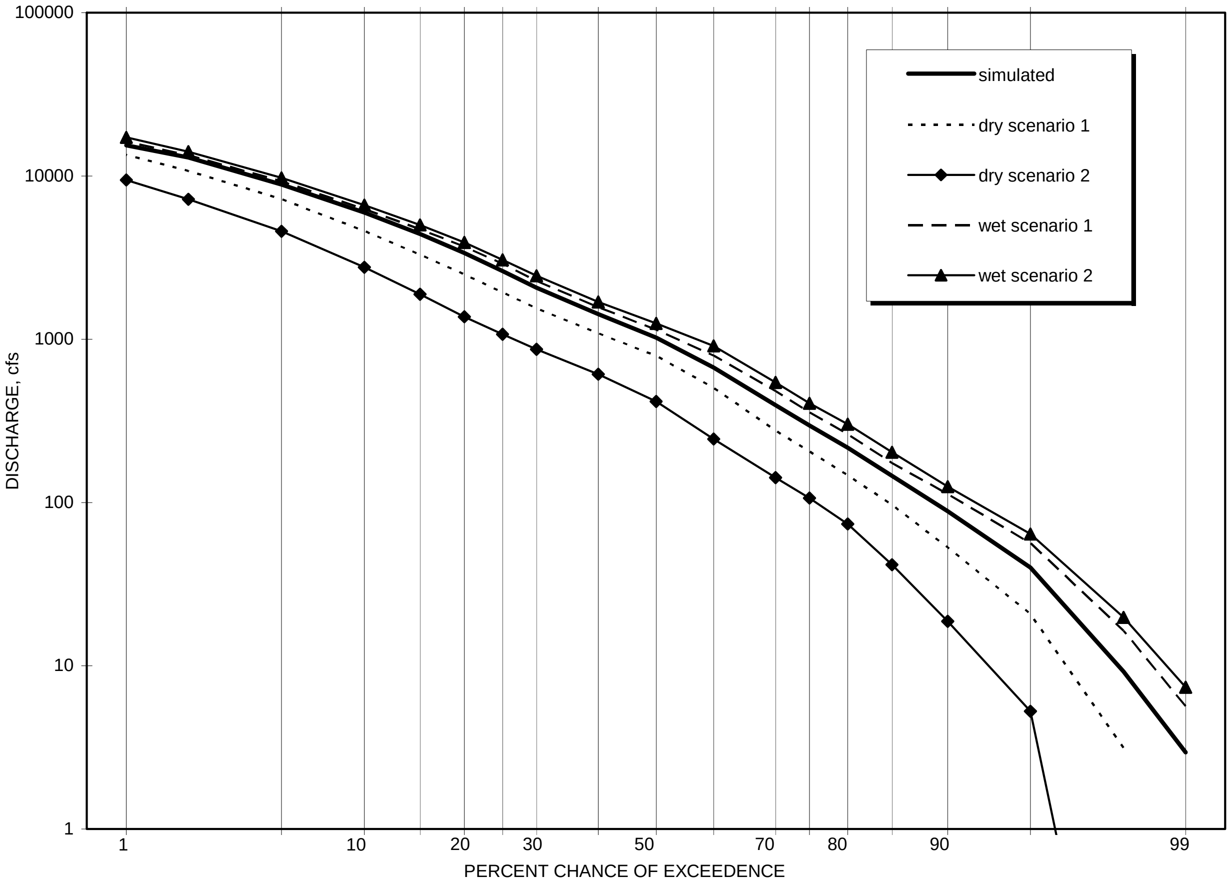

Figure 10. Comparison of the frequency characteristics of simulated flows for the present condition and four climate scenarios, Iroquois River near Chebanse 1970-1995