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Technical Memorandum No. 86-68210-2012-03

Climate Change Analysis for the Missouri River Basin

Northwest Area Water Supply Project, North Dakota

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

July 2012

Mission Statements

The mission of the Department of the Interior is to protect and provide access to our Nation's natural and cultural heritage and honor our trust responsibilities to Indian Tribes and our commitments to island communities.

The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

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Northwest Area Water Supply Project, North Dakota

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Acronyms and Abbreviations

AR4	Fourth Assessment Report
BCSD	bias-corrected and spatially downscaled
CMIP3	Coupled Model Intercomparison Project Phase 3
Corps	U.S. Army Corps of Engineers
DEM	Digital Elevation Model
DRM	Daily Routing Model
GCM	General Circulation Model
GHG	greenhouse gas
HDe	Ensemble Informed Hybrid Delta
IPCC	Intergovernmental Panel on Climate Change
km	kilometer
LLNL	Lawrence Livermore National Laboratory
MAF	million acre-feet
NAWS	Northwest Area Water supply
PCMDI	Program for Climate Model Diagnosis and Intercomparison
Reclamation	U.S. Department of the Interior, Bureau of Reclamation
SEIS	supplemental environmental impact statement
SRES	Special Report on Emissions Scenarios
VIC	variable infiltration capacity
WWCRA	West-wide Climate Risk Assessment
~	approximately
°	degree

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Introduction

Climate change analysis for the Northwest Area Water Supply (NAWS) project is being conducted by the Bureau of Reclamation (Reclamation) to support the supplemental environmental impact statement (SEIS) for the project. The SEIS was initiated in response to a March 10, 2010, U.S. District Court order that directed Reclamation to take a hard look at the cumulative impacts of water withdrawal on the water levels of Lake Sakakawea and the Missouri River. Because climate change may affect future reservoir levels and streamflows throughout the basin, Reclamation is addressing climate change in the SEIS to provide a comprehensive analysis of factors that may cumulatively affect Missouri River resources.

The NAWS climate change analysis is a collaborative effort between Reclamation and the U.S. Army Corps of Engineers (Corps). This technical report documents Reclamation's development of downscaled climate and runoff projections for the Missouri River basin. Five future climate scenarios, representing a range of potential changes in monthly runoff, were provided to the Corps for input into their Daily Routing Model (DRM) to simulate potential effects of climate change on Missouri River reservoir levels and streamflows. Results of the Corps' analysis are presented in a separate report, which is included as a supporting document for the SEIS.

The analysis methodology to study climate change impacts for the Missouri River basin above Garrison Dam was initially referred to as the ensemble-informed hybrid delta (HDe) method. The HDe methodology has been used by Reclamation in other studies, for example, the St. Mary-Milk Basin Study (Reclamation 2010a) and yield study of selected reservoirs in Oklahoma (Reclamation 2010b).

Subsequently, Reclamation, as part of the SECURE Water Act implementation activity, West-Wide Climate Risk Assessment (WWCRA), has developed time-evolving (transient) west-wide hydrologic projections from 1950–2099. Development of the west-wide hydrologic projections is described in the WWCRA hydrologic projections technical report (Reclamation 2011). In summary, the WWCRA hydrologic projections were developed by running 112 bias-corrected and spatially downscaled (BCSD) climate change projections through the calibrated macro-scale hydrology model, Variable Infiltration Capacity ([VIC], Liang et al. 1994; gridded model, spatial resolution, 1/8 degree (°) latitude by 1/8° longitude or approximately 12 kilometers (km) by 12 km).

This report first provides a summary of the BCSD Coupled Model Intercomparison Project Phase 3 (CMIP3) hydrologic projections, including background on VIC hydrologic modeling and routing of gridded VIC runoff to streamflow sites. Following these background descriptions, results of comparison of the HDe and WWCRA flows above Garrison Dam for two future periods, 2010–2039 and 2040–2069 are presented. This comparison was performed to test climate change analysis methodological choice—HDe versus WWCRA transient hydrologic projections. Subsequently, the WWCRA transient hydrologic projections were used to calculate monthly flow adjustment factors for the model nodes of the Corps' DRM. Finally, a discussion of the uncertainty based on the range of future runoff projections is provided.

Methods

Bias-corrected and spatially downscaled CMIP3 hydrologic projections were developed using the following two-step process:

1. Developing downscaled projections of hydroclimate fields (precipitation, temperature, etc.) from General Circulation Model or Global Climate Model (GCM) projections;

2. Using the downscaled hydroclimate fields in a hydrology model to develop hydrologic projections (e.g., streamflow, snow water equivalent, evapotranspiration, etc.).

These two steps are described in the following sections.

Bias-Corrected and Spatially Downscaled CMIP3 Climate Projections

Climate modeling groups have produced hundreds of simulations of past and future climates for the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) (IPCC 2007). The World Climate Research Program (WCRP) Working Group on Coupled Modeling helped to coordinate these activities through the CMIP3 effort (see Meehl et al. 2007) and worked to co-locate these simulations within a single archive, hosted by the Lawrence Livermore National Laboratory (LLNL) Program for Climate Model Diagnosis and Intercomparison (PCMDI).

The native-scale outputs from the climate models collected in the AR4 archive are not designed to provide results at the finer scales required for watershed and basin-scale impact studies and related decisions. This has led to development of a number of techniques to 'downscale' the native model scales to finer temporal and spatial scales more relevant to watershed decisions. Multiple downscaling approaches exist for deriving regional climate from coarse resolution model output. One such method is the statistical approach to downscale spatially continuous fields, which was developed for hydrologic impact studies by Wood et al. 2004. This method, referred to as BCSD, is computationally efficient and can be easily applied to ensembles of projections.

A total of 112 climate projections were analyzed. These projections were based off three scenarios for future greenhouse gas emissions—B1 (low), A1b (medium), and A2 (high)—forcing global climate (defined in the IPCC Special Report on Emissions Scenarios [SRES] [IPCC 2000]) and each emission scenario simulated by 16 CMIP3 general circulation models with one or more simulations featuring unique initial conditions. Next, monthly total precipitation and average temperature from each of the 112 climate projections were bias-corrected and spatially downscaled to 1/8° latitude by 1/8° longitude (approximately[~] 12-km by 12-km grid) using the BCSD methodology to develop the BCSD archive of 112 projections of monthly total precipitation and average temperature (Maurer et al. 2007).

Hydrologic Modeling and Developing Hydrologic Projections from Climate Projections

As part of the WWCRA effort, each of the 112 BCSD CMIP3 climate projections were run through existing calibrated version of VIC models to develop gridded (1/8° by 1/8° or ~12-km by 12-km spatial grid) hydrologic projections. The VIC model simulates water balance for each area element in a 1/8° spatial grid (coincident with BCSD climate projections' 1/8° spatial grid) and on a daily time step, with an hourly time step for the snow model.

The gridded hydrologic projections archive at the BCSD climate and hydrology projections Web site (http://gdo-dcp.ucllnl.org/downscaled_cmip3_projections/dcpInterface.html) includes VIC model outputs of total runoff (surface runoff plus base flow), snow water equivalent, and evapotranspiration for approximately 36,000 grid cells covering the 17-State Reclamation region, and the eight major Reclamation river basins (Colorado, Columbia, Klamath, Missouri, Rio Grande, Sacramento, San Joaquin, and Truckee) described in the SECURE Water Act.

To calculate streamflow results at a given location, a two-step process is used. The first step is to run VIC independently for each grid cell in the watershed, producing surface runoff and base flow (hence, total runoff). This total runoff information for each of the grid cells (over 9,000, 1/8° by 1/8° cells) covering the Missouri River Basin can be accessed from the BCSD climate and hydrology projections Web site. The second step involves hydraulic routing where the runoff from the grid cells are transported to streamflow gauges or locations of interest in a stream or river channel network. The routing model used in this second step is described in Lohmann et al. (1996) and is part of the VIC model setup.

The routing model has two steps. First, surface runoff and base flow simulated by the hydrology model at the centre of the VIC grid cell are moved to the edge of the cell where it enters the channel network. The runoff then is routed through the channel network specified above a streamflow location of interest (e.g., nodes of the Corps' Daily Routing Model). Such setup requires specifying the coordinates of the streamflow location within the basin grid; identifying tributary grid cells and flow directions through these grid cells; and, ultimately, fraction-area contribution from tributary grid cells to streamflow at the location of interest.

For this report, the analysis were based on runoff and routing data developed as part of the West-Wide Climate Risk Assessment effort described in the WWCRA technical report (Reclamation 2011).

Comparison of HDe and WWCRA Flows above Garrison Dam

Development of the HDe flows for the Missouri River above the Garrison Dam (North Dakota) is described in detail in the report, "Investigation of Climate Change Impact on Reservoir Capacity and Water Supply Reliability," being drafted by the Reclamation Technical Service Center, Sedimentation and River Hydraulics Group. In summary, the 112 BCSD climate projections were partitioned into five groups based on projection-specific paired changes in precipitation and temperature between a look-ahead period and a reference period. Two look-ahead periods, 2010–2039 and 2040–2069 were considered, with 1950–1999 as the reference hydroclimate period. The result is a set of five climate change scenarios for each look-ahead period. These five climate change scenarios correspond to changes from the reference hydroclimate conditions and represent the following conditions.

- Wetter, more warming (q1)
- Wetter, less warming (q2)
- Drier, more warming (q3)
- Drier, less warming (q4)
- Middle (q5)
- Middle (q5)

Figure 1 shows the five climate change scenarios (q1–q5) for the 2010–2039 period. The four quadrants are defined by the median of the mean annual change in precipitation (%) and temperature (°F) for the period 2010–2039 from 1950–1999 for the Missouri Basin above Garrison Dam. These four quadrants represent the wetter, more warming (q1); wetter, less warming (q2); drier, more warming (q3), and drier less warming (q4) climate scenarios. A middle climate change scenario (q5) is defined by the box bounded by the 25th and 75th percentile of precipitation and temperature change.

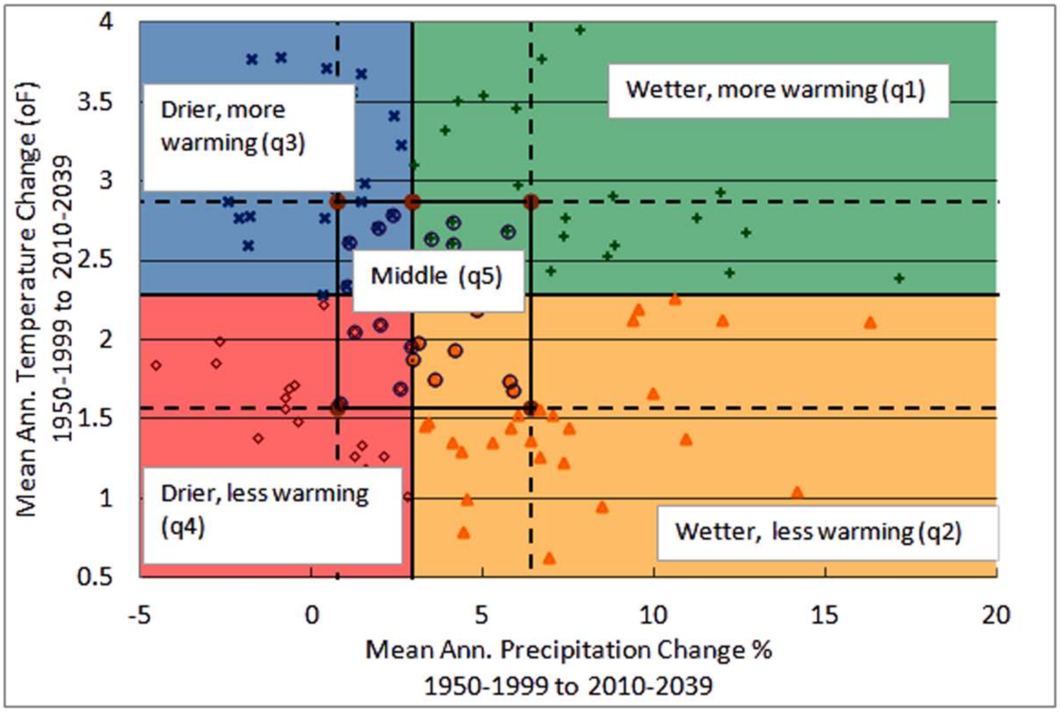

Figure 1. HDe climate change scenarios for 2010–2039.

The solid horizontal and vertical lines correspond to the median change in mean annual temperature and precipitation respectively between the two periods, 1950–1999 and 2010–2039. The dashed lines represent the 25th or 75th percentile of change. Also shown are the labels of the five climate change scenarios—shaded regions (green – wetter, more warming, q1; yellow – wetter, less warming, q2; blue – drier, more warming, q3; red – drier, less warming, q4), and the middle climate change scenario (q5). The symbols in the quadrants and in the middle correspond to the individual climate projections out of the total 112 climate projections.

Once the climate projections for each of the climate change scenarios (q1 through q5) for a given look-ahead period are identified, daily weather forcings were developed by adjusting the historical (1950–1999) VIC weather inputs (precipitation, minimum temperature, and maximum temperature). These adjusted precipitation and temperature time-series were run through the calibrated VIC model to develop gridded VIC runoff that were subsequently routed to the Garrison Dam site to develop climate change flow time-series.

In the case of the WWCRA simulations, each of the 112 BCSD climate projections (these projections cover the period 1950–2099) were individually run through the calibrated VIC model to develop gridded runoff, which subsequently then were routed to develop the flow time-series at the Garrison Dam site. The result is a set of 112 flow time-series for the period 1950–2099.

Some assumptions should be noted before discussing and comparing the results between HDe and WWCRA climate change flow simulations.

1. The WWCRA flow simulations are based on continuous hydrologic model (VIC) simulations for the period 1950–2099 individually for each of the 112 BCSD climate projections. The HDe runs are based on five climate scenarios derived from the 112 BCSD climate projections, and hydrologic simulations are performed after adjusting the 50-year historical climate for the respective climate change scenarios.

2. In doing the comparisons, only the scenarios q1 through q4 are aggregated to equal the 112 BCSD projections. Since the q5 scenario overlaps the q1–q4 scenarios, including this would result in more than 112 projections.

3. Each look-ahead period is 30-years long; therefore, for any given look-ahead period and projection in the WWCRA simulation, only 30 years of data are used. For example, for the period 2010–2039, to calculate the mean flow for July, only 30 July values are used for a given projection. But, for the HDe flows, 50 values of July are used per climate change scenario because the length of any climate scenario run matches the length of the historical hydroclimate time-series (1950–1999)—except for October, November, and December for which 49 values were used, because the HDe analysis originally used a water-year basis.

4. Exactly the same VIC setup—calibrated hydrology and routing model—were used both for the HDe and WWCRA simulations.

Development of Monthly Flow Adjustment Factors for the Daily Routing Model

The calculation of monthly changes in flow between a future hydrology period (either 2010–2039 or 2040–2069) and the reference hydrology period (1950–1999) is estimated using the following steps:

Step 1. The first step is to develop the VIC routing model for each of the 15 DRM nodes (table A.1). For each DRM node (site), all upstream VIC grid cells contributing to that site were first identified. Two separate routing model input files, one describing the flow fraction (i.e., the fraction of a 1/8° VIC grid cell contributing to flow at the specified site) and a second file describing flow out of each contributing VIC grid cell were developed. The routing model inputs were developed from 15 arc-second (~ 450 meters) Digital Elevation Model (DEM), flow accumulations and flow direction data available from the U.S. Geological Survey hydrological data and maps based on Shuttle Elevation Derivatives at Multiple Scales (HydroSHEDS) archive using ArcGIS®. The gridded runoff data for each of the 112 projections were extracted from the BCSD climate and hydrologic projections Web site.

Step 2. For each projection and site (DRM node), mean monthly flows for the reference hydrology period (1950–1999) and future hydrology periods (2010–2039, 2040–2069) are calculated.

Step 3. Calculate change in mean monthly flows between the future period (either 2010–2039 or 2040–2069) and the reference hydrology period (1950–1999) for each projection for the given site. The percentage change (*PC*) in mean monthly flow for a given projection and site is calculated as follows,

$$PC = \frac{(\bar{Q}_{2010-2039\ or\ 2040-2069} - \bar{Q}_{1950-1999})}{\bar{Q}_{1950-1999}} \times 100$$

where, $\bar{Q}_{1950-1999}$ is the mean flow for a month for the given projection and site calculated from the 50 monthly values in the reference hydrology period, 1950–1999; $\bar{Q}_{2010-2039\ or\ 2040-2069}$ is the mean flow for a month for the given projection and site calculated from the 30 monthly values in a future period, either 2010–2039 or 2040–2069.

For example, for projection 1 (SRES scenario A1B, WCRP CMIP3 ID bccr_bcm2_0.1) for site 15 (Missouri River at Hermann, Missouri), the mean January flow estimated from the 50 January values from 1950-1999 is about 4.061919 million acre-feet (MAF). Similarly, for the same projection and site, the mean January flow estimated from the 30 January values from 2010–2039 is about 3.438777 MAF. Therefore, the change in January flow is [(3.4388 - 4.0619)/4.0619] * 100 ≈ -15.34%, which is nearly a 15% reduction in flow in January for this one projection and location.

Step 4. Repeat steps 2 and 3 for all the 112 climate projections and then estimate the five quantiles, 5^{th}, 25^{th}, 50^{th}, 75^{th}, and 95^{th}-percentiles from all the 112 projections.

These quantiles capture the uncertainty (lower bound, 5^{th} percentile; upper bound, 95^{th} percentile) in changes to mean monthly flows between the reference hydrology (1950–1999) and future hydrology periods (2010–2039; 2040–2069).

Results and Discussions

Comparison of HDe and WWCRA Flows above Garrison Dam

Monthly boxplots of the HDe and the WWCRA simulations for the period 2010–2039 and 2040–2069 are shown in figure 2 and figure 3, respectively. The box in the boxplots represents the 25th and 75th percentiles of the flow time-series. The whiskers represent the 5th and 95th percentiles of the time-series, and the horizontal line within the box corresponds to the median of the flow time-series. Outliers (values outside the 5th and 95th percentiles) are represented with open circles. WWCRA results show greater variability compared to the HDe simulations for both look ahead periods. Though there is a sample size issue in estimating the statistics between the two simulations (30 years for WWCRA; 50 years for HDe), the likely reason for this greater variability is that the WWCRA simulations are based on continuous hydrologic simulations for each of the 112 BCSD projections beginning in 1950. The HDe simulations are restricted to historical variability. In the HDe approach, only the intensity of the historical weather forcings are adjusted, and there is no change in the duration and frequency of the wet/dry, warm/cool spell lengths beyond what is observed in the historical hydroclimate record (1950–1999).

Mean annual hydrographs comparing HDe- and WWCRA-simulated flows for the periods 2010–2039 and 2040–2069, along with the historical mean hydrograph are shown in figure 4. For the 2010–2039 period, both the HDe and the WWCRA hydrographs are very similar; and most difference is seen in the recession part of the hydrograph. Similarly, for the 2040–2069 period, the HDe and WWCRA hydrographs have a similar shape; but there is a somewhat larger difference from the 2010–2039 period. However, both the methods in the two look-ahead cases show increased flows over the reference hydroclimate period 1950–1999 during the runoff season.

Figure 5 shows the impact—difference in mean monthly flows between the historical simulated flow and the two climate change simulations—HDe and WWCRA for the two look-ahead periods, 2010–2039 and 2040–2069. In all cases (except for November), the direction of the change between the HDe and WWCRA are the same, though the impact by month varies between the two climate change simulations. This difference is represented more in the 2040–2069 period.

In general, the HDe and WWCRA methods showed similar results in regard to potential effects of climate change on Missouri River flows. The WWCRA method was used to develop flow adjustments for input into the Corps' DRM as described in the next section. Results of the DRM simulations are summarized in the NAWS SEIS and documented in a separate report provided with the SEIS as a supporting document.

Development of Monthly Flow Adjustment Factors for the Daily Routing Model

Locations of DRM nodes are shown in appendix A, table A.1. The VIC-simulated runoff from each of the 112 WWCRA projections was routed to these nodes to calculate the percentage change in mean monthly flow from the reference hydrology period 1950–1999 to the two look ahead periods (2010–2039 and 2040–2069) for the 15 DRM nodes. Figure 6 shows boxplots that illustrate the range of monthly flow changes for the 2040–2069 look ahead period at Garrison Dam (a representative upper basin location) and Kansas City (a representative lower basin location). At Garrison Dam, the median monthly changes show increased flow from December–June, and decreased flows from July–November, with a net increase in mean annual flow (median change in mean annual flow estimated from the 112 projections and 1950–1999 reference hydrology period) of 5.93% over the period 2040–2069. Similarly, at Kansas City, the median monthly changes show increased flow in most months, with a net increase in mean annual flow of 10.38% over the 2040–2069 period. Percentile changes in mean annual flow from the 1950–1999 reference hydrology period estimated from the 112 projections for all the 15 DRM nodes and for the two future periods, 2010–2039 and 2040–2069, are summarized in tables 1 and 2, respectively. Boxplots of change factors for the 2010–2039 and 2040–2069 periods for all 15 DRM nodes are shown in appendix A, figures A.1 and A.2.

Monthly change factors developed in this analysis are summarized in appendix A, table A.2–table A.6 (2010–2039) and table A.7–table A.11 (2040–2069). For example, table A.2 corresponds to the 5th percentile change in the mean monthly flows estimated for each node from the 112 climate projections between the 2010–2039 and 1950–1999 periods. These change factors are used to adjust runoff in the DRM to simulate how a range of future climate scenarios could affect Missouri River streamflow and reservoir levels.

Uncertainties

This analysis is designed to provide quantitative representation of how runoff in the Missouri River Basin might respond to a range of future climate projections. The activity was designed to take advantage of best available datasets and modeling tools and to follow methodologies documented in peer-reviewed literature. However, there are a number of analytical uncertainties that are not fully reflected in study results, including uncertainties associated with climate projection and assessing hydrologic impacts.

Table 1. Percentiles of change in mean annual flow, 2010–2039

Node	Description	Percentiles of Change in Mean Annual Flow				
		5th	25th	50th	75th	95th
1	Fort Peck Lake at Fort Peck, MT	-12.80%	-5.56%	0.03%	9.32%	23.64%
2	Missouri River at Garrison Dam, ND	-9.66%	-2.60%	3.66%	10.80%	19.15%
3	Lake Oahe nr Pierre, SD	-8.88%	-1.59%	3.92%	10.69%	19.69%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	-8.78%	-1.60%	3.92%	10.83%	19.75%
5	Missouri River at Fort Randall Dam, SD	-8.63%	-1.07%	3.98%	11.23%	19.99%
6	Lewis and Clark Lake nr Yankton, SD	-8.56%	-0.69%	4.01%	11.40%	20.47%
7	Missouri River at Sioux City, IA	-6.34%	0.39%	5.73%	13.06%	21.63%
8	Missouri River at Omaha, NE	-6.55%	1.19%	5.93%	13.12%	22.62%
9	Missouri River at Nebraska City, NE	-8.10%	0.14%	5.47%	12.19%	21.88%
10	Missouri River at Rulo, NE	-8.37%	0.12%	5.54%	12.40%	22.34%
11	Missouri River at St. Joseph, MO	-8.68%	-0.03%	5.42%	12.45%	22.59%
12	Missouri River at Kansas City, MO	-9.67%	-0.75%	4.67%	13.08%	25.40%
13	Missouri River at Waverly, MO	-9.64%	-0.74%	4.67%	13.08%	25.45%
14	Missouri River at Boonville, MO	-9.99%	-1.65%	4.44%	13.77%	25.55%
15	Missouri River at Hermann, MO	-10.75%	-2.30%	4.58%	13.20%	25.16%

Table 2. Percentiles of change in mean annual flow, 2040–2069

Node	Description	Percentiles of Change in Mean Annual Flow				
		5th	25th	50th	75th	95th
1	Fort Peck Lake at Fort Peck, MT	-13.89%	-5.29%	1.38%	11.97%	38.50%
2	Missouri River at Garrison Dam, ND	-7.99%	-0.65%	5.93%	14.17%	34.62%
3	Lake Oahe nr Pierre, SD	-7.47%	0.57%	6.60%	16.07%	37.95%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	-7.54%	0.58%	6.64%	16.33%	38.13%
5	Missouri River at Fort Randall Dam, SD	-7.77%	0.86%	7.17%	17.31%	38.19%
6	Lewis and Clark Lake nr Yankton, SD	-7.35%	0.92%	7.74%	17.99%	38.29%
7	Missouri River at Sioux City, IA	-7.13%	1.60%	10.95%	21.51%	40.18%
8	Missouri River at Omaha, NE	-6.69%	2.56%	11.35%	22.12%	39.76%
9	Missouri River at Nebraska City, NE	-10.05%	0.92%	9.39%	22.34%	39.92%
10	Missouri River at Rulo, NE	-10.72%	0.72%	9.54%	22.83%	39.24%
11	Missouri River at St. Joseph, MO	-11.41%	1.09%	9.54%	22.85%	38.48%
12	Missouri River at Kansas City, MO	-15.64%	-0.10%	10.38%	24.57%	40.82%
13	Missouri River at Waverly, MO	-15.99%	-0.06%	10.32%	24.62%	40.78%
14	Missouri River at Boonville, MO	-16.73%	-0.16%	10.57%	24.36%	39.24%
15	Missouri River at Hermann, MO	-18.14%	-1.11%	10.69%	23.68%	35.49%

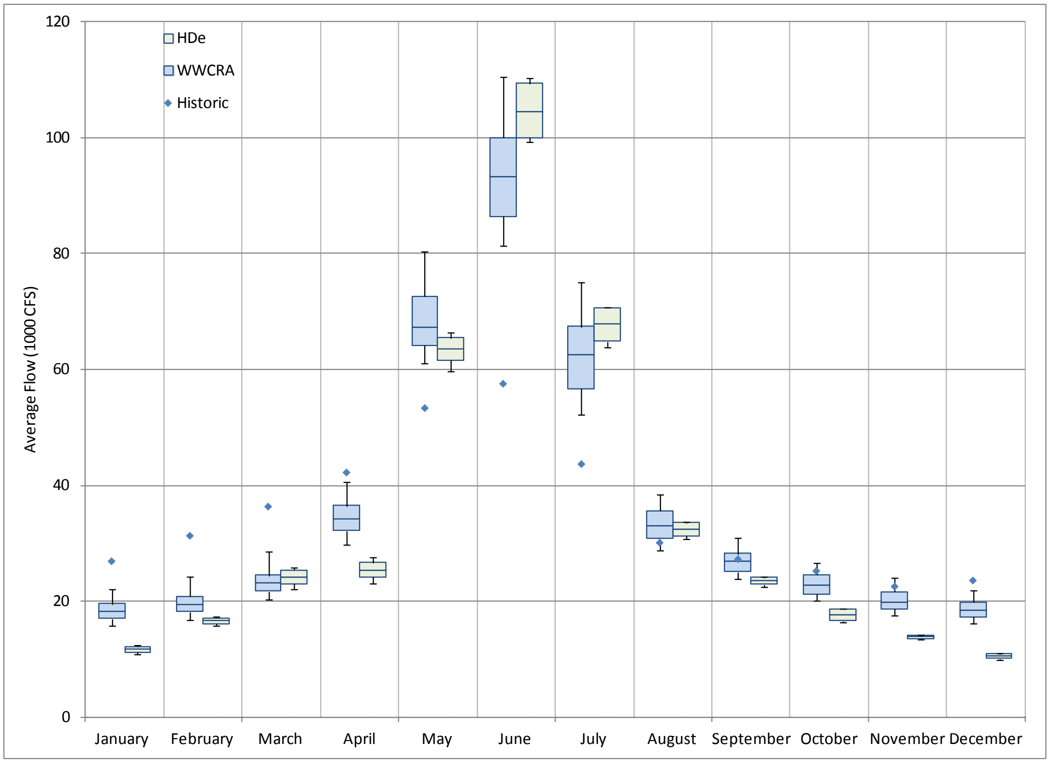

Figure 2. Boxplot of the HDe (light green) and the WWCRA (light blue) simulations for the period 2010–2039. The simulated mean monthly historical flows (diamond) also are shown for reference.

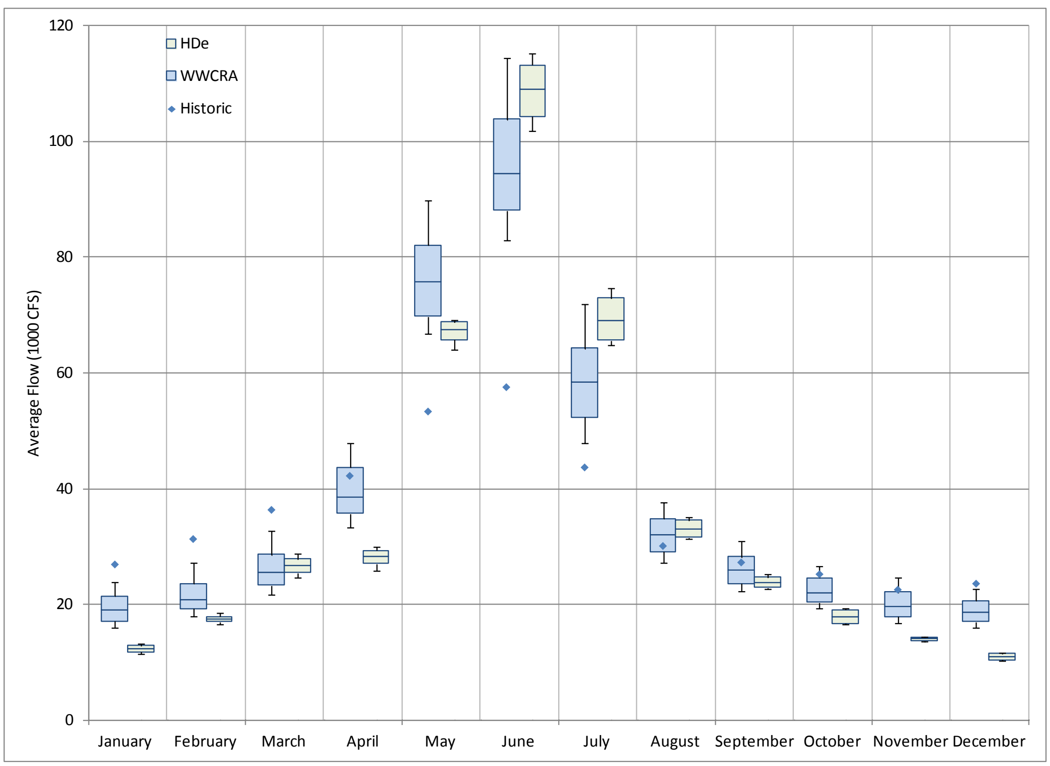

Figure 3. Same as figure 2 but for 2040–2069.

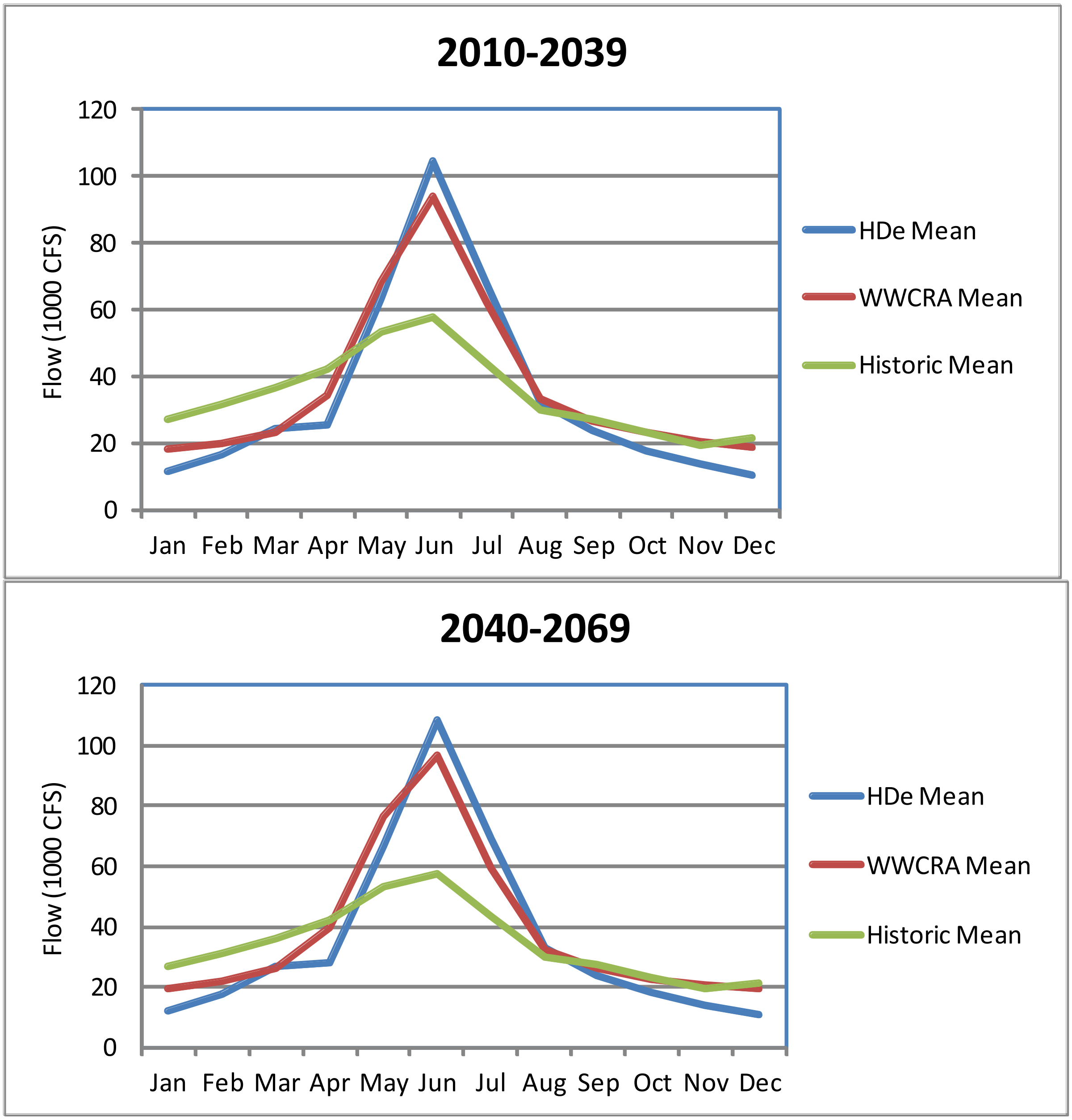

Figure 4. Mean annual hydrographs comparing HDe and WWCRA simulated flows for the period 2010–2039 (top panel) and 2040–2069 (bottom panel).

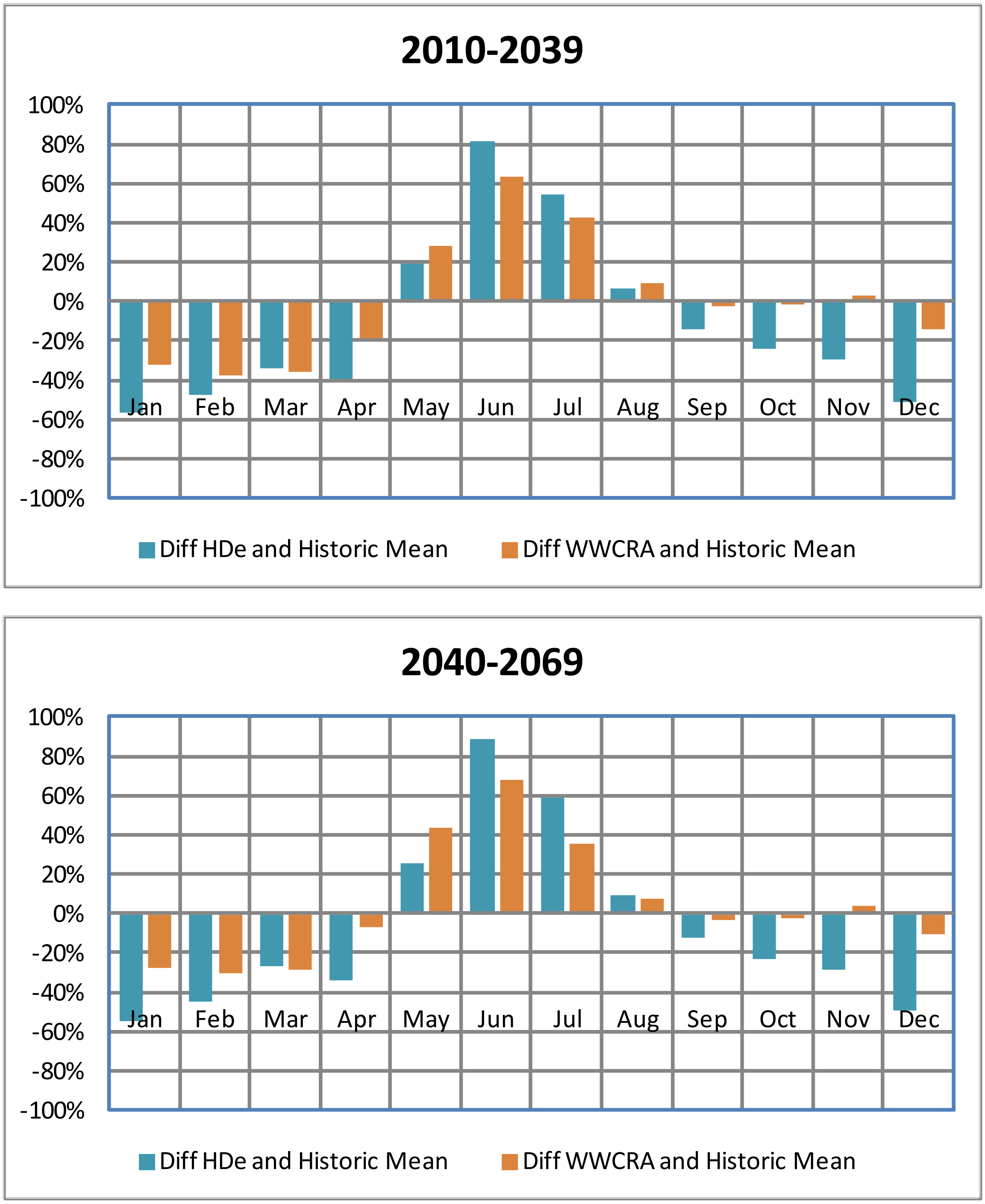

Figure 5. Monthly difference in flows between simulated historic and HDe flows, and simulated historic and the WWCRA flows for the period 2010–2039 (top panel) and 2040–2069 (bottom panel).

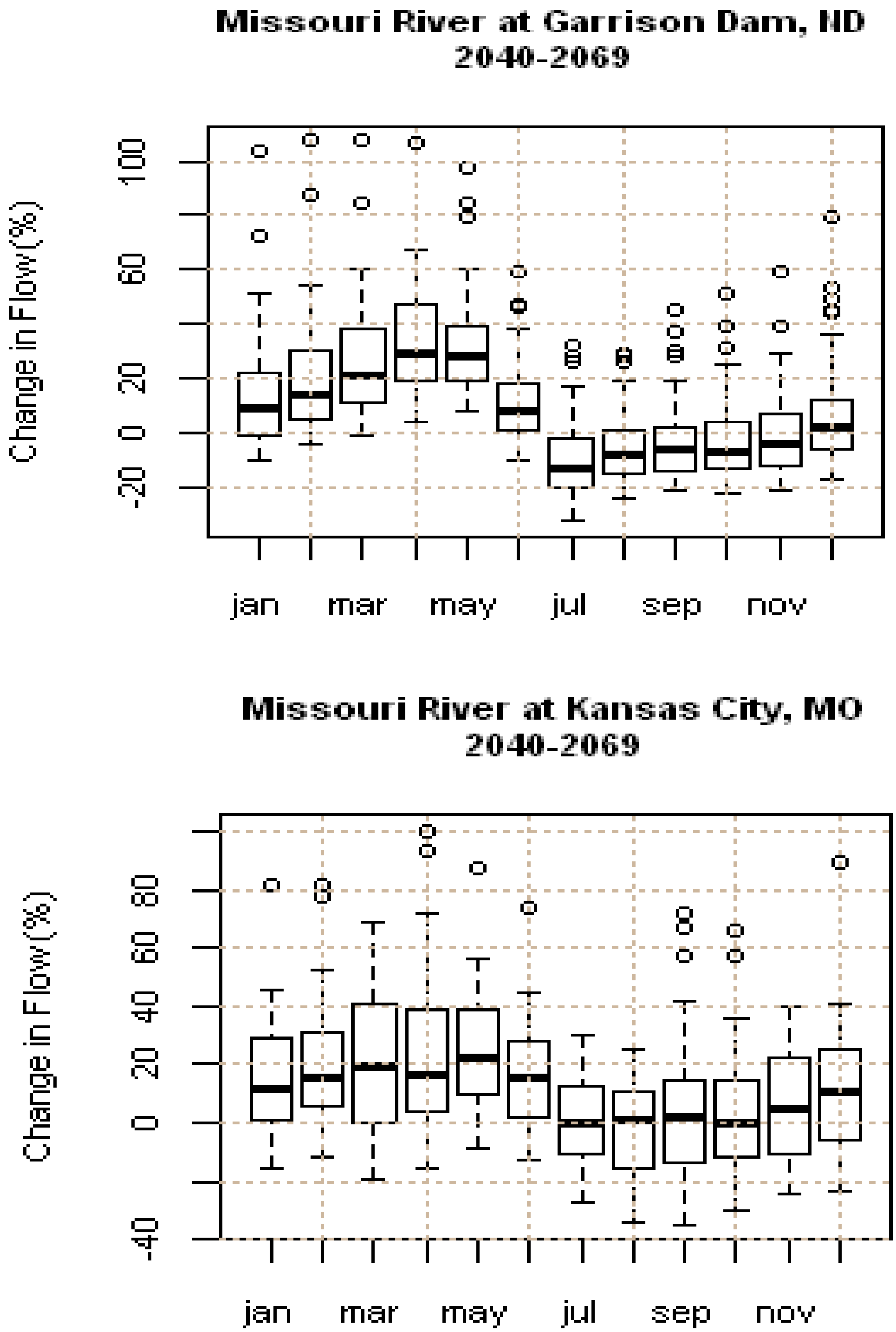

Figure 6. Boxplot of monthly change factors for the period 2040–2069 at representative locations in the Missouri River Basin. Reference hydrologic period, 1950–1999.

Although this surface water hydrologic projection activity considers future climate projections representing a range of future greenhouse emission paths, the uncertainties associated with these pathways are not explored. Such uncertainties include those introduced by assumptions about technological and economic developments, globally and regionally; how those assumptions translate into global energy use involving greenhouse gas (GHG) emissions; and biogeochemical analysis to determine the fate of GHG emissions in the oceans, land, and atmosphere. Also, not all of the uncertainties associated with climate forcing are associated with GHG assumptions. Considerable uncertainty remains associated with natural forcings, with the cooling influence of aerosols being regarded as the most uncertain on a global scale (e.g., figure SPM-2 in IPCC 2007).

While the activity presented in this report considers climate projections produced by state-of-the-art coupled ocean-atmosphere climate models and even though these models have shown an ability to simulate the influence of increasing GHG emissions on global climate (IPCC 2007), there are still uncertainties about the scientific understanding of physical processes that affect climate; how to represent such processes in climate models (e.g., atmospheric circulation, clouds, ocean circulation, deep ocean heat update, ice sheet dynamics, sea level, land cover effects from water cycle, vegetative and other biological changes); and how to do so in a mathematically efficiently manner given computational limitations.

This activity analyzes natural runoff response to changes in precipitation, temperature, and change in natural vegetation potential evapotranspiration while holding other watershed features constant. Other watershed features might be expected to change as climate changes and affects runoff (e.g., vegetation affecting evapotranspiration and infiltration, etc.). On the matter of land cover response to climate change, the runoff models' calibrations would have to change if land cover changed, because the models were calibrated to represent the historical relationship between weather and runoff as mediated by historical land cover. Adjustment to watershed land cover and model parameterizations are difficult to consider due to lack of available information to guide such an adjustment. Ecohydrological frameworks, perhaps involving dynamic vegetation response, may be suitable to represent such land surface changes for studies in which such sensitivities are important.

Further details on uncertainties associated with climate and runoff modeling used in this analysis are available from the WWCRA technical report (Reclamation 2011).

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Appendix A

Monthly Change Factors Developed for Use in U.S. Army Corps of Engineers Daily Routing Model

Table A.1. Location of the 15 daily routing model (DRM) nodes

Node	Latitude	Longitude	Location Description
1	48.0068480257	-106.4145283190	Fort Peck Lake at Fort Peck, MT
2	47.5022000000	-101.4310000000	Missouri River at Garrison Dam, ND
3	44.4551802472	-100.3973981370	Lake Oahe nr Pierre, SD
4	44.0392115851	-99.4383700480	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD
5	43.0650000000	-98.5531000000	Missouri River at Fort Randall Dam, SD
6	42.8515081520	-97.4818710264	Lewis and Clark Lake nr Yankton, SD
7	42.4882835211	-96.4137194001	Missouri River at Sioux City, IA
8	41.2589000000	-95.9222000000	Missouri River at Omaha, NE
9	40.6819000000	-95.8448212978	Missouri River at Nebraska City, NE
10	40.0536573120	-95.4198940791	Missouri River at Rulo, NE
11	39.7533382080	-94.8595891853	Missouri River at St. Joseph, MO
12	39.1117000000	-94.5881000000	Missouri River at Kansas City, MO
13	39.2150000000	-93.5150000000	Missouri River at Waverly, MO
14	38.9801877591	-92.7535179235	Missouri River at Boonville, MO
15	38.7098000000	-91.4385000000	Missouri River at Hermann, MO

Table A.2. 5th percentile change in the mean monthly flows, 2010–2039

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	-15.02%	-14.02%	-9.95%	-1.16%	-2.21%	-22.54%	-37.27%	-24.05%	-19.21%	-21.32%	-19.27%	-16.98%
2	Missouri River at Garrison Dam, ND	-12.04%	-10.79%	-7.63%	-2.51%	-0.17%	-7.88%	-24.28%	-19.32%	-16.59%	-18.27%	-17.18%	-15.59%
3	Lake Oahe nr Pierre, SD	-12.02%	-10.65%	-7.75%	-3.34%	-1.88%	-6.54%	-21.89%	-19.29%	-15.79%	-18.40%	-15.83%	-14.02%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	-12.08%	-10.50%	-7.89%	-4.14%	-2.16%	-6.11%	-21.47%	-19.29%	-15.87%	-18.13%	-15.52%	-13.91%
5	Missouri River at Fort Randall Dam, SD	-12.15%	-9.87%	-8.22%	-5.88%	-2.80%	-5.38%	-20.91%	-19.64%	-15.59%	-17.94%	-14.77%	-13.65%
6	Lewis and Clark Lake nr Yankton, SD	-12.05%	-9.39%	-8.32%	-7.05%	-3.40%	-4.83%	-20.44%	-19.72%	-15.43%	-17.90%	-14.24%	-13.39%
7	Missouri River at Sioux City, IA	-10.41%	-9.59%	-8.86%	-11.48%	-4.91%	-5.12%	-19.93%	-18.47%	-14.01%	-17.94%	-13.49%	-10.86%
8	Missouri River at Omaha, NE	-10.19%	-9.22%	-11.99%	-11.88%	-5.90%	-4.81%	-18.95%	-18.56%	-14.26%	-17.41%	-13.25%	-10.96%
9	Missouri River at Nebraska City, NE	-9.96%	-10.11%	-14.04%	-12.79%	-6.78%	-6.14%	-19.76%	-20.13%	-15.73%	-17.47%	-13.82%	-12.38%
10	Missouri River at Rulo, NE	-10.13%	-9.63%	-14.86%	-13.43%	-7.16%	-6.05%	-19.36%	-20.02%	-16.64%	-16.88%	-14.18%	-12.52%
11	Missouri River at St. Joseph, MO	-10.95%	-9.07%	-15.40%	-13.91%	-7.33%	-6.01%	-18.99%	-20.13%	-16.96%	-16.97%	-14.58%	-13.54%
12	Missouri River at Kansas City, MO	-12.14%	-10.92%	-16.81%	-17.76%	-9.80%	-9.03%	-20.21%	-21.22%	-18.45%	-19.19%	-17.18%	-15.89%
13	Missouri River at Waverly, MO	-12.18%	-10.75%	-17.21%	-17.57%	-10.20%	-9.55%	-20.15%	-21.43%	-19.22%	-18.81%	-17.55%	-16.23%
14	Missouri River at Boonville, MO	-14.37%	-10.81%	-16.85%	-15.77%	-10.55%	-10.24%	-19.73%	-22.56%	-20.42%	-19.76%	-18.04%	-18.05%
15	Missouri River at Hermann, MO	-14.71%	-11.71%	-16.40%	-15.57%	-11.44%	-10.86%	-19.71%	-22.65%	-22.51%	-20.36%	-20.68%	-18.91%

Table A.3. 25th percentile change in the mean monthly flows, 2010–2039

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	-3.12%	-1.89%	3.56%	7.53%	6.68%	-10.82%	-25.78%	-16.62%	-13.06%	-10.68%	-9.96%	-6.56%
2	Missouri River at Garrison Dam, ND	-1.64%	-0.91%	3.52%	6.98%	8.55%	-0.86%	-14.45%	-11.54%	-8.19%	-9.58%	-8.29%	-6.48%
3	Lake Oahe nr Pierre, SD	-2.24%	-0.81%	4.11%	6.66%	7.68%	1.32%	-11.44%	-10.25%	-7.67%	-10.25%	-7.54%	-5.94%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	-2.14%	-0.97%	4.32%	6.47%	7.56%	1.41%	-11.14%	-10.59%	-7.16%	-10.00%	-7.14%	-6.04%
5	Missouri River at Fort Randall Dam, SD	-2.32%	-1.01%	4.64%	5.81%	7.29%	1.24%	-10.20%	-10.16%	-6.27%	-10.43%	-6.70%	-6.09%
6	Lewis and Clark Lake nr Yankton, SD	-2.41%	-0.98%	5.13%	6.32%	6.67%	2.09%	-9.22%	-10.06%	-5.79%	-9.73%	-6.14%	-5.82%
7	Missouri River at Sioux City, IA	-1.26%	-0.05%	7.05%	5.70%	6.64%	2.12%	-8.15%	-8.46%	-5.07%	-8.95%	-4.27%	-4.23%
8	Missouri River at Omaha, NE	0.15%	-0.06%	6.34%	3.36%	6.68%	2.21%	-7.82%	-8.57%	-4.56%	-7.52%	-3.65%	-2.70%
9	Missouri River at Nebraska City, NE	-1.28%	0.06%	3.08%	0.95%	5.81%	-0.01%	-8.42%	-8.96%	-5.29%	-9.13%	-4.42%	-3.07%
10	Missouri River at Rulo, NE	-0.81%	0.60%	2.54%	0.97%	5.58%	0.06%	-8.47%	-9.66%	-4.95%	-8.48%	-4.93%	-3.14%
11	Missouri River at St. Joseph, MO	-0.53%	1.10%	1.17%	0.78%	5.22%	0.29%	-8.01%	-9.99%	-5.48%	-7.82%	-5.49%	-3.38%
12	Missouri River at Kansas City, MO	-2.64%	0.34%	-1.55%	-2.17%	2.18%	-1.69%	-7.63%	-11.90%	-8.14%	-7.99%	-7.41%	-4.49%
13	Missouri River at Waverly, MO	-3.11%	0.20%	-1.46%	-2.63%	1.76%	-1.29%	-7.13%	-12.05%	-7.91%	-7.49%	-7.90%	-4.67%
14	Missouri River at Boonville, MO	-3.89%	-1.09%	-3.62%	-3.69%	0.22%	-0.33%	-6.61%	-12.14%	-8.43%	-8.28%	-7.92%	-5.97%
15	Missouri River at Hermann, MO	-4.83%	-1.22%	-3.71%	-4.63%	-1.46%	0.03%	-7.04%	-11.83%	-10.24%	-8.67%	-7.10%	-8.57%

Table A.4. 50th percentile change in the mean monthly flows, 2010–2039.

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	4.44%	5.91%	10.28%	16.34%	13.40%	-0.78%	-15.38%	-8.61%	-5.38%	-4.98%	-3.53%	0.86%
2	Missouri River at Garrison Dam, ND	4.45%	6.47%	10.16%	14.69%	14.15%	6.44%	-5.76%	-5.29%	-2.21%	-3.73%	-3.19%	0.17%
3	Lake Oahe nr Pierre, SD	5.26%	7.54%	11.53%	15.26%	14.29%	7.43%	-4.01%	-4.93%	-1.23%	-3.08%	-1.58%	1.68%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	5.48%	7.33%	11.82%	14.99%	14.41%	7.83%	-3.84%	-4.89%	-1.18%	-2.95%	-1.66%	1.78%
5	Missouri River at Fort Randall Dam, SD	6.00%	7.21%	12.15%	15.00%	14.59%	8.36%	-3.38%	-4.86%	-1.10%	-2.15%	-1.70%	1.42%
6	Lewis and Clark Lake nr Yankton, SD	6.24%	7.12%	12.73%	15.11%	15.24%	8.50%	-3.15%	-5.09%	-0.36%	-2.09%	-0.83%	1.58%
7	Missouri River at Sioux City, IA	7.12%	9.22%	13.97%	16.48%	14.89%	9.47%	-2.15%	-4.46%	0.49%	-0.57%	0.87%	3.20%
8	Missouri River at Omaha, NE	7.47%	10.78%	14.10%	16.20%	14.04%	10.12%	-1.61%	-4.40%	1.00%	0.33%	1.55%	5.10%
9	Missouri River at Nebraska City, NE	7.37%	10.87%	13.45%	15.50%	12.13%	10.05%	-1.71%	-4.33%	-1.05%	-0.03%	1.01%	4.64%
10	Missouri River at Rulo, NE	7.91%	11.15%	12.52%	15.86%	11.92%	9.83%	-1.86%	-4.09%	-1.04%	0.36%	0.92%	4.57%
11	Missouri River at St. Joseph, MO	7.55%	10.61%	11.50%	15.28%	10.95%	9.85%	-1.58%	-4.17%	-0.94%	0.45%	1.26%	4.42%
12	Missouri River at Kansas City, MO	7.09%	9.15%	10.62%	12.51%	9.81%	9.26%	-1.33%	-3.44%	-0.24%	0.28%	0.91%	4.55%
13	Missouri River at Waverly, MO	6.59%	9.28%	11.02%	13.03%	9.73%	9.43%	-0.87%	-3.70%	-0.20%	0.60%	0.73%	4.45%
14	Missouri River at Boonville, MO	6.83%	8.21%	9.60%	11.62%	9.99%	10.11%	-0.41%	-3.19%	-0.42%	0.14%	0.38%	3.71%
15	Missouri River at Hermann, MO	4.34%	7.32%	7.57%	9.12%	8.83%	8.89%	0.56%	-2.05%	0.33%	0.23%	1.45%	4.41%

Table A.5. 75th percentile change in the mean monthly flows, 2010–2039

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	15.68%	14.86%	18.51%	25.74%	21.11%	8.22%	-4.55%	-0.02%	2.17%	3.43%	6.45%	9.28%
2	Missouri River at Garrison Dam, ND	12.10%	13.87%	16.94%	22.04%	22.94%	14.07%	1.66%	2.86%	3.33%	3.96%	4.40%	7.14%
3	Lake Oahe nr Pierre, SD	13.17%	14.39%	21.39%	23.75%	23.26%	15.49%	3.24%	3.95%	5.08%	6.27%	4.11%	8.30%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	13.13%	14.36%	21.91%	23.84%	23.34%	15.54%	3.43%	4.24%	5.00%	6.51%	4.18%	8.15%
5	Missouri River at Fort Randall Dam, SD	13.34%	14.15%	22.92%	24.61%	23.47%	15.66%	3.87%	4.43%	4.26%	7.36%	4.85%	8.11%
6	Lewis and Clark Lake nr Yankton, SD	13.36%	14.18%	22.70%	25.04%	23.67%	15.76%	4.35%	4.36%	4.50%	7.01%	4.73%	8.56%
7	Missouri River at Sioux City, IA	15.69%	16.40%	26.51%	27.01%	25.13%	16.61%	4.98%	4.75%	7.33%	9.40%	7.39%	10.37%
8	Missouri River at Omaha, NE	15.82%	17.43%	26.21%	26.59%	25.18%	17.24%	5.43%	5.21%	8.23%	10.14%	8.84%	11.78%
9	Missouri River at Nebraska City, NE	16.20%	18.01%	25.91%	25.76%	22.97%	16.95%	3.95%	3.86%	7.51%	9.59%	8.97%	11.53%
10	Missouri River at Rulo, NE	16.94%	19.60%	24.02%	24.59%	22.79%	16.38%	4.42%	4.01%	7.74%	10.41%	10.29%	12.83%
11	Missouri River at St. Joseph, MO	17.29%	19.43%	22.98%	23.47%	21.81%	16.65%	4.98%	4.15%	8.99%	10.62%	10.65%	14.41%
12	Missouri River at Kansas City, MO	17.19%	20.79%	22.53%	23.91%	21.58%	18.84%	6.84%	4.64%	11.66%	13.28%	14.77%	17.09%
13	Missouri River at Waverly, MO	16.98%	20.57%	20.78%	23.20%	21.55%	19.21%	7.65%	4.24%	11.13%	14.31%	14.95%	17.58%
14	Missouri River at Boonville, MO	18.59%	19.85%	18.82%	21.32%	21.67%	19.64%	7.70%	5.06%	10.22%	16.52%	15.01%	19.15%
15	Missouri River at Hermann, MO	18.59%	16.90%	17.28%	19.74%	21.56%	19.49%	8.04%	5.43%	12.75%	16.13%	16.48%	20.92%

Table A.6. 95th percentile change in the mean monthly flows, 2010–2039

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	28.25%	35.77%	43.01%	46.15%	42.70%	24.14%	8.76%	14.64%	16.26%	16.27%	16.96%	23.94%
2	Missouri River at Garrison Dam, ND	27.11%	33.48%	37.14%	35.71%	36.53%	26.30%	13.58%	10.68%	12.79%	12.04%	15.30%	18.60%
3	Lake Oahe nr Pierre, SD	28.28%	32.93%	39.64%	35.56%	34.27%	25.26%	12.74%	11.93%	14.13%	16.22%	15.81%	19.09%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	27.87%	32.50%	39.57%	36.18%	33.75%	25.29%	12.68%	12.03%	14.60%	16.44%	15.63%	18.99%
5	Missouri River at Fort Randall Dam, SD	27.35%	31.58%	38.55%	35.86%	33.87%	25.81%	13.37%	12.14%	14.92%	16.22%	15.83%	18.61%
6	Lewis and Clark Lake nr Yankton, SD	27.37%	30.77%	39.93%	36.79%	34.74%	25.84%	14.00%	12.27%	15.15%	16.89%	17.01%	18.50%
7	Missouri River at Sioux City, IA	27.74%	32.40%	41.16%	42.50%	37.61%	27.02%	14.70%	11.98%	16.96%	24.01%	24.45%	21.52%
8	Missouri River at Omaha, NE	28.63%	35.17%	44.58%	41.80%	38.46%	28.17%	14.95%	12.46%	18.32%	26.13%	26.54%	23.99%
9	Missouri River at Nebraska City, NE	28.52%	35.15%	46.51%	40.14%	38.93%	28.75%	13.01%	12.61%	20.12%	26.46%	26.49%	23.40%
10	Missouri River at Rulo, NE	29.86%	35.85%	44.49%	39.59%	39.27%	28.77%	13.60%	13.08%	20.30%	26.69%	27.64%	25.48%
11	Missouri River at St. Joseph, MO	30.97%	36.31%	43.93%	39.11%	40.62%	29.49%	14.91%	13.80%	21.71%	26.90%	28.58%	27.17%
12	Missouri River at Kansas City, MO	35.35%	36.49%	41.69%	46.10%	43.23%	33.73%	19.51%	17.72%	27.31%	31.88%	30.69%	34.44%
13	Missouri River at Waverly, MO	35.60%	36.05%	41.49%	47.12%	42.99%	34.08%	19.68%	17.96%	26.85%	31.01%	31.02%	34.62%
14	Missouri River at Boonville, MO	35.47%	36.29%	40.33%	45.97%	41.27%	34.65%	21.61%	19.67%	27.71%	32.13%	33.10%	36.82%
15	Missouri River at Hermann, MO	36.31%	33.37%	34.80%	43.13%	40.25%	34.20%	24.48%	21.49%	30.16%	34.32%	35.38%	37.98%

Table A.7. 5th percentile change in the mean monthly flows, 2040–2069

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	-12.12%	-5.64%	-2.63%	6.97%	3.05%	-25.74%	-44.84%	-30.66%	-24.83%	-25.30%	-21.64%	-16.48%
2	Missouri River at Garrison Dam, ND	-10.49%	-3.89%	-1.08%	3.80%	7.67%	-10.18%	-32.72%	-24.75%	-21.07%	-22.48%	-21.80%	-16.95%
3	Lake Oahe nr Pierre, SD	-10.27%	-2.88%	-0.86%	3.31%	4.97%	-8.56%	-28.29%	-25.51%	-23.67%	-21.12%	-19.29%	-15.05%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	-10.54%	-3.05%	-0.81%	2.28%	4.76%	-7.34%	-27.52%	-25.89%	-23.67%	-21.01%	-19.18%	-14.77%
5	Missouri River at Fort Randall Dam, SD	-10.42%	-2.60%	-2.04%	-0.19%	3.70%	-6.25%	-26.20%	-26.26%	-24.42%	-21.09%	-18.71%	-13.84%
6	Lewis and Clark Lake nr Yankton, SD	-10.29%	-2.82%	-3.54%	-1.36%	3.17%	-6.17%	-25.26%	-26.52%	-25.07%	-20.95%	-18.04%	-13.64%
7	Missouri River at Sioux City, IA	-7.94%	-2.01%	-1.60%	-3.29%	3.80%	-6.59%	-23.24%	-27.29%	-26.19%	-21.45%	-15.49%	-11.35%
8	Missouri River at Omaha, NE	-7.92%	-0.87%	-4.60%	-6.45%	2.77%	-6.54%	-22.67%	-28.19%	-27.27%	-21.50%	-15.91%	-11.88%
9	Missouri River at Nebraska City, NE	-9.16%	-3.52%	-10.03%	-9.89%	-1.57%	-9.75%	-25.20%	-30.18%	-29.79%	-24.01%	-16.99%	-15.04%
10	Missouri River at Rulo, NE	-9.25%	-4.45%	-12.41%	-10.53%	-2.76%	-9.79%	-25.03%	-30.56%	-30.41%	-24.43%	-16.82%	-15.22%
11	Missouri River at St. Joseph, MO	-11.01%	-5.74%	-14.30%	-11.37%	-3.39%	-9.54%	-24.64%	-31.00%	-31.46%	-25.48%	-17.92%	-15.85%
12	Missouri River at Kansas City, MO	-15.96%	-12.08%	-19.15%	-15.94%	-8.63%	-12.49%	-27.23%	-33.74%	-34.65%	-29.80%	-24.19%	-22.89%
13	Missouri River at Waverly, MO	-16.89%	-12.49%	-19.73%	-15.98%	-8.59%	-12.52%	-26.88%	-33.97%	-34.92%	-30.19%	-24.93%	-23.44%
14	Missouri River at Boonville, MO	-20.50%	-15.10%	-21.10%	-16.10%	-8.76%	-13.27%	-27.14%	-35.05%	-37.95%	-30.63%	-26.53%	-24.80%
15	Missouri River at Hermann, MO	-24.35%	-17.17%	-20.77%	-18.31%	-10.74%	-13.88%	-27.72%	-35.87%	-40.91%	-33.04%	-30.31%	-30.05%

Table A.8. 25th percentile change in the mean monthly flows, 2040–2069

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	0.06%	4.47%	12.23%	21.00%	15.13%	-17.23%	-35.56%	-23.94%	-17.40%	-17.54%	-12.92%	-7.51%
2	Missouri River at Garrison Dam, ND	-0.91%	4.76%	11.27%	18.74%	18.44%	0.60%	-20.10%	-15.44%	-14.53%	-13.66%	-12.44%	-6.63%
3	Lake Oahe nr Pierre, SD	-0.39%	6.60%	11.94%	17.38%	19.57%	2.40%	-18.66%	-14.78%	-11.81%	-13.28%	-10.54%	-4.06%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	-0.60%	6.56%	12.29%	17.36%	20.15%	3.00%	-18.11%	-15.04%	-11.46%	-12.89%	-9.97%	-4.31%
5	Missouri River at Fort Randall Dam, SD	-0.94%	5.86%	11.95%	17.58%	19.77%	3.37%	-17.28%	-14.86%	-11.08%	-12.86%	-9.19%	-4.24%
6	Lewis and Clark Lake nr Yankton, SD	-0.85%	5.62%	11.72%	15.19%	19.06%	4.00%	-16.24%	-14.67%	-10.57%	-12.95%	-9.39%	-4.31%
7	Missouri River at Sioux City, IA	1.21%	8.49%	13.89%	15.94%	16.77%	4.78%	-14.37%	-15.19%	-7.66%	-12.16%	-6.98%	-0.76%
8	Missouri River at Omaha, NE	1.81%	8.92%	11.58%	13.72%	16.79%	5.87%	-13.28%	-14.21%	-8.72%	-12.30%	-6.50%	-0.14%
9	Missouri River at Nebraska City, NE	1.98%	8.29%	8.91%	10.84%	13.57%	3.45%	-13.35%	-14.76%	-11.05%	-13.17%	-6.94%	-2.26%
10	Missouri River at Rulo, NE	1.99%	8.12%	7.58%	9.69%	12.36%	4.33%	-12.55%	-14.45%	-11.64%	-12.90%	-6.89%	-2.19%
11	Missouri River at St. Joseph, MO	2.26%	7.26%	6.14%	8.79%	11.50%	4.44%	-11.41%	-14.15%	-12.35%	-12.07%	-7.76%	-2.76%
12	Missouri River at Kansas City, MO	1.09%	5.88%	-0.07%	4.28%	9.59%	1.78%	-11.13%	-15.66%	-13.41%	-11.89%	-10.35%	-5.80%
13	Missouri River at Waverly, MO	0.60%	5.50%	-0.32%	4.17%	9.31%	2.05%	-10.99%	-15.75%	-13.50%	-11.58%	-10.36%	-5.89%
14	Missouri River at Boonville, MO	2.04%	3.64%	-0.71%	2.07%	9.39%	2.20%	-10.76%	-14.38%	-13.12%	-10.53%	-10.68%	-5.96%
15	Missouri River at Hermann, MO	-1.85%	0.11%	-2.33%	-0.42%	5.90%	2.17%	-10.37%	-13.54%	-13.53%	-12.47%	-11.56%	-4.71%

Table A.9. 50th percentile change in the mean monthly flows, 2040–2069

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	10.08%	14.45%	23.59%	34.19%	22.06%	-7.35%	-27.44%	-15.75%	-11.28%	-9.80%	-4.20%	2.85%
2	Missouri River at Garrison Dam, ND	8.76%	14.30%	21.23%	29.26%	27.59%	7.71%	-13.03%	-8.61%	-6.02%	-7.25%	-4.19%	2.12%
3	Lake Oahe nr Pierre, SD	9.98%	14.25%	21.78%	29.95%	27.44%	10.70%	-9.02%	-6.53%	-4.32%	-4.13%	-2.46%	2.72%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	10.06%	14.20%	21.43%	29.50%	27.52%	11.56%	-8.45%	-6.44%	-3.74%	-4.08%	-2.65%	2.34%
5	Missouri River at Fort Randall Dam, SD	10.32%	14.17%	21.47%	29.48%	27.55%	12.66%	-7.31%	-5.73%	-3.15%	-3.75%	-2.47%	2.34%
6	Lewis and Clark Lake nr Yankton, SD	10.40%	14.67%	20.67%	29.17%	28.35%	13.76%	-6.53%	-5.10%	-2.43%	-3.40%	-1.34%	2.47%
7	Missouri River at Sioux City, IA	13.11%	17.76%	23.83%	28.61%	30.01%	15.15%	-5.28%	-2.97%	-0.06%	1.70%	4.25%	6.52%
8	Missouri River at Omaha, NE	13.51%	19.20%	25.96%	26.72%	29.34%	15.96%	-3.65%	-2.41%	1.87%	1.35%	6.63%	8.20%
9	Missouri River at Nebraska City, NE	13.57%	19.27%	25.37%	23.62%	26.04%	14.36%	-4.65%	-1.81%	0.68%	0.51%	5.83%	8.44%
10	Missouri River at Rulo, NE	14.03%	18.76%	23.70%	22.38%	25.01%	14.45%	-4.34%	-1.53%	1.23%	0.75%	5.59%	9.58%
11	Missouri River at St. Joseph, MO	13.76%	18.87%	21.77%	20.66%	24.47%	14.77%	-3.20%	-1.28%	1.83%	0.37%	5.52%	11.02%
12	Missouri River at Kansas City, MO	11.62%	15.77%	19.09%	16.32%	22.87%	15.19%	-0.33%	1.31%	2.28%	0.04%	5.30%	10.46%
13	Missouri River at Waverly, MO	11.41%	15.55%	17.89%	16.30%	22.45%	15.55%	-0.13%	1.21%	2.65%	-0.45%	5.39%	10.54%
14	Missouri River at Boonville, MO	10.57%	14.27%	13.19%	15.65%	22.47%	16.48%	-0.28%	1.29%	3.14%	1.50%	4.74%	11.39%
15	Missouri River at Hermann, MO	11.35%	11.55%	10.92%	14.71%	20.64%	16.33%	0.14%	2.39%	3.61%	0.68%	4.87%	11.27%

Table A.10. 75th percentile change in the mean monthly flows, 2040–2069

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	27.51%	35.52%	43.45%	56.62%	37.76%	6.68%	-14.59%	-1.62%	-0.80%	1.55%	5.70%	12.07%
2	Missouri River at Garrison Dam, ND	21.89%	29.93%	38.11%	47.02%	39.19%	18.17%	-2.37%	0.53%	2.16%	4.12%	6.41%	11.90%
3	Lake Oahe nr Pierre, SD	20.78%	30.44%	40.65%	42.34%	38.18%	21.47%	1.97%	3.25%	4.82%	5.61%	9.42%	11.86%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	20.42%	30.02%	40.69%	42.43%	37.50%	22.36%	2.84%	3.66%	4.90%	5.49%	9.79%	12.05%
5	Missouri River at Fort Randall Dam, SD	20.29%	29.09%	40.41%	41.59%	38.27%	23.36%	3.63%	4.12%	5.11%	6.39%	10.07%	12.68%
6	Lewis and Clark Lake nr Yankton, SD	20.29%	28.23%	39.82%	42.13%	38.56%	24.15%	4.34%	4.93%	5.83%	6.91%	10.38%	13.59%
7	Missouri River at Sioux City, IA	24.91%	31.61%	43.32%	44.43%	41.53%	24.85%	6.13%	7.36%	10.60%	11.47%	16.10%	19.26%
8	Missouri River at Omaha, NE	26.87%	32.32%	42.54%	42.44%	40.79%	24.37%	7.21%	6.95%	12.07%	12.27%	17.43%	20.91%
9	Missouri River at Nebraska City, NE	24.87%	33.87%	44.59%	42.57%	38.91%	25.44%	6.67%	7.50%	12.84%	11.80%	16.50%	19.73%
10	Missouri River at Rulo, NE	26.38%	33.14%	44.34%	41.38%	38.57%	25.60%	7.75%	8.05%	14.29%	11.53%	17.35%	20.21%
11	Missouri River at St. Joseph, MO	26.13%	31.31%	42.94%	39.38%	39.00%	26.07%	8.12%	8.30%	14.97%	12.25%	18.87%	20.54%
12	Missouri River at Kansas City, MO	29.36%	30.91%	40.49%	39.27%	38.91%	28.02%	12.58%	10.45%	14.72%	14.68%	22.22%	24.84%
13	Missouri River at Waverly, MO	29.40%	30.72%	40.22%	38.27%	39.08%	27.71%	13.20%	10.01%	15.47%	16.16%	21.79%	24.52%
14	Missouri River at Boonville, MO	27.54%	28.97%	35.27%	35.74%	38.83%	28.30%	15.16%	10.86%	16.94%	18.46%	20.11%	23.60%
15	Missouri River at Hermann, MO	26.23%	25.50%	29.64%	33.49%	37.89%	27.49%	16.35%	12.44%	18.43%	17.20%	19.64%	22.98%

Table A.11. 95th percentile change in the mean monthly flows, 2040–2069

Node	Location Description	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
1	Fort Peck Lake at Fort Peck, MT	56.40%	67.79%	79.51%	90.11%	67.80%	28.52%	3.57%	18.49%	22.53%	30.14%	30.26%	42.38%
2	Missouri River at Garrison Dam, ND	50.98%	54.07%	60.24%	67.01%	60.14%	38.53%	16.41%	19.00%	18.48%	24.64%	29.47%	36.06%
3	Lake Oahe nr Pierre, SD	51.94%	50.28%	60.01%	69.85%	58.55%	41.66%	19.33%	18.68%	20.54%	26.64%	34.29%	40.90%
4	Misso. R. blw Big Bend Dam nr Ft.Thompson, SD	51.79%	49.99%	60.69%	70.98%	59.42%	41.84%	19.92%	18.94%	21.19%	26.89%	34.34%	41.28%
5	Missouri River at Fort Randall Dam, SD	51.45%	50.05%	60.46%	73.96%	59.85%	42.61%	21.19%	19.36%	22.08%	27.31%	33.95%	41.17%
6	Lewis and Clark Lake nr Yankton, SD	51.55%	50.38%	59.39%	73.87%	59.86%	43.53%	22.48%	19.83%	22.95%	27.59%	33.72%	40.82%
7	Missouri River at Sioux City, IA	50.15%	52.46%	63.54%	78.06%	64.32%	43.32%	25.25%	20.47%	30.11%	32.48%	36.86%	43.19%
8	Missouri River at Omaha, NE	51.79%	55.31%	64.89%	75.57%	63.43%	45.47%	26.67%	20.78%	33.28%	31.78%	37.15%	43.72%
9	Missouri River at Nebraska City, NE	48.03%	53.22%	64.40%	75.36%	57.27%	41.88%	24.66%	21.86%	36.54%	29.72%	33.57%	39.79%
10	Missouri River at Rulo, NE	47.93%	54.58%	63.89%	73.24%	56.92%	41.26%	24.74%	22.88%	36.62%	30.03%	34.71%	40.72%
11	Missouri River at St. Joseph, MO	47.33%	55.35%	63.80%	72.61%	56.69%	41.46%	25.14%	22.84%	38.36%	30.56%	35.85%	39.32%
12	Missouri River at Kansas City, MO	45.83%	52.58%	69.09%	71.76%	56.31%	45.01%	29.70%	25.14%	41.72%	35.90%	39.88%	41.26%
13	Missouri River at Waverly, MO	45.30%	52.12%	67.45%	72.68%	56.35%	45.72%	30.55%	25.38%	42.18%	37.46%	39.43%	41.88%
14	Missouri River at Boonville, MO	45.01%	50.87%	59.46%	68.19%	55.57%	45.79%	32.40%	28.32%	47.45%	41.69%	40.34%	44.13%
15	Missouri River at Hermann, MO	43.27%	47.60%	51.14%	60.56%	55.77%	45.35%	33.67%	28.80%	54.94%	42.38%	42.77%	44.70%

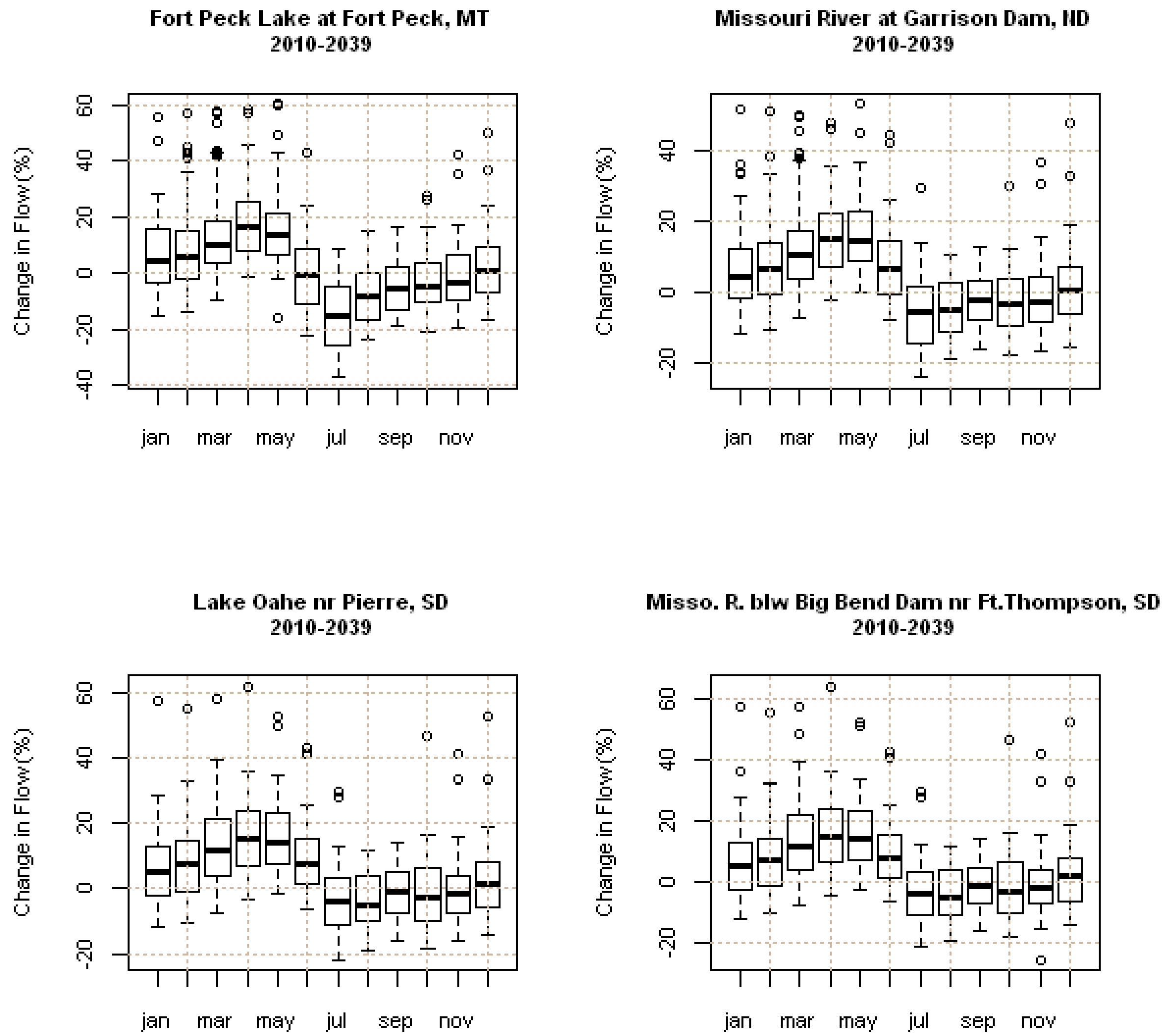

Figure A.1. Boxplot of monthly change factors for the period 2010–2039. Reference hydrologic period, 1950–1999.

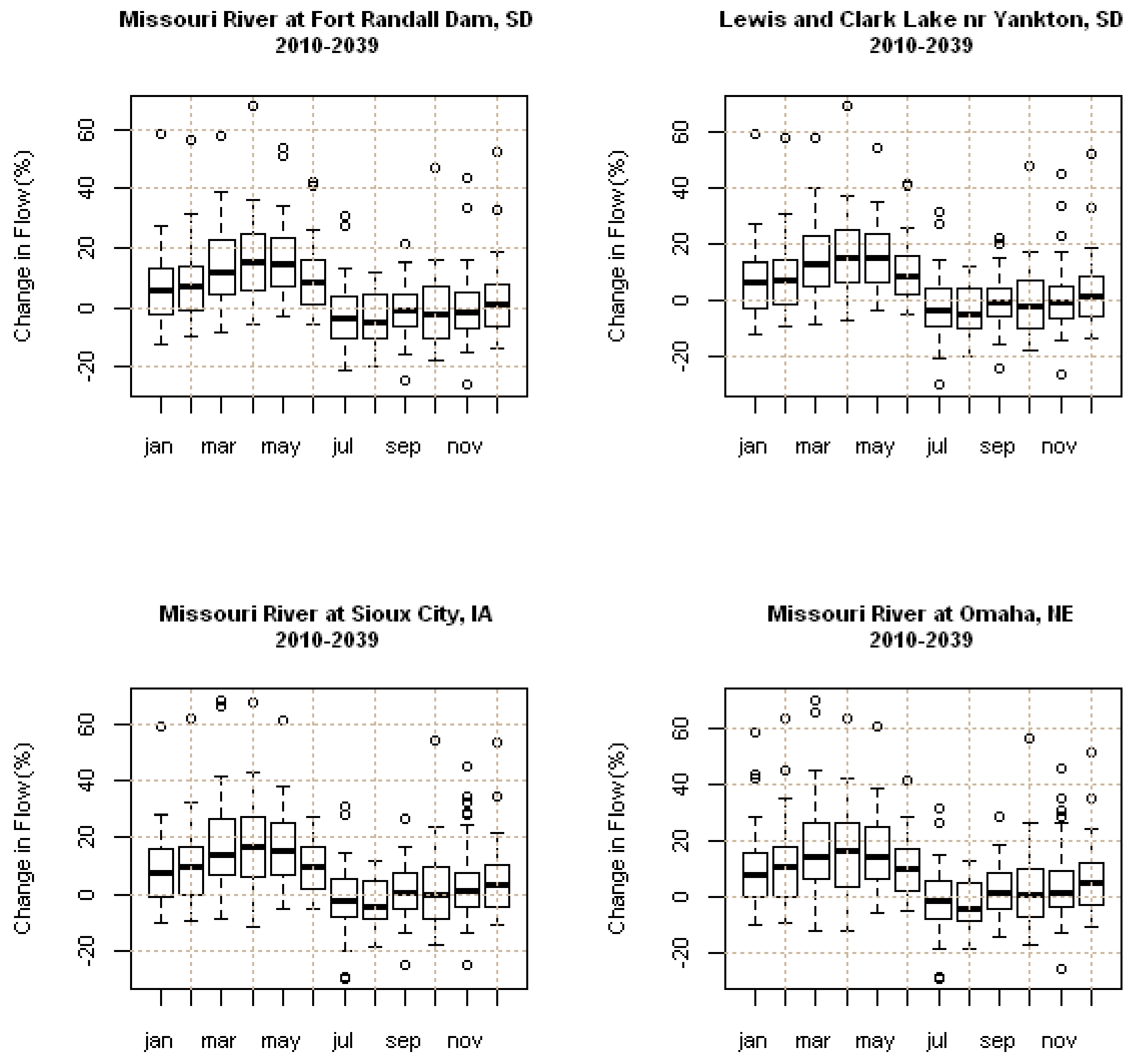

Figure A.1 (continued). Boxplot of monthly change factors for the period 2010–2039. Reference hydrologic period, 1950–1999.

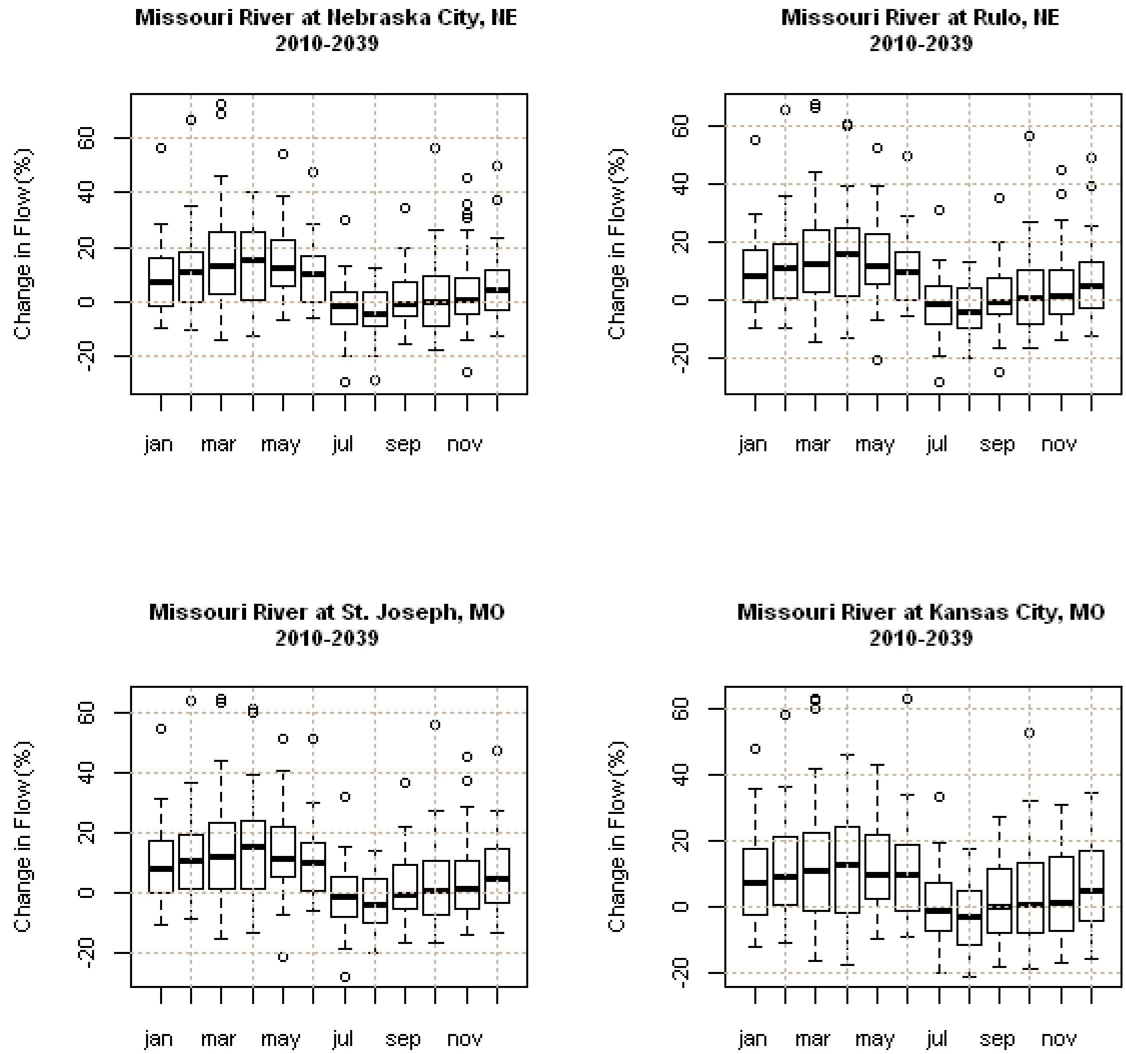

Figure A.1 (continued). Boxplot of monthly change factors for the period 2010–2039. Reference hydrologic period, 1950–1999.

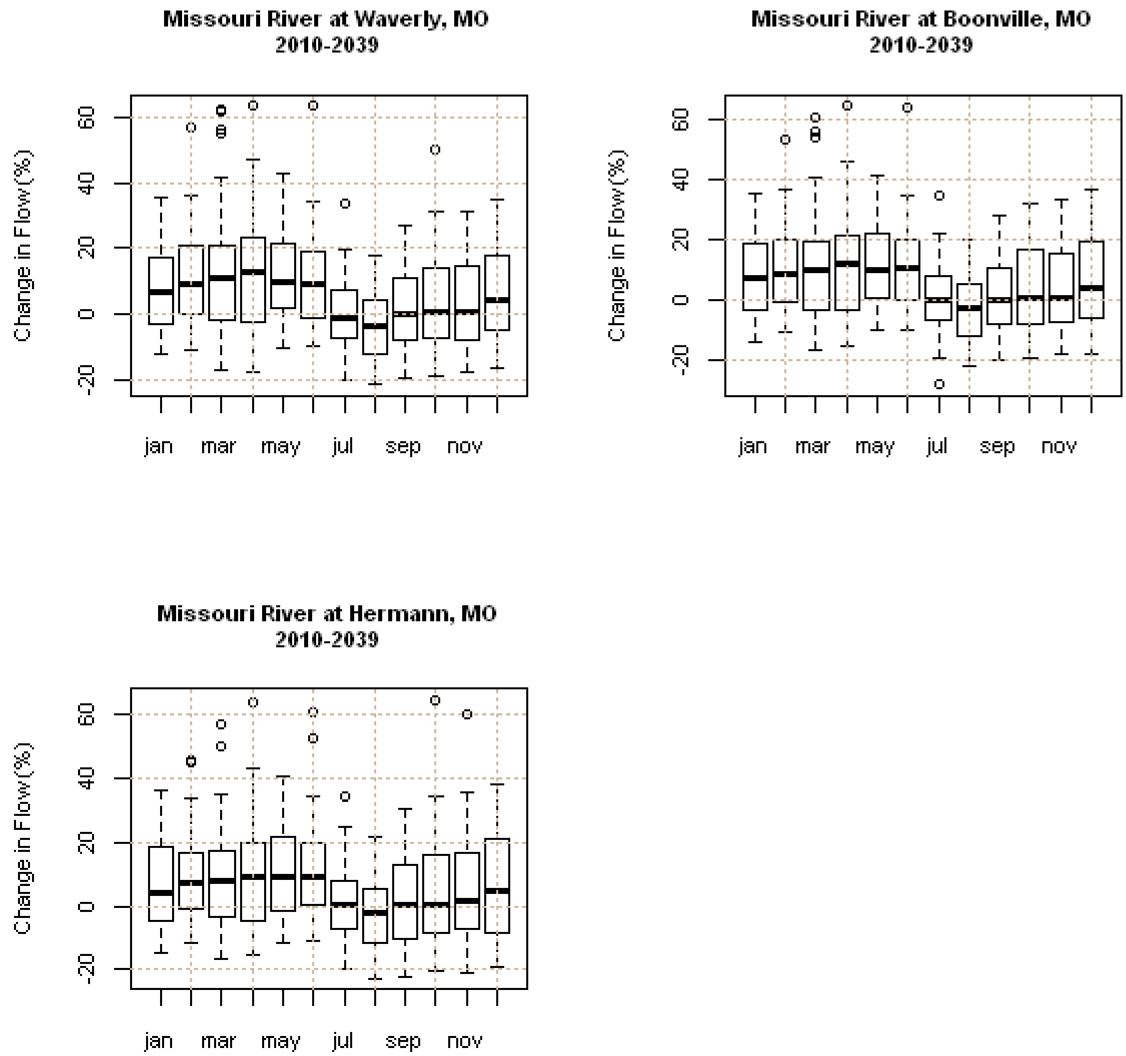

Figure A.1 (continued). Boxplot of monthly change factors for the period 2010–2039. Reference hydrologic period, 1950–1999.

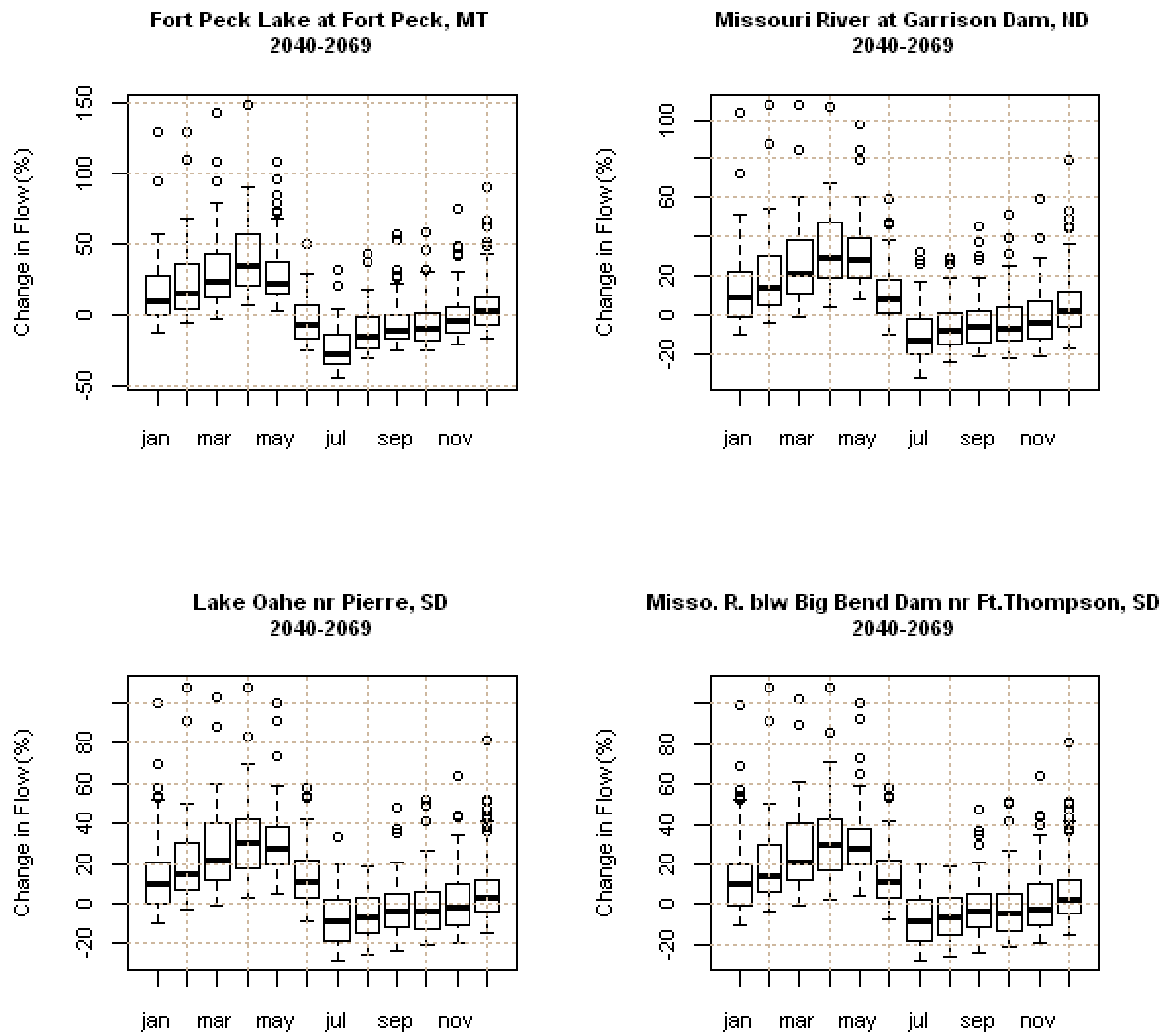

Figure A.2. Boxplot of monthly change factors for the period 2040–2069. Reference hydrologic period, 1950–1999.

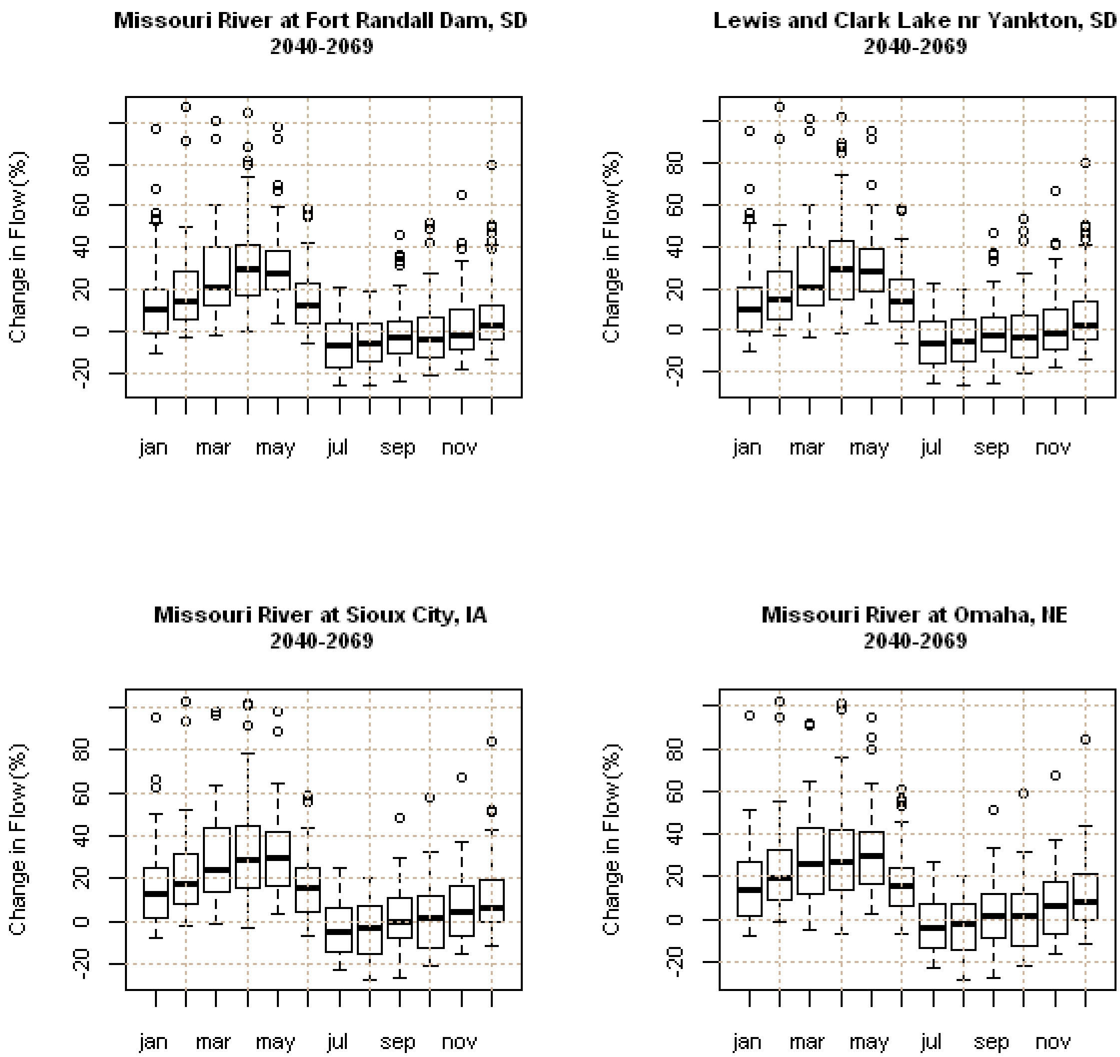

Figure A.2 (continued). Boxplot of monthly change factors for the period 2040–2069. Reference hydrologic period, 1950–1999.

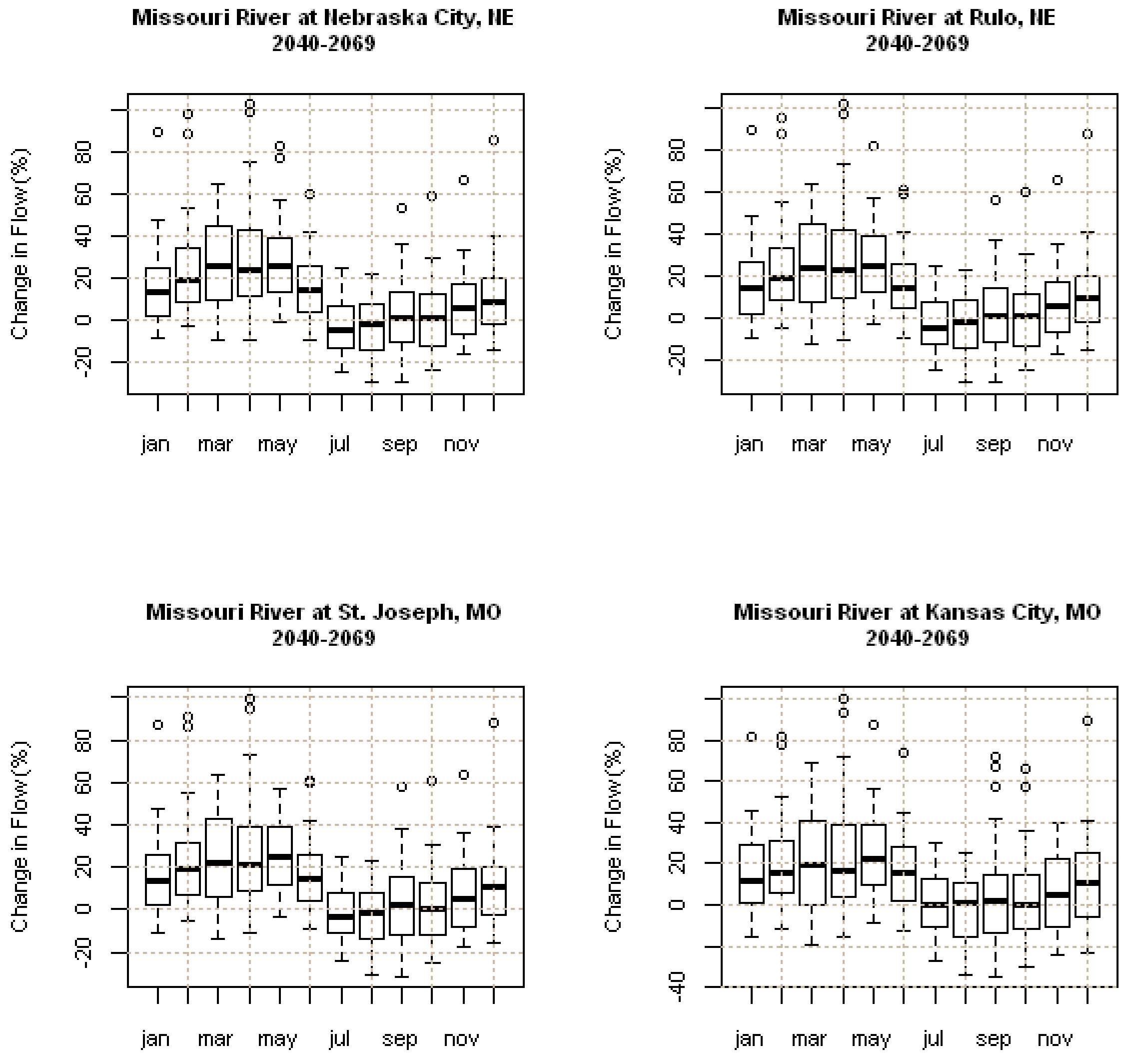

Figure A.2 (continued). Boxplot of monthly change factors for the period 2040–2069. Reference hydrologic period, 1950–1999.

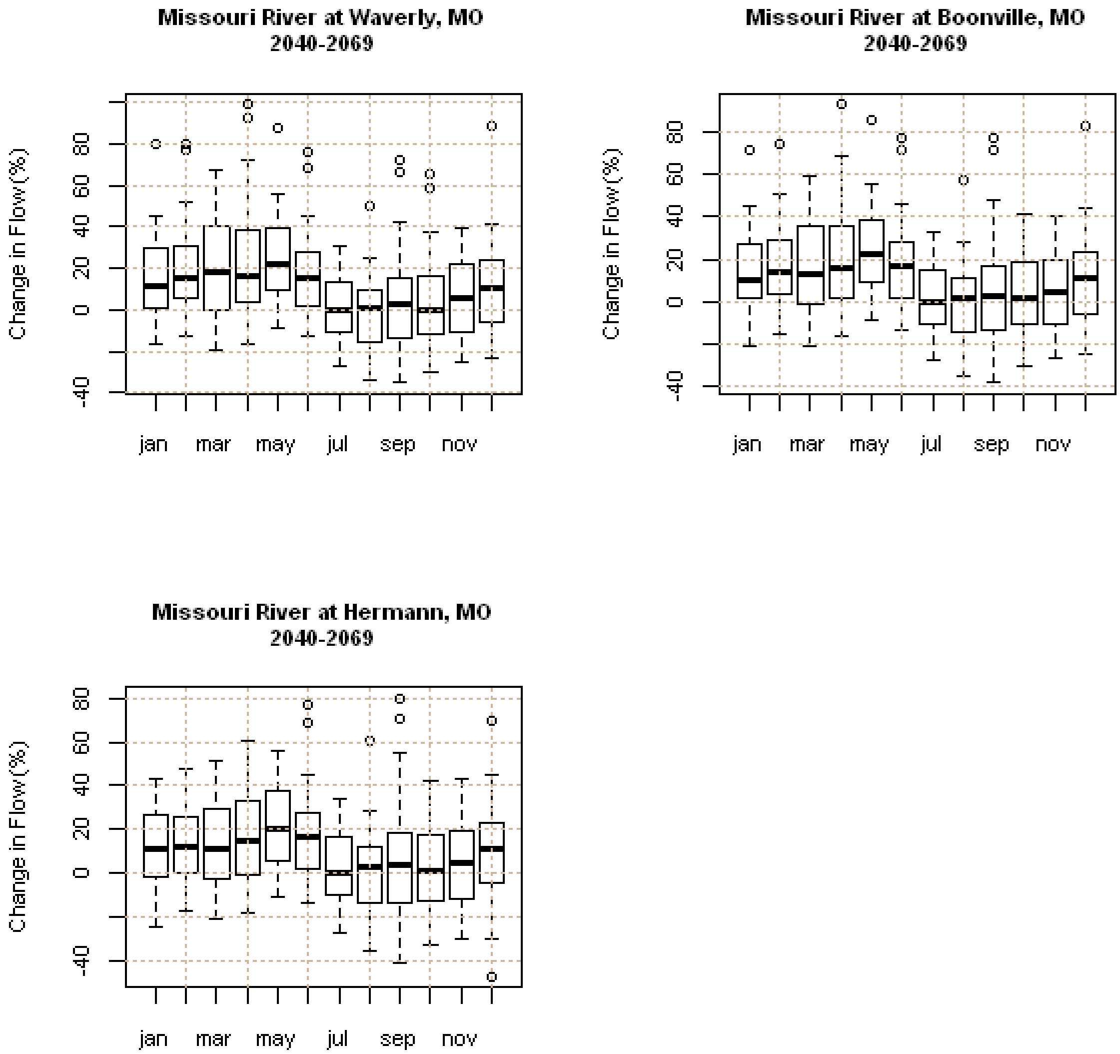

Figure A.2 (continued). Boxplot of monthly change factors for the period 2040–2069. Reference hydrologic period, 1950–1999.