Climate Change Impacts on USACE Water Supply Reservoirs: A Pilot Study of the Marion Reservoir Watershed in Kansas
EXECUTIVE SUMMARY

Marion Reservoir, located on the Cottonwood River in Marion County, Kansas, was selected for an assessment of its water supply and demand vulnerabilities in relation to climate change and variability. The water supply in this reservoir (44,730 acre-feet) is owned by the State of Kansas. The water supply contract held by the State of Kansas was originally approved in 1976, with a subsequent reallocation of additional water supply storage in 1996. The Kansas Water Office currently has water marketing contracts totaling 1,834 acre-feet that extend through the year 2039.

There have been three prolonged periods of drought recorded in the Cottonwood River basin. The most prolonged (and most severe) occurred between 1952 and 1957. The average monthly inflow during this period was 12% of the period average (1922–1988), and it included 6 months of zero inflow. The lowest Palmer Drought Severity Index (PDSI) value during this period was –6.06, which is considered to be an extreme drought.

Prior to beginning this study, a gridded dataset of bias-corrected, spatially disaggregated (BCSD) statistically downscaled climate projections was obtained from a joint archive maintained by several Federal and academic partners, including the U.S. Army Corps of Engineers (Brekke et al., 2013). A subset of this data, extracted for the Marion Reservoir watershed, was converted from a native general circulation model (GCM) grid cell size and redistributed into 1/8° (latitude by longitude) spacing (A. Wood, personal communication, 2011). The resulting grid cells, each with an area of 57 square miles, were superimposed across the Marion Reservoir watershed; 10 grid cells were used in the analysis.

Hydrographs were developed from the BCSD dataset by running simulations in the Variable Infiltration Capacity (VIC) model (Liang, 1994). Several steps were required, including incorporation of the vegetation and soil dataset for the watershed, generation of the computational grid for the watershed by overlaying watershed polygons and extracting grid cells, compilation of the source code for VIC and routing models, definition of the state variables and pathnames for VIC and routing models, execution of the VIC model and generation of cell flux output, and execution of the routing model and generation of time series hydrographs for the watershed.

Numerical routing was then used to project each of the hydrographs into a long-term simulation of pool elevations so that droughts could be identified and the critical period for each could then be identified. A mass balance approach was used, and iteration proceeded automatically through all time steps in the spreadsheet until an outflow value was found that resulted in a single minimum pool elevation of 1,320.0 feet, which constituted the occurrence of both the critical period and the firm yield.
The VIC simulation, with historical data as input, accurately reproduced the critical period. The timing and duration of historical droughts, including the 1952–1957 drought of record, were generally correct. However, the VIC simulation did not replicate firm yield. Differences between the observed and simulated firm yield were minimized when the simulated hydrograph was bias corrected to the observed hydrograph for the historical overlap period (1949-2008).

All model projections were in agreement that future conditions will be warmer over the Marion Reservoir watershed, with a median increase in temperature of +4.76°F by the year 2050. No consensus existed with respect to future precipitation trends in the Marion Reservoir watershed. Half of the models in the BCSD dataset predicted an increase in annual rainfall by the year 2050, while the other half predicted a decrease in annual rainfall. Most of the models fall within a ±20% range by the year 2050 based on current climatology.

This study provides a methodology from which climate change can be included as a factor when planning for long-term water supply use. The results of this study suggest that mean annual temperature will increase across the basin while mean annual precipitation will remain about the same. Yield modeling of projected hydrographs shows little change in 30-year mean values. Furthermore, the capacity for additional water supply contracts currently exists. Although future demand was not considered, the Marion Reservoir watershed is a small, rural area with stagnant demand growth. There is no current basis for the expectation of an increase in future demand. Since the reservoir has existing water supply capacity that significantly exceeds the contracted amount, it appears to be well positioned to meet future water supply obligations.
PURPOSE

The primary objective of this project was to assess the vulnerability of water supply and demand at Marion Reservoir in relation to climate change and variability.

An initial assessment was performed to assess the reservoir’s vulnerability to drought under current conditions. The assessment included the review of the current water supply contracts, customers, and uses. The assessment considered what combination of drought duration and magnitude would cause the reservoir to no longer meet its contracts. The findings of this assessment can be used to consider the water supply customer’s potential vulnerability to drought by determining what alternative sources of supply are available, what conservation measures could be employed, and how much water demand exists during drought.

This project was completed with funding from the U.S. Army Corps of Engineers (USACE) Institute for Water Resources (IWR) and was prepared for Mr. Ted Hillyer, Manager of the Water Supply Business Line. Climate model forcing data were provided by Dr. Andrew Wood, Development and Operations Hydrologist, National Oceanographic and Atmospheric Agency (NOAA), National Weather Service (NWS), Northwest River Forecast Center. The analysis and findings in this report were developed in collaboration with Dr. David Raff, Senior Hydraulic and Hydrologic Engineer, USACE IWR Climate and Global Change Team.

We acknowledge the modeling groups, the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the WCRP’s Working Group on Coupled Modelling (WGCM) for their roles in making available the WCRP CMIP3 multi-model dataset. Support of this dataset is provided by the Office of Science, U.S. Department of Energy.

Any questions regarding the technical information contained in this report should be directed to the author, Dr. David Williams, Lead Hydraulic Engineer, USACE Tulsa District.
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INTRODUCTION

The U.S. Army Corps of Engineers (USACE) has numerous water supply contracts at reservoirs in the Tulsa District (SWT). Among these multi-purpose projects is Marion Reservoir, located on the Cottonwood River in Marion County, Kansas. This reservoir was chosen for a pilot study that assessed the vulnerability of water supply and demand to climate variability based on the following criteria:

- The reservoir provides water supply as an allocated purpose.
- The watershed associated with the reservoir is relatively small.
- The reservoir is not a downstream project in a system.

Marion Reservoir met these criteria since it has a small total capacity, it maintains a contracted water supply allocation to the State of Kansas, and it is a headwater reservoir in a watershed of a manageable size. Additionally, a long observed and simulated period of record is available from USACE (Tulsa District).

Downscaled climate change projections derived from the World Climate Research Programme’s third phase of the Coupled Model Intercomparison Project (CMIP3) were used as the basis for the analysis. This study utilized the Variable Infiltration Capacity (VIC) hydrologic model to examine a range of climate change scenarios to determine whether or not the Federal water supply contractual obligations will be met during future climate conditions. In other words, how vulnerable is the water supply contract at Marion Reservoir to climate change?

Answering this question required not only hydrologic climate modeling using VIC, but also reservoir simulation using numerical routing methods. Operational rules contained in the Marion Reservoir water control manual were used to simulate pool elevations in conjunction with the inflow hydrograph that was computed with the VIC model. Development of water supply reservoir modeling with projected climate variables provides an opportunity for USACE to assess the vulnerability of these projects with modified precipitation and runoff parameters.

Collaboration on this project with researchers at the U.S. Bureau of Reclamation (USBR) and the National Oceanic and Atmospheric Administration (NOAA) was beneficial, given the technical expertise that has been gained through similar efforts. The selection of Marion Reservoir for this pilot study complements the ongoing modeling efforts of other Federal agencies in the Great Plains region and allows the use of existing datasets and modeling technology.
PROJECT DESCRIPTION

Marion Reservoir is located at mile 126.7 on the Cottonwood River, about 3 miles northwest of Marion in Marion County, Kansas (Figure 1). It is a multi-purpose project for flood control, water quality control, recreation, and water supply. Marion Reservoir, Council Grove Lake, and John Redmond Reservoir are integral components in a three-unit system. This system is part of the multi-purpose plan for flood control, hydroelectric power generation, navigation, and allied water uses on the Arkansas River and tributaries in Kansas, Arkansas, and Oklahoma.

FIGURE 1: Map of region surrounding Marion Reservoir (from Kansas Department of Transportation).

The Cottonwood River, a principal tributary in Kansas, rises in east central Kansas near Marion and flows in a general easterly direction from its source to its confluence with the Neosho River at mile 382.8. The watershed is about 70 miles long, averaging about 26 miles in width and draining an area of approximately 1,908 square miles, which is 70% of the total drainage area above the confluence of the Cottonwood and Neosho Rivers.

The climate of the Cottonwood River watershed is characterized by moderate winters and comparatively long summers with relatively high temperatures. Summer rains generally occur as thunderstorms with very intense rainfall of short duration and limited areal coverage. The winter rains are generally of low intensity but cover a large area and are of considerably longer duration. The Gulf of Mexico is the source of much of the precipitation that falls on the basin.

Most of the flood-producing storms over the watershed above Marion Reservoir have been from 3 to 8 days duration and have occurred in the spring and fall months. The longer storms have generally been made up of two or three periods of intense precipitation, with moderate
precipitation on the intervening days saturating the watershed and resulting in a high percentage of runoff from subsequent periods of heavy precipitation.

Maximum rainfall occurs in May and June, with a noticeable decrease in the average rainfall in November, December, January, and February (Figure 2). The maximum storm over the watershed above Marion Dam during the period of record was 10.16 inches over four days in July 1951. Over the period of record, about 71.8% of the rainfall occurred during the months of April through September. The averages were computed from published precipitation records of rainfall recorded for the basin. These records do not necessarily report the center of intense storms. Antecedent precipitation, season of the year, and many other factors influence storm runoff, and floods have frequently followed periods of relatively small amounts of recorded rainfall. Conversely, some storms with greater amounts of recorded rainfall have caused only minor flooding.
There have been three prolonged periods of drought recorded in the Cottonwood River basin. The most severe occurred between 1952 and 1957 (Figure 3). The average monthly inflow during this time period was 12% of the period average (1922–1988), and it included 6 months of zero inflow. The lowest Palmer Drought Severity Index (PDSI) value during this period was –6.06, which is considered to be an extreme drought. The second-most severe drought of record occurred during 1963–1964. The average monthly inflow during this time period was 14% of the period average. The lowest PDSI value during this period was –4.89, also classified as an
The drought of 1952–1957 occurred across much of the Great Plains. Conditions during the “Dust Bowl” of the 1930s were more severe in many locations, but that drought pre-dated stream flow records across much of the region. The 1950s drought affected an area ranging from the Texas panhandle to central and eastern Colorado, western Kansas and central Nebraska; all of these areas experienced prolonged drought conditions. Kansas experienced severe drought conditions during much of the five-year period, which peaked in 1956. The PDSI reached a record low in September 1956. The recurrence interval for the 1950s drought was greater than 25 years across most of Kansas. As a result of its severity, the 1952–1957 drought is defined as the extreme drought. The third-most severe drought occurred between 1932 and 1934. The average monthly inflow during this time period was 25% of the period average. The lowest PDSI value during this period was −4.5. In addition to these exceptional droughts, there have been many years with consecutive dry months.

FIGURE 3: Historical PDSI for the Marion Reservoir watershed, 1895-2008 (from Guttman and Quayle, 1996; NCDC, 2013).
critical drought for water supply studies at Marion Reservoir and many other reservoirs across Kansas.

Construction of Marion Reservoir was authorized by the Flood Control Act of 17 May 1950 (Public Law 516, 81st Congress, 2nd Session). Excavation began in 1964, and embankment closure occurred in 1968. The initial fill (maximum conservation storage) occurred in February 1969. At the time of construction, 38,300 acre-feet of conservation storage was designated for water supply, while 44,600 acre-feet of storage was reserved for water quality. Yields corresponding to these volumes were developed based on the 1950s drought (Figure 4).

![FIGURE 4](image)

**FIGURE 4:** Original computation of firm yield for Marion Reservoir (from USACE, 1974).

The original water control manual for Marion Reservoir, published in 1974, reported the contract yield as 3,359 acre-feet (4.6 ft³/s) and the water supply yield as 3,924 acre-feet (5.4 ft³/s) for a firm yield of 7,283 acre-feet (10.0 ft³/s). It is interesting to note that the corresponding storage-yield curve published in the 1974 manual indicates that the originally calculated firm yield was 6,805 acre-feet (9.4 ft³/s), slightly lower than the tabulated value reported in the same document.

The Kansas Water Office, acting on behalf of the State of Kansas, entered into a contractual agreement with the U.S. Army Corps of Engineers in March 1976 for the right to utilize water
supply storage in Marion Reservoir. This agreement gave the State of Kansas exclusive rights to 46.20% of the total storage space in the reservoir within the conservation pool. As defined in the agreement, this storage was to be used for municipal and industrial water supply purposes. The Federal government retained rights to the other 53.80% of the conservation storage volume for “such purposes as the United States may deem desirable,” with water quality being the typical use. Use of the water supply storage commenced in December 1981.

Following the initial agreement between the U.S. Army Corps of Engineers and the State of Kansas in 1976, a second agreement was signed in June 1996 that allocated an additional 17.92% (12,500 acre-feet) of storage for the purposes of water supply, bringing the total allocation to 64.12% (44,730 acre-feet). This reallocation was the result of a study that was authorized following a memorandum of understanding signed by both parties in December 1985. A simulation of pool routing and corresponding storage was developed using a HEC-3 model with period-of-record inflow data beginning in 1940. This study, which captured the exceptional 1950s drought, assumed a conservation pool volume of 69,770 acre-feet, the projected year 2018 storage resulting from sedimentation losses (USACE 1996). A contract yield of 12.5 ft³/s (9,074 acre-feet) resulted from the HEC-3 model computation. Since a water quality low-flow requirement of 13.1 ft³/s exists during each July–August period, the firm yield established during this study is 25.6 ft³/s (18,534 acre-feet).

Water quality releases for the Cottonwood River are issued by the Kansas Department of Agriculture, Division of Water Resources. Releases from Marion Reservoir are made at the request of the Kansas Water Office to satisfy these requirements. The largest water quality releases from Marion Reservoir are required during the summer months (Table 1).

| TABLE 1: Seasonal water quality release schedule (ft³/s) for Marion Reservoir. |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| Jan             | Feb             | Mar             | Apr             | May             | Jun             | Jul             | Aug             | Sep             | Oct             | Nov             | Dec             |
| 1.0             | 1.0             | 1.0             | 2.3             | 6.5             | 9.0             | 13.1            | 13.1            | 9.0             | 6.5             | 2.4             | 1.0             |
Several general circulation models (GCMs) have been evaluated as part of the World Climate Research Programme’s third phase of the Coupled Model Intercomparison Project (CMIP3). Each of these models has been run based on climate scenarios that differ based on the magnitude and timing of CO₂ emissions. Therefore, over 100 final model runs are available for analysis. Each GCM varies based on physical processes and feedbacks. Since future conditions are unknown, a robust set of models should be analyzed to fully capture the range of possible scenarios.

In the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios, four emissions “storylines” were defined to represent plausible economic, population, and technological scenarios for the 21st century (Nakicenovic & Swart, 2000). These scenarios can be used to bracket future climate conditions. The four scenario families are A1, A2, B1, and B2:

**A1**: Rapid economic growth, global population peak in the mid-21st century, global emphasis, and the rapid introduction of new and efficient technologies.

**A2**: Slow economic growth, continuously increasing population, regional emphasis, and slow technological change.

**B1**: Rapid economic growth, global population peak in the mid-21st century, global emphasis, reductions in material intensity, and introduction of ecologically friendly technology.

**B2**: Intermediate economic growth, continuously increasing population, regional emphasis, and fragmented technological change.

Scenario A1 has been further subdivided into three groups: A1FI, A1T, and A1B. The differences between these subgroups are based on energy technologies. Specifically, energy use for A1FI is deemed to be fossil fuel intensive, A1T is biased toward renewable energy, and A1B is a compromise between fossil fuels and renewable energy sources (Figure 5).
GCM simulations in the CMIP3 archive used in this study were typically run with grid spacing in excess of 1° latitude by 1° of longitude, which is too coarse for water resources modeling with the exception of the planet’s largest river systems. For example, 1° (latitude by longitude) spacing in the central United States covers an area equal to nearly 4,000 square miles. By contrast, the watershed that contributes runoff to Marion Reservoir has an area equal to 200 square miles. It is therefore necessary to resample GCM output at a finer resolution to produce meaningful data for a reservoir and its upstream basin.

Watershed studies typically use GCM output scaled to 1/8°. Based on 1/8° (latitude by longitude) spacing, the Marion Reservoir watershed occupies all or part of 10 grid cells. The grid cell arrangement was developed for previous studies and encompasses the contiguous United States.
One technique used for downscaling GCM climate variables utilizes statistical methods. Statistical downscaling re-samples coarse GCM output to a scale appropriate for watershed studies by determining empirical relationships between large-scale processes and local variables. This type of downscaling relies on accepted statistical methods and has been widely implemented in climate studies.

In contrast to statistical downscaling, dynamic methods can also be used to translate GCM output into meaningful data on a scale appropriate for watershed studies. Dynamic downscaling uses regional climate models (RCMs), which are nested in GCM simulation output domains and simulate the finer scale physical hydrometeorological processes. This technique is computationally intensive when compared with statistical downscaling.

Although dynamic downscaling offers a physically based approach to GCM downscaling, it requires more knowledge of the underlying processes and is significantly more complex than empirically based statistical downscaling. Therefore, statistical downscaling was selected for this study, even though several disadvantages exist, including a translation of bias from the GCM, no change in the empirical relationship of the variables (stationarity), and no feedback within the climate system (Werner, 2011). Despite these drawbacks, statistical downscaling has enjoyed widespread implementation in hydrologic climate modeling studies and was deemed appropriate for this study.

According to Brekke et al. (2010), a statistical downscaling technique chosen for analysis should be:

- Well tested and documented, especially in applications in the United States.
- Automated and efficient enough to feasibly permit the downscaling of many 21st century climate projections, thereby permitting more comprehensive assessments of regional to local climate projection uncertainty.
- Capable of producing output that statistically matches historical observations.
- Capable of producing spatially continuous, fine-scale gridded output of precipitation and temperature suitable for water resources and other watershed-scale impacts analysis.

Prior to beginning this study, a gridded dataset of bias-corrected, spatially disaggregated (BCSD) statistically downscaled climate data was obtained from Dr. Andrew Wood (personal communication, 2011; Brekke et al., 2013). This dataset, which was customized for the Marion Reservoir watershed, was converted from a native GCM grid cell size and redistributed into 1/8° (latitude by longitude) spacing. The resulting grid cells, each with an area of 57 square miles, were superimposed across the Marion Reservoir watershed so that a total of 10 grid cells were used in the analysis (Figure 6).
FIGURE 6: Computational grid cell arrangement for VIC analysis of the Marion Reservoir watershed.

What advantages do the BCSD outputs provide for this study? As implied by its name, BCSD is a two-step process in which the data are first corrected for bias in the GCM simulation followed by the interpolation of GCM output to a 1/8° grid cell (Wood et al., 2004). The bias-correction step operates at the GCM (2°) scale, where adjustment is made to the simulated future variables based on the overlap between simulated past variables and observed climate.

The BCSD dataset includes GCM output from the A2, A1B, and B1 emissions scenarios, as these represent high, medium, and low emissions, respectively. A total of 16 GCMs were provided for the Marion Reservoir watershed study, and output from several of the primary models included multiple generations in which adjustments were made to the underlying parameters. A total of 112 GCM model projections were analyzed in this study.

TABLE 2: Summary of GCM output included in BCSD dataset (adapted from Werner, 2011).

<table>
<thead>
<tr>
<th>Model</th>
<th>Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>BCCR-BCM2.0</td>
<td>Bjerknes Centre for Climate Research (Norway)</td>
</tr>
<tr>
<td>CGCM3.1</td>
<td>Canadian Centre for Climate Modeling and Analysis</td>
</tr>
<tr>
<td>CSIRO-Mk3.0</td>
<td>CSIRO Atmospheric Research (Australia)</td>
</tr>
<tr>
<td>CNRM-CM3</td>
<td>Centre National de Recherches Meteorologiques (France)</td>
</tr>
</tbody>
</table>
Several options exist for selecting a statistical analysis method for use in a watershed study, including period-change (delta) approaches as well as transient methods. Period-change approaches, which compare differences between observed and simulated datasets, are generally categorized as follows:

- Delta method
- Hybrid-Delta method
- Ensemble-informed method

The most straightforward of these techniques is a simple delta period-change method. This technique analyzes the change in variables (temperature, pressure) between and overlapping observed and simulated climate time periods (e.g., 1950–1999) and then applies the change to a future time period (e.g., 2030–2059). The Delta method is applied on a monthly basis (Brekke et al., 2010).

Another technique similar to the Delta method is the Hybrid-Delta method, where adjustment factors are also computed based on an analysis between changes in the overlapping observed and simulated climate time periods. Unlike the Delta method, the Hybrid-Delta method uses adjustment factors that are based on monthly variability (instead of monthly means) (Brekke et al., 2010). Therefore, monthly climate changes are treated differently by year type.

<table>
<thead>
<tr>
<th>Model Name</th>
<th>Institution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ECHO-G</td>
<td>Meterological Institute of the University of Bonn (Germany) and the Meteorological Institute of KMA, Model and Data Group (Korea)</td>
</tr>
<tr>
<td>GFCL-CM2.0</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory (United States)</td>
</tr>
<tr>
<td>GFCL-CM2.1</td>
<td>NOAA Geophysical Fluid Dynamics Laboratory (United States)</td>
</tr>
<tr>
<td>GISS-ER</td>
<td>NASA Goddard Institute for Space Studies (United States)</td>
</tr>
<tr>
<td>INM-CM3.0</td>
<td>Institute for Numerical Mathematics (Russia)</td>
</tr>
<tr>
<td>IPSL-CM4</td>
<td>Institut Pierre Simon Laplace (France)</td>
</tr>
<tr>
<td>MIROC3.2 (medres)</td>
<td>Center for Climate System Research, University of Tokyo, and the National Institute for Environmental Studies, Frontier Research Center for Global Change (Japan)</td>
</tr>
<tr>
<td>MRI-CGCM2.3.2</td>
<td>Meteorological Research Institute (Japan)</td>
</tr>
<tr>
<td>ECHAM5/MPI-OM</td>
<td>Max Planck Institute for Meteorology (Germany)</td>
</tr>
<tr>
<td>CCSM3</td>
<td>National Center for Atmospheric Research (United States)</td>
</tr>
<tr>
<td>PCM</td>
<td>National Center for Atmospheric Research (United States)</td>
</tr>
<tr>
<td>UKMO-HadCM3</td>
<td>Hadley Centre for Climate Prediction and Research (United Kingdom)</td>
</tr>
</tbody>
</table>
Ensemble-informed methodology is nearly identical to the Hybrid-Delta method except for one key point: variable distributions are constructed from an ensemble of all simulations instead of from individual model runs (Brekke et al., 2010). Climate projections are categorized by type (e.g., warm and dry, hot and dry, etc.). Each class of ensembles (typically four categories plus a central tendency) is then analyzed in the same manner as the Hybrid-Delta method.

One significant drawback of the period-change approaches discussed so far is their inability to represent climate variation in the context of a continuous time series. Instead, the period-change approaches provide “snapshots” of some future period as compared with the present. This is a distinct limitation when investigating the impact of climate change on hydrologic processes, which are generally expressed in the form of a time series.

An alternative to the period-change approach is the transient (time-evolving) method of analysis. Unlike the period-change approach, transient analysis does not capture the step change in climate variables between two specific time periods. Instead, it captures the envelope of possibility over the duration of the simulation (Gangopadhyay & Pruitt, 2011). This approach is advantageous for a dynamic system such as reservoir storage and water supply because it incorporates time-series information into the analysis.
MODEL DEVELOPMENT

The basis of the relationship between storage volume and yield is that stream flow is variable over time, and to provide water for a continuous flow rate (demand) that is at times greater than stream flow, water must be stored when stream flow is greater than demand (surplus) for use when stream flow is less than demand (deficit). Firm yield is defined as the largest consistent demand that can be provided throughout a period of record of stream flow (USACE, 2011). The storage requirement is based on the demand of water supply coupled with the variability of stream flow. The ability to store water increases firm yield by allowing demand to be met using water held as conservation storage when stream flow falls below the level of demand. Diversion of the firm yield brings the stored water volume exactly to zero once during the period of record, during what is defined as the critical period for that yield and storage capacity (USACE, 2011). The periods that require the use of stored water occur multiple times during the period of record, with the most extreme occurrence constituting the critical period.

The development of a yield model for Marion Reservoir began with the analysis of a statistically downscaled BCSD dataset for the Marion Reservoir watershed. The gridded 1/8° cells were disaggregated to a daily time step. Even with the downscaling of the climate variables, the Marion Reservoir watershed is sufficiently small that it only occupies all or part of 10 grid cells.

Disaggregation of the climate model output to a daily time step is a key process in the development of a hydrologic model. Also, since the ultimate goal was an analysis of the firm yield of the reservoir based on future climate, the period-change methods of analysis (e.g., the Delta method) were deemed inappropriate for this study. Instead, a time-transient analysis was chosen. Transient analysis is particularly useful for a long-term hydrologic analysis because it treats the simulation as a time series instead of a snapshot in time. This distinction is especially important for a reservoir yield study because firm yield is defined by a critical period in either the observed past or the simulated future, which can only be determined by analyzing a continuous time series. If a period-change approach were used instead, the critical period could be missed.

The Variable Infiltration Capacity (VIC) model, which has been used in many previous hydrologic climate studies, was chosen for this study. This model is distributed and physically based, and it treats evapotranspiration and infiltration as separate processes instead of lumping them together as a single loss category. An advantage of the VIC model is that it treats the subsurface soil layers as distinct horizons instead of a single zone. Other attributes include energy balance and aerodynamic calculations for evapotranspiration and nonlinear recession for base flow (AMEC, 2011).

Development of the VIC model began over a decade ago in the Climate Studies Group at the University of Washington, where the source code continues to be maintained (Liang, 1994). The model is written for UNIX/LINUX operating systems and must be compiled before running.
One important aspect of the VIC model is that it operates on a daily time step. As previously noted, downscaled GCM output was disaggregated to a daily interval for this reason. Requirements for grid cell spacing are variable, and a 1/8° grid cell size is acceptable.

Evapotranspiration and infiltration losses are computed on a cell-by-cell basis. To account for these processes, vegetation and soil parameters must be input for each cell. These parameters, which were developed during the North American Land Data Assimilation System (NLDAS) project (Mitchell et al., 2004), were also obtained from Dr. Andrew Wood (personal communication, 2011).

Once the VIC model was compiled and set up for scenario processing, it was necessary to determine which (if any) of the 112 statistically downscaled BCSD climate model scenarios should be culled from the dataset in order to manage the large amount of data available for analysis.

A significant obstacle that precludes any quick decisions about trimming the list of scenarios is the inability to weight the scenarios. In fact, the basis for culling is weak (Gangopadhyay & Pruitt 2011). Relevant literature suggests that all scenarios be carried forward in an analysis because no sound basis exists for favoring one scenario or a collection of scenarios over any of the others (Gangopadhyay & Pruitt, 2011; Werner, 2011). All scenarios were therefore included in this analysis.

The following steps (in chronological order) were required to develop Marion Reservoir inflow hydrographs using each of the 112 available climate simulations from the BCSD dataset:

1. Obtain a statistically downscaled BCSD climate dataset for the Marion Reservoir watershed.
2. Obtain the NLDAS vegetation and soil dataset for the watershed.
3. Generate a computational grid for the watershed by overlaying the watershed polygons and extracting grid cells.
4. Compile the source code for the VIC and routing models.
5. Define the state variables and pathnames for the VIC and routing models.
6. Run the VIC model and generate the cell flux output.
7. Run the routing model and generate the time series hydrographs for the watershed.

If 112 climate scenarios or even a large subset are to be analyzed, these seven steps will quickly become time consuming, as steps 5–7 must be repeated for each scenario. It is recommended that scripting be used to automate these tasks and minimize the repetitive input that must be completed. The Marion Reservoir watershed model was run on a LINUX machine, and Bourne Again Shell (BASH) scripting minimized the repetitive effort by changing pathnames, creating new subdirectories, and running the VIC and routing models automatically for each scenario.
The output for each grid cell within the VIC model is treated independently, but in a watershed study, the cumulative hydrograph at some point within the basin is of greatest interest. To compute inflow hydrographs for Marion Reservoir, a separate modeling routine developed by Lohmann et al. (1998) was required. The routing model source code, also written for UNIX/LINUX and also requiring compilation prior to running, takes VIC runoff output for each grid cell (termed “flux”) and generates a combined hydrograph for the period of analysis.

The observed and simulated inflow hydrographs were calibrated by adjusting parameters in the VIC model. Specifically, the main control parameters that were adjusted included base flow \((b_i)\), soil depth \((w_s)\), and infiltration \((d_s)\). These parameters were adjusted based on tolerances provided in the online documentation for the VIC model. Once calibration was performed, calibration (measured as \(R^2\)) was maximized at 0.86 for the annual data. Monthly inflows were calibrated so that a maximum value of \(R^2 = 0.77\) was achieved while remaining within VIC model parameter guidelines (Figure 7).

**FIGURE 7:** Correlation between daily, monthly, and annual observed and simulated inflow for Marion Reservoir.

Daily observed and simulated inflow was found to be the least correlated dataset \((R^2 = 0.40)\) following calibration. However, the overall degree of correlation was deemed acceptable because of the decision to model reservoir yield as a monthly variable. A certain amount of bias nonetheless remained in the VIC model calibration as evidenced by \(R^2 = 0.77\), and this residual bias likely resulted from an imperfect representation of soil physics in the model (USBR, 2012). Since the Marion Reservoir watershed is small, small-scale processes are going to be more important than they would be in a large basin. Relevant literature suggests that the VIC model has been used most extensively to model very large watersheds (Abdulla et al., 1996; Wood et al., 1997; Hamlet et al., 1999; Nijssen et al., 2001; USBR, 2012).
Output from the VIC (and routing) model was required for the determination of reservoir firm yield. For the Marion Reservoir water supply study, these hydrographs were used to create a mass balance depicting storage:

\[
\text{Storage}(t) = \max[\text{Storage}(t - 1) + \text{Inflow}(t) - \text{Release}(t), \text{storage capacity}] \quad (1)
\]

In theory, this mass balance equation results in a simple computation of firm yield based on the simulated hydrographs coupled with an elevation-storage function for the reservoir. In practice, however, this step is both time consuming and computationally intensive (USACE, 2011).

Iterative simulation is required to evaluate Equation 1 for the reservoir over a period of simulation. Each time step depends not only on its variables but also on the variables carried over from the previous time step. Although construction of Marion Reservoir wasn’t completed until 1968, simulated pool elevations dating to 1940 were available from USACE (Tulsa District). The historical BCSD dataset used in this study begins in 1949, however, so the initial date of the routing simulation was set as the first day of that year (01 Jan 1949). Daily ordinates were modeled through an ending date of 31 Dec 2098. Therefore, nearly 55,000 daily records were analyzed.

During the 1996 water supply reallocation study performed for Marion Reservoir, 50-year planning conditions were modeled, assuming a conservation pool volume of 69,770 acre-feet (USACE, 1996). This condition was assumed to result from continuous sedimentation beginning at the time of project completion (1968) through a 50-year planning horizon ending in 2018. The computation that was used assumed a loss of 16,626 acre-feet of conservation storage.

Since incremental losses were previously estimated for every year from 1983 through 2067, the development of this pilot study provided a good opportunity to revisit the assumed sedimentation loss rate and determine if conservation storage really has decreased as quickly as predicted. The 1996 reallocation study assumed that the conservation pool would have 72,205 acre-feet of conservation storage remaining by 2010, a loss of 12,742 acre-feet to sedimentation. The reservoir underwent a bathymetric resurvey in 2010, however, and the conservation storage was estimated to be 80,659 acre-feet, or a 4,288 acre-foot loss. The loss of available conservation storage due to sedimentation is clearly much lower than it what was assumed to have been, and it is clear that the volume adopted for the 1996 reallocation study is significantly lower than what will be observed at the end of the 50-year planning horizon in 2018.

For this study, firm yield was recalculated using elevation-area-capacity data generated from the 2010 Marion Reservoir bathymetric survey (Figure 8). Mass balance routing was used in conjunction with a monthly time step and an assumption that during the course of any given
month, flood operations would lower the reservoir elevation to the conservation pool. A simulated inflow hydrograph, which was originally developed for the USACE (Tulsa District) RiverWare model that includes Marion Reservoir, was used for the routing computation. The data were provided as a daily time step and subsequently re-averaged to a monthly time step. It is important to note that the inflow hydrograph dataset used for the development of water supply routing in this study differs from the dataset that was used in the 1996 reallocation study.

An elevation of 1,350.5 feet was entered for the first day of the routing simulation (01 Jan 1949), since this is the elevation at which 100% of conservation storage is filled. The initial storage value was calculated through linear interpolation by comparing the initial elevation with the elevation-capacity curve, and each subsequent storage value was computed as a mass balance combining the storage, precipitation, evaporation, and differential flow volumes from the previous time step. Once the storage value was determined for the current time step, elevation was calculated through linear interpolation by comparing the storage value (as volume) with the elevation-area-capacity curve. The iterative calculation then continued step-by-step to the next successive time ordinate.

Since significant changes in reservoir storage tend to occur on the order of days or even weeks, a decision was made to carry out the analysis using a monthly time step. This decision was supported in part by the assumption that flood storage in Marion Reservoir could be neglected during the analysis because the pool would likely only remain above the top of the conservation pool for periods of time not exceeding one month. By adopting a monthly time step, in other words, the total number of records could be significantly reduced while justifying the exclusion
of flood control rules from the simulation. The number of records was consequently reduced from nearly 55,000 to 1,800.

Since the mass balance for any given monthly record relies on the previous month for calculation, a change to any of the 1,800 monthly records requires that the remaining records be recalculated as well. The only practical ways in which this analysis could be carried out were by 1) using a simulation model such as HEC-ResSim or WSROUT, 2) using a spreadsheet method, or 3) using a specialized mathematical programming and analysis environment such as MATLAB. All data were available in record form, so Microsoft Excel was initially selected as the method of choice, and a spreadsheet model was created.

After consideration of possible ways to automate the iterative calculation process in Microsoft Excel, it was determined that the goal-seek function offered the most practical way to calculate firm yield. Each spreadsheet was set up so that the column of pool elevations calculated in an iterative step-by-step process was included in a MIN function. The bottom of the conservation pool (which is the minimum allocated storage of the reservoir) is at elevation 1320.0 feet. By setting up the column of outflow values with the goal-seek function and assigning the same outflow value to all time steps (since firm yield is a constant value), iteration was performed between the outflow column and the pool elevation so that the elevation defined by the MIN function was equal to 1,320.0 feet. Iteration then proceeded automatically through all time steps in the spreadsheet until an outflow value was found that resulted in a single minimum pool elevation of 1,320.0 feet. This outflow value is the constant rate of withdrawal from the conservation pool that is required to meet water supply allocation, which is by definition the firm yield.

Even with the number of records for each of the 112 scenarios pared down substantially by converting the output to a monthly time step, spreadsheet modeling in Microsoft Excel was cumbersome and time consuming. Conversion of the spreadsheet files from XML (*.xlsx) to binary format (*.xslb) was useful in keeping the files manageable as it significantly reduced the file size.

Ultimately, even the conversion of data to a binary format did not result in optimal performance of the routing computations within the spreadsheet, given the size of the data files and the number of iterative calculations required. Although the spreadsheet routing did, in fact, work for the purposes of this study, it became increasingly cumbersome and was eventually abandoned in favor of MATLAB. Dr. David Raff (USACE) wrote a numerical routing script that was used, along with the assumptions developed for the spreadsheet routing, to construct the water supply yield model.

Once the routing results were computed using the MATLAB model, a discrepancy was noted between the observed and simulated inflow hydrographs, highlighting the imperfect match of physical processes between the VIC model and the actual processes that occur in the watershed.
Since significant bias remained in the simulated inflow hydrograph following the VIC model calibration, additional bias correction was necessary. This correction was performed by independently taking the observed and simulated inflow hydrographs from the historical overlap period (1949–2008) and developing a cumulative distribution function (CDF) for each. The CDF was constructed by taking the full hydrograph for the observed dataset, binning the data by month, and then assigning probabilities ($P$) to the data by applying the Weibull formula:

$$P = \frac{m}{n+1}$$  

(2)

This expression requires that the data be sorted so that rank ($m$) is compared to the total number of data points in the series ($n$). The calculation is performed for each of the data points, resulting in a CDF for each of the monthly datasets. The same procedure was then repeated for the simulated dataset. Following the development of both cumulative distribution functions for each of the monthly datasets, each of the simulated monthly CDFs was then compared with the observed monthly CDFs. A ratio between the observed and simulated value for each probability pair was then computed, and this ratio was designated as the bias correction factor corresponding to the specific probability (Figure 9).

**FIGURE 9:** Inflow hydrograph ordinates for Marion Reservoir plotted as monthly CDF averages; the historical observed and historical
simulated distributions, which overlap, have been bias corrected, and the resulting correction factors have been applied to the model projections.

After the bias correction factors were computed for the range of probabilities of each of the monthly distributions, they were then applied to the ordinates of the historical simulation hydrograph. Although residual bias remained in the modeling process after calibration, the timing of observed inflow was for the most part replicated accurately in the VIC simulation (Figure 10).

**FIGURE 10:** Monthly observed and simulated inflows for Marion Reservoir, 1949–2008.
Application of the bias correction factors to the simulated hydrograph period within the historical overlap period improved the correlation between the two datasets (Figure 11). Although some bias remains, the adjustment to the simulated hydrograph during the historical overlap period compares favorably with the computed firm yield from the observed dataset (33.5 ft³/s), resulting in a difference of 2,244 acre-feet of water.

![Graph A] y = 0.7344x + 76.816
R² = 0.7702

![Graph B] y = 0.964x + 4.9088
R² = 0.8457

**FIGURE 11:** Improvement in correlation between A) the historical observed and VIC simulated monthly hydrographs without additional bias correction, and B) the historical observed and VIC simulated monthly hydrographs with additional bias correction developed from cumulative distribution functions of monthly-binned ordinates.

Following the bias correction of the simulated hydrograph from the historical overlap period, yield modeling with the simulated dataset was able to accurately reproduce the timing of the critical period, which occurred in 1957 (Figure 12). The 1996 study reported a firm yield of 25.6 ft³/s for the project (contract yield and water quality release), while this study found that the firm yield for the reservoir is 33.5 ft³/s. The difference between the two results is not inconsequential, as it equates to a volume of 5,719 acre-feet over a one-year period. This can be explained by the difference in data sources and by computational differences between this study and the HEC-3 routines used in the 1996 study. Since the inflow record taken from the USACE (Tulsa District) RiverWare model is considered to be the most recent dataset, and since the bathymetric survey used in this study is also the most current data available, the computed firm yield of 33.5 ft³/s is considered to be a defensible calculation and therefore carried forward in this study.
Bias correction factors were then applied to each of the hydrographs generated with VIC from the 112 unique climate projections that were analyzed in the study. Specifically, all time series data in each of the 112 climate projection hydrographs were assigned correction factors from the appropriate monthly CDF corresponding to each ordinate. Since the correction factors were distributed across a range of probabilities, linear interpolation was used to develop the corrected hydrographs.
RESULTS AND DISCUSSION

Projected temperature and precipitation trends from each of the 112 BCSD model projections were analyzed to support conclusions drawn from the A2, B1, and A1B emissions scenarios yield studies. To look at a “snapshot” of these variables, a planning horizon of 40 years was chosen. Both of these variables were analyzed based on the year 2050.

Temperature provided the most straightforward analysis with regard to climate variability across the Marion Reservoir watershed. All models projected an increase in mean temperature through the year 2050, and based on Weibull position plotting, the median increase in mean temperature is projected to be $+4.76^\circ F$ (Figure 13). A mean temperature increase of at least $2.96^\circ F$ was projected by 90% of the simulation models. Maurer and Hidalgo (2008) found that the BCSD method reproduces temperature with greater skill than precipitation.

Precipitation simulations for the year 2050 are evenly split, with half of the models projecting more annual rainfall and the other half projecting less. The majority of the models project that the change in annual rainfall will be ±20%. Within the Marion Reservoir watershed, this is within ±4 inches, which falls within the current range of annual rainfall variability. The Marion Reservoir watershed receives (on average) approximately 20 inches of snowfall a year, which equates to 2–3 inches of liquid equivalent precipitation. Although a seasonal analysis was not performed, it is assumed that the model consensus trend to a warmer climate by year 2050 may shift some of this precipitation to rainfall.
FIGURE 13: Quadrant plot of year 2050 temperature and precipitation for the Marion Reservoir watershed denoting “cooler, wetter,” “cooler, drier,” “warmer, wetter,” and “warmer, drier” conditions. Change is measured from the 1961-1990 baseline average (from Maurer et al., 2007; Zganjar et al., 2009).

The A1B projections, which represent a balance between fossil fuels and “green” energy resources, were further investigated for future trends in temperature and precipitation within the Marion Reservoir watershed. These projections all simulate warmer temperatures through the end of the study period. The change in annual mean air temperature (from present conditions) by year 2098 across the model ensemble ranges from +2°C to +8°C (Figure 14).
Model results are less straightforward with respect to future precipitation trends. It has been demonstrated with the A1B projections that the climate models project a warmer future in the watershed above Marion Reservoir. However, no clear precipitation trend emerges from the ensemble of A1B projections, which is consistent with the findings that were presented in Figure 13. The A1B ensemble mean does increase by 50 mm/year over the duration of the simulation, which is equivalent to an increase of 2 inches of annual precipitation (Figure 15).
FIGURE 15: A1B emissions scenario model projections for annual precipitation through the year 2098. The observed precipitation trend is plotted through 2009.

Results from the A2 emission scenario are more extreme than the A1B scenario with respect to the rise in mean annual air temperature during the future simulation period. This does not necessarily imply an increased vulnerability to drought in the Marion Reservoir watershed, however, as many of these model projections also forecast a wetter future.

Each of the A1B and A2 model projection hydrographs, generated by running the VIC output through the routing code developed by Lohmann et al. (1998), were then adjusted using the CDF procedure discussed in the previous section. Results for the B1 emissions scenario were omitted from the yield analysis since it represents a greater departure from a fossil fuel economy than either the A2 or A1B scenarios, so it may be less realistic than the latter two scenarios. The resulting hydrographs show no appreciable change in mean stream flow through the year 2098 (Figure 16).
The current water supply storage owned by the State of Kansas in Marion Reservoir is 44,730 acre-feet, and the contracted annual amount is 1,834 acre-feet. These contracts, which deliver water for municipal use, require a dependable yield of 2.53 ft³/s. The existing contract yield of 20.4 ft³/s can clearly meet the demand of the current water supply contracts. Does this hold true, however, for future yield?

A limited analysis to help inform an answer to this question was conducted with the A1B and A2 hydrographs presented in Figure 16 routed through the yield model for the entire study period ending in the year 2098. Future demand was not considered in this study. The watershed is small and rural; demand growth has been stagnant, and there is no reason to assume that this will change. Aside from temperature and precipitation, no other water supply variables were considered.

Changes in precipitation in conjunction with changes in evapotranspiration and hydrologic runoff produced ensembles that, for the most part, indicate no major changes in firm yield (Figure 17). The A1B and A2 model projections simulate a slight increase in firm yield through the year 2098. Ensemble mean values of firm yield for the two emissions scenarios range from 50 to 60 ft³/s (approximately) through the year 2098.
FIGURE 17: Firm yield for the A1B and A2 emissions scenarios, calculated as 30-year ensemble mean values; the upper and lower bounds of 30-year firm yields for all A1B and A2 emissions scenarios are plotted as shaded areas.

Ensemble firm yield calculations for the 1949–2008 historical period are higher than the observed firm yield for the same period. It is not surprising that the ensemble mean value is higher than the observed 33.5 ft³/s, but the lower bound computed from all projections is higher than the observed firm yield as well. This can be partially explained by remaining bias following the monthly CDF correction discussed in the previous section. The climate model projections are overestimating the Marion Reservoir inflow hydrographs during the summer months (see Figure 10). The differential volume over the course of a month is on the order of 10³ acre-feet, which in turn contributes to the overestimation of firm yield during the overlap period.

Mean ensemble values of firm yield are too general for water supply planning. Firm yield is event driven (i.e., historical drought), and knowledge of whether or not a dependable volume of water can be delivered to a customer is a key element in planning and executing the terms of a water supply contract. Projections of the mean firm yield do provide insight about model trends (in this case, firm yield computed from both emissions scenarios remains nearly stationary).
Water supply planning is well suited for risk-based analysis, and the interpretation of results from this type of study would ideally be characterized in terms of probability. Contracts are based on the dependable yield that a reservoir can deliver, which is derived from an analysis of historical droughts. If drought(s) of greater magnitude may occur in conjunction with future climate conditions, it would be important to plan for these. Likewise, if future climate conditions are likely to be less susceptible to drought, renegotiating existing contracts with an increase in dependable yield may be a viable option.

Characterization of the ensemble of climate model projections used in this study in terms of absolute risk would require a random sample of the entire range of possible outcomes. As has previously been stated, however, this is not the case. The individual members of the ensemble are mutually dependent. Any statistical analysis of the ensemble therefore reveals characteristics that pertain to the models themselves, not to the true risk as applied to the range of all possible outcomes.

Unfortunately, climate projections cannot be used to characterize absolute risk. Each climate model represents an outcome from state-of-the-art knowledge, or in other words, a “best guess.” Even when a collection of models is analyzed as an ensemble, which in the case of this study is 112 climate projections generated from a combination of 16 GCMs and 3 emissions scenarios, the results must be considered as a collection of best guesses and not a robust sampling of possible outcomes. What can be addressed, however, is the relative confidence in being able to meet existing water supply contracts. Since absolute risk cannot be quantified for future dependable yield, the results of the study must be characterized either in terms of consensus-based risk or in terms of specific outcomes.

Existing contracts at Marion Reservoir, which deliver water for municipal use, require a dependable yield of 2.53 ft³/s. Since the current firm yield of the reservoir is 33.5 ft³/s, or 24,250 acre-feet, existing contracts with the City of Hillsboro, City of Marion, and City of Peabody will be met, and additional contracts may be viable (Table 3). Since only 1,834 acre-feet of water supply storage is currently utilized, over 22,000 acre-feet remains available for potential use.

**TABLE 3:** Terms of existing Marion Reservoir water supply contracts.

<table>
<thead>
<tr>
<th>Contract No.</th>
<th>Customer</th>
<th>Ending Date</th>
<th>Ann. Contract (ac-ft)</th>
<th>Dependable Yield (ft³/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>80-1</td>
<td>City of Hillsboro</td>
<td>12/22/2021</td>
<td>921</td>
<td>1.27</td>
</tr>
<tr>
<td>81-4</td>
<td>City of Marion</td>
<td>10/3/2023</td>
<td>729</td>
<td>1.01</td>
</tr>
<tr>
<td>99-1</td>
<td>City of Peabody</td>
<td>4/9/2039</td>
<td>184</td>
<td>0.25</td>
</tr>
</tbody>
</table>
The envelope of possible future outcomes, based on T and P projections from the A1B and A2 scenarios, suggests that future firm yield will not differ significantly from the current firm yield. The upper and lower bounds of the analysis expand with respect to time due to model uncertainty and differences between the emissions scenarios (the upper bound more aggressively than the lower bound), but given the nearly stationary behavior of the ensemble means, the model consensus portrays future water supply conditions that look similar to present conditions. Based on the model results, the existing contracts at Marion Reservoir appear to be sustainable through the lifetime of the agreements with additional contract capacity that is not currently utilized.

A prudent approach to managing water supply contracts at Marion Reservoir may therefore include monitoring the firm yield on a regular interval, such as a moving 30-year mean. The existing water supply contracts expire between 2021 and 2039, and prior to the expiration and presumable extension of these agreements, the future firm yield can be recomputed, taking advantage of new climate forcings and general improvements in the state of climate modeling. Upper and lower firm yield thresholds can be set that trigger analysis, either because additional contracts are sought or because changing conditions have jeopardized existing contracts. If, for example, a firm yield threshold on the lower bound is reached, then an individual projection or collection of projections that track closely with the threshold criteria can be analyzed in greater detail to make informed decisions about future water supply contracts.

Unlike coastal or mountainous areas where changes in sea level or snowpack elevation may be more easily observed, climate impacts on water supply reservoirs in the Great Plains are less obvious. Climate projection ensembles do not show pronounced uniformity in precipitation changes in this region, although the ensemble mean does trend toward more net precipitation. Since mean annual temperature does show an upward trend, the inter-annual distribution of precipitation will be critical, as evaporative losses may increase. Other factors, including soil moisture, base flow, and sedimentation rates, will also affect the water budget of the basin and available storage in Marion Reservoir. All of these variables will require detailed study as the practice of climate prediction evolves if the long-term impacts on water supply at Marion Reservoir (or any USACE-owned dam at which water supply is an authorized purpose) are going to be quantified.

The results of this study do support the formulation of important qualitative conclusions with respect to the Marion Reservoir watershed. Climate model projections unanimously simulate warmer temperatures in the future. Half of them predict an increase in annual precipitation. Most of the model projections indicate that future precipitation will remain within ±10% of current annual values. When viewed as an ensemble, the model projections do not indicate that stream flow will change appreciably during the future. Yield modeling of projected hydrographs shows little change in 30-year mean values. Although future demand was not considered, the Marion Reservoir watershed is a small, rural area with stagnant demand growth. There is no current basis for the expectation of an increase in future demand. Since the reservoir has existing water...
supply capacity that significantly exceeds the contracted amount, it appears to be well positioned to meet future water supply obligations.
SUMMARY OF FINDINGS

• The VIC model can be successfully applied to a study of future water supply yield that incorporates climate change, even in a watershed as small as the one that contributes to Marion Reservoir.

• All projections were in agreement that future conditions will be warmer over the Marion Reservoir watershed, with a median increase in temperature among all models of +4.76°F by the year 2050.

• No consensus existed with respect to future precipitation trends in the Marion Reservoir watershed through the year 2050. Some of this variation can be attributed to differences in the emissions scenarios. Most of the models fall within a ±20% range of the current annual mean by the year 2050 based on current climatology.

• Unlike coastal or mountainous areas where changes in sea level or snowpack elevation may be more easily observed, climate impacts on water supply reservoirs in the Great Plains are less obvious.

• The Marion Reservoir watershed receives (on average) approximately 20 inches of snowfall a year, which equates to 2–3 inches of liquid equivalent precipitation. It can be assumed that the model consensus trend to a warmer climate by year 2050 will shift some of this precipitation to rainfall.

• The VIC simulation using historical data exhibited good skill when replicating the critical period. The timing and duration of historical droughts, including the 1952–1957 drought of record, were generally correct.

• The VIC simulation using historical data initially exhibited poor accuracy when replicating firm yield, but this improved significantly with additional bias correction using a monthly CDF derived from the historical and simulated overlap period, which was then applied to the hydrographs from all projections.

• A consensus of model projections suggests that stresses resulting from simulated changes in T and P at Marion Reservoir will not increase over time.

• Based on the modeling results, Marion Reservoir appears to be well positioned to meet future water supply obligations, particularly since no future additional allocations are contracted.
REFERENCES


