FALL RIVER LAKE: COMPARISON OF RESERVOIR INFLOW AND LOCAL BIAS-CORRECTION TECHNIQUE FOR CMIP3 AND CMIP5 CLIMATE PROJECTIONS, AND LEGAL ANALYSIS OF LOW-FLOW REGULATION

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Major Field: BIOSYSTEMS ENGINEERING

Scope and Method of Study: This case study compares the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 5 (CMIP5) against the phase 3 (CMIP3) guidance for a case study location of Fall River Lake in Kansas. A new method of locally calibrating reservoir inflow climate-change ensembles using monthly factors derived by averaging correction factors calculated from a range of exceedance values was proposed and compared against calibrating only the mean and median of the ensemble. Federal agency reservoir operations and statutory, regulatory, and compact legal provisions affecting Verdigris Basin in Kansas were also analyzed.

Abstract: Reservoir inflow from CMIP3 and CMIP5 climate-change ensembles was compared against each other and observations. CMIP5 inflows were generally lower than CMIP3 and both had wet biases for low flows and dry for high flows. CMIP3 projections are the recommended generation of climate-change model projections that should be used for current climate-change studies for this reservoir as the ensemble mean of the CMIP3 projections from the hydrology dataset came closer to reproducing the monthly mean from observations.

A new method of calibrating monthly correction factors based on averaging local bias-correction factors for the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities resulted in higher the flows in summer than calibrating using a local bias-correction factor developed from only the 50% exceedance or ensemble mean values. This new approach provides for a more flexible methodology to accommodate areas with highly skewed hydrologic patterns like typical low streamflows with occasional or rare extreme flows. Other reservoirs with similar highly skewed hydrologic patterns could also benefit.

It is recommended that Kansas State statutes and U.S. Army Corps of Engineers regulations regarding low-flow control in the entire Verdigris Basin be consolidated to minimize potential conflicts. Inviting the Cherokee and Osage tribes to be partners in the Kansas-Oklahoma Arkansas River Compact discussions would also minimize potential legal issues.

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LIST OF ABBREVIATIONS

AWRBIAC	Arkansas White Red Basin Interagency Committee
CMIP3	Coupled Model Intercomparison Project phase 3
CMIP5	Coupled Model Intercomparison Project phase 5
IPCC	Intergovernmental Panel on Climate Change
KWA	Kansas Water Authority
KWO	Kansas Water Office
DWR	(Kansas Department of Agriculture's) Division of Water Resources
ESA	Endangered Species Act
MOA	Memorandum of Agreement
MOU	Memorandum of Understanding
NARCCAP	North American Regional Climate Change Assessment Program
PCMDI	Program for Climate Model Diagnosis and Intercomparison
SECURE Act	Science and Engineering to Comprehensively Understand and Responsibly Enhance) Act
SRES	Special Report on Emissions Scenarios
RCP	Representative Concentration Pathways
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation

USDA	United States Department of Agriculture
USFWS	United States Fish and Wildlife Service
USGS	United States Geological Survey
VIC Model	Variable Infiltration Capacity Model
WCRP	World Climate Research Programme
WGCM	Working Group on Coupled Modelling
WWCRA	West-Wide Climate Risk Assessments

CHAPTER I

INTRODUCTION

1.1 PLANNING FOR CLIMATE CHANGE

Scientists have demonstrated with physics-based models that increasing concentrations of greenhouse gases in the Earth's atmosphere are likely to increase the global temperature about 2.0 to 4.5º C by the end of the 21st century and that this rate of temperature rise corresponds with recent temperature observations from various sites on Earth (Schlesinger 2011). It is still unresolved if this change in temperature will affect precipitation and hydrologic patterns in the middle latitudes (Dai 2006), including the area of southeast Kansas.

Planning for a changing climate is now incorporated into the design of engineering projects with engineers using climate-modeling concepts and methods as design aids (Scott 2014). All practicing civil engineers should become familiar with methodologies that can be used to determine the future reliability of the current infrastructure as well as plan potential new infrastructure (Scott 2014).

Typically, climate change possibilities are presented as an ensemble of projections (Wood et al. 1997). Various climate models with slightly different initial or final constraints, different concentrations of greenhouse gases, different radiative forcings, or differing model dynamics are grouped together and viewed as a collection of equally possible alternatives in order to capture the uncertainties in the modeling processes and forcings (Wood et al. 1997). A wider spread in the ensemble of projections signifies a greater amount of uncertainty in the potential future outcome while the ensemble mean shows the signal of climate-change projections (Zhang et al.2016). It is important to consider the entire range of possible outcomes when planning for climate change (Brekke et al. 2009).

1.2. CLIMATE-CHANGE MODELS

Climate-change modeling is typically accomplished as a simulation of the physics of various interactions between the different processes, with a focus on energy, water, and mass balances (Ghosh and Misra 2010). The Earth's climate is a complex interplay of the amount of radiation that enters the Earth's atmosphere or is re-radiated from the Earth's surface, the amount and types of gases in the atmosphere, the hydrologic cycle, ocean currents and temperature, soil moisture and temperature, chemical interactions, and human activity (Ghosh and Misra 2010). Climate models can be made with various levels of complexity. Parameters are used to simulate processes that are too small or too complicated to be handled by traditional modeling techniques (Ghosh and Misra 2010). As climate science develops, models have become increasingly more complex with additional parameters, refined physics, and smaller spatial and temporal scales. However, it is important to remember that these models remain tools to facilitate decision-making, not an ends in themselves (Brekke et al. 2009).

Climate modeling centers, universities, and other institutions that develop and support climate models, provide information about possible outcomes for various future climate scenarios (Brekke et al. 2009). These scenarios help to tell the story of what the climate patterns could look like based on a specific set of assumptions about factors that could include greenhouse gases, population trends, land use, political and policy decisions, adaptive and mitigation strategies, hydrologic response and soil types (Wood et al. 1997)

Both global and regional climate scenarios are available to the public. Although the spatial and temporal resolution is typically smaller on a regional model, this does not necessarily indicate that the model has greater value than available global climate models (Zhang et al. 2016). Smaller spatial resolution and time steps can incite confidence that isn't supported by the model (Zhang et al. 2016). In fact, regional models often offer fewer future climate scenarios for planning purposes than are available from modeling centers offering output from global models.

The U.S. Bureau of Reclamation (USBR) has begun draft work on several watersheds studies throughout the western states where they own and operate projects but as of 2016, there are no Bureau of Reclamation projects in the Verdigris basin or its tributaries. However, the USBR has made resources available for climate-change studies in this basin.

A climate-change watershed analysis was performed by Qiao et al. (2014) using North American Regional Climate Change Assessment Program (NARCCAP) data for Oologah Lake on the mainstem of the Verdigris River in Oklahoma, but the upstream reservoir projects in Kansas were excluded from the study. The Qiao et al. study is discussed in greater detail in Chapter 2.

The SECURE (Science and Engineering to Comprehensively Understand and Responsibly Enhance) Water Act authorizes the USBR to assess climate-change risks in major Reclamation river basins (Reclamation 2011). As the USBR has projects throughout the western United States, the USBR was a collaborator on the climate analysis archive dataset for the entire area of the western U.S. The USBR West-Wide Climate Risk Assessments (WWCRA) that include the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5) hydrology datasets complement the ongoing work being done by the USBR through the SECURE Water Act and through work with other agencies and organizations (Reclamation 2011).

A wide range of climate projections has been made available by the USBR and their collaborators, including the Climate Analytics Group, Climate Central, Lawrence Livermore National Laboratory, Santa Clara University, Scripps Institution of Oceanography, U.S. Army Corps of Engineers, U.S. Geological Survey, and the National Center for Atmospheric Research. These projections can be found on an archive website that provides climate projections for multiple climate aspects and also a hydrology dataset (Reclamation 2011). The archived data are available to anyone interested in research or planning. A description of proposed research is not required. Multiple scenarios from various climate models from around the world are presented as a part of the archive (Reclamation 2011). The hydrology portion of the archived dataset also includes runoff from user-defined basins that has been calculated using the Variable Infiltration Capacity (VIC) model (Reclamation 2011). Information about the data available in this archive is described in further detail in the following sections.

The state of the art is constantly evolving in the field of climate change and models are constantly improving. Spatial resolutions are getting smaller and more parameters are being utilized. Currently climate-change studies use both CMIP3 and CMIP5 projections, as well as other climate-change projections. Without recommending specific action for policy makers and gaining consensus of the public, climate studies might remain in the academic realm. Demonstrating publicly available climate projection tools on an existing small reservoir, such as Fall River Lake, can help bridge the gap in southeast Kansas between academia and the social and legal realities and limitations in the real world.

1.2.1. CMIP3 PROJECTIONS

The WCRP CMIP3 contains sixteen global climate models with multiple initial conditions (a total of 112 separate projections) that are included in the CMIP3 hydrology dataset provided by the USBR and their collaborators. CMIP3 hydrology dataset includes three emissions scenarios from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES): A1B, A2, and B1. Not included in the hydrology dataset are the B2 scenario (which assumes the utopian scenario of local and regional climate solutions and an emphasis on environmental protection and social equity) and the other two members of the A1 family (IPCC 2000). Table 1.1. provides information about the assumptions of the economic, population, and technological development assumptions included in these scenarios.

A high rate of greenhouse gas emissions continuing into the future is represented by the A2 emission scenario. B1 represents a low rate of emissions to continue into the immediate future and then emissions are assumed to decrease at some point in the long term (IPCC

2000). The A1 emission scenario represents a medium rate of greenhouse gas emissions to continue into the foreseeable future, with the assumption that there will be new and more efficient technologies developed over time. Three different sub-scenarios make up the A1 family. A1F1 depicts emissions that rely heavily on fossil fuel, while the A1T scenario assumes that newer non-fossil energies will be developed during the 21st Century. A1B is a blended scenario of both fossil and non-fossil fuels (IPCC 2000). The A1B scenario is included in the available hydrology dataset.

Table 1.1. Description of CMIP3 Special Report on Emissions Scenarios (SRES) Available in CMIP3 Hydrology Dataset. (Developed from IPCC 2000.)

SRES	Concentration of Carbon Dioxide	Technological Advancement Assumptions	Economic Assumptions	Population Assumptions
A1B	Middle concentration	Blended sources of non-fossil and fossil to be used in the future	Rapid economic growth until middle of 21st Century, then decline	Rapid growth until middle of the 21st Century, then decline
A2	High concentration	Regionalized technological development with slow global change	Regionalized economic growth with slow global improvement	Regional birthrates slowly converge, continuously growing worldwide population
B1	Low concentration	Rapid changes in the future toward clean and efficient technologies		

1.2.2. CMIP5 PROJECTIONS

The hydrology dataset provided by USBR and their collaborators includes WCRP's CMIP5 31 global climate models that incorporate four different Representative Concentration Pathways (RCPs), for a total of 97 separate projections (Reclamation 2014). RCPs represent different radiative forcings instead of using the greenhouse gas emission scenarios modeled as part of CMIP3. RCPs are based upon radiative forcings above a pre-industrial background, around the year 1850 (RCP Database 2009).

Each RCP was developed by a separate modeling group and they do not represent any specific climate policy or "technological, economic, or political viability of specific future pathways or climates" (RCP Database 2009). Although the radiative forcing estimates are based on greenhouse gases, including carbon dioxide and several others, changes in the Earth's albedo due to land use or the anticipated natural variations of forcing of mineral dust, such as from volcanic eruptions, are not included (RCP Database 2009).

There is a complex relationship between the atmospheric carbon dioxide concentration and radiative forcings. Prior to 1980, when the amount of carbon dioxide in the atmosphere increased, the radiative forcing increased in a similar fashion. Over the long term, it is expected that radiative forcings will remain at higher levels or continue to increase even if the yearly amount of carbon dioxide decreases. Table 1.2. provides information about the assumptions of the economic, population, and technological development assumptions included in these scenarios. Figure 1.1 shows the measured and estimated amount of carbon dioxide in the Earth's atmosphere from 1950 to 2100 for selected CMIP5 RCPs and CMIP3 SRES.

Table 1.2. Representative Concentration Pathways in CMIP5 Model Projections

CMIP5	Radiative forcing	Concentration (ppm)	Pathway
RCP8.5	>8.5 W m^{-2}in 2100	>1370 CO_2 in 2100	Rising
RCP 6.0	~6.0 W m^{-2}after 2100	~850 CO_2 (stabilization after 2100)	Stabilization without overshoot
RCP4.5	~4.5 W m^{-2}after 2100	~650 CO_2 (stabilization after 2100)	Stabilization without overshoot
RCP 2.6	~3 W m^{-2}before 2100 then Declines	Peak at ~490 CO_2 (peak near 2100 then Declines)	Peak and Declines

Developed from Moss et al. 2011

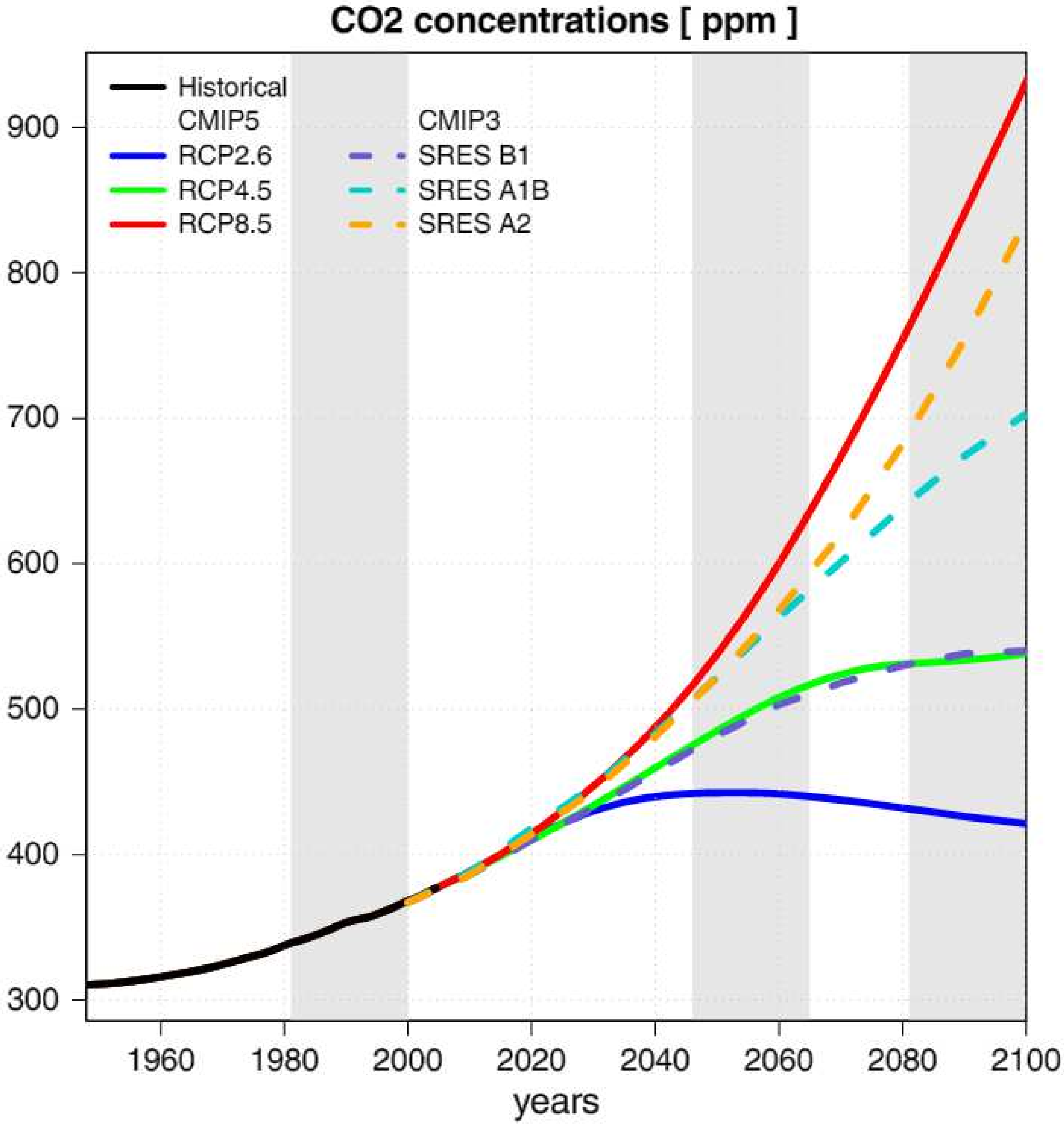

Figure 1.1. Estimated Carbon Dioxide Concentrations (in parts per millions) for the CMIP5 Representative Concentration Pathway (RCP) 2.6, 4.5, and 8.5. and CMIP3 Special Report on Emissions Scenarios (SRES) B1, A1B, and A2. Historical Observations are Shown in Black (Sillman et al. 2013.)

1.2.3. VARIABLE INFILTRATION CAPACITY MODEL

Both hydrology datasets utilize the Variable Infiltration Capacity (VIC) model, which has been run and calibrated in multiple drainage basins by the USBR and their collaborators. Each main basin is available as a separate application of the VIC model. Fall River Lake, the location for this case study, falls within the Arkansas-Red VIC application. A water balance or water-and-energy balance is calculated for each 1/8 degree (12 kilometer) grid cell within the model, with the water balance mode being controlled by precipitation, maximum and minimum temperatures and wind speed (Gaol et al. 2009). All other required variables can be derived from these original four inputs by the VIC model (Gaol et al. 2009).

The VIC model allows for subgrid variability in land surface vegetation classes and soil. A variable infiltration curve is used to represent the spatial variability of runoff. However, soil characteristics for each cell must be uniform. An assumption that there is no lateral flow is made for the top two layers of soil (typically three layers are included in the model) and the percolation is calculated by the one-dimensional Richard's Equation which combines Darcy's Law for the vertical unsaturated flow of water with the principle of the conservation of mass. Baseflow is calculated using the unsaturated Darcy's Law. Potential evapotranspiration is calculated using the Penman-Monteith Equation with the inputs of mean daily temperature, wind speed, relative humidity and solar radiation. Subsurface runoff is calculated using the semi-distributed rainfall-runoff ARNO model (Gaol et al. 2009).

Runoff and baseflow are modeled for each cell. Hydraulic routing is not explicitly modeled within the VIC. However, routing of streamflow using the routines in Lohmann et al. (1996 and 1998) is done separately from the calculations of runoff and baseflow (Gaol et al. 2009).

The climate model inputs and other information available on the archive have previously been bias-corrected and spatially downscaled to 1/8 degree (12 kilometer) for January 1950 to December 2099. Since wide variations in weather can occur daily, the runoff values were aggregated to an average monthly value. Temperature and precipitation inputs were averaged to a corresponding monthly value in the dataset for the CMIP5 data and the input to the VIC was prepared by disaggregating these monthly precipitation and temperature values into daily time steps (Reclamation 2014). Because extreme values could occur in the precipitation values, restraints were imposed to prevent excessive daily values (Gaol et al. 2009). In the CMIP3 hydrology dataset only a monthly projection of mean daily-average temperature was used in the VIC model (Reclamation 2014).

The CMIP3 hydrology dataset used VIC version 4.0.7, while the CMIP5 hydrology dataset utilized VIC version 4.1.2 (Reclamation 2014). The USBR has noted that any possible impacts of changing the VIC version update should show smaller effects for long-term water balances (such as the annual mean runoff) than for shorter durations like monthly or seasonal runoff , possibly leading to increased variability between the CMIP3 and CMIP5 hydrology runoff projections (Reclamation 2014). To test this variability, several basins were evaluated for runoff sensitivity to the change in the VIC model as a part of the data assurance of the CMIP5 hydrology dataset (Reclamation 2014). However, none of the evaluated sites were in the Arkansas-Red Basin.

Although snowpacks are modeled in the VIC model, this area of southeastern Kansas does not build a season-long snowpack. Large snow events can and do occur, but the temperatures do not stay cold enough for the snowpack to build or remain for long. Snow typically melts within a couple of days, thus a seasonal snowpack does not develop.

1.3. JUSTIFICATION AND DISSERTATION STRUCTURE

This dissertation is divided into three parts. Each chapter is designed to help provide insight to specific questions that will arise during a climate-change analysis using a case study location of Fall River Lake in Kansas, namely:

1. At the current time, would it be more prudent to use CMIP3 or CMIP5 hydrology dataset?
2. What is the most reasonable way to locally calibrate the runoff projections from the CMIP3 and CMIP5 hydrology dataset?
3. What legal issues should be taken into consideration when analyzing reservoir operations in this basin?

The current state of climate-change research in the Verdigris Basin in Kansas is that there are various climate projection datasets available, but the data have yet to be applied to small reservoirs within the basin. Fall River Lake makes an excellent opportunity for a case study to compare different generations (CMIP3 versus CMIP5) of climate models against quality-controlled monthly observations at a lake with no water supply storage. Reservoir releases from Fall River Lake are only for flood control and water quality purposes. Using the runoff from the archived hydrology dataset will allow for the comparison of more models and different scenarios than would be available from available regional climate models.

A case study in Kansas is important because the Kansas State Plan sets the goal of evaluating different reservoir management practices at each federal reservoir by the year 2020 (KWO 2015). Analyzing the range of possible hydrologic outcomes to Fall River Lake can allow for changes to the current water control plan in time to try to mitigate possible problems that may become evident when the water control plan is analyzed for sufficiency using climate-change projections. The first step in the process of evaluating Kansas reservoir management plans would be to determine which set of climate-change projections would be the most practical for the region. Another task that must be done as part of the evaluation of the reservoir management plans would be to determine an appropriate methodology to use monthly reservoir data to locally calibrate climate-change projections. The analysis and methodology set out in the following chapters are meant to serve as a planning tool to meet those needs.

In order to study the potential effects of climate change on regional hydrologic systems such as reservoirs, monthly inflow data can be used to help assess potential needed operational changes. WCRP's CMIP3 and CMIP5 multi-model hydrology datasets include projections of monthly runoff for locations in the western United States (Reclamation 2014). Using the CMIP3 and CMIP5 hydrology datasets can help analyze climate change at a specific reservoir, but there is little guidance on which set of climate-change projections should be used for a particular region. Calibrating the runoff projections with observed reservoir inflow increases the credibility of the projections. Chapter 2 makes a comparison between the runoff projections based on climate change and the inflow at Fall River Lake in the Verdigris Basin in Kansas. Three methodologies of using monthly localized bias-correct calibration factors are compared in Chapter 3.

The Verdigris Basin system within Kansas is actively managed to control the flow in rivers. Federal reservoirs are used to mitigate damaging flood flows and to provide a reliable source of minimum river flow and water supply if adequate natural river flow is not available

(USACE 2012). However, this active management is complicated under Kansas water law, which is addressed in Chapter 4.

Impacts of climate change on the federal reservoirs in the Verdigris Basin may have negative consequences. Increased storm intensities would make the reservoirs more expensive to maintain and operate due to increased flood releases. More intense storms could increase runoff, therefore extending the time that structures make flood releases, causing wear and tear on the structures. Increased storm intensity would likely bring more sediment and debris into the lake, which would accelerate the filling of the available sediment storage. Increased debris could cause damage to outlet works or shoreline stabilization projects, such as protective riprap.

1.4. OBJECTIVES AND OVERVIEW

The objectives of this research are to determine if the CMIP3 or CMIP5 projections are more credible for use in reservoir climate-change studies in southeast Kansas, to prescribe a methodology of using monthly reservoir data to locally calibrate climate-change runoff projections, and to provide a legal analysis of using federal reservoirs to regulate the river flow in the Verdigris basin.

Chapter 2 is a comparison of the monthly inflow to Fall River Lake based on the WCRP's CMIP3 and CMIP5 multi-model datasets of projections, using a subset of available ensemble members. Ensembles of projected runoff were also compared to observed reservoir inflow for October 1979-September 2015. Climate-change ensembles should be locally calibrated using regional observations for use on a specific study. Chapter 3 is an analysis that of three methodologies of local bias-correction calibration factors for the ensemble of inflows for Fall

River Lake. The fourth chapter of this paper provides an overview of legal issues created by river flow regulation in the Verdigris Basin.

1.5. RESULTS OF STUDY

The results of this comparison between the CMIP3 and CMIP5 runoff projections show that the CMIP3 hydrology dataset continues to remain the more credible and appropriate tool in this basin. Runoff from the ensemble means for both the CMIP3 and CMIP5 hydrology datasets were higher for the lowest observed exceedance probabilities and lower for the highest exceedance probabilities when compared to the observed reservoir inflows. This means that while the ensemble means show the general trend, the entire ensemble of projections should be considered when planning for extreme events.

A comparison was made in Chapter 3 between the monthly local bias-correction calibration factors developed for runoff in the CMIP3 and CMIP5 hydrology datasets calculated using the ensemble mean, the 50% exceedance value (the median), and by a new methodology of averaging factors calculated from the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities for the calibration period of October 1979 –September 2007. Observed monthly reservoir inflow was used to calculate these factors as well. The proposed new methodology of averaging bias-correction factors calculated from the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities is the recommended technique for Fall River Lake and the surrounding area due to the mostly low lake inflows, with occasional extreme inflows.

The local bias-correction calibration factors were generally less than 1.0 during the cooler months and above 1.0 for the warmer months. Comparing the sets of monthly local bias-correction calibration factors, the calibration factors developed for the CMIP5 hydrology data were typically larger than those for the CMIP3 data for most months and for most exceedance values. A validation period of October 2007 to September 2015 was used to corroborate the monthly factors used.

Regulating the natural flow in the Verdigris River in Kansas creates nuances in the legal framework of a state system of prior appropriation with vested riparian rights, a water marketing program, and an interstate compact. The potential for Native American Nations to assert water rights in the Verdigris Basin in Oklahoma complicates the already complex legal framework. It is highly recommended that the Cherokee and Osage Nations of Oklahoma be involved in the future Kansas-Oklahoma Arkansas River Compact proceedings.

Further complicating matters is the minimum target river flows being addressed through a Memorandum of Understanding between the State of Kansas and the U.S. Army Corps of Engineers concerning the operation of federally-owned reservoirs in the basin. It is recommended that minimum target flows in the Verdigris Basin be set in State statute, instead of relying on Memoranda. The recent listing of rivers within the Verdigris Basin as critical habitat for the Neosho mucket may complicate the current regulations for determining minimum flow in the river by the Kansas Water Office and Corps of Engineers by bringing in the involvement of the US Fish and Wildlife Service.

1.6. PROPOSED FUTURE WORK

Chapters 2 and 3 set out recommendations of using the CMIP3 inflow climate-change projection and the proposed new methodology of averaging bias-correction factors calculated from the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities. However, there are other issues that must be addressed in order to complete a full analysis of analyzing the impacts of climate change on the Fall River Lake reservoir management plan. The most important issue is the establishment of a new reservoir management plan that will allow Fall River Lake to continue to provide a reliable source of water quality releases in the future. Without these releases to help sustain the river flow, there could be detrimental ecological and monetary impacts. Fish and other aquatic wildlife depend on the river flow for survival. Farmers depend on the low-flow releases as a source of irrigation water. Municipalities and industries depend on the river system for a source of potable water and cooling water.

To fully integrate the different aspects of how Fall River Lake reservoir operations might be affected by future climate change, an array of differing management criteria should be included as a part of the modeling process. The policy analysis presented in Chapter 4 can be used in this endeavor. Policy makers and the public should be able to visualize the impacts of decreasing or increasing minimum monthly reservoir releases. Approximations of future operations and maintenance costs for Fall River Lake can be developed based on the estimated increase in storm intensity for large precipitation events using the increases in estimated monthly exceedance probabilities developed in this case study as a starting point. Along the same lines, the monetization of expected future drought impacts downstream of the lake can also be quantified using the expected changes in the lower monthly exceedance probabilities as an initial foundation. As a part of the establishment of a new reservoir management plan, it would be the most opportune time to use the same techniques to analyze climate-change impacts at the other federal reservoirs in southeast Kansas since they are regulated as a unit.

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CHAPTER II

FALL RIVER LAKE CASE STUDY: CMIP3 AND CMIP5 CLIMATE PROJECTIONS AND OBERSERVED DATA

2.1. ABSTRACT

Should more recent climate modeling methodologies replace older ones as guidance? The World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 5 (CMIP5) climate projections are generally similar to phase 3 (CMIP3) projections, but there are locations where differences have been noted. This case study analyzes whether the newer CMIP5 should replace the CMIP3 guidance for Fall River Lake in the Verdigris Basin in Kansas. Basin runoff (reservoir inflow) based on climate change is available from the previously bias-corrected and statistically downscaled CMIP3 and CMIP5 hydrology datasets that utilize the Variable Infiltration Capacity (VIC) model. Ensemble mean monthly inflows based on the CMIP5 projections were generally lower than the CMIP3 inflows. Both the ensemble means for the CMIP3 and CMIP5 predicted inflows were lower than observed data for high flows and higher for

low flows. The mean monthly runoff from the CMIP3 hydrology dataset is closer to the observed data, so it remains the more credible ensemble for this basin. However, the use of CMIP5 guidance should not be completely disregarded in this basin, particularly if a proposed climate study wished to specifically capitalize on the generally lower CMIP5 inflows.

2.2. INTRODUCTION

The Kansas Comprehensive Water Plan calls for the investigation of different reservoir management practices by the year 2020 (KWO 2015). Evaluating how climate change may affect the reservoir management practice will be an integral part of that evaluation. Vulnerability of water resources in response to climate change can be assessed using ensembles of climate-change projections that incorporate multiple models and scenarios (Sivakumar 2011; Wood et al. 1997). Climate science is rapidly evolving and new modeling methodologies can result in different results in the projected temperature and precipitation (Reclamation 2013). Since public involvement and approval is an essential part of implementing reservoir management changes, establishing credibility of the climate-change projections is necessary.

2.2.1. CMIP3 AND CMIP5 CLIMATE PROJECTIONS

The CMIP3 hydrology dataset includes 16 global climate models with multiple initial conditions, with 112 separate projections. Global climate model inputs and hydrologic model predictions have already been bias corrected and spatially downscaled to 1/8 degree (12 kilometer). Monthly precipitation, temperature, and runoff from the various applications of the VIC model are available for January 1950 to December 2099.

The CMIP5 hydrology dataset includes 31 global climate models that incorporate four different radiative forcing scenarios, for a total of 97 separate projections. Like the CMIP3 dataset, the global climate model inputs and hydrologic model predictions have already been bias-corrected and spatially downscaled to 1/8 degree (12 kilometer). Similar to the CMIP3 dataset, monthly runoff, precipitation, and temperature data are available from January 1950 to December 2099.

Scenarios in the CMIP5 models are called Representative Concentration Pathways and represent different radiative forcings instead of the greenhouse gas emission scenarios that were modeled as part of CMIP3. Unlike the emission scenarios from the CMIP3, the RCPs do not represent any specific policy. RCP 8.5 generally corresponds to the A1F1 in the CMIP3. RCP 6.0 is similar to A2 until around 2050, then emissions associated with it increase more slowly, until they reach levels between A1B and A2 by the middle of the 22nd Century. RCP 4.5 is also similar to A2 until around 2050, but the emissions associated with this scenario match well with B1 at the beginning of the 22nd Century.

The CMIP3 projection ensemble encompasses different scenarios of greenhouse gas emissions, while the CMIP5 projections use different scenarios of different radiative forcings above a preindustrial baseline (IPCC 2007; IPCC 2000). This case study incorporates climate projections from the CMIP3 A2 and B1 scenarios, representing a high rate and low rate, respectively, of greenhouse gas emissions to continue into the future. From the CMIP5 Representative Concentration Pathways (RCPs), this case study uses projections from the 4.5 and 8.5 RCPs, as shown in Table A.1. Table 2.1. lists the radiative forcing and associated greenhouse gas concentrations from these RCPs.

Table 2.1. Representative Concentration Pathways in CMIP5 Hydrology Dataset

CMIP5	**Radiative Forcing**	**Carbon Dioxide Concentration (ppm)**	**Pathway**
RCP8.5	>8.5 W m^{-2}in 2100	>1370 CO_2 in 2100	Rising
RCP4.5	~4.5 W m^{-2}after 2100	~650 CO_2 (stabilization after 2100)	Stabilization without overshoot

Developed from Moss et al. 2011

The ensemble for this case study consists of 17 members from the 4.5 Representative Concentration Pathways and 17 members from 8.5 Representative Concentration Pathways, as shown in Table A.2.

2.2.2. FUTURE BASIN CLIMATE PROJECTIONS

The Fall River and Verdigris River basins are located on or near the gradient where scientists believe the United States will change from wetter to drier as a result of climate change (Dai 2006). It is anticipated that the northern portion of the Fall River and Verdigris River basins will have slightly more precipitation annually, while predictions about the southern portion of the basin in Oklahoma are not quite as settled. However, there is little confidence in either the quantity or sign of change in future annual precipitation in this area (Dai 2006).

Kansas climate has always been variable. A recent study of annual precipitation at selected locations shows that for Independence, Kansas there was a downward trend in precipitation from 1893 to 1965 and then an upward trend from 1966 to 2011 (Rahmani et al. 2015). The future climate in Kansas is projected to be just as variable. It is expected that average daily temperatures in this area will increase in the future. Figure 2.1 shows that an increase in mean daily maximum temperature is expected to continue into the future. Maximum daily temperature lower both higher and lower greenhouse emissions scenarios, along with observed past mean daily maximum temperatures are shown in Figure 2.2.

Annual precipitation is expected to continue to be variable in this basin. As shown in Figure 2.3, there are years when higher emission scenarios indicate that this region will experience more precipitation. However, there are also years that show that lower emission scenarios are associated with increased precipitation. Figure 2.4 shows that changes in monthly expected precipitation are not quite settled as the observed monthly precipitation falls within the range of future possibilities. The ensemble means for both the higher and lower emission scenarios are generally higher than the observed past precipitation for most months. However, less monthly precipitation is still a possibility in this basin.

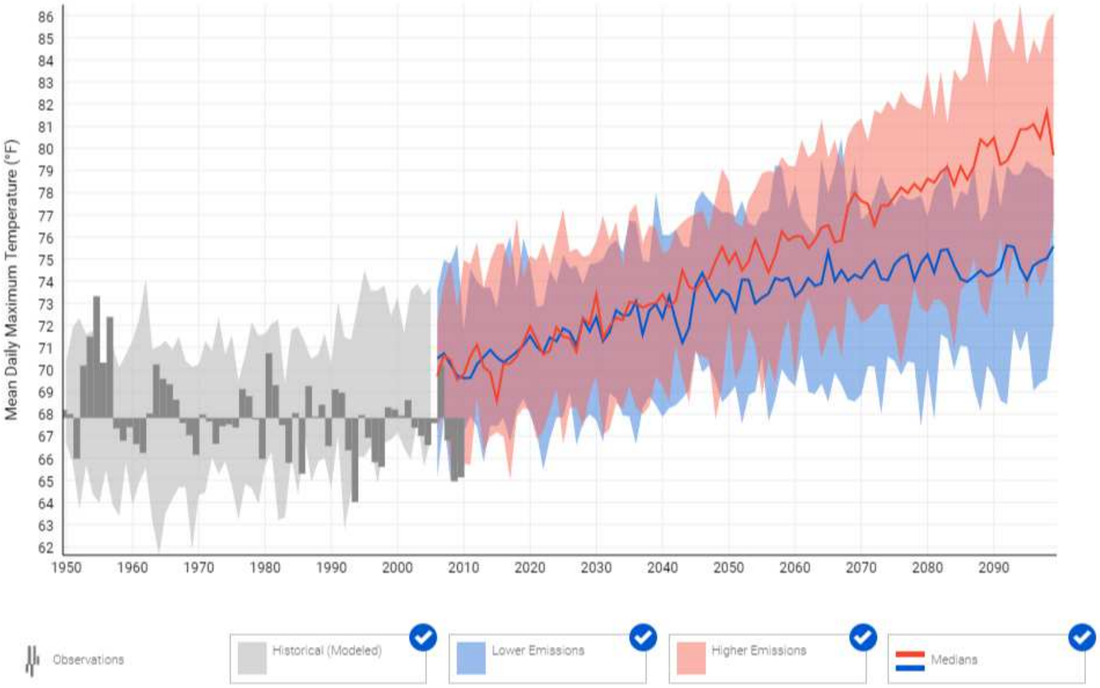

Figure 2.1 Observed and Projected Mean Daily Maximum Temperatures in Greenwood County Kansas. Projections for lower greenhouse gas emission scenarios are shown in blue. Projections based on high emissions scenarios are shown in red. Observations are shown in gray (NOAA Climate Toolkit 2016).

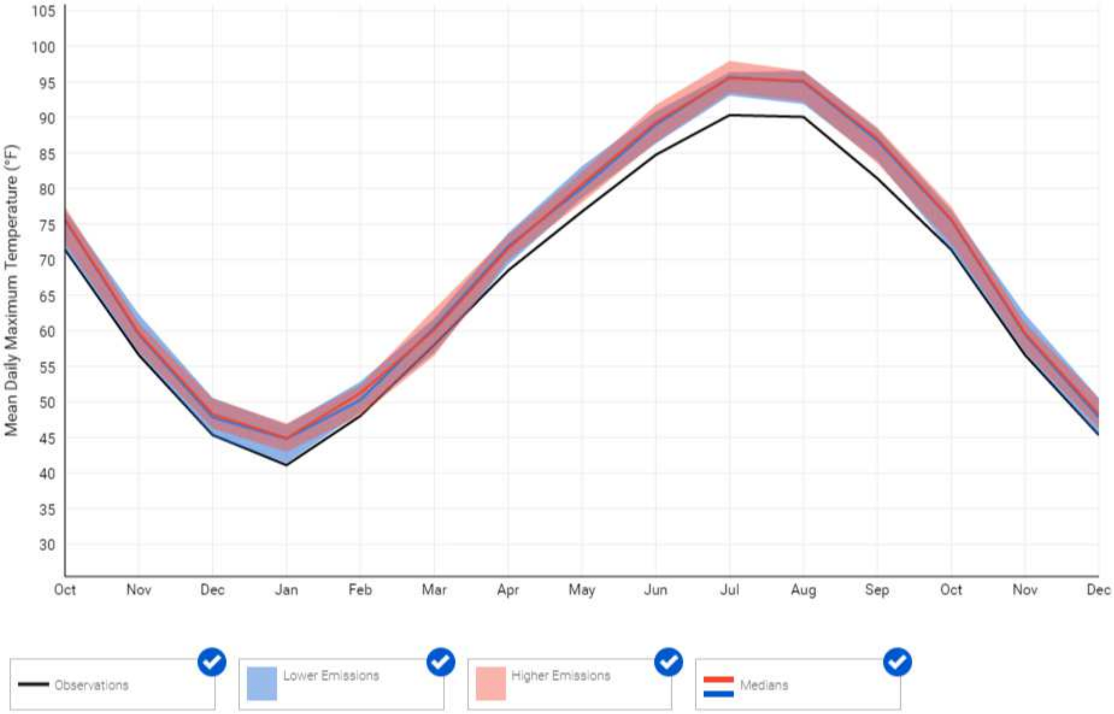

Figure 2.2. Mean Daily Maximum Temperature in Greenwood County Kansas for 30-Year Average Centered Around 2025 Projections for lower greenhouse gas emission scenarios are shown in blue. Projections based on high emissions scenarios are shown in red. Observations are shown in black (NOAA Climate Toolkit 2016).

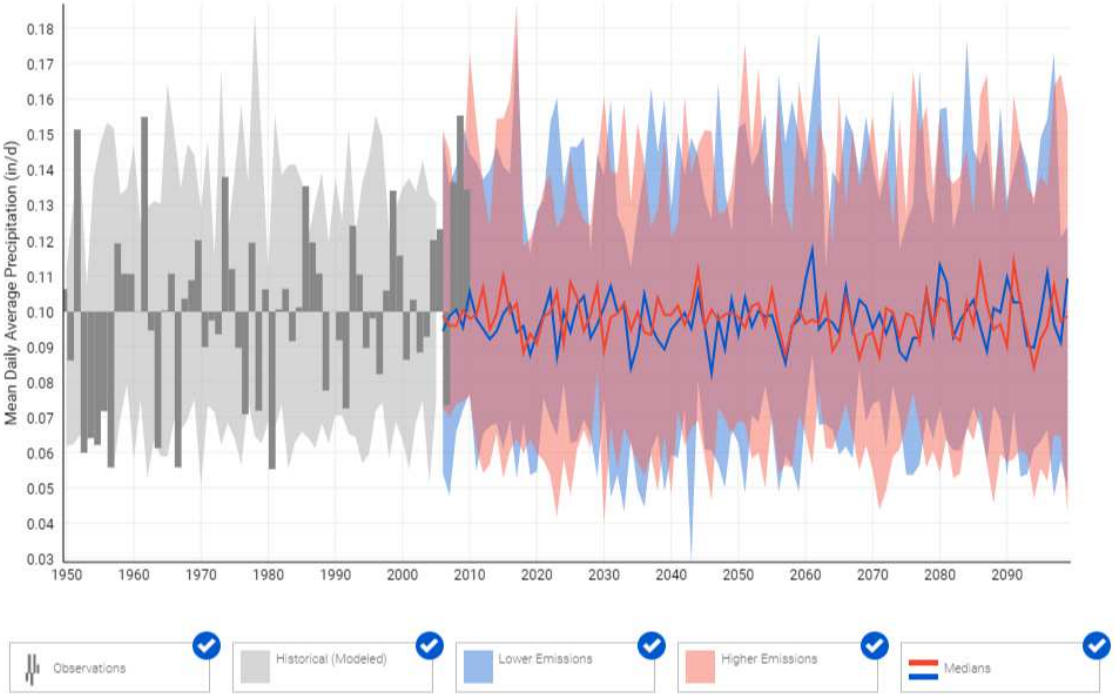

Figure 2.3. Mean Annual Precipitation Greenwood County Kansas Showing Modeled Data from Years 2010 to 2100. Projections for lower greenhouse gas emission scenarios are shown in blue. Projections based on high emissions scenarios are shown in red. Observations are shown in gray (NOAA Climate Toolkit 2016).

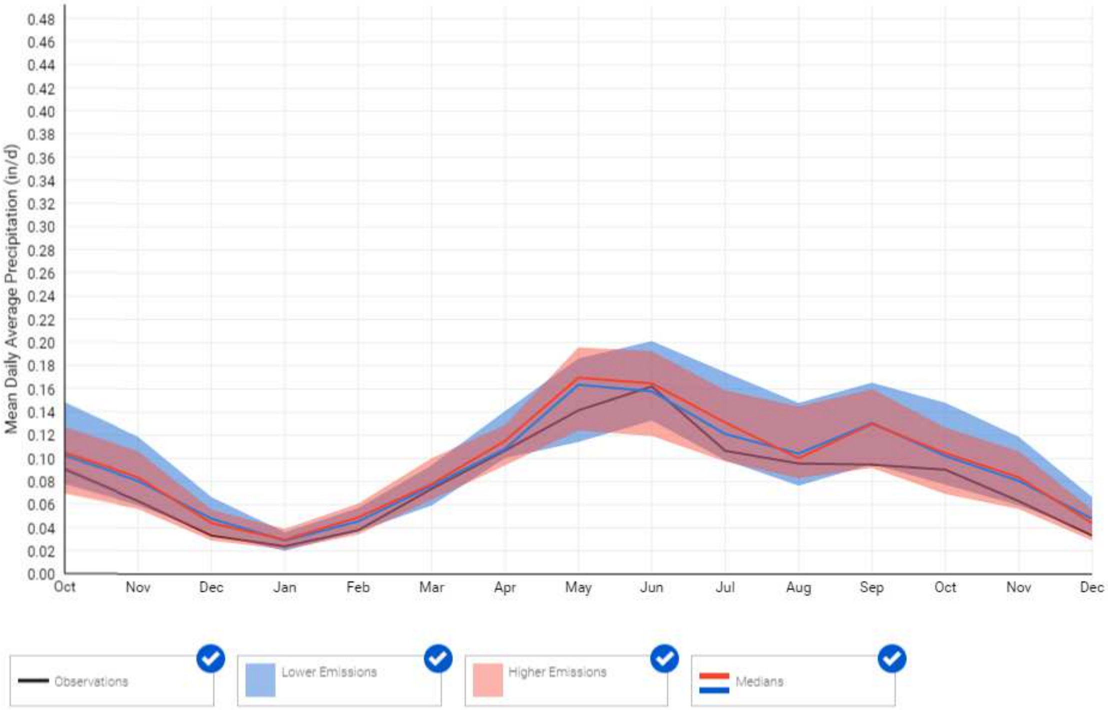

Figure 2.4. Mean Daily Average Precipitation (shown in inches per Day) in Greenwood County Kansas for a 30-Year Average Centered around 2025. Projections for lower greenhouse gas emission scenarios are shown in blue. Projections based on high emissions scenarios are shown in red. Observations are shown in gray (NOAA Climate Toolkit 2016).

For the Fall River Basin, the CMIP5 hydrology datasets predicts a slightly different future story than the CMIP3 projections. For the area around the Fall River and Verdigris Basins, the CMIP5 projections are warmer and wetter than the CMIP3 projections until the end of the 21st Century (Brekke et al. 2014). As shown in Figure 2.5, the CMIP5 hydrology projections foretell a slight increase (0 to 0.2 degrees Celsius) in the 30-year average temperature for 2010-2039 and 2040-2069, as compared to the observed annual temperature from 1950 -1999. However, the CMIP5 temperature projections for 2070-

2099 are slightly cooler (0 to 0.2 degrees Celsius) than the CMIP3 projections as compared to the same period. Similarly, as compared to the observed annual average from 1950 -1999, slightly more annual precipitation (0 to 3%) and runoff (0-15%) are projected by the CMIP5 than the in the 30-year average precipitation and runoff for 2010-2039 and 2040-2069, but less is projected for 2070-2090 than the CMIP3 projections.

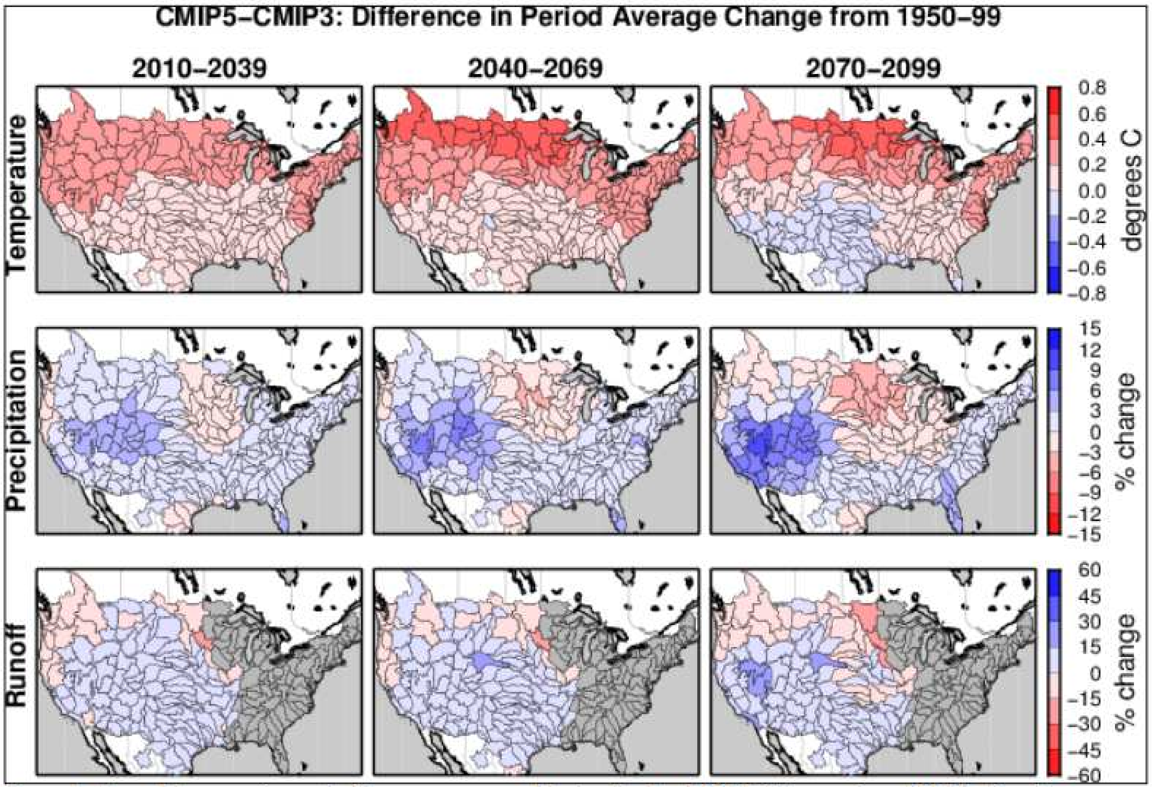

Figure 2.5. Ensemble-mean change in the 30-year mean annual hydrologic climate (the different CMIP5 from CMIP3 hydrologic projections) shown for Temperature (-0.6 to 0.6 degrees Celsius), precipitation (-10 to +10%), and Runoff (30% to +30%). Grayed out basins are not included in the hydrology archive. USGS subregions (HUC4) are outlined (Brekke et al. 2014).

2.2.3. BASIN BACKGROUND INFORMATION

Fall River Lake was constructed on the Fall River, a tributary to the Verdigris River in southeast Kansas. Three other federal reservoirs were also constructed on the Verdigris River and its tributaries in Kansas. A location map showing the location of Fall River Lake in the central United States is shown in Figure 2.6 and a more detailed map of the basin prepared by the Kansas Water Office is shown in Figure 2.7.

Figure 2.6. Location of Fall River Lake in Relation Surrounding Area of United States (GoogleMaps 2016).

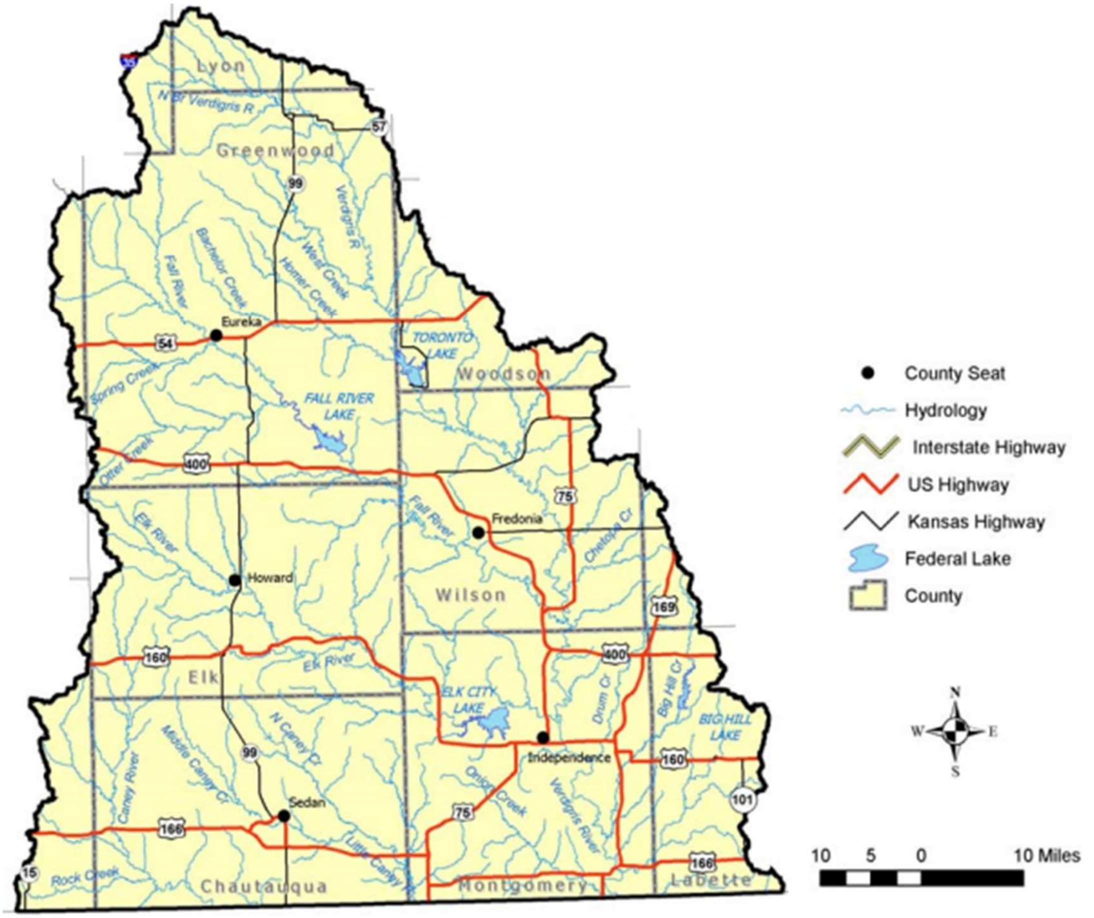

Figure 2.7. Map of Verdigris Basin in Kansas (KWO 2009).

Consisting of approximately 1,515 square kilometers (585 square miles), the drainage area contributing inflow to Fall River Lake is about 40 miles long and typically around 20 miles wide. Another 774 square kilometers (299 square miles) of the basin of the Fall River remains uncontrolled downstream of the Fall River Lake damsite (USACE 1993).

Geologically, the drainage area for Fall River Lake is in the Osage Cuestas and Chautauqua Hills regions (Kansas Geological Survey 1997). Rocks in this area are limestone and sandstone created through sedimentary processes. However, there are outcropping of lamproites in the Fall River drainage basin. Lamproites formed from the cooling of magma and were pushed into other rock formations (Kansas Geological Survey 1999). Silt loam and silty clay loam are found throughout the region (US Department of Energy Atmospheric Radiation Measurement Program 2006).

The Osage Cuestas region has east-facing ridges with steep limestone faces and gentle rolling slopes on the west and northwest. Heights of the cliff-like faces of these cuestas range from 15 meters (50 feet) to 61 meters (200 feet) (Kansas Geological Survey 1999). Underlying the gentle slopes are layers of shale. Sandstone capped small rolling hills are the defining feature of the Chautauqua Hills region. Due to the rock formations, this area is typically used as grassland pastures instead of being cultivated (Kansas Geological Survey 2005).

Approximately 90.3 percent of the drainage area contributing to Fall River is grassland. Cropland covers around 4.4 percent of the drainage area contributing to Fall River Lake (USGS 2015). All other land uses comprise the remaining 5.3 percent.

The drainage basin has moderate winters and long, hot summers. Daily average temperatures in the winter and summer are around 1.1 to 26.1 degrees Celsius (34 degrees and 79 degrees Fahrenheit), respectively. Average precipitation is approximately 33 inches per year (annual average from January 1930 to December 1989), mostly as convective high-intensity isolated thunderstorms during the summer months. Rainfall in the winter is mostly widespread low-intensity synoptic patterns**.** Typically between 279.4 to 457.2 mm (11 to 18 inches) of snow falls each year, however, no long-term snowpack is formed in the winter, due to the moderate character of the winters (USACE 1993).

Fall River and the Verdigris River downstream of the confluence of Fall River travels through four counties in Kansas: Greenwood, Elk, Wilson, and Montgomery. This area of Kansas is generally rural and has been experiencing population loss since the late 20th Century, as shown in Table 2.2. Flows also pass through Nowata County in Oklahoma before the mainstem Verdigris River is controlled by Oologah Lake.

Table 2.2. Population of Counties in the Fall River Basin and in the Verdigris River Basin Downstream of the Confluence with Fall River Has Been Decreasing (US Census 2016).

County	1980 Population	2010 Population	2015 Population	Percentage Change (1980 to 2015)
Greenwood, Kansas	8,764	6,689	6,244	-40.4%
Elk, Kansas	3,918	2,882	2,605	-50.4%
Wilson, Kansas	11,208	9,409	8,8056	-26.6%
Montgomery, Kansas	42,281	35,471	33,314	-26.9%
Nowata, Oklahoma	11,486	10,536	10,539	-9.0%

2.2.4. RESERVOIR REGULATION IN THE VERDIGRIS BASIN

Fall River Lake is one of four federal reservoirs in the upper Verdigris Basin in Kansas that are owned and operated by the United States Army Corps of Engineers, Tulsa District. The main stem of the Verdigris River is also regulated by Oologah Lake in Oklahoma (USACE 2012). Toronto Lake near Toronto, Kansas, on the main stem of the Verdigris, controls flooding and provides water supply, and water quality storage in the Verdigris headwaters (USACE 2012). Elk City Lake, near Elk City, Kansas provides flood control, water quality and water supply storage on the Elk River, a major tributary of the Verdigris (USACE 1993). Fall River Lake, near Fall River, Kansas provides flood control and water quality storage on the Fall River, another major tributary of the Verdigris (USACE 1995). The Pearson-Skubitz project (Big Hill Lake) near Cherryvale, Kansas provides flood control and water supply storage on Big Hill Creek (USACE 1982).

A two-level regulation scheme is used for the reservoirs in the Verdigris Basin where the reservoirs in the Verdigris are managed as part of the larger Arkansas River system, as well as a subsystem of five reservoirs. The Arkansas River Master Water Control Manual provides for some flexibility for the regulation operation of the larger system for flood control, but within the Verdigris Basin subsystem there is little flexibility in flood control (USACE 2012). Within the Verdigris Basin Subsystem, the goal of flood control storage in the Toronto, Fall River, and Elk City Lakes is to balance the available storage in each of the lakes as a percentage of the flood pool utilized (USACE 2012). Big Hill Lake is not actively balanced with controlled reservoir releases unlike the other federal reservoirs because the outflow from Big Hill Lake is through a drop inlet structure with an auxiliary overflow spillway (USACE 1982).

Because the entire upper Verdigris Basin is controlled at the lower end by Oologah Lake, flood pool percentages in Oologah Lake are triggers for a balancing regulation scheme. When the utilized flood control storage in Oologah Lake is below 20%, attempts are made to empty the flood control storage in the federal reservoirs in the Verdigris Basin in Kansas. The goal is for Toronto, Fall River and Elk City Lakes to have emptied their flood control storage once the flood pool at Oologah Lake is 20% full (USACE 2012).

When the flood control storage in Oologah Lake is between 20% and 30%, the objective is for flood water to begin to be stored in Toronto, Fall River and Elk City Lakes in an equitable manner based on the percentage of the flood control pool utilized (USACE 2012). The goal is for the storage used in each of the upper Verdigris lakes to be at 30% once the flood storage at Oologah Lake is also at 30% full (USACE 2012). If Oologah Lake uses above 30% of its flood capacity, then Toronto, Fall River and Elk City Lakes are expected to have their used flood capacity to match the percentage of flood control storage used at Oologah Lake (USACE 2012).

Floodwater discharges from Oologah Lake are directly subject to regulation as a part of the Arkansas River Master Plan. A tapered recession of flood water releases from all the federal reservoirs in the Arkansas River Basin is attempted into the Arkansas River in order to alleviate the natural flashy nature of the Arkansas River and some its tributaries (USACE 2012).

2.2.5. PREVIOUS CLIMATE CHANGE STUDY IN THE VERDIGRIS BASIN

A climate-change study done by Qiao et al. (2014) included the Verdigris basin. However, that study was completed for the overall watershed of Oologah Lake and focused only on the inflow to Oologah Lake, as measured by the Lenapah, Oklahoma United States Geological Service (USGS) gage. Inflows to Oologah Lake include the Verdigris River and multiple tributaries, including Fall River and Elk River, and a large local area of approximately 755 square miles. Approximately 17.4% of the entire drainage basin to Oologah Lake is local drainage that flows to the lake downstream of the Lenapah gage site.

Results of Qiao et al. (2014) stated the dynamically downscaled North American Regional Climate Change Assessment Program (NARCCAP) projections performed better than the statistically downscaled CMIP3 study, likely due to better modeling of mesoscale convective precipitation events. However, they also stated that CMIP3 projections were a better fit to the observed temperature and precipitation (Qiao et al. 2014). The Qiao et al. (2014) study estimates that future water availability in this watershed will increase annually by three to four percent from 2040 to 2069, compared to the mean runoff from 1968 to 1997. However, the reservoir inflow to Oologah Lake, as measured in flow past the Lenapah, Oklahoma USGS gage, performed worse with the CMIP3 projections than the NARCCAP projections (Qiao et al. 2014).

The Qiao et al. 2014 study began by statistically fitting the CMIP3 projections to the historical observations for this area based on the Lenapah, Oklahoma USGS gage. However, measuring the hydrologic response of the overall Oologah basin by the flowrate observed at Lenapah, Oklahoma is not appropriate because the four reservoirs in the Upper Verdigris Basin in Kansas control the majority of the flow from the upper basin. The system of federal reservoirs and state fishing lakes that provide flood control and sustained year-round minimum streamflows in the Fall River, Elk River, and Verdigris River were completed ignored in the Qiao et al. study.

In reality, the Verdigris Basin is a highly regulated system of reservoirs that detain high flows to provide flood control and provide sustained low-flow releases when the river would have run dry. The reservoirs in the Verdigris Basin in Kansas are operated as a system with Oologah Lake. The only natural river flows are into the furthest upstream reservoirs in the system. Including these reservoir operations into a hydrologic model would have likely made a very different result to the USACE assessment of the hydrologic performance of the CMIP3 projections.

2.2.6. BACKGROUND INFORMATION ABOUT DATA SOURCES USED IN CASE STUDY

Meteorological and hydrological uncertainty can be described in an ensemble that includes multiple members from various different climate models (Wood et al. 1997). The CMIP3 and CMIP5 hydrology datasets incorporate multiple global climate models as inputs. For this study, a selection of 10 models from the CMIP3 hydrology data and 17 models from the CMIP5 hydrology datasets, listed in Tables A.1. and A.2., respectively, were used. The models selected were subjectively chosen based on the general reputation of modeling centers. In order to prevent influence from a single country or a single model projection, a more equal weighting in the overall ensemble was attempted by including only a single model run for modeling centers that had multiple ensemble members available for use in the hydrology dataset. As there are no large reservoirs (greater than approximately1,000 acre-feet of conservation storage) and no Corps of Engineers or Bureau of Reclamation reservoirs upstream of Fall River Lake and negligible quantities of groundwater that provide inflow to the reservoir, the monthly reservoir inflow to Fall River Lake would be the monthly runoff for the drainage area upstream of the Fall River damsite in the CMIP3 and CMIP5 hydrology datasets. The monthly reservoir inflow for Fall River Lake was available in monthly reservoir reports from the Corps of Engineers Tulsa District Office.

CMIP3 and CMIP5 hydrology datasets include runoff (flow) from the Arkansas-Red River application of the Variable Infiltration Capacity (VIC) model that incorporates projected precipitation and temperature on a monthly scale (Reclamation 2013). A distributed gridded hydrologic model, the VIC model solves a water balance equation at each grid cell (Reclamation 2013). The VIC has been used worldwide for large scale hydrologic and water resources climate-change studies (Reclamation 2013).

There are three emissions scenarios included in the CMIP3 hydrology dataset: the A1B, A2, and B1 emission scenarios. Only projections from the A2 and B1 scenarios are used in this case study. The ensemble for this case study consists of 10 members from the A2 scenario and 10 members from the B1 scenario, as shown in Table A.1.

The available hydrology is a monthly dataset. Downscaling to a daily time step can frequently cause unrealistic daily precipitation estimates (Maurer et al. 2014). This is especially true in smaller basins due to the smaller spatial extents compared to the larger extents of the macro-hydrologic model such as the VIC. Monthly time steps work well for Fall River Lake as it is a reasonable assumption that runoff from precipitation that falls each month is the reservoir inflow for that month. The drainage area to Fall River Lake is a basin of 1,515 square kilometers (585 square miles) and the area does not typically develop a snowpack. Precipitation that falls each month within the basin travels down to the reservoir within several days, with the peak flow arriving a little more than twelve hours after the start of rainfall in excess (USACE 1993). All the runoff from excessive rainfall in the drainage basin is expected to arrive as inflow to the reservoir within four days (USACE 1993).

The entire contents of the flood control storage in the reservoir can be emptied in a little over eighteen days, assuming a constant release rate of 184 cubic meters per second (6,500 cubic feet per second). Each month's runoff was treated as an independent occurrence, meaning that precipitation and hydrologic responses fall within each single month and do not span over more than one month.

2.3. METHODOLGY

The objective of this study is to determine if the CMIP3 or CMIP5 archived hydrology dataset is more credible for a reservoir inflow case at Fall River Lake. Reservoir inflow based on both the CMIP3 and CMIP5 projections is compared to observed reservoir inflow to determine which ensemble is currently more credible. The ensemble of climate-change projections that were used in this case study from the CMIP3 and CMIP5 hydrology datasets are shown in Tables A.1. and A.2., respectively.

Using the monthly projected runoff from the CMIP3 and CMIP5 hydrology datasets makes this case study different from previous efforts. Few studies have been completed that show monthly and annual changes in stream and river flow using both CMIP3 and CMIP5 climate-change projections (Schnorbus and Cannon 2014). Monthly inflow projections were used instead of a projection of meteorological inputs because recent studies have shown that bias-correcting streamflow to assess climate change is likely more effective than bias-correcting the meteorological inputs with an appropriate model, running a hydrologic model, and then bias-correcting the resulting ensemble of streamflow (Yuan and Wood, 2012). Annual changes in reservoir inflow were not addressed. CMIP3 and CMIP5 runoff projections were downloaded from the archive site and copied into HEC-DSSVue and an Excel Worksheet. The monthly ensemble mean runoff was then computed from HEC-DSSVue. The projections were also then analyzed in Microsoft Excel and Minitab 17.

2.3.1. ENSEMBLE MEANS AND EXCEEDANCE PROBABILITIES CALCULATED

Monthly basin runoff using the Arkansas-Red Basin application of the VIC model from a selected group of CMIP3 and CMIP5 hydrology projections (Reclamation 2013) was downloaded and input into a HEC-DSSVue (Version 2.0, Release Update 1) database. HEC-DSSVue was chosen to analyze the data because it was developed specifically to analyze time series data. HEC-DSSVue provides built in mathematical and statistical functions that easily provide cyclic analysis of data based on the month or season. Two ensemble means were calculated in HEC-DSSVue, one for the CMIP3 and CMIP5 runoff projections. HEC-DSSVue was used to calculate the 5, 10, 25, 50, 75, 90, and 95% monthly exceedance probabilities and monthly standard deviations for the CMIP3 and CMIP5 monthly ensemble mean inflows and the standard deviation for each month. The exceedance probability is defined as the percent of months that it is expected that reservoir inflow is expected to exceed a certain value. For example, a monthly 90% exceedance value of 5 mm indicates that 90% of the months will have inflows of 5 mm or larger.

The same exceedance probabilities and standard deviations were also calculated for the observed reservoir inflow, gathered from monthly reservoir reports from the U.S. Army Corps of Engineers Tulsa District for October 1979 to September 2015. A comparison was performed in Microsoft Excel of the runoff probabilities calculated from HEC-

DSSVue of the CMIP3 and CMIP5 data for the same time period as the observed lake inflow. Figure 2.8 shows the CMIP3 and CMIP5 ensemble mean and observed monthly inflow for October 1979 to September 2015.

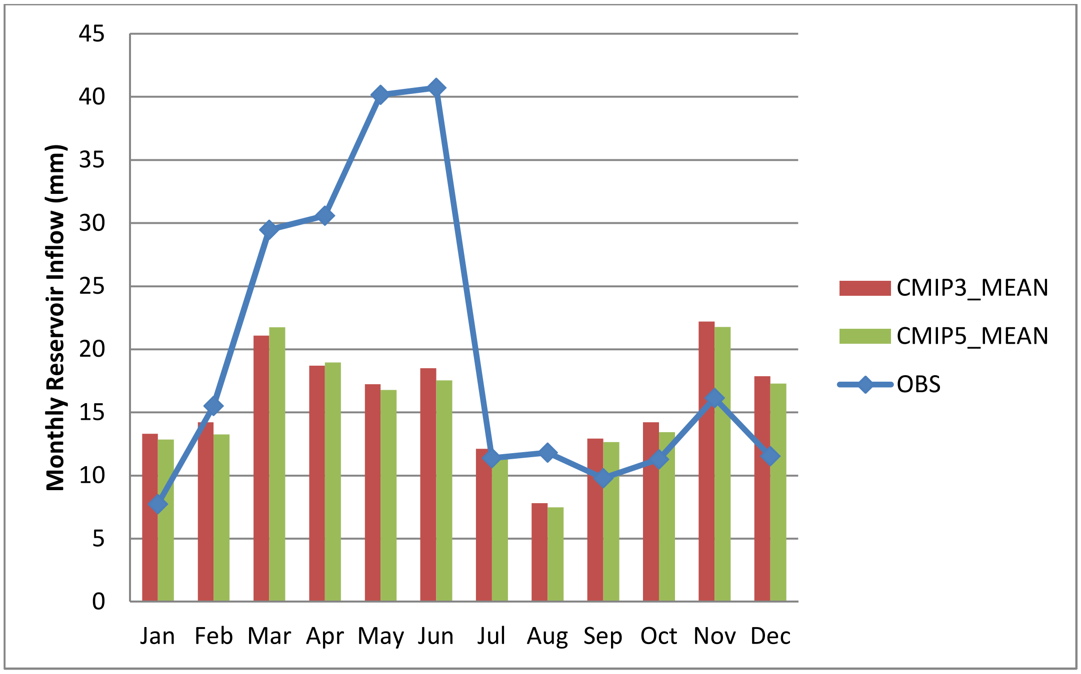

Figure 2.8. Monthly Average Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections (October 1979 – September 2015)

It is important to note that CMIP3 and CMIP5 ensemble means underestimate the runoff as compared to past observations during the months of March, April, May, and June, when the basin has historically experienced the most runoff in the past. Precipitation in the spring and early summer month is typically convective in nature, with rainfall in irregular locations, or frontally-driven rainfall events. Isolated convection is notoriously difficult to model, especially with a global model. Even with frontal systems, the timing and location of the front is quite difficult to ascertain with a global model. The CMIP3 and CMIP5 ensemble means also slightly overestimate the basin runoff in the cooler winter months.

The extreme underestimation of the CMIP3 and CMIP5 ensemble mean basin runoff in the spring and early summer and the slight overestimation in the cooler months highlights the necessity of applying local bias correction to the to the climate-change ensemble of projections. While the CMIP3 and CMIP5 ensembles of runoff projections are planning tools, their efficacy can be greatly enhanced by applying local data to bias correct the ensembles for use in a study.

2.3.2. GRAPHICAL COMPARISONS OF OBSERVATIONS WITH CMIP3 AND CMIP5 ENSEMBLES

The monthly ensemble means of the CMIP3 and CMIP5 runoff projections were plotted with the observed monthly data as a first check for reasonableness of runoff projections using Microsoft Excel. An interval plot of the observed reservoir inflow, the CMIP3 runoff projections and the CMIP5 runoff projections was also done in Minitab for October 1979 to September 2015. This plot graphically compares the means of the projected runoff and the observed data.

2.3.3. NUMERICAL COMPARISON CMIP3 AND CMIP5 ENSEMBLE MEANS AND OBSERVATIONS

The monthly ensemble means for the CMIP3 and CMIP5 projections were also numerically compared to the observed data. Comparisons were made against the 5, 10, 25, 50, 75, 90, and 95% monthly exceedance probabilities and monthly standard deviations for the CMIP3 and CMIP5 monthly projected reservoir inflow.

2.3.4. STATISTICAL COMPARISON IN MINITAB 17 OF OBSERVATIONS WITH CMIP3 AND CMIP5 ENSEMBLE MEANS

The ensemble means for the CMIP3 and CMIP5 ensemble dataset and the observed reservoir inflow were compared to each other using the Minitab 17 statistical program. The monthly ensemble means for all 432 months (October 1979 to September 2015) were compared for the CMIP5 and CMIP3 runoff projections using a two-sample T-test for equivalent means that did not assume similar variances. The tests done were done with alpha = 0.05. The null hypothesis was the monthly mean of the CMIP3 runoff projections subtracted from the monthly mean of the CMIP5 runoff projections was greater than or equal to zero. The alternative hypothesis was that this difference was less than zero.

2.3.5. STATISTICAL ANALYSIS OF DISTRIBUTIONS

Projection data were broken down into months as the initial first step to analyze the distributions in Microsoft Excel. Next the monthly distributions were analyzed for normality using the Kolmogorov-Smirnov test for normality. Then the monthly data were reorganized in ascending order in order to plot the distribution of the data. Next the Weibull plotting position was determined for each set of data. Afterwards the probability of each value in the projected data and Z values were calculated. Distributions of the entire group of projections for each month were then compared against the distribution of the observations using the Kolmogorov-Smirnov test methodology for two samples. Monthly runoff from both the CMIP5 and CMIP3 ensemble mean projections was compared to observed data for each month as well as to each other using the Kolmogorov-Smirnov test for two samples.

2.4. RESULTS AND DISCUSSION

Figure 2.9, with supporting data found in Table A.3., shows the monthly runoff ensemble means runoff from the CMIP5 and CMIP3 hydrology datasets as well as observed reservoir inflow. Inspecting Figure 2.9 visually, the monthly runoff from the CMIP5 ensemble projections appears to be generally lower than the runoff from the ensemble mean in the CMIP3 hydrology dataset. Plotting the ensemble means shows the general trend of the ensemble of possibilities, but the averaging smooths out any extreme values within the ensemble. This is why the monthly mean runoff from both the CMIP3 and CMIP5 ensemble means poorly match the observed runoff for the months of extremely high inflow or extremely low flows.

When compared numerically, monthly runoff predicted using the ensemble of CMIP5 projections was lower than the runoff based on the ensemble of the CMIP3 projections for each month for the 95 and 90% exceedance probabilities. For the 75% exceedance values, the CMIP3 runoff was larger for every month but September and for the 50% exceedance values, the CMIP3 runoff values were greater for every month but April, November, and December. For the months with the largest precipitation values, the CMIP5 monthly runoff projections were larger than the CMIP3. CMIP5 runoff was larger than CMIP3 runoff for every month except February and December for the 5% exceedance values. The majority of the 10% exceedance values had larger CMIP5 runoff than CMIP3 runoff, except for February, July, September, October, and December.

Tables A.4. and A.5.. show the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities and standard deviation calculated from reservoir inflow ensemble means incorporating CMIP3 and CMIP5 climate projections, respectively. On Table A.6., the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities and standard deviation calculated from the observed reservoir inflow for October 1979-September 2015 are shown. Monthly runoff from both the CMIP3 and CMIP5 hydrology datasets were larger than the monthly reservoir inflows for October 1979-September 2015 when compared to the lowest observed exceedance probabilities and lower monthly reservoir.

Using year-round data for the entire period (all 432 months between October 1979 to September 2015), the ensemble mean for the CMIP3 is closer to replicating the observed monthly values at the 95% confidence interval, as shown in Figure 2.10. There is overlap in the 95% confidence intervals of the CMIP3 ensemble mean projected runoff and the observed runoff. However, there is no overlap in the 95% confidence intervals of the CMIP5 ensemble mean projection and the observations. The detailed descriptive statistics of the year-round data are located in the Table A.7.

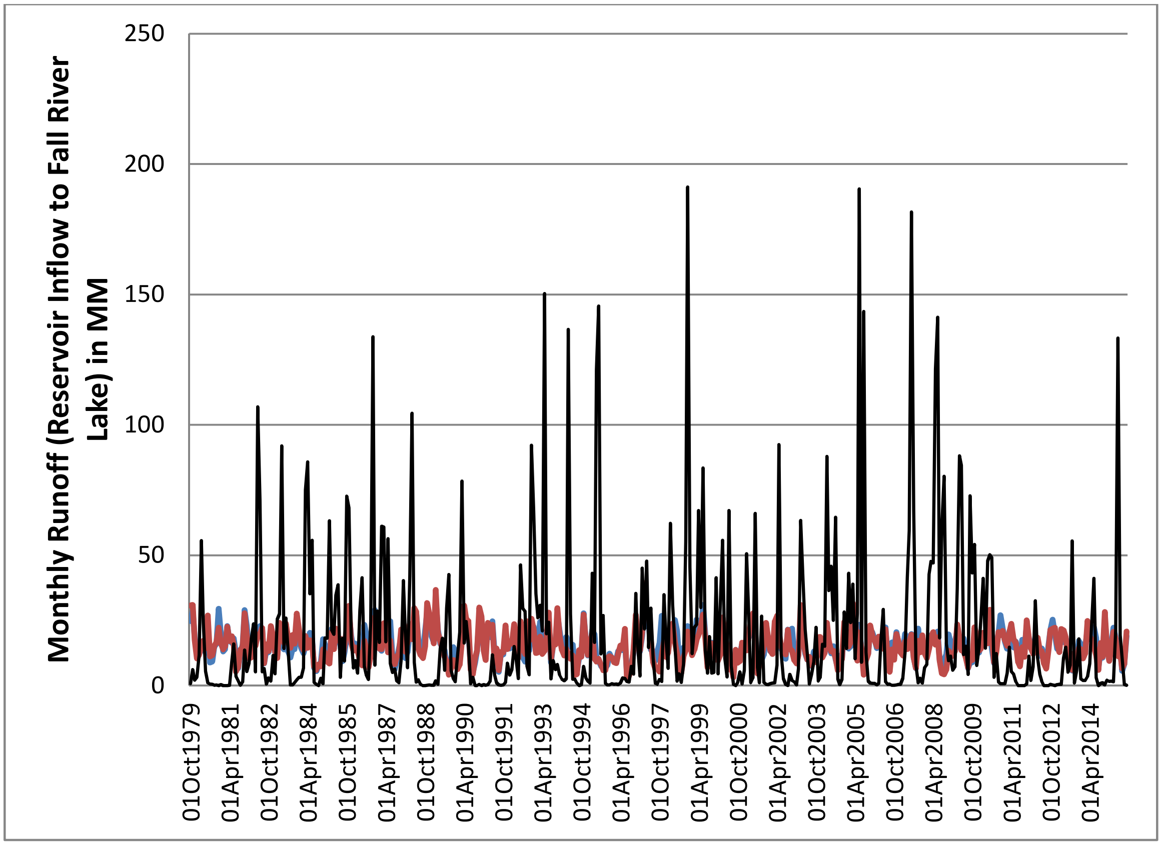

Figure 2.9. Comparison of Runoff (in mm) from Coupled Model Intercomparison Project phases 3 and 5 (CMIP3 and CMIP5) Hydrology Dataset Ensemble Means and Observed Data.

The results of the two-sample T-test for equivalent means (not assuming similar variances) for the CMIP3 and CMIP5 projection ensemble indicates the CMIP5 ensemble is statistically significantly less than the CMIP3 ensemble mean projections when using an alpha of 0.05. Detailed output from Minitab is found in Appendix Table A.8.

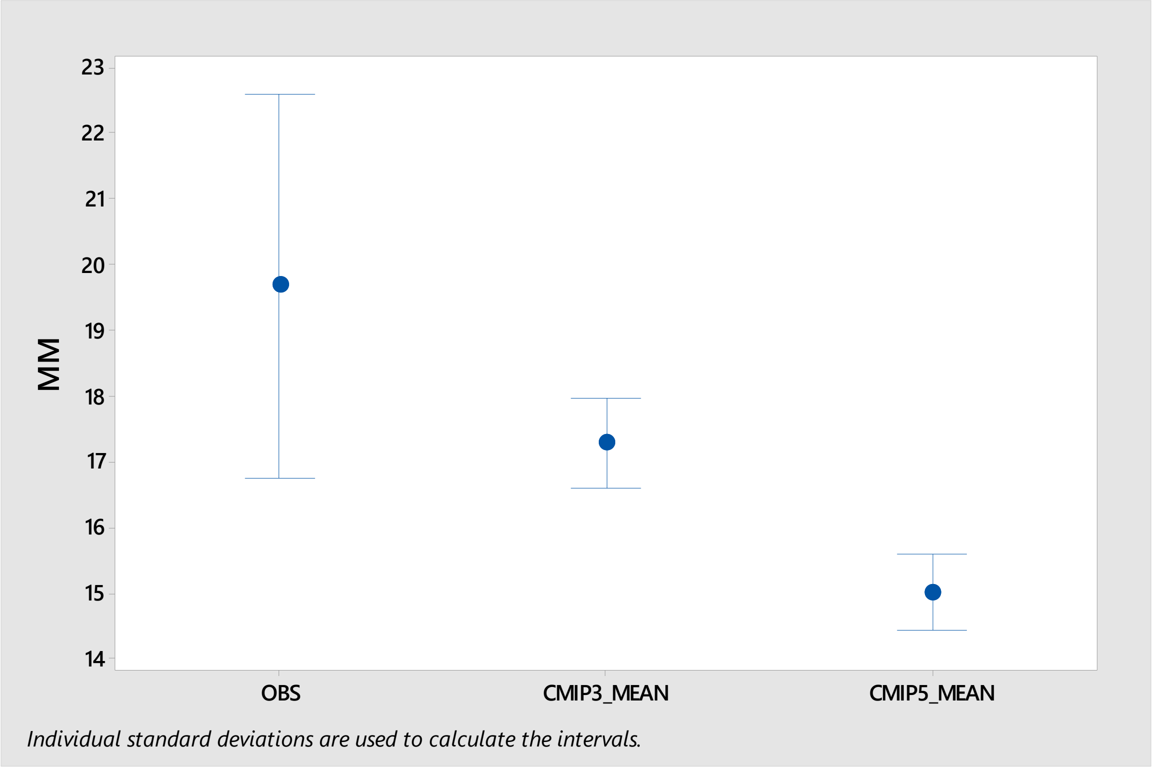

Figure 2.10 Interval Plot of Observed, CMIP3 Ensemble Mean, and CMIP5 Ensemble Mean Monthly Reservoir Inflow in mm with a 95% Confidence Interval for the Means (October 1979 – September 2015)

Based on the Kolmogorov-Smirnov test for normality, none of the distributions for the observations, CMIP3 or CMIP5 runoff projections were normal at the 90% confidence interval. A two-sample Kolmogorov-Smirnov test on the distribution of the CMIP3 ensemble mean monthly runoff and the observed monthly reservoir inflow indicates these distributions are not significantly different from the observed data for any individual month, even with an 80% confidence interval. The same results were found when comparing the CMIP5 ensemble mean observed monthly reservoir inflow. Comparing the monthly CMIP3 and CMIP5 runoff ensemble means with each other using the two-sample Kolmogorov-Smirnov test on the distributions also shows these distributions are not significantly different from one another using an 80% confidence interval.

Distributions were also plotted using the Minitab17 software. The histograms for year-round data (including all months), shown in Figure 2.11, appear to have a shape similar to a lognormal distribution. Histograms for the CMIP3 runoff projections and the CMIP5 runoff projections, as shown in Figure 2.12 and 2.13, respectively, appear to be almost normal in shape, although they both did not pass the Kolmogorov-Smirnov test for normality.

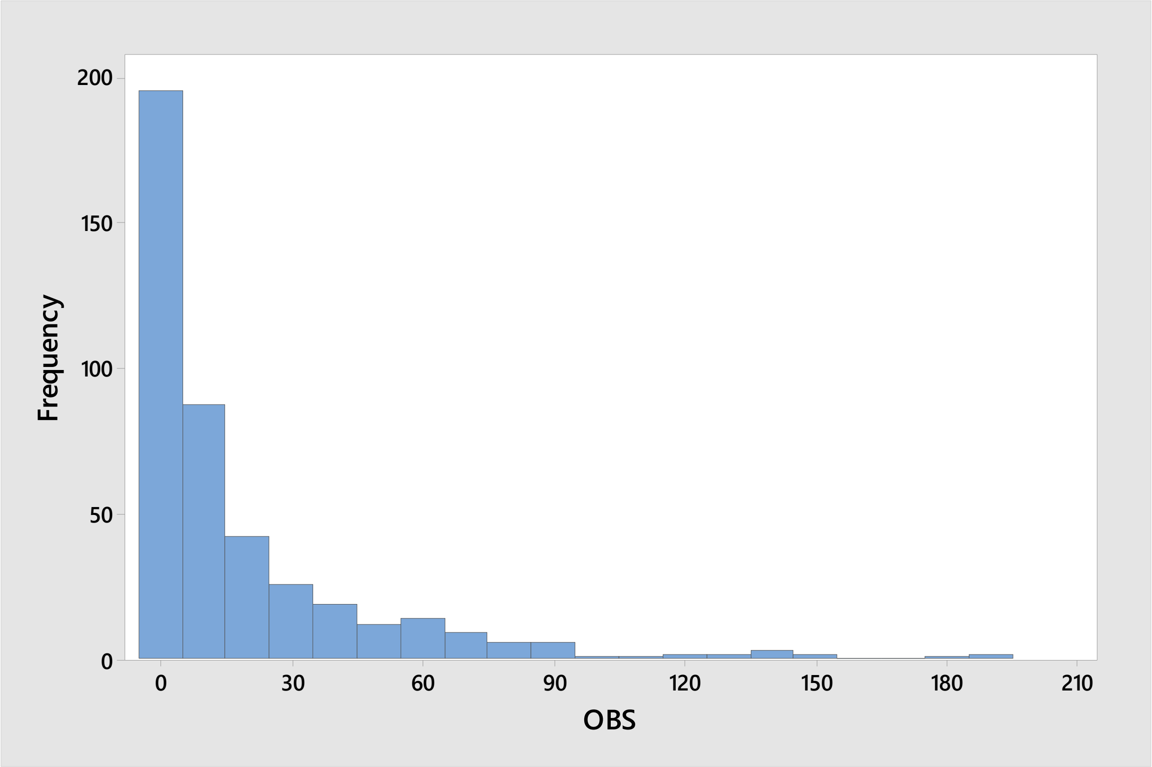

Figure 2.11 Year-Round Distribution of Observed Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

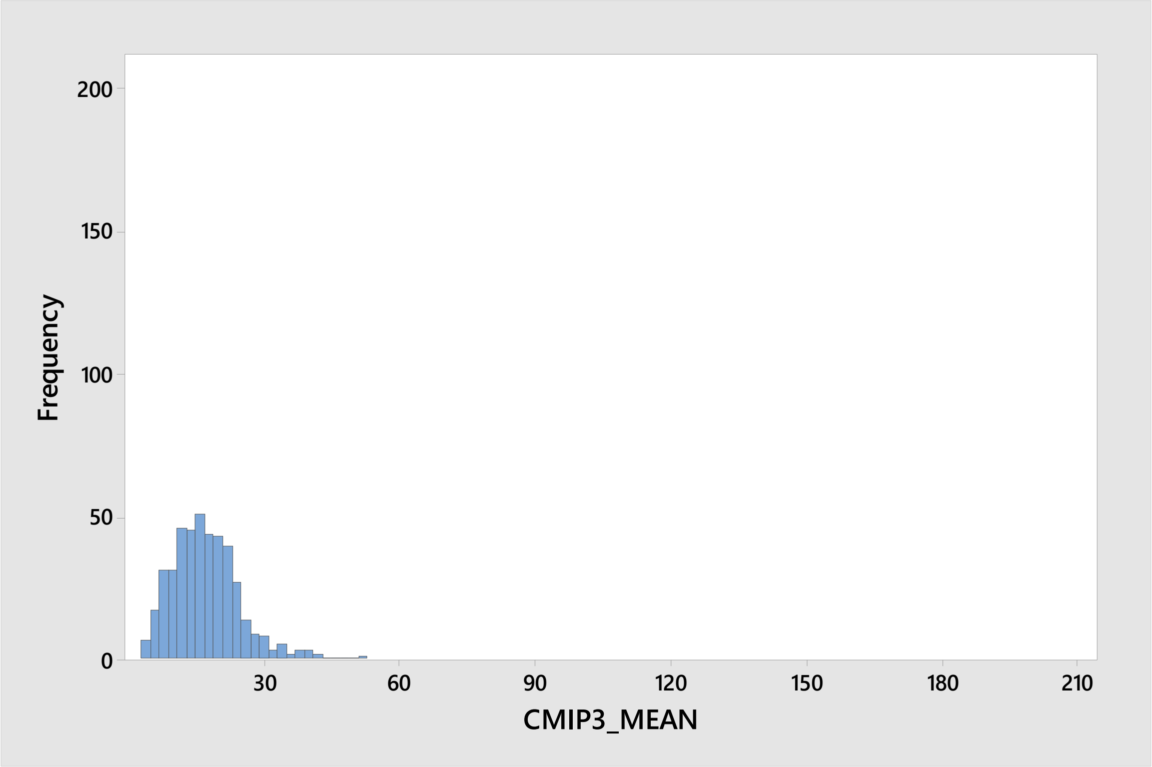

Figure 2.12 Year-Round Distribution of CMIP3 Projections (not bias corrected) of Reservoir Inflow (in MM over the basin) to Fall River Lake (October 1979 - September 2015).

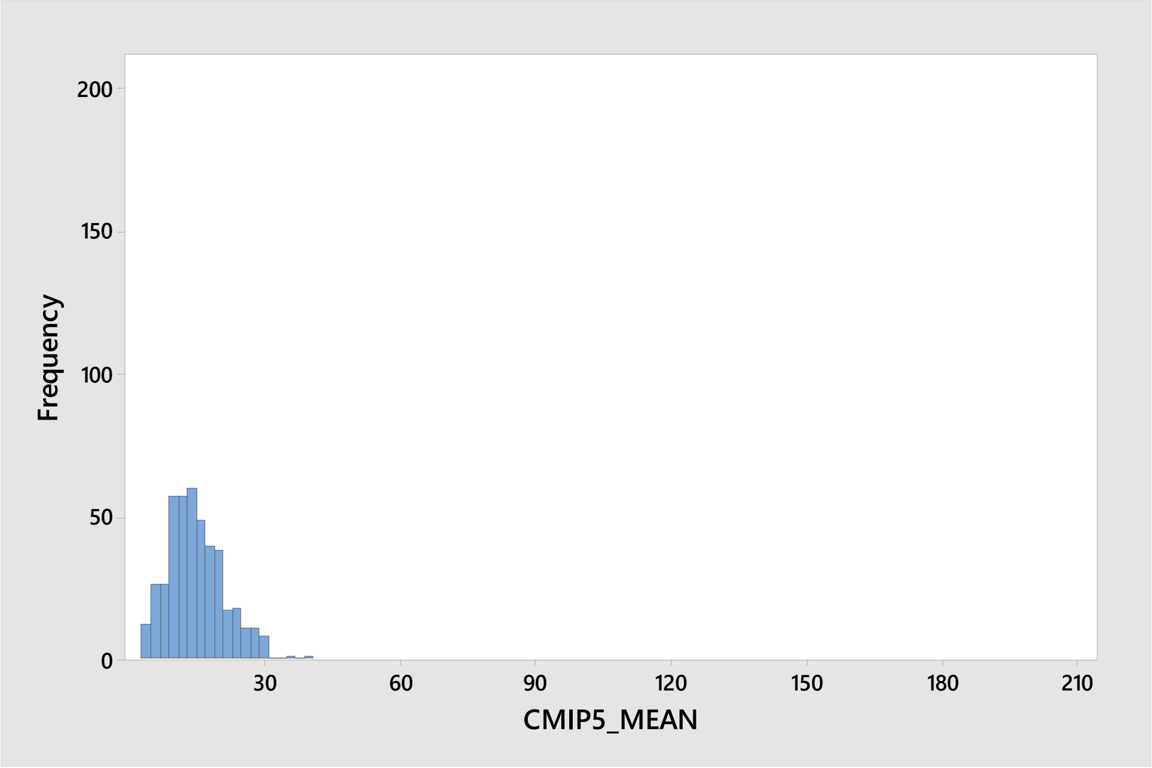

Figure 2.13 Year-Round Distribution of CMIP5 Projections (not bias corrected) of Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

The following graphics show the distribution for the month of January for observations (Figure 2.14), the CMIP3 projection runoff (Figure 2.15), and the CMIP5 projected runoff (Figure 2.16), along with an idealized lognormal distribution.

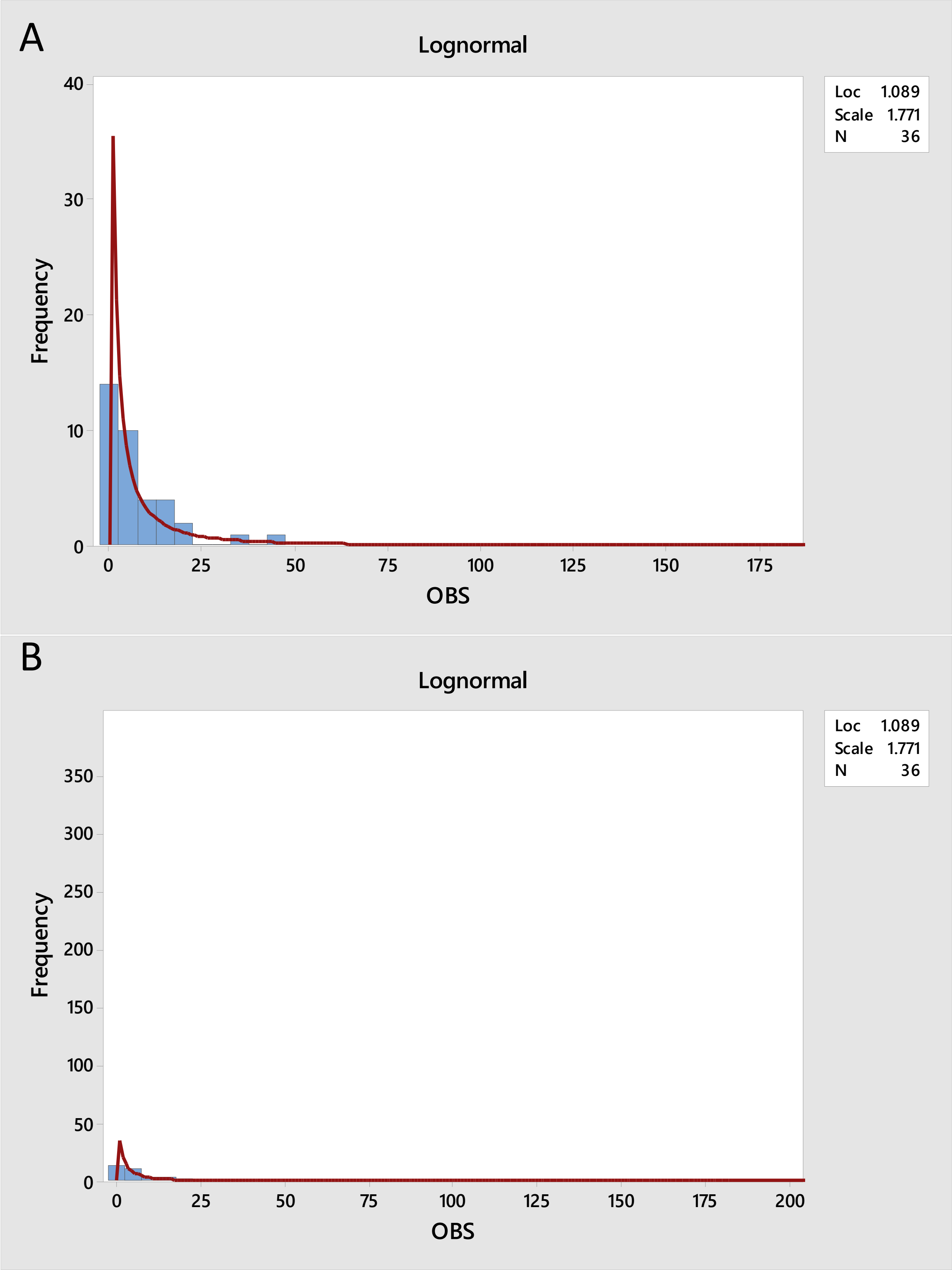

Figure 2.14 January Distribution of Observed Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015). A) Top graphic shows detail of distribution. B) Bottom graphic shows the distribution on the same scale as Figures 2.15 and 2.16

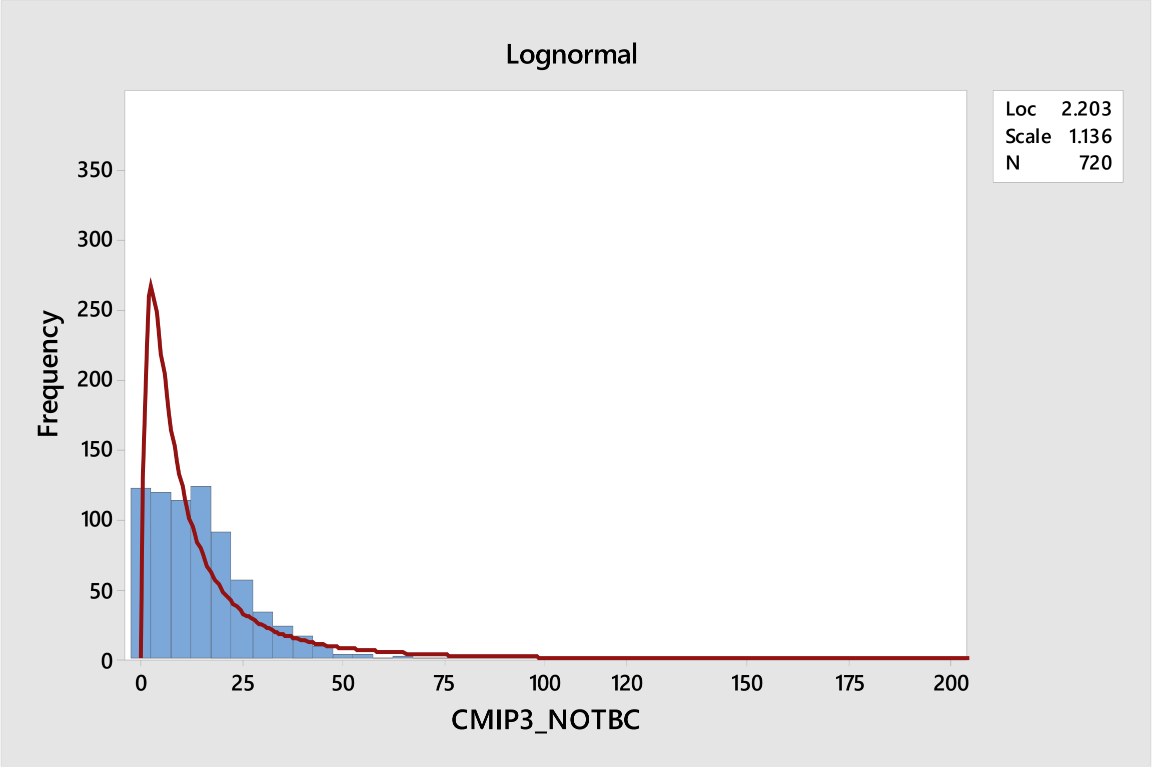

Figure 2.15 January Distribution of CMIP3 Projections (NOTBC indicates that the projections were not bias corrected) of Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

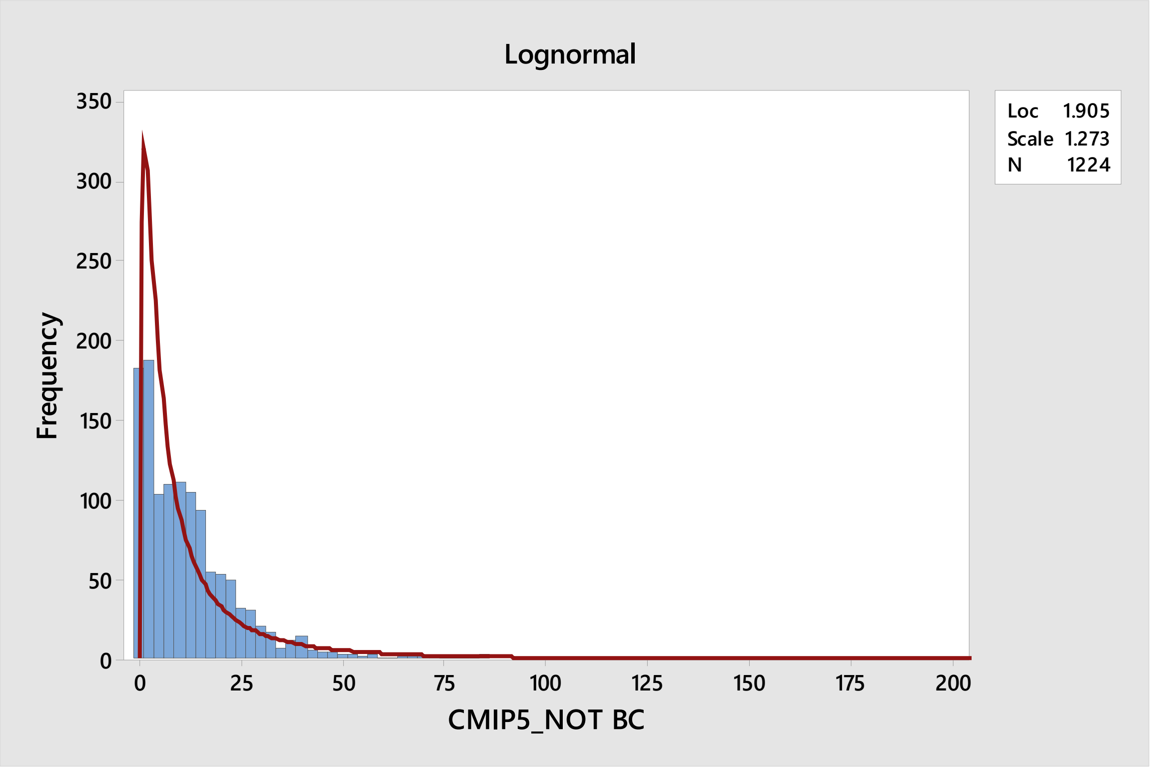

Figure 2.16 January Distribution of CMIP5 Projections (NOTBC indicates that the projections were not bias corrected of Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

2.5. CONCLUSION

Knowing which climate-change projection is more credible for a particular location is helpful for water resources studies. A previous study showed that projections from CMIP3 better matched the observed temperature and precipitation observations that had been experienced for most of the United States (Kumar et al. 2014). However, it is important to note that a model temperature and precipitation that is more consistent with observations does not necessarily mean the model will also replicate observed streamflow well.

Although newer, the hydrology dataset based on the CMIP5 runoff projections should not replace the CMIP3 runoff projections for the climate studies at Fall River Lake. CMIP3 projections continue to be useful as planning and study guidance for assessing the climate change vulnerability of this reservoir. Based on the period of October 1979 to September 2015, the CMIP3 ensemble mean runoff projections are more credible than the CMIP5 runoff projections because the projections come closer to the range of observed reservoir inflow for this period, as shown on the interval plot in Figure 2.10.

While the CMIP3 runoff projections are recommended for use in studies, if a climate-change study were particularly interested in studying only the effects of drought, utilizing the hydrologic prediction from the available CMIP5 hydrology dataset might be helpful. Similarly, a study that wishes to concentrate on the effects of flooding may wish to use the CMIP3 hydrology dataset.

Until a more credible climate projection becomes available in the future, CMIP3 projections are the recommended generation of climate-change runoff projections that should be used for climate-change streamflow studies for Fall River Lake. However, because the monthly standard deviation in the observation data is much higher than either the runoff based on the ensemble means from the CMIP3 runoff projections, the entire projection in the ensemble of possible future runoff scenarios should be considered in addition to the ensemble mean.

The comparison between the runoff CMIP3 and CMIP5 projections was performed as a case study to demonstrate the credibility of the projections and to highlight the need to utilize tools like the available CMIP3 and CMIP5 hydrology datasets to facilitate reservoir studies to determine appropriate changes to reservoir operation plans. Because public input and endorsement are necessary to modify Water Control Manuals, establishing credibility of the climate-change projections is imperative.

2.6. ACKNOWLEDGEMENTS

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I also acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and I thank the climate modeling groups (listed in Tables A.1 and A.2. of this paper) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

2.7. DISCLAIMER

The views expressed in this paper are those of the author and do not necessarily represent the views of, and should not be attributed to, the U.S. Army Corps of Engineers or the Department of Defense.

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CHAPTER III

COMPARISON OF BIAS-CORRECTION METHODS FOR MONTHLY RUNOFF USING CMIP3 AND CMIP5 HYDROLOGY DATASETS

3.1. ABSTRACT

When using guidance from global or regional climate models for local studies, the model predictions should be locally calibrated based on local or regional observations. However, there is no standard methodology to accomplish this task. In this case study, observed reservoir inflow is used as the local data to calibrate projected streamflow ensembles from the hydrology datasets from the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project phase 3 (CMIP3) and phase 5 (CMIP5).

A new method of calculating a monthly bias correction factor by averaging factors based on multiple exceedance values from the projection ensemble is proposed in this paper. Local bias- correction calibration factors were calculated using observed reservoir inflow data for the mean, 50% exceedance (median), and also a new method of creating a single bias-correction factor from averaging multiple factors developed from a range of exceedance values of the ensemble of CMIP3 and CMIP5 runoff projections. Monthly local bias-correction calibration factors developed for the runoff from the CMIP3 and CMIP5 hydrology datasets were applied to the individual ensemble members and the differences in the monthly distributions of the unbias-corrected ensemble mean and the bias-corrected projections were analyzed using two-sample Kolmogorov-Smirnov tests. Results show that while none of the bias-correction methods provided a statistically significant difference from the unbias-corrected ensemble mean for every month, using bias-correction calibration factor developed from the multiple exceedance values corrects the CMIP3 and CMIP5 model undersimulation present in the months with the most convective rainfall (March, April, May, and June) and provides a smooth monthly distribution of values for the individual runoff projections in both the CMIP3 and CMIP5 ensembles.

3.2. INTRODUCTION

The absence of conventional calibration strategies for climate-change scenarios carries substantial risks of models becoming overly complicated and overly parameterized (Bellprat et al. 2012). Following the recommendations of calibration set forth in Bellprat et al. (2012), calibration procedures should “(1) be transparent and reproducible, (2) target a small list of key tunable parameters, (3) optimize a pre-defined performance score that accounts for uncertainties associated with observations and predictability, (4) employ an objective optimization methodology, and (5) allow for a clear separation between calibration and validation/verification periods.”

Bias removal by statistical manipulation of climate-change projections of temperature and precipitation has been done before, especially for the correction of the ensemble mean (Huang et al. 2014). This study uses that same methodology. The reason that streamflow, instead of meteorological inputs, was bias corrected is that recent studies have shown that bias-correcting streamflow to assess climate change with an appropriate model is likely more effective than bias-correcting the meteorological inputs, running a hydrologic model, and then bias-correcting the resulting ensemble of streamflow (Yuan and Wood 2012).

Biases in river flows become evident when compared to basin-scale observations, such as observed reservoir inflow, and can be removed or minimized by statistical processing techniques. Typically bias calibration factors are developed for each individual month and then these calibration factors are multiplied to the ensemble mean for each month.

Applying bias-correction calibration factors can greatly affect the outcome of a climate-change study, thus it is important to investigate different methodologies of bias correction. As bias-correcting flows to assess climate change can be more effective than bias-correcting the meteorological inputs, running a hydrologic model, and then bias-correcting the resulting ensemble of flows (Yuan and Wood 2012), only the reservoir inflow was bias-corrected in this case study. Since the projected runoff for this basin that incorporates the CMIP3 and CMIP5 climate projections is available for use in planning studies, it is also more efficient to utilize the runoff projections instead of working directly with precipitation and temperature climate projections.

Monthly calibration factors were also developed to match the mean, median, as well as multiple exceedance values of the CMIP3 and CMIP5 runoff projection ensembles to the observed reservoir inflow. Matching the multiple exceedance factors is a new methodology proposed in this paper of calculating multiple calibration factors based on replicating the 5, 10, 25, 50, 75, 90, and 95% exceedance values of the observations and the CMIP3 and CMIP5 runoff ensembles, and then averaging all these factors into a single monthly factor. Comparisons of the different bias-correction methods were performed by statistical analysis of monthly distributions of ensemble means of the monthly distributions of individual ensemble members.

3.3. BACKGROUND

The Kansas Comprehensive Water Plan calls for the investigation of different reservoir management practices by the year 2020 (KWO 2015). Evaluating how climate change may affect the reservoir management practices should be an integral part of that evaluation. Discerning applicable local bias-correction calibration techniques will be vital to that process.

Even though a comparison of the CMIP3 and CMIP5 projections against observed data does not specifically state that one set of models is more correct than the other for all purposes involving future planning, knowing which ensemble of projections more closely replicates the observed data can help provide more credibility to the study (Brekke et al. 2008). Changes in the management scheme in federal reservoirs require updating the water control manual for each project. Alterations to the water control manual not only require detailed studies, but also require public meetings and the opportunity for the public to comment. Maximizing credibility in the climate change aspects of the evaluation is critical for public acceptance.

The Verdigris River basin in Kansas is subject to hydraulic control with a two-level regulation scheme by federal reservoirs owned and operated by the Corps of Engineers. Within the Verdigris Basin subsystem, the goal of regulating the flood control storage in the Toronto, Fall River, Big Hill, and Elk City Lakes is to balance the available storage in each of the lakes as a percentage of the flood pool utilized (USACE 2012). A tapered recession of flood water releases from all the federal reservoirs in the Arkansas River Basin is attempted in order to prevent property damage and minimize disruption to the navigation system (USACE 2007).

3.4. CMIP3 AND CMIP5 HYDROLOGY DATASETS

Ensembles are used to describe meteorological and hydrological uncertainty (Wood et al. 1997). As described in Section 2.3.2, a selection of models that are available from the CMIP3 and CMIP5 hydrology datasets, and shown in Tables A.1. and A.2., respectively, were used for this study.

3.5. METHODS

The objective of this study is to compare three methodologies of calculating local bias calibration factors for reservoir inflow based on observed reservoir inflow for the CMIP3 and CMIP5 runoff projections to Fall River Lake. Developing monthly calibration factors designed to cause the ensemble mean to match the observed data or to force the distributions of the ensemble to match the observed distribution has been done in multiple studies (Huang et al. 2014). Averaging local bias calibration factors using multiple exceedance values is a new methodology proposed in this case study.

This case study calculated monthly bias-correction factors using three methodologies that were applied to the ensemble mean and each individual projection of the basin runoff from the CMIP3 and CMIP5 hydrology dataset. Monthly local bias-correction factors were developed using the reservoir inflow data for Fall River Lake. The goal of the local bias calibration was to calculate monthly factors that, when multiplied with the CMIP3 and CMIP5 runoff ensemble means, would replicate the observed data. Calibration and validation periods were determined to ensure the integrity of the calibration factors outside of the calibration period.

3.5.1. INVESTIGATING STATIONARITY

The assumption of stationarity was investigated for the reservoir inflow to Fall River Lake from October 1979 to September 2015. Minitab 17 was used to do an autocorrelation made for the monthly inflow data, a trend analysis, and residential plots for the reservoir inflow. Figure 3.1 shows the Minitab 17 autocorrelation plot. The presence of months of extremely high reservoir inflow is evident in Figures 3.2 and 3.3, where the high outlier values cause the observations to not fit well into a distribution. Because of the lack of a consensus on a trend due to several outliers, stationarity was assumed for Fall River Lake reservoir for October 1979 to September 2015. A subjective look at the past records to evaluate this decision was also done. During October 1979 to September 2015, there were months of exceptionally large reservoir inflow as well as years of drought. Subjectively, this period encompasses many of the past measured climate extremes and it is expected that this very high variability in the reservoir inflow will continue into the future.

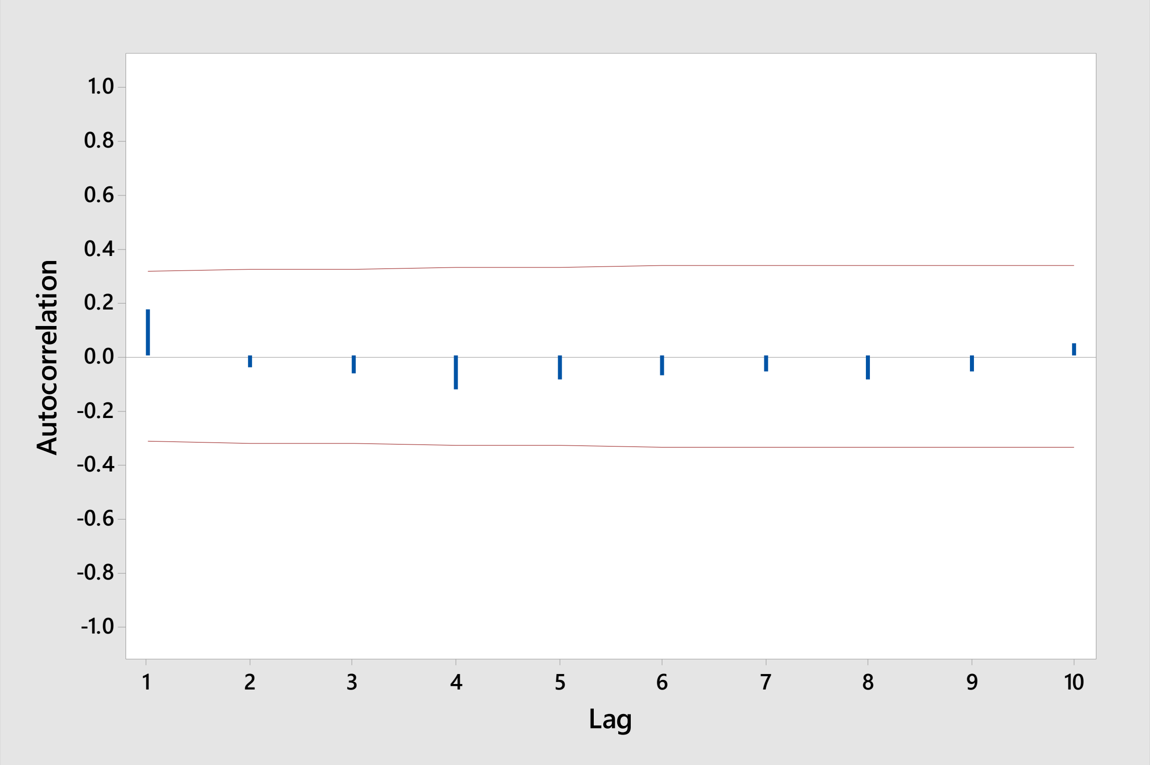

Figure 3.1 Minitab 17 Autocorrelation of Fall River Lake Reservoir Inflow on a Monthly Time Step with a 5% Significance Limits for October 1979 - September 2015.

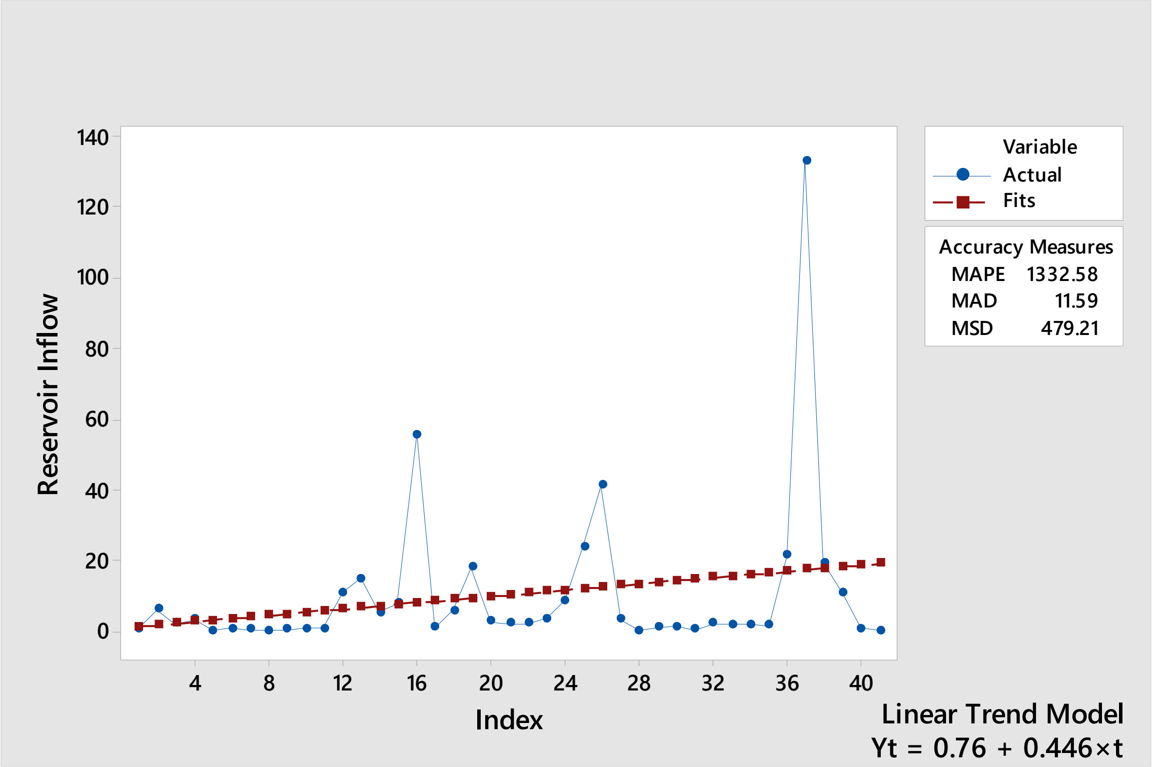

Figure 3.2 Minitab 17 Trend Analysis of Fall River Lake Reservoir Inflow (in mm) on a Monthly Time Step with a 5% Significance Limits for October 1979 - September 2015.

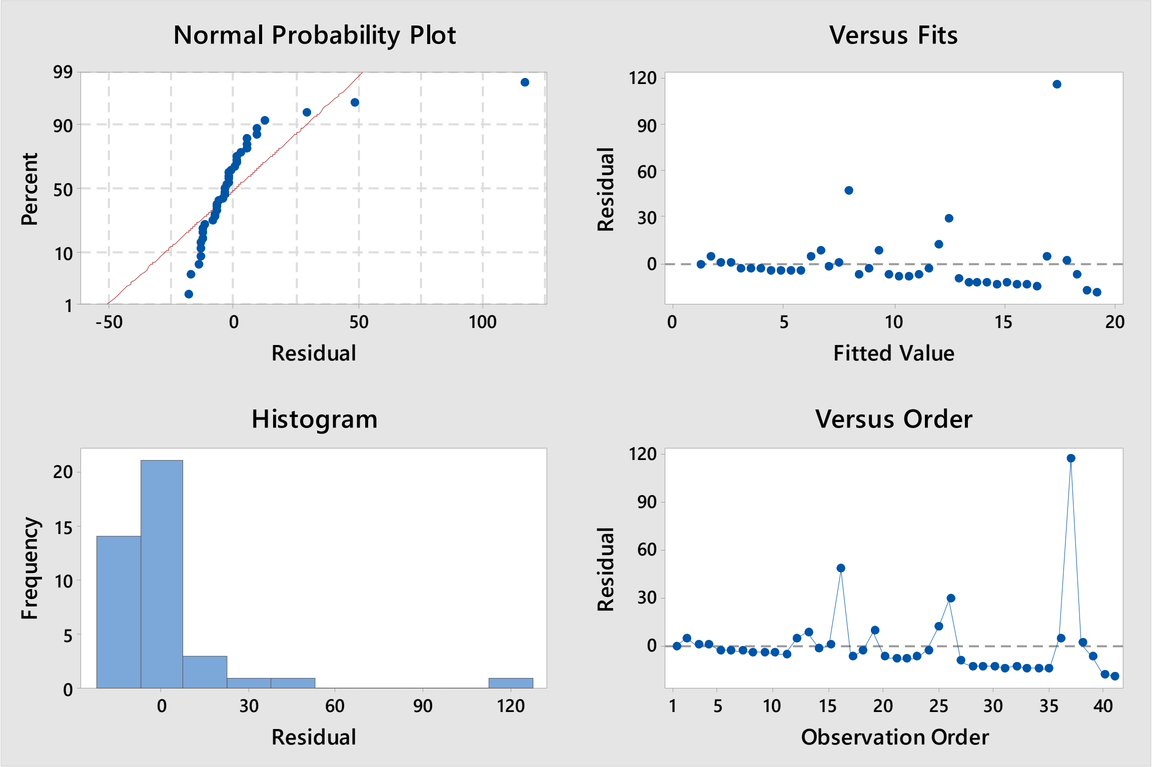

Figure 3.3 Minitab 17 Residual Plots for Reservoir Inflow for October 1979 - September 2015.

3.5.2. DETERMINING CALIBRATION AND VALIDATION PERIODS

Observed reservoir inflow for October 1979-September 2015 was broken down into separate calibration and validation periods by attempting to keep similar monthly means for both periods. Data were kept in water year (1 October – 30 September) groupings and the calibration and validation periods were arranged in sequential periods. Standard deviations for the monthly calibration and validation data were also checked to ensure that it was similar. The grouping of water years with the most similar monthly mean data inflow data was 1979-2007for the calibration and 2007-2015for the validation, as shown in Table 3.1.

Table 3.1. Means and Standard Deviations of Observed Reservoir Monthly Inflow Data for the Calibration, Validation, and Full Data Period (October 1979 – September 2015)

Period	Mean (mm)	Months	Standard Deviation (mm)
October1979 – September 2007 (calibration (period)	19.8	336	31.4
October 2007 – September 2015 (validation period)	19.3	96	29.9
October1979 – September 2015 (full data period)	19.7	432	31.0

3.5.3. BIAS-CORRECTION METHODOLOGY

A traditional method of statistical correction of an ensemble would be to utilize monthly calibration factors developed from mean monthly observations, and then to multiply these calibration factors by the ensemble mean in order to replicate the observed monthly means (Ho et al. 2012). This case study uses the traditional method of trying to replicate the observed monthly mean plus two other statistical methods for comparison. Monthly calibration factors were also developed to try to match the 50% exceedance (median) value of the CMIP3 and CMIP5 runoff projections to the observed reservoir inflow. A new methodology of calculating multiple calibration factors based on replicating the 5, 10, 25, 50, 75, 90, and 95% exceedance values of the observations and the CMIP3 and CMIP5 runoff ensembles and then averaging all these factors into a single monthly factor is also proposed. These exceedance values were chosen because they represent a spread of the monthly runoff projection ensemble data that includes both low and high frequency flows and they are also standard calculation options in HEC-DSSVue. If a distribution of observed runoff values is skewed, either having many large runoff events or having many small runoff events, using a range of the multiple exceedance values to calculate a bias-correction factor may be beneficial in helping reproduce skewed distributions in ensembles of runoff projections from climate-change models, instead of only utilizing the observed mean or median to calculate a bias-correction factor to calibrate runoff projections.

For this case study, monthly bias calibration factors were calculated for the monthly mean and the 50% exceedance (median) value. An averaged monthly local bias calibration factor was calculated from a range of exceedance probabilities (5, 10, 25, 50, 75, 90, and 95%). This methodology was chosen in order to demonstrate the differences between the various methodologies available when applying bias correction to climate-change projections. It is common practice to apply the bias correction to the ensemble mean (Ho et al. 2012), but this methodology could miss the value that may come from considering the months with minimal runoff as part of the planning process.

Runoff projections from the CMIP3 and CMIP5 hydrology datasets for the Fall River Lake drainage basin were calibrated using the monthly inflow to the reservoir from the monthly reservoir reports from October 1979 to September 2007 prepared by the Corps of Engineers Tulsa District Office. Monthly bias-correction factors (to be multiplied to each value for each month over the entire set of years for every member of the ensemble) were calculated based on minimizing the mean squared error (the cumulative squared error) from the monthly observed runoff (the reported reservoir inflow) and the runoff from both the CMIP3 and CMIP5 hydrology ensemble datasets. These correction factors were then applied to the means of the runoff ensembles from the CMIP3 and CMIP5 hydrology datasets.

HEC-DSSVue (Version 2.0, Release Update 1) math functions were used to calculate monthly ensemble mean, monthly standard deviation, and the exceedance probabilities for the 5, 10, 25, 50, 75, 90, and 95% exceedances for the CMIP3 and CMIP5 runoff projections for the calibration period of October 1979 – September 2007. The mean monthly runoff, exceedance probabilities (5, 10, 25, 50, 75, 90, and 95%) and the monthly standard deviation were also calculated using HEC-DSSVue for the monthly observed runoff (reservoir inflow) for the same period.

Microsoft Excel was used to calculate a bias-correction factor each month for mean monthly inflow and for the following exceedance probabilities: 5, 10, 25, 50, 75, 90, and 95% for the reservoir inflow observation from October 1979 – September 2007. Bias-correction factors were calculated using the Excel Solver function to minimize the mean absolute error from the difference from the mean monthly observed runoff (the observed reservoir inflow) and the runoff from the both the CMIP3 and CMIP5 hydrology ensemble datasets. The bias-correction factors for each exceedance probability were also averaged to create a single value for each month.

Equation 3.1 was used to compute the monthly bias-correction factor based on the ensemble mean, for each month. Equation 3.2 was used to calculate the monthly bias-correct factor based on the ensemble median. The proposed new methodology of calculating monthly bias-correction factors based on an average of monthly factors developed for the 5, 10, 25, 50, 75, 90, and 95% exceedance probabilities is shown in Equations 3.3 and 3.4.

$$\begin{gathered}\sum[(Monthly\ Factor * Monthly\ Ensemble\ Mean) \\ - Observed\ Monthly\ Mean]^2 = 0\ ; \\ \text{solved for each month}\end{gathered} \tag{3.1}$$

$$\begin{gathered}\sum[(Monthly\ Factor * Monthly\ Ensemble\ Median) \\ - Observed\ Monthly\ Median]^2 = 0; \\ \text{solved for each month}\end{gathered} \tag{3.2}$$

$$\begin{gathered}\sum[(Monthly\ Factor * Monthly\ Exceedance\ Value\ from\ Ensemble) \\ - Observed\ Monthly\ Exceedance\ Value]^2 = 0\ ; \\ \text{solved for each month for the 5, 10, 25, 50, 75, 90, and exceedance values}\end{gathered} \tag{3.3}$$

$$\begin{aligned} & Monthly\ Averaged\ Factor\ Based\ on\ Multiple\ Exceedances \\ & \quad = \ (Monthly\ Factor_{5\%\ Exceedance} \\ & \quad + \ Monthly\ Factor_{10\%\ Exceedance} \\ & \quad + \ Monthly\ Factor_{25\%\ Exceedance} \\ & \quad + \ Monthly\ Factor_{50\%\ Exceedance} \\ & \quad + \ Monthly\ Factor_{75\%\ Exceedance} \\ & \quad + \ Monthly\ Factor_{90\%\ Exceedance} \\ & \quad + \ Monthly\ Factor_{95\%\ Exceedance}\ ) \ \div 7: \end{aligned} \tag{3.4}$$

Monthly local bias calibration factors calculated from the monthly mean, the 50% exceedance of the ensemble of runoff projections, and an averaged value of the multiple calculated from all the exceedance probabilities (5, 10, 25, 50, 75, 90, and 95%) were then applied to the validation period data (October 2007 – September 2015). Monthly means and standard deviations were calculated for the validation period.

3.5.4. STATISTICAL ANALYSIS OF MONTHLY DISTRIBUTIONS OF ENSEMBLE MEANS

Differences between the CMIP3 runoff ensemble mean for the calibration period of October 1979 to September 2007 and the validation period of October 2007 – September 2015 were investigated with a two sample Student's t test (with an alpha of 0.05) to determine if the runoff projection of the ensemble mean runoff projection was statistically significantly different for the calibration and validation periods. This was done to assess if the validation period had a significantly different mean than the calibration period. The same test was conducted on the CMIP5 runoff ensemble mean.

3.5.5. STATISTICAL ANALYSIS OF MONTHLY DISTRIBUTIONS OF INDIVIDUAL ENSEMBLE MEMBERS

Local bias-correction calibration factors were applied to ensemble means for the entire period of reservoir inflow projections, October 1979 to September 2015. A comparison was made in Minitab 17 of the CMIP3 and CMIP5 projection ensemble monthly distributions and the distribution of observations.

Projection data for the unbias-corrected projections and each of the three bias-correction treatments for each month for each individual member of the ensemble were broken down into individual months as to analyze the distributions in Microsoft Excel. Monthly distributions were analyzed for normality using the Kolmogorov-Smirnov test for normality. First, each set of projection data of the ensemble were reorganized in ascending order in order to plot the distribution of the data and the Weibull plotting position was calculated. Then the probability of each value in the projected data and Z values were calculated. Distributions of the entire group of projections for each month were then compared against the distribution of the observations using the Kolmogorov-Smirnov test methodology for two samples. Each method of bias correction was also compared against the unbias-corrected projection for that ensemble member as well.

Projection data for each month for the entire ensemble was input into Minitab 17 for analysis. Probabilities plots for each month for the entire ensemble were made for each month to determine the distribution for each month and to investigate any changes to this distribution resulting from the application of the three bias-correction techniques.

Differences between the three different methods of bias correction were also investigated with a two sample Student's t test (with an alpha of 0.05) to determine if the runoff projection of the CMIP3 and CMIP5 ensemble mean runoff projections were statistically significantly different between the bias-corrected and unbias-corrected means.

3.6. RESULTS AND DISCUSSION

3.6.1. COMPARISON OF BIAS-CORRECTION FACTORS

For the CMIP3 data, the bias-correction factors developed from the 50% exceedance (median) values of the ensemble were smaller than those calculated from the ensemble mean and those calculated from averaging factors developed from multiple ensemble exceedance values. The bias-correction factors developed from the mean were smaller than those calculated from averaging factors based on multiple exceedance values, but larger than the bias-correction factors developed from the 50% exceedance (median) values. This same was generally true for the CMIP5 bias-correction factors, with the exception that the bias-correction factor developed from averaging the factors based on multiple exceedances was slightly smaller than the factor calculated from the 50% exceedance for March. For most months and for most exceedance values, the calibration factors developed for the CMIP5 hydrology data were typically larger than those for the CMIP3 data.

For the cooler and mostly nonconvective winter months, the bias-correction factors were generally less than 1.0, which would lower the ensemble mean when applied. The warm month typically had bias-correction factors greater than 1.0, which would raise the ensemble mean when applied. Notably, the local bias-correction factors were less than 1.0 for the month of July, a likely result of the heavy rains experienced in the area in 2007.

Bias-correction factors are shown in Tables 3.2. and 3.3. A comparison of the percentage difference between the CMIP3 and CMIP5 monthly bias-correction factors is shown in Table 3.4.

Table 3.2. Local Bias-correction Calibration Factors Developed For Monthly Runoff in CMIP3 Hydrology Dataset

Month	Factor Based on Ensemble Median	Factor Based on Ensemble Mean	Factor Based on Multiple Exceedance Values
January	0.6	0.3	0.6
February	1.0	0.4	1.0
March	1.2	1.2	1.5
April	1.4	1.0	1.6
May	1.8	1.4	1.9
June	1.6	1.0	2.0
July	0.7	0.4	0.8
August	0.7	0.2	1.2
September	0.4	0.1	0.5
October	0.5	0.1	0.7
November	0.5	0.1	0.7
December	0.6	0.2	0.7

Table 3.3. Local Bias-correction Calibration Factors Developed For Monthly Runoff in CMIP5 Hydrology Dataset

Month	Factor Based on Ensemble Median	Factor Based on Ensemble Mean	Factor Based on Multiple Exceedance Values
January	0.6	0.3	0.7
February	1.3	0.6	1.3
March	1.2	1.2	1.5
April	1.5	1.0	1.8
May	1.9	1.6	2.2
June	2.1	1.1	2.3
July	0.9	0.4	1.0
August	0.9	0.3	1.4
September	0.5	0.1	0.5
October	0.8	0.1	0.9
November	0.7	0.1	0.8
December	0.7	0.2	0.8

Table 3.4. Percentage Difference in Local Bias-correction Calibration Factors Developed For Monthly Runoff in the CMIP3 and CMIP5 Hydrology Datasets

	95% Excd. *	90% Excd. *	75% Excd. *	50% Excd. *, **	25% Excd. *	10% Excd. *	5% Excd. *	Ensemble Mean	Averaged Multiple Exceed-ances
January	16%	19%	15%	15%	16%	3%	12%	14%	11%
February	6%	29%	15%	22%	17%	24%	30%	19%	25%
March	6%	8%	4%	4%	0%	-11%	-1%	1%	-3%
April	12%	14%	-4%	8%	18%	4%	16%	8%	11%
May	25%	4%	9%	11%	11%	3%	-4%	11%	4%
June	22%	-18%	-8%	11%	9%	28%	30%	14%	23%
July	20%	24%	29%	7%	26%	22%	15%	17%	18%
August	0%	15%	19%	15%	5%	19%	27%	16%	20%
September	0%	12%	-9%	10%	15%	21%	19%	10%	19%
October	0%	27%	13%	8%	16%	25%	33%	19%	29%
November	11%	26%	23%	2%	3%	16%	28%	11%	23%
December	18%	32%	4%	11%	16%	20%	13%	15%	17%

*Excd. = Exceedance

** = 50% Exceedance is the Ensemble Median

3.6.2. APPLICATION OF BIAS-CORRECTION FACTORS TO CALIBRATION AND VALIDATION PERIODS

Monthly local bias calibration correction factors were applied to the CMIP3 reservoir inflow projections for both the calibration period and validation periods. The Student's t test, as shown in Table A.9 through A. 14, indicated that for the months of February, March, April, and September the monthly ensemble means after applying the local bias calibration correction factors were statistically significantly different at the 90% confidence interval. This was the case for all three methodologies for developing the local bias calibration correction factors. The reason could be that early spring weather in this area is hard to predict, especially with a global model. During February and March, precipitation patterns could be either convective in patchy locations or widespread stratiform in nature. Precipitation during these months could also be liquid, frozen, or mixed phase. April and September precipitation can be driven frontally. The timing of fronts is difficult to ascertain with global models as well.

For the reservoir inflow data for the CMIP5 projections, when the monthly local bias calibration correction factors were applied to both the calibration period and validation periods, the Student's t test indicated that for the months of February, May, June, August, November, and December the ensemble means were statistically significantly different at the 90% confidence interval after applying the factors calculated by all three methodologies. These results indicate that for the months which historically received the most precipitation, the local bias-correction calibration factors may not be adequately calibrating the ensemble of reservoir inflow projections.

3.6.3. APPLICATION OF LOCAL BIAS-CORRECTION CALIBRATION FACTORS TO ENTIRE PERIOD OF OBSERVATIONS

None of the distributions for the observations, CMIP3 or CMIP5 runoff projections were normal at the 90% confidence interval based on the Kolmogorov-Smirnov test for normality. The shape of the distribution of the exceedances of monthly reservoir inflow data are negatively skewed, with a long tail of small events (high exceedance values), and then the majority of the higher events would be clustered in the very low exceedance values. Examples of January monthly distributions of observed data are shown in the previous chapter in Figure 2.13. Figure 2.14 shows the unbias-corrected data CMIP3 runoff projection data. Examples of the distributions for the CMIP3 data that show the three methods of bias correction applied to the CMIP3 projection data are shown in Figure 3.4, 3.5, and 3.6. Upon visual inspection, it can be noted the application of the bias correction results in a better fit with the idealized lognormal distributions also shown in these graphics.

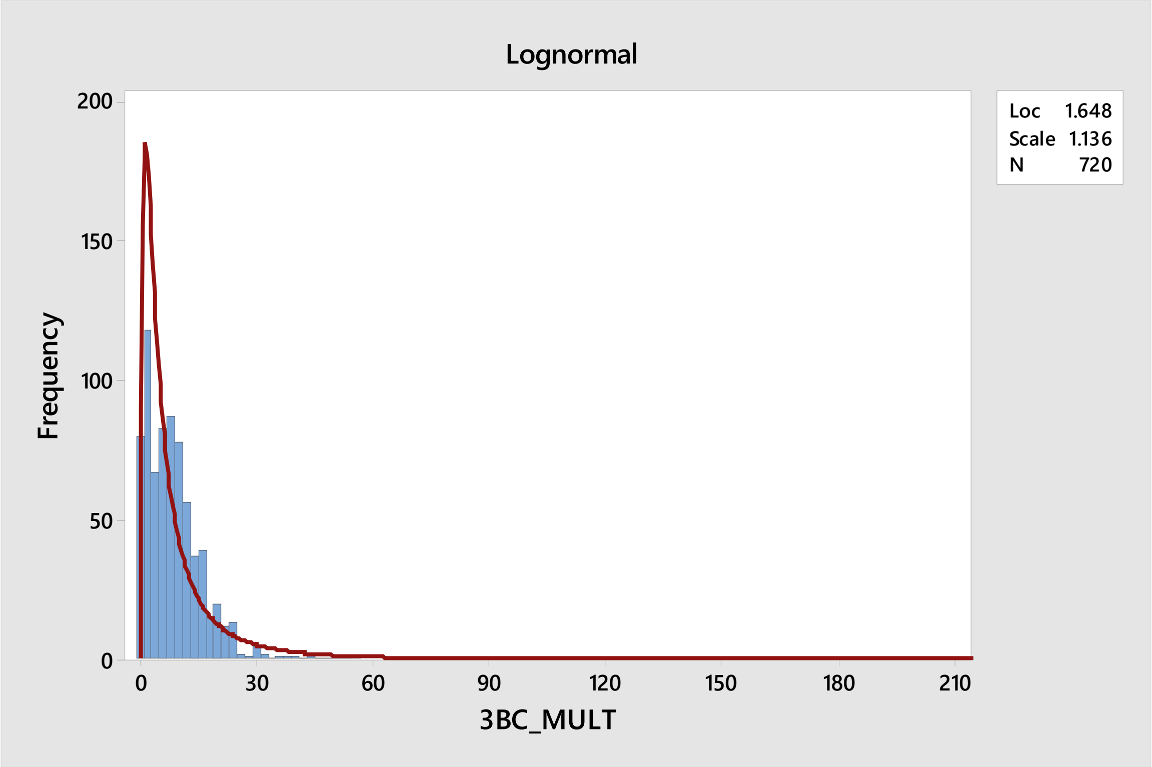

Figure 3.4 January Distribution of CMIP3 Projections (BC_MULT denotes using a monthly correction factor based on multiple exceedance values was used) of Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

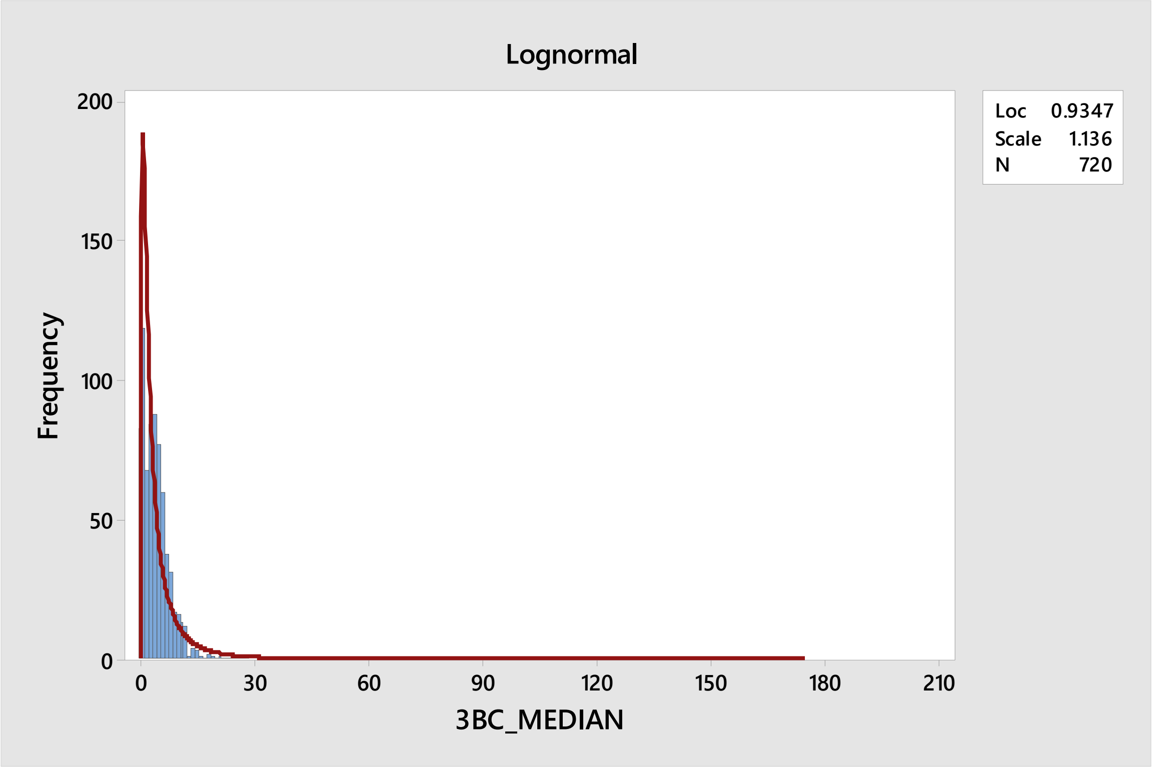

Figure 3.5 January Distribution of CMIP3 Projections (BC_ MEDIAN denotes using a monthly correction factor based on the ensemble median was used) of Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

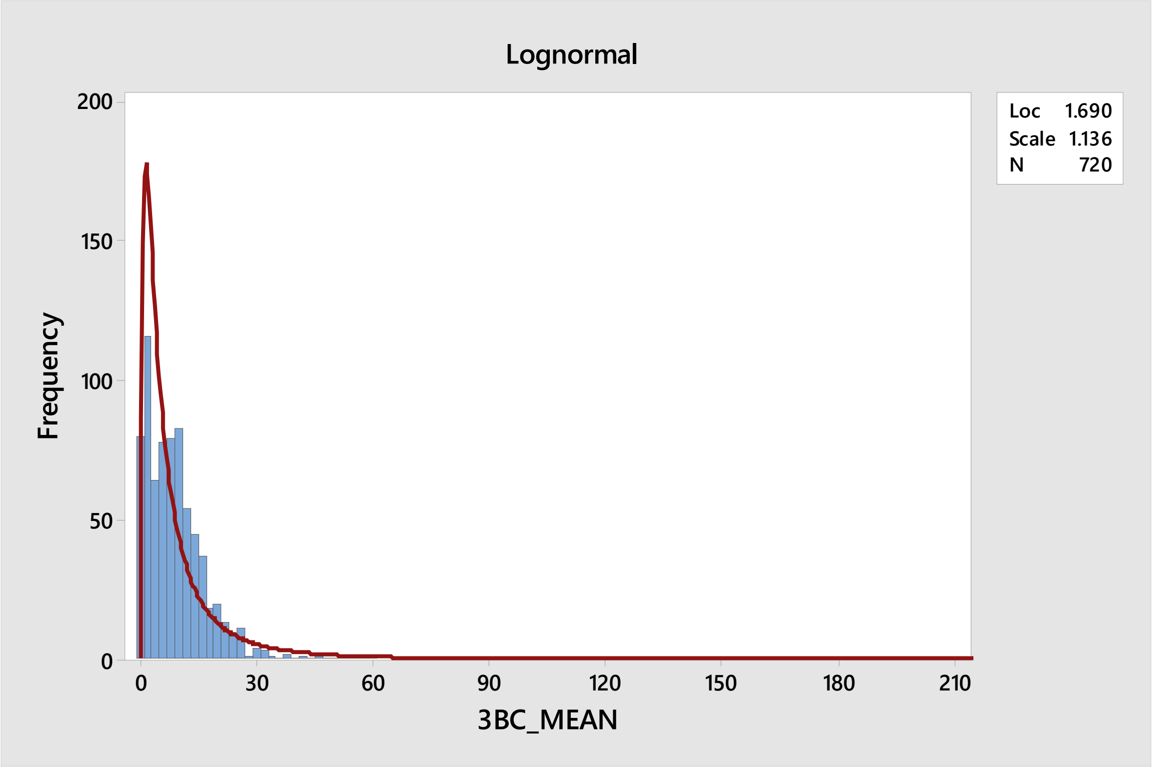

Figure 3.6 January Distribution of CMIP3 Projections (BC_MEAN denotes using a monthly correction factor based on the ensemble mean) of Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

The distribution of the monthly projections from the entire CMIP3 and CMIP5 ensembles did not fit well as any specific distribution type. As an example, Figure 3.7 shows the probability plot for the CMIP3 inflow projections for the monthly inflow from October 1979 – September 2015 shown plotted in the Weibull, lognormal, exponential, and loglogistic distributions. Shifting of the entire distribution is apparent when bias-correction factors are applied to each individual member of ensemble.

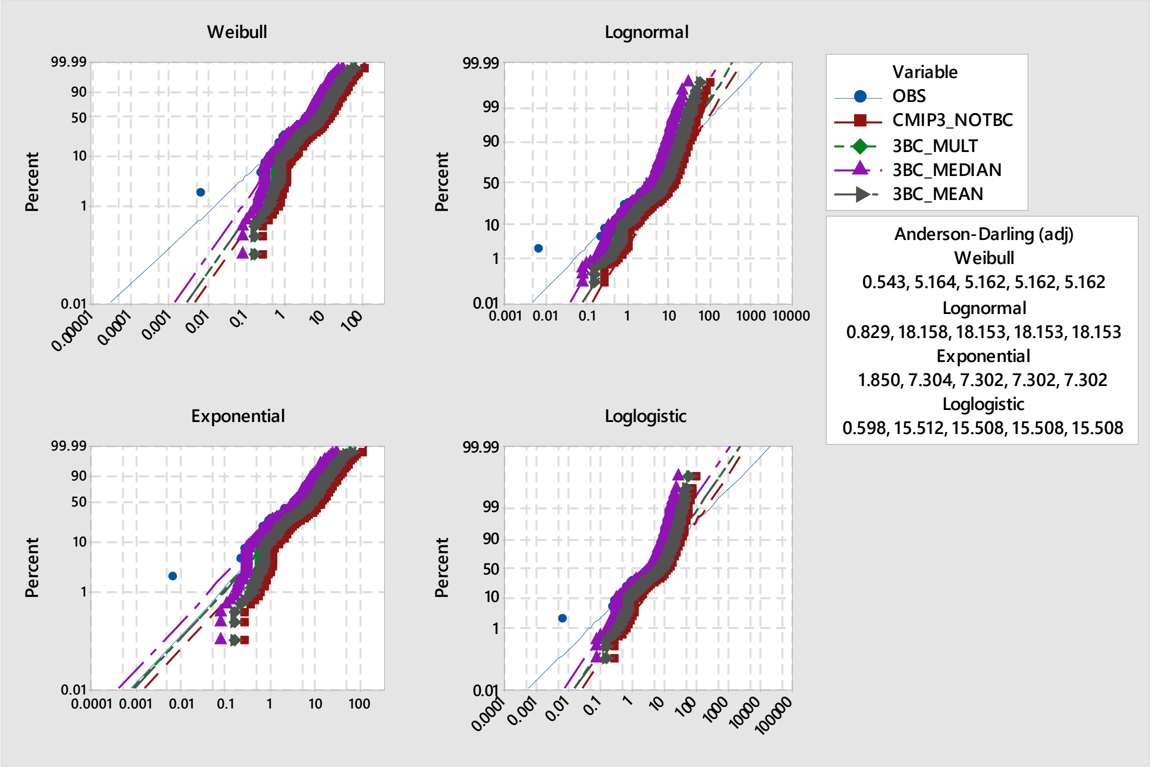

Figure 3.7. Minitab 17 Probability Plot for Monthly Inflow October 1979 - September 2015 for Observed Reservoir Inflow, CMIP3 Ensemble of Projections for the Unbias-corrected (denoted NOTBC) and Three Methods of Bias-correction. BC_MULT denotes using a monthly correction factor based on multiple exceedance values; MEDIAN denotes using a monthly correction factor based on the ensemble median; MEAN denotes using a monthly correction factor based on the ensemble mean.

To test if the application of the bias-correction factors caused a statistically significant difference in the distribution between the unbias-corrected projection and the bias-corrected projection, a two-sample Kolmogorov-Smirnov test was performed. Each CMIP3 and CMIP5 projection within the ensemble was tested for each individual month at multiple confidence intervals. The majority of the distributions were determined not to be significantly different, even with an 80% confidence interval. The projections that were significantly different for CMIP3 and CMIP5 are shown in Table A.15. and A.16, respectively. Distributions in the months of August, October, and November were the most affected by the application of bias-correction factors. January, September, and December were less affected. Examples of how the distributions of the observations, runoff projections, and bias-corrected runoff projections for a single month compare with one another for Fall River Lake are shown in Figures 3.8 through 3.12.

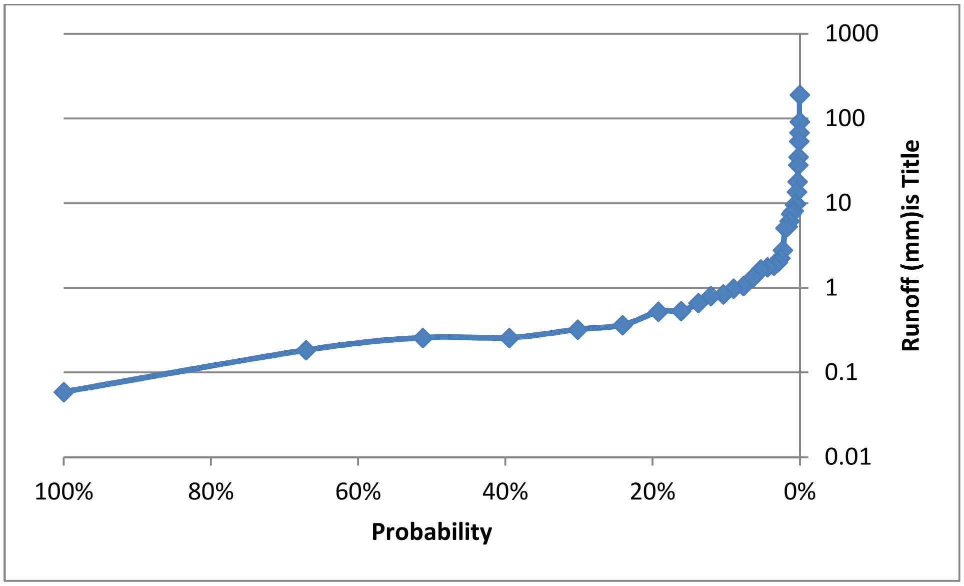

Figure 3.8 November Distribution of Observed Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

Observed data shown in Figure 3.8 shows that for the month of November there have been many Novembers with very small amount of reservoir inflow and much fewer Novembers with larger quantities of observed inflow.

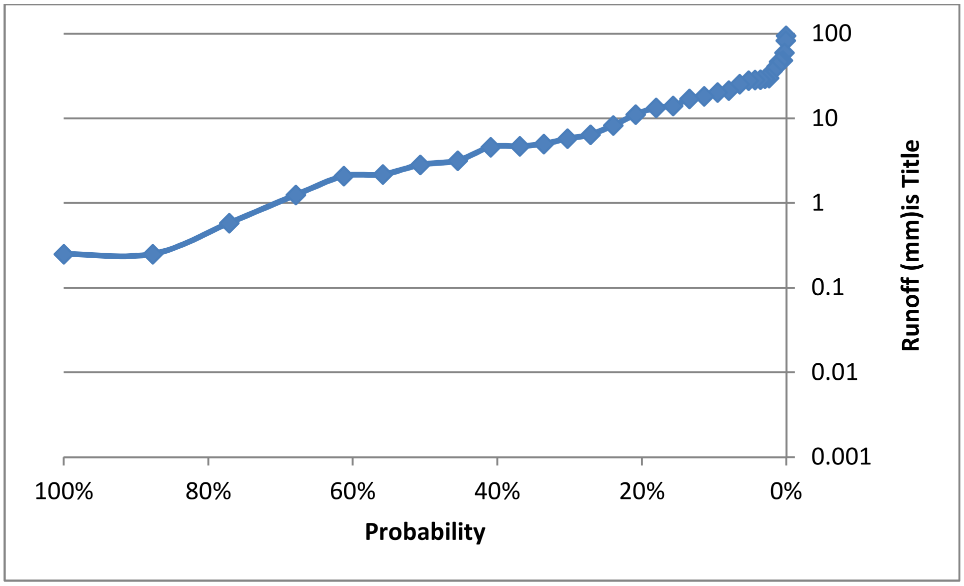

Figure 3.9 November Distribution of CMIP3 Projections for the MIUB_ECHO_1_G.1 Model Using the A1B SRES for Reservoir Inflow (in mm over the basin) to Fall River Lake (October 1979 - September 2015).

The unbias-corrected projection for the A1B SRES for the MIUB_ECHO-1_G.1 Model predicts a much smoother distribution of monthly runoff in November, with more midrange and higher events, as shown in Figure 3.9. The maximum amount of monthly reservoir inflow during November is near the same as has been observed in the past.

Bias-correction factors based on multiple ensemble exceedance values factors applied to the A1B SRES projection of the MIUB_ECHO-1_G.1 model predicts a more smooth distribution of monthly runoff in November, with more midrange events, as shown in Figure 3.10. The maximum amount of monthly reservoir inflow during November is expected to be lower than what has been observed during October 1979 to September 2015.

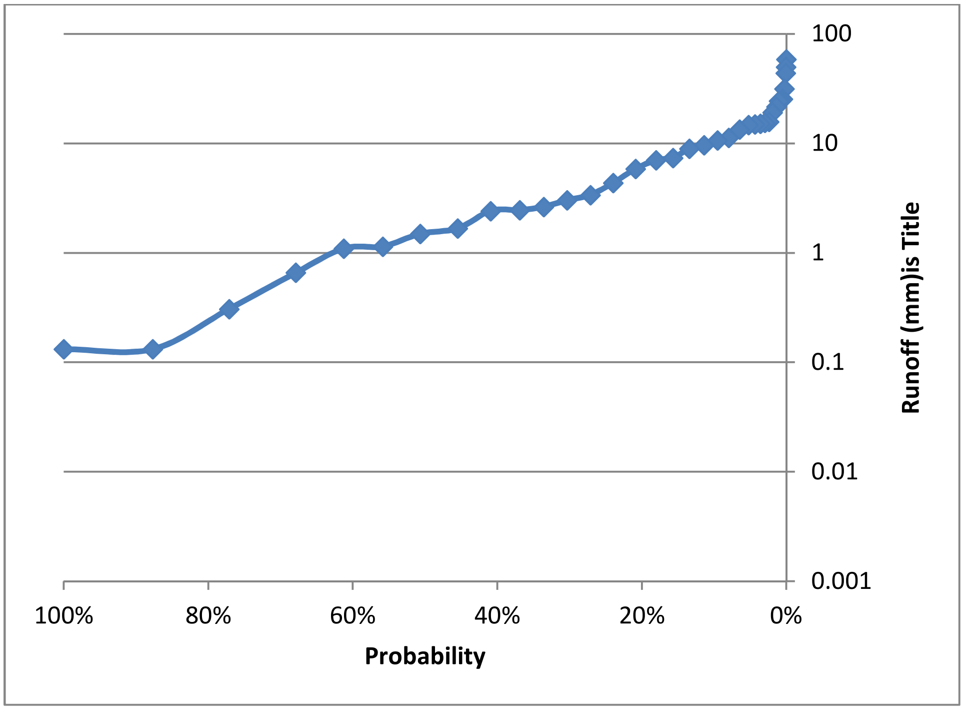

Figure 3.10 November Distribution of CMIP3 Projections for the MIUB_ECHO_1_G.1 Model Using the A1B SRES for Reservoir Inflow (in mm over the basin) to Fall River Lake Bias-Corrected using Factor Developed from Multiple Exceedance Values From the Ensemble (October 1979 - September 2015).

Projections that were bias-corrected using the factor developed from the ensemble median also show also predicts a much smoother distribution of monthly runoff in November for the A1B SRES projection of the MIUB_ECHO-1_G.1 model, as shown in

Figure 3.11. The maximum amount of monthly reservoir inflow during November is expected to be much lower than previous observations.

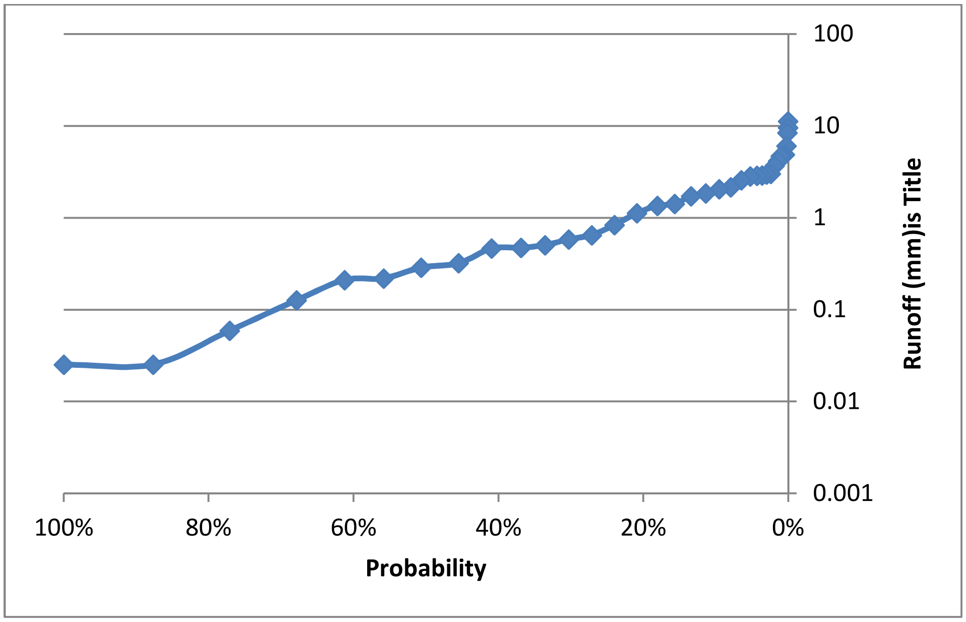

Figure 3.11 November Distribution of CMIP3 Projections for the MIUB_ECHO_1_G.1 Model Using the A1B SRES for Reservoir Inflow (in mm over the basin) to Fall River Lake Bias-corrected using Factor Developed from Ensemble Median (October 1979 - September 2015).

The ensemble of projections when bias-corrected using a correction factor developed from the ensemble mean lowered the expected values of the A1B SRES projection of the MIUB_ECHO-1_G.1 model and predicted a smoother distribution of monthly runoff in November, with more midrange and higher events, as shown in Figure 3.12. The maximum amount of monthly reservoir inflow during November is expected to be somewhat lower than what has been observed in the past when this bias-correction factor is applied.

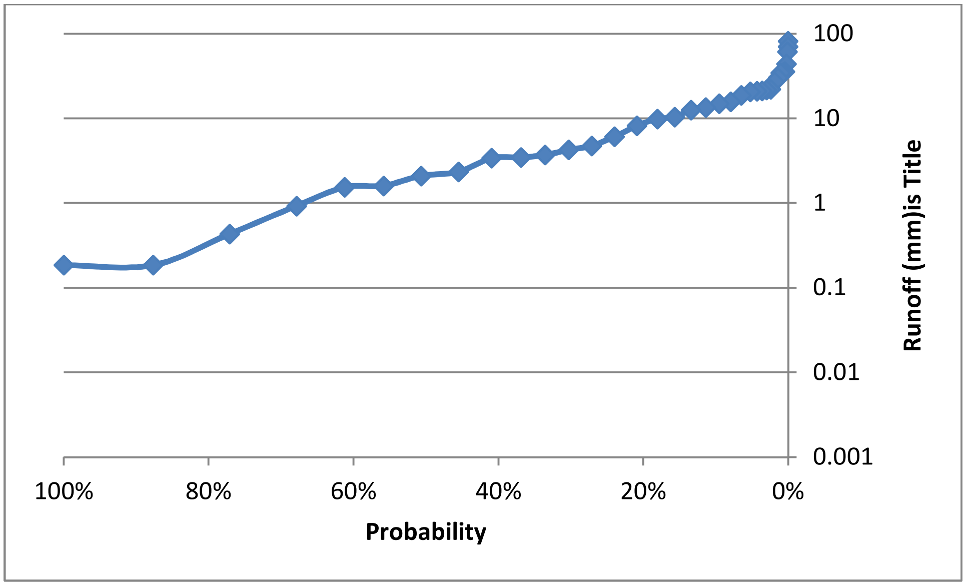

Figure 3.12 November Distribution of CMIP3 Projections for the MIUB_ECHO_1_G.1 Model Using the A1B SRES for Reservoir Inflow (in mm over the basin) to Fall River Lake Bias-corrected using Factor Developed from Ensemble Medan (October 1979 - September 2015).

The improvement in the CMIP3 and CMIP5 runoff ensemble projections can be seen by looking at the monthly mean and median of the runoff ensembles compared to the average observed monthly runoff. Bias correcting with a factor that was developed from multiple exceedance average (shown in Figure 3.13) better matches the observed monthly averages. Using a bias-correction factor developed from the ensemble median (shown in Figure 3.14) shows the monthly averages are below the past observed monthly runoff averages.

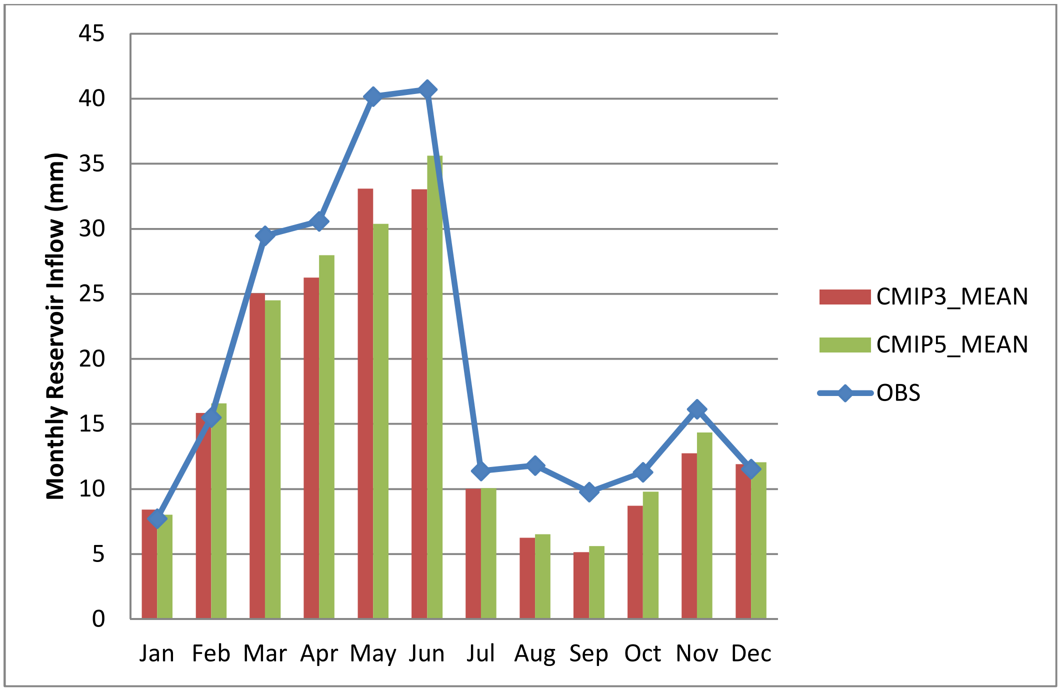

Figure 3.13. Monthly Average Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections That Have Been Bias-Corrected Using Factor Developed from Multiple Exceedance Values From the Ensemble (October 1979 – September 2015)

The corrections based on the bias-correction factors developed from the ensemble mean (shown in Figure 3.15) match the past observed monthly average runoff except for differences due to rounding, as this was how the bias-correction factors were calculated. However, when the average medians of the ensembles that were bias-corrected using the factors based on the ensemble mean, the bias-corrected ensembles are above the observed average monthly median runoff for each month, as shown in Figure 3.16.

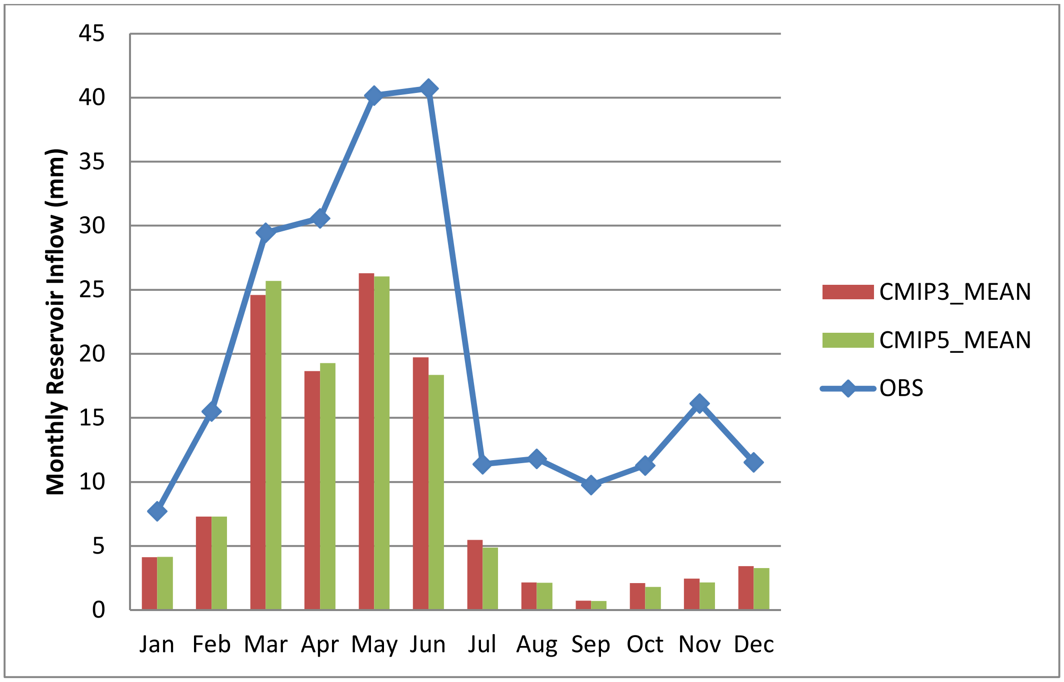

Figure 3.14. Monthly Average Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections That Have Been Bias-Corrected Using Factor Developed from the Ensemble Median (October 1979 – September 2015)

The average medians of the ensembles that were bias corrected using the factors based on the multiple exceedance factors (shown in Figure 3.17), are above the observed average median runoff for each month. Using this method of bias correction allows for data correction that takes into account that the median of the ensembles and observed data could be either higher or lower than the mean.

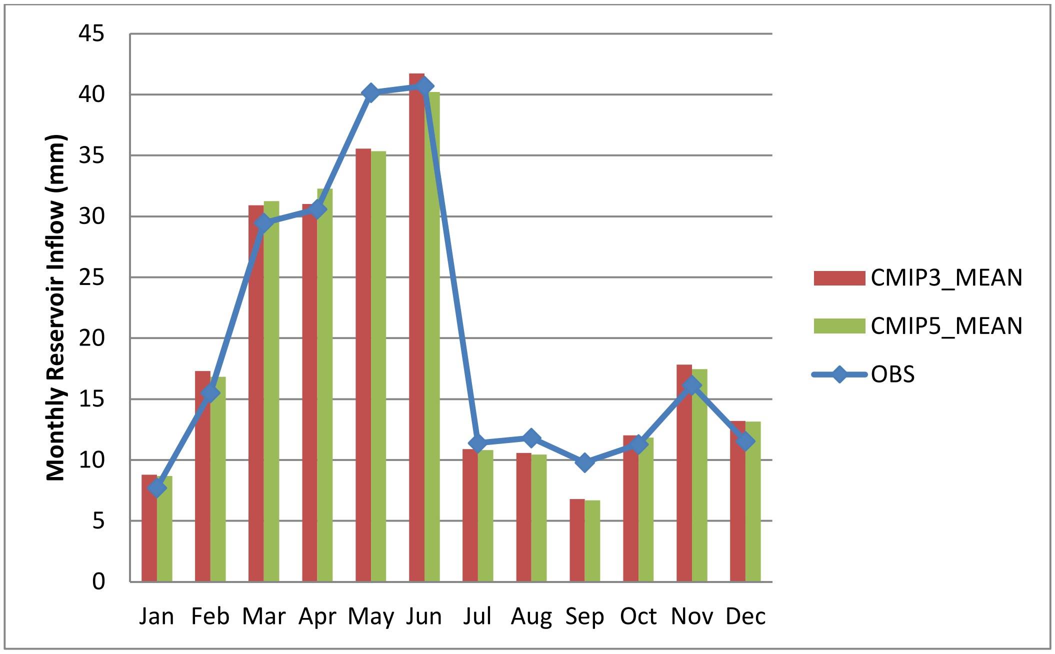

Figure 3.15. Monthly Average Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections That Have Been Bias-Corrected Using Factor Developed from the Ensemble Mean (October 1979 – September 2015)

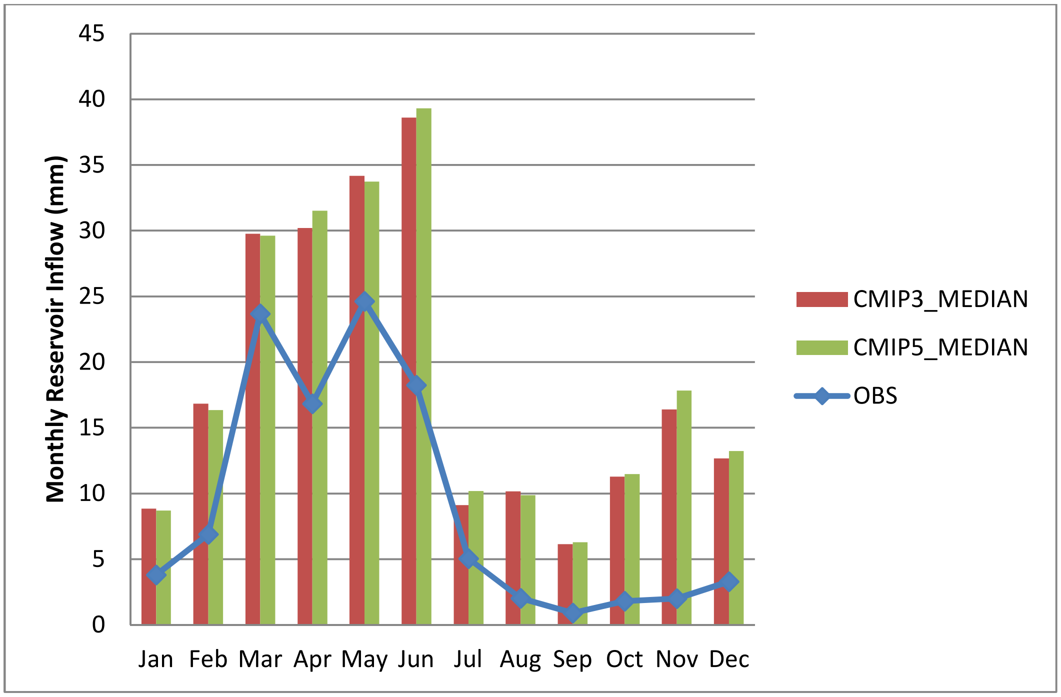

Figure 3.16. Monthly Average Median Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections That Have Been Bias-Corrected Using Factor Developed from the Ensemble Mean (October 1979 – September 2015)

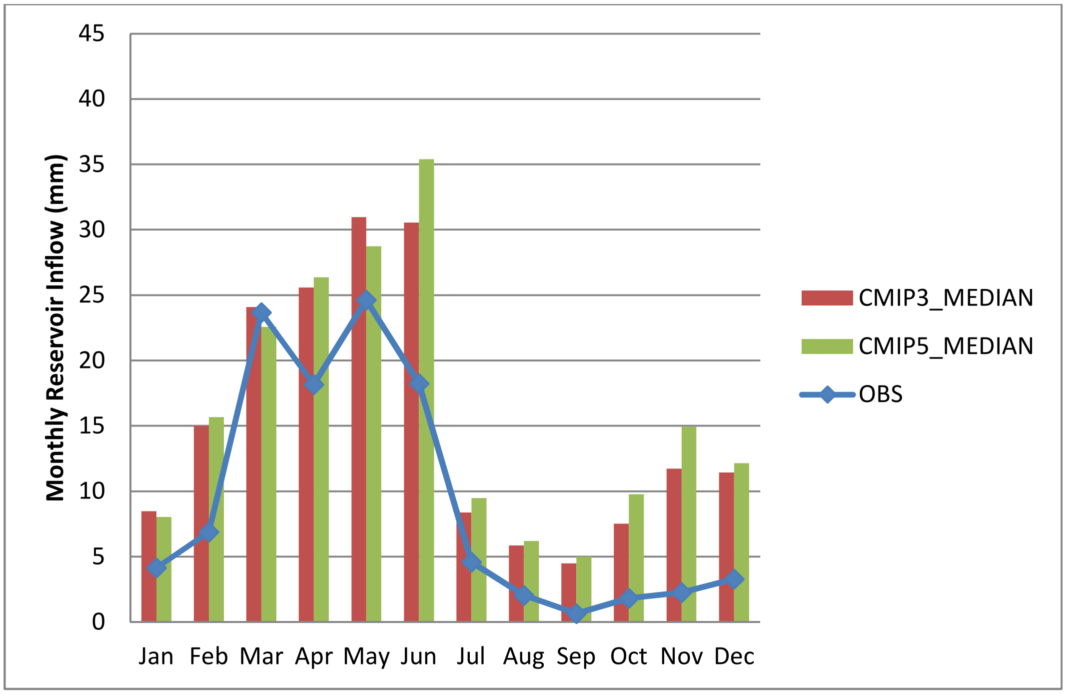

Figure 3.17 Monthly Average Median Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections That Have Been Bias-Corrected Using Factor Developed from Multiple Exceedance Values From the Ensemble (October 1979 – September 2015)

Based on the two sample Student's T test with a 90% confidence interval, as shown in Table A.17 through A. 21, none of the CMIP3 and CMIP5 monthly means were significantly different for the observed runoff data and the bias-corrected ensemble using a bias-correction factor based on the ensemble median for the period of record analyzed (October1979 – September 2015).

For the months of March, April, May, June, July, August, September, and October were significantly different at the 90% confidence interval for the CMIP3 ensemble mean with a bias-correction factor developed from multiple exceedance values applied. Similarly, the CMIP5 ensemble using this same bias-correction factor has statistically significant differences in March, April, May, June, August, and September. These are the months that experience the most precipitation in this basin. Corrections applied to these months and the methodology likely made a significant difference to more months in the CMIP3 ensemble than the CMIP5 ensemble due to the CMIP3 ensemble being more credible at reproducing past observations in this basin.

At the 90% confidence interval for the CMIP3 ensemble mean with a bias-correction factor developed from the ensemble mean, the months of January, February, May, September, and December were significantly different after bias correction was applied. Likewise, for the CMIP5 ensemble mean, the months of January, May, September, and December were significantly different after bias correction.

3.6.4. DEMONSTRATION OF POSSIBLE FUTURE RESERVOIR OPERATIONS

As a demonstration, a simplified reservoir model for Fall River Lake was constructed in Excel using the preferred generation of climate change (CMIP3) and recommended bias-correction technique of developing a factor based on multiple exceedances from the climate-change ensemble of runoff projections. The reservoir model was run for a period from October 2015 to December 2099.

No single stage-discharge relationships that fit the flood control operations of this reservoir as decisions about releases are made based on multiple reservoirs acting in concert. Downstream conditions are analyzed for each precipitation event and a release plan that minimizes downstream impacts is created for each specific scenario. This demonstration was not meant to serve as an exhaustive analysis of future or current reservoir operations and evaluations of alternate reservoir operation schemes are beyond the scope of this paper.

The reservoir operations for this demonstration were simulated using the total monthly reservoir flood control releases plotted against the historical storage at the end of the previous month. An additional point was added to denote the maximum possible lake storage and flood control releases. This maximum storage quantity is the storage at the top of the surcharge pool (above the flood pool) created by the temporary storage caused by raising the Tainter gates at the project. Maximum flood control releases for a month would equate to making full capacity discharge through the Tainter gates for the entire month. A trend line using a sixth order polynomial was found to be the best for the data, as shown in Figure 3.18. The change in storage in the simplified spreadsheet model was calculated as inflow minus outflow to be the change in lake storage. No monthly adjustments were made to the conservation storage and flood pool storage to adjust for capacity losses due to sedimentation, evaporation, or leakage losses. Minimum monthly reservoir releases were the minimum low-flow requirements from the Water Control Manual for Fall River Lake (USACE 1993) for downstream water quality.

Simplified reservoir logic was used to calculate monthly releases was developed using the equation of the sixth order trend line determined from historical monthly lake volume and release records. The release logic was as follows:

- Step 1: If the low-flow releases were greater than the inflow, and the lake storage at the end of the previous month was less than or equal to 22,000 ac-ft, then the release would be the low-flow requirements per the Water Control Manual.

- Step 2: If Step 1 is not met, then if the lake volume at the end of the preceding month plus the monthly inflow for the current month plus the release calculated by the polynomial equation is less than 22,000 ac-ft, and the lake volume at the end of the last month was less than or equal to 22,000 ac-ft, then the release would equal the inflow for the current month.
- Step 3: If Step 2 is not met, then if the lake volume for the previous month's lake plus the inflow for the current month minus 22,000 ac-ft is less than the release calculated by the polynomial equation, then the lake release would be set equal to the lake volume at the end of the previous month plus the inflow for the current month minus 22,000 ac-ft.
- Step 4: If Step 3 is not met, then the release would equal the release calculated by the polynomial equation.

Figure 3.19 shows the simulated reservoir releases based on the starting reservoir storage at the end of September 2015. This simulation shows that Fall River Lake can continue to operate with the current release plan of minimum low-flow and flood releases throughout the 21st Century.

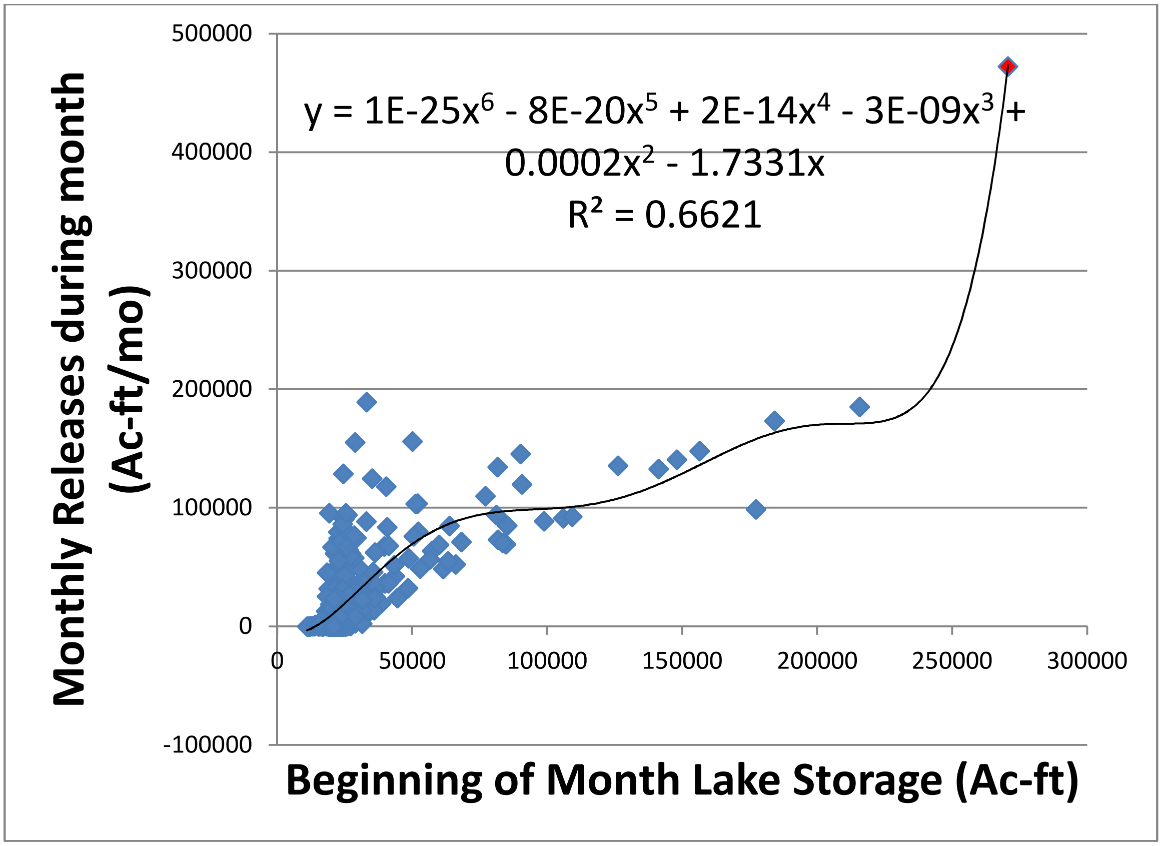

Figure 3.18 Historical Monthly Reservoir Releases from Fall River Lake Compared to Historical Reservoir Storage at the End of the Prior Month (October 1979 – September 2015)

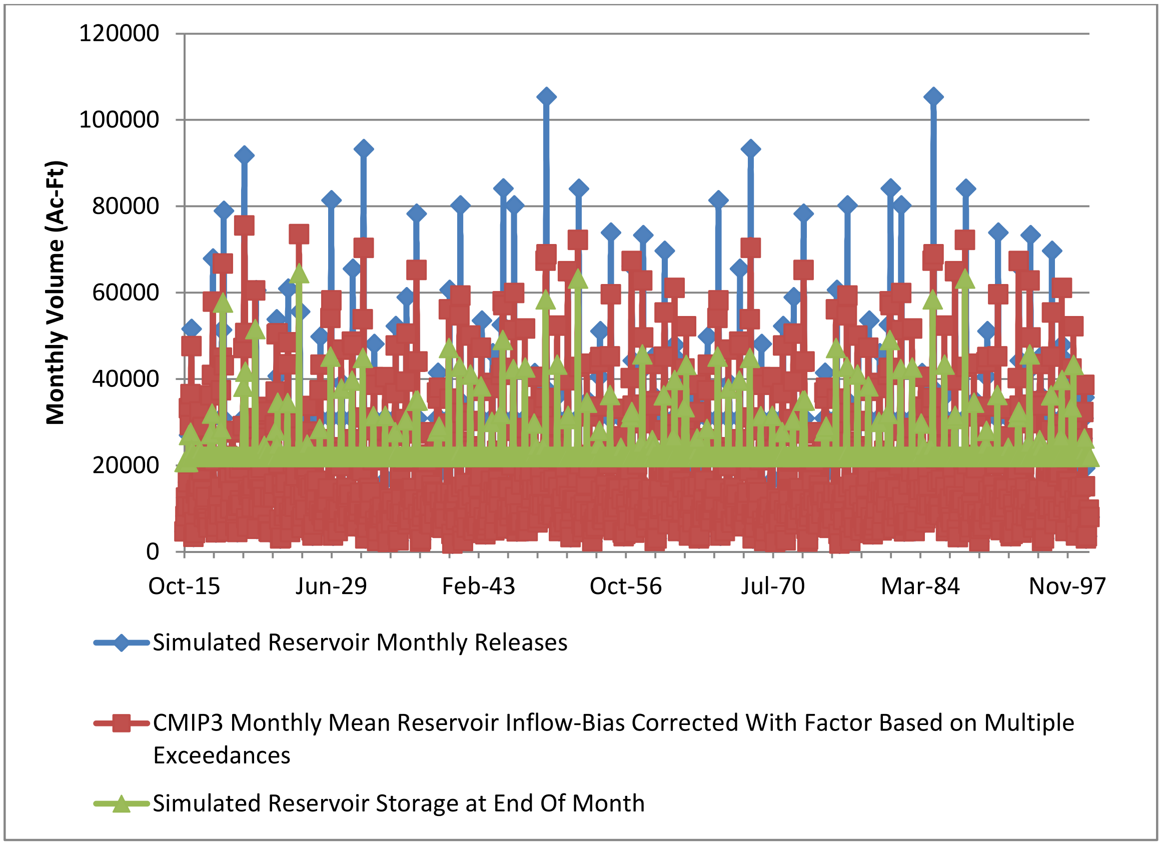

Figure 3.19 Monthly Average Median Reservoir Inflow (in mm) to Fall River Lake for Observations, CMIP3 and CMIP5 Ensemble Mean Projections That Have Been Bias-Corrected Using Factor Developed from Multiple Exceedance Values From the Ensemble (October 1979 – September 2015)

However, there are changes that can be expected over the long-term annual average inflow, and releases, and reservoir storage volumes. In the middle of this century (2050-2069), the ensemble of CMIP3 runoff projections which were bias-corrected with a factor developed from multiple exceedance values, indicate that the inflows to Fall River Lake are expected to smaller and that the lake will make less annual releases than the average values in the years of 2016-2035 or 2080-2099. Average annual inflow and releases are also expected to be higher from Fall River Lake at the end of this century (2080-2099) than the average annual inflow and releases in the near future (2016-2035). The average annual volume of water stored in Fall River Lake is expected to increase from now through 2099.

Table 3.5. Average Annual Simulated Inflow, Releases, and Reservoir Storage in Acre-Feet from Simplified Simulation Using CMIP3 Ensemble Mean Bias-Corrected with Factor Developed from Multiple Exceedance Values

Years	Average Annual Inflow From Simulation (ac-ft)	Average Annual Releases Simulation (ac-ft)	Average Annual Reservoir Storage From Simulation (ac-ft)
2016-2035	212,000	211,938	258,992
2050-2069	207,221	207,221	259,110
2080-2099	216,249	216,249	261,122

3.7. CONCLUSIONS

Results of the comparison of bias-correction methodologies show the choice of methodology in developing the bias-correction factors for the available runoff data from the CMIP3 and CMIP5 hydrology datasets does impact the final results for the inflow to Fall River Lake. Use of a local bias-correction calibration factor developed from the ensemble median would lower the CMIP3 and CMIP5 climate-change reservoir inflow projections lower than factors developed from the ensemble mean or from averaging factors based on multiple exceedance values. Using local bias calibration factors calculated from the ensemble mean would increase the resulting ensemble mean when applied more than the other two methodologies and would match the observed monthly means.

However, credible results can be obtained using bias-correction factors obtained by averaging correction factors for multiple exceedance values. This statistical approach would provide a planning basis with more credible extreme monthly flows than simply bias correcting using ensemble means to match the observed monthly mean values, as demonstrated in the example shown in Figures 3.8.through 3.12. As this reservoir has experienced typically low monthly inflows but occasionally has very large inflows, the methodology using bias-correction factors obtained by averaging correction factors for multiple exceedance values is recommended. The reservoirs in the surrounding area in southeast Kansas that also experience similar runoff flow patterns would likely also benefit from using the same methodology to develop local bias-correction factors.

Although the recommended bias-correction methodology using factors obtained by averaging correction factors for multiple exceedance doesn't provide a statistically significant difference from the unbias-corrected projections in all months, it is important to note that the other methodologies of bias correction are not creating statistically significant difference in the distributions either. It becomes necessary to look beyond statistical calculations and concentrate on the focus of the climate-change study. The decision on what type of local bias correction that should be used in a climate-change study should always be based on the application. If a study to analyze climate-change impact is focused on the potential with smaller typical flows with larger infrequent precipitation events, it may be more conservative to use the factors calculated by averaging correction factors for multiple exceedance values, instead of factors calculated only with the ensemble mean. If a study were dedicated to focusing on potential drought indicators, using the bias-correction factors based on the 50% exceedance (the median) values might help identify future drought planning precipitation thresholds.

The choice between using CMIP3 or CMIP5 projections or a combination of the two for a climate-change study can be based on which dataset produces the more reasonable results for a project's location. A part of this decision will be if the ensemble can incite credibility by being able to adequately reproduce observed data. Public involvement and approval is an essential part of planning and implementing reservoir management changes. This case study maintained separate scenarios and calculations for the CMIP3 and CMIP5 reservoir inflow projections. However, if it is deemed desirable to incorporate climate-change projections from both generations of climate models, the methodology of calculating local bias-corrections calibration factors would need to be reviewed in order to determine the most reasonable and credible model results for the resulting ensemble.

3.8. ACKNOWLEDGEMENTS

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I also acknowledge the World Climate Research Programme's Working Group on Coupled Modelling, which is responsible for CMIP, and I thank the climate modeling

groups (listed in Tables A.1. and A.2. of this paper) for producing and making available their model output. For CMIP, the U.S. Department of Energy's Program for Climate Model Diagnosis and Intercomparison provides coordinating support and led development of software infrastructure in partnership with the Global Organization for Earth System Science Portals.

3.9. DISCLAIMER

The views expressed in this paper are those of the author and do not necessarily represent the views of, and should not be attributed to, the U.S. Army Corps of Engineers or the Department of Defense.

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CHAPTER IV

LOW-FLOW RIVER REGULATION KANSAS VERDIGRIS BASIN: STATE, FEDERAL, AND TRIBAL LEGAL INVOLVEMENT

4.1. ABSTRACT

Federal agency reservoir operations and statutory, regulatory, and compact legal provisions affecting water in the Verdigris Basin in Kansas were analyzed for consistency. State statutes create a system of prior appropriation that incorporate vested riparian rights and a water marketing contract program for state-owned storage in federal reservoirs. Minimum streamflow target flows for the Verdigris Basin in Kansas are outlined as a part of federal reservoir operations instead of state statute. The Kansas-Oklahoma Arkansas River Compact sets flow expectations and maximum reservoir conservation storage that can be developed in the basin, but doesn't address issues of reliance on current flows, climate change, or the possibility of the assertion of water rights by the tribes in Oklahoma and Kansas. Although the Kansas water management system works well in the field, potential legal issues could be minimized by consolidation

of statutes and regulations regarding flow regulation in the Verdigris Basin and inviting other parties to future Kansas-Oklahoma Arkansas River Compact discussions.

4.2. INTRODUCTION

The minimum desired river flows in the Verdigris Basin in Kansas are highly regulated by state and federal agencies. Because so many legal provisions are enforced at the same time, an analysis of these provisions is necessary to ensure there are no conflicts and the desired minimum river flows can be provided under the regulation scheme.

The legal framework of surface water law in Kansas is a prior appropriation system that incorporates vested riparian rights and a water marketing contract program for state-owned storage in federal reservoirs accommodates this flow regulation. There has been interest in a Water Assurance Program in the Verdigris Basin in the past, but this has not been organized. There is also the potential for the operation of a non-profit entity water bank in the Verdigris Basin.

The Kansas-Oklahoma Arkansas River Compact provides the opportunity for more conservation storage in Kansas reservoirs, which could dramatically impact the water supply for municipalities and industries in northeastern Oklahoma. Although the compact gives the expectation of continued similar levels of river flow in the basin, the compact doesn’t address issues of reliance on these current flows or the potential hydrologic impacts due to climate change. As the compact was only signed between the states of Kansas and Oklahoma, the possibility the assertion of water rights in the Verdigris River in Oklahoma by the Cherokee or Osage Nations should be considered.

The objective of this paper is to analyze the federal agency reservoir operations and statutory, regulatory, and compact legal provisions specifically affecting minimum river flows in the Verdigris Basin in Kansas. Recommendations on how to improve the system are also provided.

4.3. KANSAS WATER LAW—STATE AGENCIES

All surface water and groundwater in Kansas is subject to regulation by the Kansas Department of Agriculture's Division of Water Resources (DWR). The DWR regulates all aspects of water use and regulation of development in water courses, including construction in streams and floodplain management. The DWR also administers interstate river compacts (KWO 2011c).

Established in 1981, the Kansas Water Office (KWO) is the planning and coordination water resource agency. KWO's purpose is "to achieve proactive solutions for resource issues of the state and to ensure good quality water to meet the needs of the people and the environment of Kansas" (KWO 2011c). The Kansas State Water Plan is developed by the KWO. KWO also manages the water marketing program for state-controlled waters stored in federal reservoirs (KWO 2011c).

The Kansas Water Authority (KWA) is a part of the KWO. The KWA advises the governor, the state legislature and the director of the KWO on water policy issues. The KWA also approves the State Water Plan, federal contracts and water storage agreements, and administrative regulations developed by KWO (KWO 2011c).

Regional Basin Advisory Committees bring local issues to KWO's attention (KWO 2011b). The Verdigris Basin Advisory Committee is a group that studies current issues within the basins. Some of these issues currently include increasing water storage capacity through potential project modification or the development of new reservoirs and ensuring available water supply exceeds demand by 10% through 2050 (KWO 2015).

4.4. KANSAS WATER LAW—STATUTES, RULES, AND REGULATIONS

Surface water in Kansas is controlled through permits under a system of appropriations, but with grandfathered riparian rights (Krause 2001). The water use permits now issued can be conditioned so the water user is required to stop withdrawing water when the flow in the river decreases to a designated flowrate. The Kansas water law administration scheme includes provisions for natural and regulated flows. The natural flow in the river systems are appropriated on an available basis, but typically conditional water rights are issued with pumping rights associated with the river system being at or above desired target flowrates (Kansas Department of Agriculture 2015).

Kansas's prior appropriation system dates back to the Kansas Water Appropriation Act of 1945, but Kansans were acquiring riparian water rights before this time by making beneficial use of the water (Rogers et al. 2013). A new version of the Kansas Water Appropriation Act was issued in June 2013 in the Kansas Rules and Regulations. While Kansas water rights are not personal property rights, they are more than licenses (Peck et al. 1988). These water rights can be changed and transferred.

In the past, riparian water users gained vested rights by making beneficial use of the water. However, the registration requirements today to acquire a water right involve a multifaceted analysis by the Kansas Department of Agriculture's DWR to secure a water right. Water users typically have to exercise their water rights within five years and maintain use of the water. However, there is flexibility in maintaining that use through flexible withdrawal plans and conservation plans (Rogers et al. 2013). State statutes also allow for the creation of a water banking system so water users can commit their previous beneficial use to conservation purposes for a period of time without sacrificing their right to regain use to that water again in the future (Rogers et al. 2013).

Historical riparian uses were grandfathered as vested rights when the 1949 legislation was passed, but no statutory mechanism was put into place giving these grandfathered riparian water users priority over one another (Krause 2001). The original Kansas Water Appropriation Act provided that the civil court system would be used to continue adjudicating water rights between opposing water users, but could utilize the studies and decisions of the Chief Engineer of the Kansas Department of Agriculture’s DWR as an aid (Krause 2001). Water users can continue to use their grandfathered riparian rights today as those rights have now been converted to appropriated rights.

Users with vested rights and other appropriated water rights can request that reservoir releases be made for their use. However, more than just these water users can request reservoir releases. Under Kansas Statute Title 82a-1305 allows for water storage rights in reservoirs. However, the water storage rights cannot be issued at the detriment of other appropriated and vested water rights.

Kansas Statute Title 12-852 provides that small cities (second and third class) can impound water for public water supply and these cities have the right natural flow in a watercourse to their water works intakes. The quantity of water that these small municipalities can impound is not defined by the statute and the statutes are also silent as to the rights available when there is not a natural flow regime in the river. Another statute Title 12 -2713 maintains that “nothing contained in this act shall be held to alter or abridge the powers and duties of the secretary of health and environment or of the division of water resources of the Kansas department of agriculture over water supply matters.”

4.5. KANSAS WATER OFFICE AND FEDERAL RESERVOIR OPERATIONS

Water stored in Kansas reservoirs is subject to regulation by the KWO and DWR. The DWR establishes the minimum streamflow desired in the Verdigris River and the KWO works with the U.S. Army Corps of Engineers (USACE) to ensure the minimum flow targets are met partially through federal reservoir releases. Fall River and Toronto Lakes and a portion of Elk City Lake are used as water quality storage (USACE 2012, 1995, 1993). This water is released throughout the year as small releases that maintain water quality downstream in the Verdigris by diluting pollution sources, such as discharge from sanitary and storm sewage systems. This water is also used by downstream water users.

There is a Memorandum of Agreement (MOA) between KWO and DWR that the first 0.14 m3/s (5.0 cubic feet per second, c.f.s.) per day flowing out of Toronto, Fall River and Elk City Lakes would be considered natural flow. Downstream water users that have permits issued after 1984 have the condition that they may withdraw water from the Verdigris River as long as the natural flow is sufficient to meet the water rights. If the water flow is less than this amount, then the water users are directed that they must discontinue their pumping from the river system.

The KWO-DWR MOA agrees that a minimum of release of 0.14 m3/s (5.0 c.f.s.) per day will be bypassed for use downstream. However, this minimum release is not directly incorporated into the Corps of Engineers regulations for Toronto and Fall River Lakes as there are winter months when the required minimum reservoir release is 0.08 m3/s (3.0 c.f.s.) per day as shown in Table 4.1.

Table 4.1. Monthly Minimum Reservoir Releases in the Verdigris Basin in cubic meters per second

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Toronto Lake	0.08	0.08	0.08	0.08	0.08	0.08	0.14	0.14	0.14	0.08	0.08	0.08
Elk City Lake	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Fall River Lake	0.08	0.08	0.08	0.08	0.08	0.08	0.14	0.14	0.14	0.08	0.08	0.08

(Adapted from KWO 2011a).

USACE has the ability to control the reservoirs based on the Flood Control Acts that authorized the reservoirs. Separate Congressional authorizations are made for the authorization of a project and then the funding for the project's construction. Three of the federal reservoirs in the Verdigris Basin in Kansas were authorized by the Flood Control Act of 1941 (Public Law 77-228). Big Hill Lake was authorized by the River and Harbors Act of 1962 (Public Law 87-874). USACE control of these reservoirs is prescribed in Water Control Manuals for the projects as well as in a Master Water Control Manual for the entire Arkansas River Basin (USACE 2012, 2007, 1995, 1993).

Actions that are in compliance with these manuals are considered governmental action and are generally absolved from liability caused by the actions due to the sovereign immunity of the United States government. However, if the reservoirs are operated outside the regulations set forth in the water control manuals or the water control manuals are not updated, USACE might incur liability for the resultant actions. An example of a situation where USACE did not properly update and follow the water control manuals for their projects can be found in the Tri-State (Georgia, Alabama, and Florida) Water Wars where litigation has been ongoing since 1990 (Atlanta Regional Commission, 2016).

4.6. MINIMUM FLOW TARGET REQUIREMENTS IN KANSAS RIVERS

Minimum desirable flowrates at designated USGS gage locations have been set by statute for the many Kansas watersheds. The DWR determines the minimum desired streamflow in the river system and uses this threshold flow to determine when to issue orders for water users to stop pumping (Kansas Department of Agriculture 2015). All the locations where the DWR has determined the minimum desired streamflows for locations are not listed in the Kansas Statutes. The minimum desired streamflow in the Verdigris Basin are instead considered minimum flow targets because they are handled by an agreement regarding Corps of Engineers operations for the reservoirs in the basin. In the Verdigris Basin, the State of Kansas maintains minimum flow targets set by the Kansas Department of Agriculture's DWR at the locations and minimum flowrates by KWO negotiations for federal reservoir and state fishing lake releases, as shown in Table 4.2. Locations where minimum desirable streamflow have been set by statute are shown in Figure 4.1.

Table 4.2. Year-Round Target Streamflow Values in the Verdigris Basin in Kansas in cubic meters per second

	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Altoona, KS	0.08	0.08	0.08	0.08	0.14	0.14	0.14	0.14	0.14	0.08	0.08	0.08
Fredonia, KS	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14	0.14
Independence, KS	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99

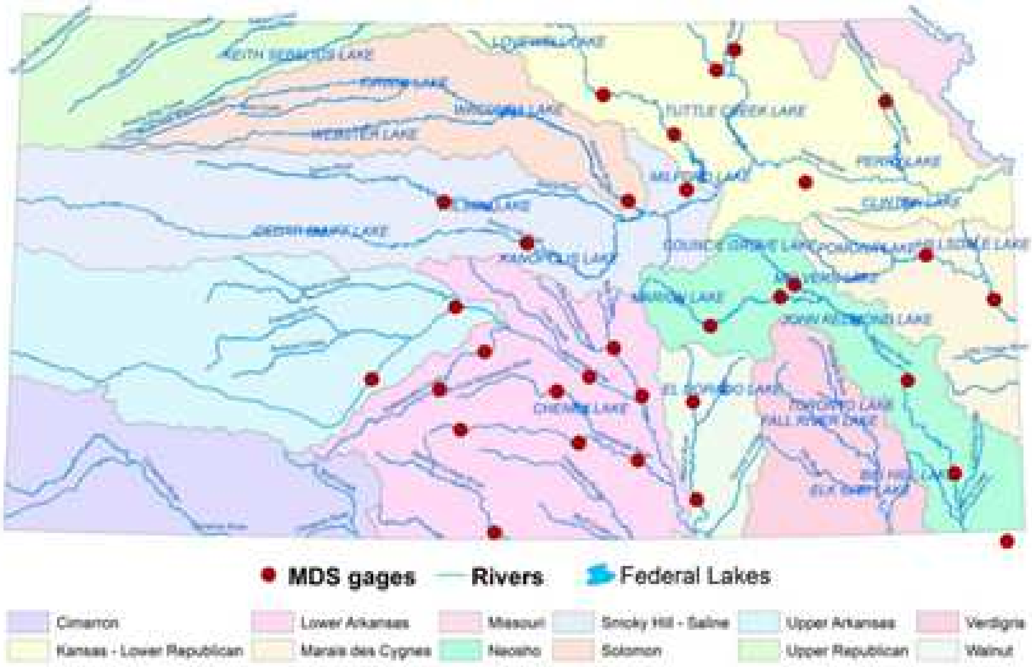


Figure 4.1. Minimum Desirable Streamflow (MDS) Gage Locations (Kansas Department of Agriculture, 2015).

The minimum river flow target values in the Verdigris basin and minimum reservoir releases at Elk City, Toronto and Fall River Lakes are included in the USACE water control manuals by referencing the MOU between KWO and USACE regarding operations in the Verdigris Basin (USACE 2012, 1995, 1993). Both minimum reservoir releases as well as monthly target minimum flows at selected downstream gage locations are in the MOU, but there is not a specific emphasis on maintaining the downstream target flows. The schedule of minimum target flows and minimum reservoir releases are shown in Tables 4.2. and 4.1., respectively. The MOU also describes the operation of the reservoirs in the Verdigris in a coordinated system for maximum flood protection. By not directly incorporating the streamflow target flows into the release schedule, USACE has flexibility in providing releases that would meet the desired streamflow targets. USACE negotiates the reservoir release quantities with KWO to try to achieve the desired Verdigris Basin target flows. The target flowrates do trigger orders to water users to stop pumping on the Verdigris River, the same effect as if the target flowrates had been defined by statute.

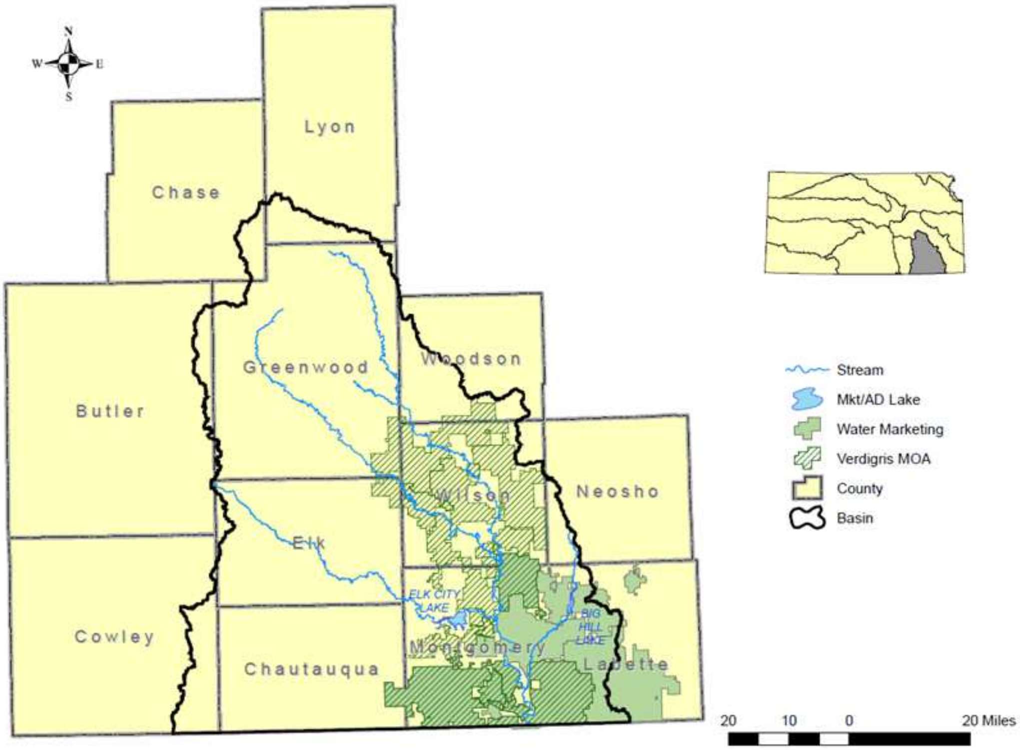
By not statutorily declaring minimum desirable streamflow, it has the potential effect of possibly limiting DWR and KWO involvements in potential water disputes in the Verdigris Basin. Achieving minimum flow through USACE operations brings a coloring of federal immunity to the regulated river system, even if this immunity does not exist. USACE is generally protected from liability created through flood control operations through the various Flood Control Acts. However, operations to provide minimum streamflow on behalf of a water storage holder, such as KWO, may not be covered.

Kansas cities have the ability to contract for water storage directly from a federal reservoir. Kansas Statute 12-817b provides that two or more cities may contract for water supply with the United States government or any agency thereof for a water supply or part thereof for any one or more of such contracting cities. The statute also details that if the contractual arrangement with the federal reservoir is voided, then the State of Kansas would be liable to make payments to the federal government. The affected cities would indemnify the State of Kansas and would keep their existing state-issued rights to the water in the reservoir.

4.7. KANSAS WATER MARKETING PROGRAM

The Kansas Water Marketing Program is the only program of its kind in the nation. Downstream municipalities and industries have the flexibility to contract for the water supply that they anticipate they would reasonably use in the near future. Future storage quantities are held in trust by the KWO for future water users or for later increased water usage by existing contracted users (KWO 2011c). Water users do not have to build infrastructure or provide assurances in order to keep instream water rights active. This allows the water usage and financial outlay by each contracted water user to adapt to local economic and population patterns.

Water available for purchase in the Water Marketing Contract Program in the Verdigris Basin is stored in Elk City Lake and Big Hill Lake in the Verdigris Basin. Municipalities and industrial water users have contracts for water supply directly with KWO (instead of with USACE) for the storage. When the users desire to utilize this storage, they contact KWO to request the water be released from the federal reservoir for downstream use. In turn, KWO requests a water release to be made from the structure from USACE, since the structures are operated with USACE employees. Water quality releases are also requested by KWO from USACE in a similar manner. The quantity of the water released is a collaborative effort between KWO and USACE. The municipal and industrial users can then request reservoir releases and be charged only for the water for only the quantity that they requested and not have to pay for the storage costs directly with USACE for the water (KWO 2011c). A map showing the Federal reservoir storage customers for both the Water Marketing Contract Program as well as the customers reliant on the other Federal conservation storage is shown in Figure 4.2.



Kansas Water Office, February 2008

Figure 4.2. Federal Reservoir Storage Customers in the Verdigris Basin. Customers of the Kansas Water Office's Water Marketing Contract Program are shown in solid green. Other customers reliant on the river flow provided by the Federal reservoirs are shown in the striped green and denoted as Verdigris Memorandum of Agreement (MOA) (KWO 2008).

Water conservation is both encouraged and required in the Water Marketing Program. A water conservation plan is required to participate in the program. Conservation is also financially encouraged because water users are charged for only the amount of water that they request to be released from the reservoir. Municipalities and industries in the lower portion of the Verdigris Basin were encouraged to join the Water Marketing Contract Program. However, not all of the municipalities in the area joined the program at its inception.

This water marketing program is an ingenious way of incorporating both natural flow and regulated flow into a permit and withdrawal system. Although it requires continuous monitoring and cooperation between state and federal agencies, the system works remarkably well in practice. However, if a municipality chose not to participate in the water marketing program and chose to rely on grandfathered riparian water rights based on the natural flow and/or water rights that predate the federal reservoir construction, those water rights would have been based on the natural flow in the Verdigris River, predating the current water marketing program. There could be a legal dispute on whether the Water Marketing Program can effectively force a holder of a more senior grandfathered water right to participate in the program in order to access water in times of low river flow.

4.8. KANSAS-OKLAHOMA ARKANSAS RIVER COMPACT

Kansas water law is also affected by interstate compact. The Kansas-Oklahoma Arkansas River Compact sets expectations about the river flow quality and quantity crossing the state line. Public Law 340 (1955) gave Congressional consent for Kansas and Oklahoma to negotiate and enter into an interstate compact to allocate the waters of the Lower Arkansas River and associated tributaries, including the Verdigris River. The resulting product of these negotiations, the Kansas-Oklahoma Arkansas River compact, allows for future storage of water in both states. Acceleration clauses were put in place that allows Kansas to build more conservation storage based on the amount of storage that Oklahoma builds in each drainage subbasin of the Lower Arkansas River (Krause 2001).

Another progressive feature of the Kansas-Oklahoma Arkansas River Compact is that it does not provide a final allocation of water between Oklahoma and Kansas in the basins. A provision was included in the compact that the Kansas–Oklahoma Arkansas River Commission could reassess and review the provisions of the compact at any time after 25 years from the compact’s effective date. In fact, the entirety of the compact can be rescinded by actions of both the Kansas and Oklahoma legislatures, with the caveat that the rights created under the compact would remain intact (Krause 2001).

The need for temporary impoundment of conservation storage for later release or other uses is also covered in Kansas–Oklahoma Arkansas River Compact. Either state may temporarily impound water with the consent of the operating agency of the reservoir (Kansas Department of Agriculture 2014). Theoretically, this would provide the ability for USACE to approve an operating plan for the reservoirs in these basins to be able to have a range of conservation pools, instead of one designated pool elevation. If the commission, water users, KWO, and USACE agree, then a permanent seasonal pool could be approved that would allow for the temporary storage of water for later water quality releases.

The original Kansas-Oklahoma Arkansas River Compact allocated that conservation storage of no more than 370,044,556.6 cubic meters (300,000 acre-feet) plus the capacity included in reservoirs constructed in Oklahoma (with the exception of the navigation storage in Oologah Lake) be constructed in the Verdigris Basin after July 1, 1963. This maximum conservation storage capacity includes all reservoirs with a conservation storage capacity in excess of 123,348.2 cubic meters (100 acre-feet), but it excludes any portion of the storage capacity allocated to flood and sediment control and inactive storage capacity that may currently be allocated to other uses. As of 2014, an additional 1,498,594,110.48 cubic meters (1,214,930 acre-feet) of storage could still be developed in Kansas in the Verdigris Basin due to the construction of Oologah Lake on the main steam of the Verdigris River in Oklahoma (Kansas Department of Agriculture 2014). Potential impacts from climate change are not discussed in the compact.

Attempts to estimate future water usage through the year 2000, while allowing for future population and economic expansion, were made in the original Kansas-Oklahoma Arkansas River compact. Kansas has rights under the compact to construct as much reservoir conservation storage in Kansas as is available in Oklahoma (Kansas Department of Agriculture 2014). If additional reservoirs are built in Oklahoma, the recourse that Kansas would have would be to build reservoir conservation storage, up to the same conservation storage that exists in Oklahoma.

However, building larger upstream reservoirs in Kansas could effectively cut off flow to downstream reservoirs. This could prove devastating to the local sponsors who are invested financially in the downstream reservoirs. If Kansas fully develops the conservation storage in the Verdigris Basin under the Kansas-Oklahoma Arkansas River

Compact, the resulting loss of flow in Oklahoma could bring economic chaos. The reservoir yield in Oologah Lake would be substantially decreased by the creation of new conservation storage in the Verdigris Basin in Kansas in the same magnitude of the amount of conservation storage already available in Oologah Lake.

The Kansas-Oklahoma Arkansas River Compact also states that federal reservoirs in each of the basins be operated “in the best interests of the states and the United States” (Krause 2001). However, in practice federal reservoirs are not operated for the benefit of any individual states. The cost benefit ratio on any federal project includes the total costs and benefits of a project as they accrue to the United States, not to individual areas or states. While local benefits do accrue, it is not the impact to the local area or state that matter most in the required benefit cost analysis done to justify any federal project.

Expectations about the Arkansas River and its tributaries for pollution control and maximum conservation storage quantities for reservoir development in Kansas are set in the Kansas-Oklahoma Compact (Krause 2001). Although both Kansas and Oklahoma agreed to “the principle that neither state may require the other to provide water for the purpose of water-quality control as a substitute for adequate waste treatment,” water quality releases from the federal reservoirs in the Verdigris Basin are incidentally fulfilling this role (Krause 2001).

4.9. COMPREHENSIVE STATE WATER PLANS

As a part of the Kansas Comprehensive State Water Plan, there are three main goals in the Verdigris Basin. These goals are to decrease per capita water consumption by 10% of 2015 levels by 2025, to increase reservoir water storage capacity, and to ensure that water supply storage exceeds demand by at least 10% through 2050. Priority will be given to existing reservoirs for the goal of increasing reservoir water storage capacity by 10 % every 10 years. In furtherance of these goals, different reservoir management practices and additional potential reservoir sites will be evaluated by 2020 (KWO 2015).

Per the Oklahoma Comprehensive Water Plan executive report, several municipal watersheds in the Verdigris basin in Oklahoma are already designated as sensitive water supplies. The alluvial aquifer under the Verdigris river in Oklahoma has a capacity of approximately 199,823,760 cubic meters (162,000 acre-feet) with a temporary limit on pumping 609,599.1 cubic meters per square kilometer per year (2.0 acre-feet per acre per year) until the Oklahoma Water Resources Board can further study the alluvial aquifer to make a better determination of pumping limits (Oklahoma Water Resources Board, 2012).

Like Kansas, Oklahoma also has water conservation goals. Under the Water for 2060 Act, Oklahoma set a goal of using the same amount of fresh water in 2060 as was used in 2010 (Oklahoma Water Resources Board, 2016).

4.10 POTENTIAL FOR NEW RESERVOIRS

There is a potential for new reservoir development in the Verdigris Basin. The previously-authorized USACE reservoir of Neodesha Lake was deauthorized in the Water Resources Development Act of 1986. According to the Arkansas White Red Basin Interagency Committee (AWRBIAC) documents from 1984, Neodesha Lake had previously been approved without a federal sponsor, but later failed the cost/benefit tests during subsequent years. However, this site on the main stem of the Verdigris River will likely be reevaluated, along with other potential reservoir sites. If Neodesha Lake is constructed as a USACE federal reservoir, it will need to go through the same planning process it did many years ago, with the only difference is that now a local sponsor is required.

Even if USACE is not involved in the construction and planning of another Federal reservoir in the Verdigris Basin, it would still be involved in the flood control operations of potential new reservoirs if Federal funds are expended. Colloquially known as "Section 7 projects," reservoirs can be built by other federal agencies, typically the United State Bureau of Reclamation in this region, that have their flood control operations dictated by the Corps of Engineers. The projects conform with the regulations (as found in 33 CFR 208.11) in Section 7 of the Flood Control Act of December 22, 1944, that states that flood control operations must be coordinated with USACE. Additional regulations for the Section 7 projects through the years have been published in 33 CFR Chapter 208

4.11. POTENTIAL TRIBAL WATER RIGHTS IN THE VERDIGRIS BASIN IN OKLAHOMA

If the Cherokee or Osage Nations of Oklahoma were to make claims to the flows in the Verdigris Basin in Oklahoma, the Kansas-Oklahoma Compact would need to be renegotiated to include potential tribal interests. The Kansas-Oklahoma Arkansas River Compact was only negotiated between the two states. The Verdigris River Basin in Oklahoma includes Cherokee and Osage tribal lands, starting directly at the Kansas border (Thomas 1913). In Choctaw Nation v. Oklahoma (397 U.S. 620 (1970)), it was found that Choctaw, Chickasaw, and Cherokee Nations obtained "virtually complete sovereignty over their new lands" in Oklahoma. According to Oklahoma v. Tyson Foods (2010), the Cherokee Nation has a "colorable claim" to exclusive ownership over water within its territory. The Cherokee territory includes much of the Verdigris Basin in Oklahoma (USDA 1984). A map of tribal jurisdictions in Oklahoma is shown in Figure 4.3.

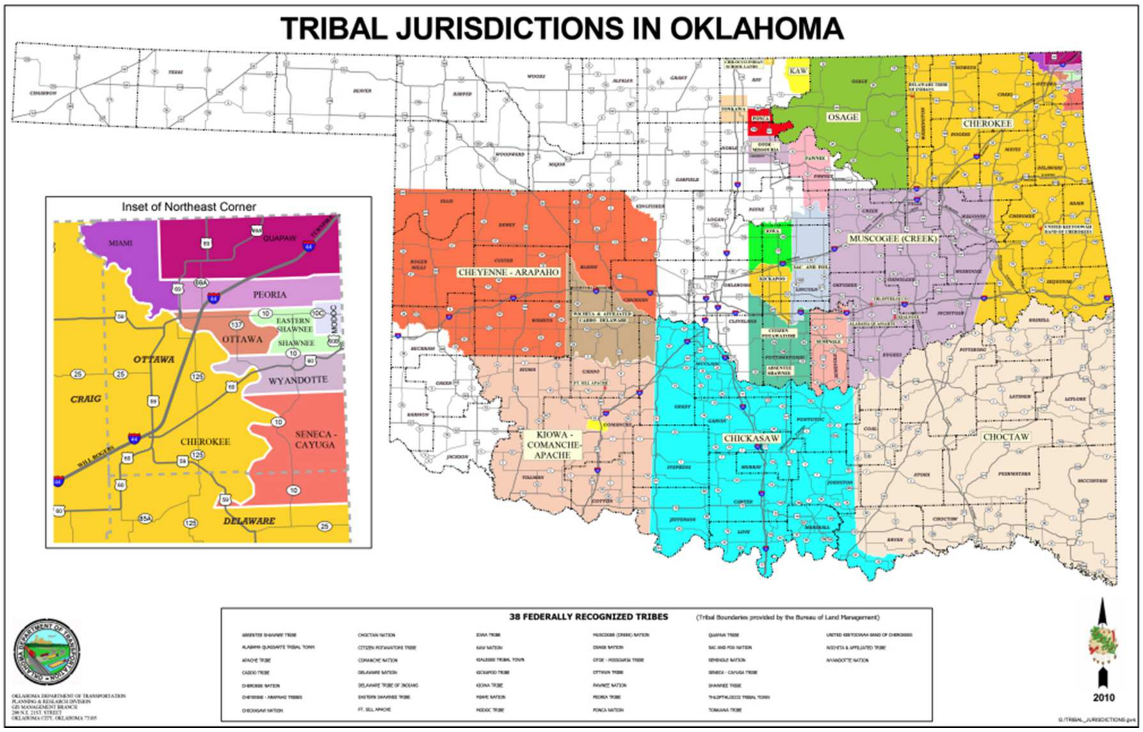


Figure 4.3. Tribal Jurisdictions in Oklahoma. The Osage Nation is shown in green and the Cherokee Nation is shown in golden yellow (ODOT 2016).

The Cherokee Nation of Oklahoma, as the successor in interest to the historical tribal towns and bands throughout the southeastern Unites States, may someday assert claims to the water in the Verdigris Basin. The Cherokee Nation received its lands in a fee patent from the U.S. Government, with no reservations made excluding water or river beds.

Congress has expressed the intent to protect the rights in the water and river beds as recently as 2002 (Work 2010).

The Cherokee have had multiple breakaway groups over time. When pressure began to be exerted by the United States to obtain lands held by Cherokee groups in the southeastern United States, many groups voluntarily left before the forced removal. These peoples generally moved into areas of Arkansas, Missouri, and Oklahoma. Multiple groups of Cherokee heritage can still be found in these states. There are three Federally recognized Cherokee Nations—the Cherokee Nation of Oklahoma, the United Keetoowah Band of Cherokee Indians, and the Eastern Band of the Cherokee, headquartered in North Carolina. Many of the other tribal groups have obtained state recognition as tribes and have petitioned the United States government for federal recognition.

Although the position was created over 15 years ago, the Cherokee Nation of Oklahoma has recently appointed a Secretary of Natural Resources to administer natural resources programs as well as water rights (Cherokee Nation, 2015). The Cherokee Nation was been working on a comprehensive water plan for several years, the addition of the Secretary of Natural Resources will likely help further the water planning process. The Cherokee Nation has also recently been very involved with the State of Oklahoma in considering tribal interests as part of the Oklahoma Comprehensive Water Plan.

The Osage Nation originally had land in Kansas, but the land was sold back to the federal government. Using the money from the land sale, the Osage Nation purchased land in Oklahoma from the federal government, complete with all mineral rights. The land that the Osage Nation purchased was originally a portion of the Cherokee Nation land that had been ceded back to the federal government (Thomas 1913).

The potential for water rights to be asserted by the Osage Nation is not as clear. In Brewer-Elliott Oil & Gas Co. v. United States (260 U.S. 77 (1922)), it was previously found that the Osage Nation had rights to the minerals and land under the nonnavigable rivers, essentially finding that the Osage Nation has sovereignty over their lands and mineral interests. The issues of groundwater and surface water being considered mineral interests is not straightforward due to multiple treaties between the Osage Nation and the US federal government and the Osage Nation and the State of Oklahoma. The Osage Nation currently has a Water Rights Task Force that is studying water resources within Osage County (Duty 2013).

4.12. APPLICABLE FEDERAL LAW

The United State Constitution's commerce clause does not address water as a commodity. However, recent water shortages and court cases such as Tarrant Regional Water District v. Herrmann have demonstrated that water is a commodity good. Exactly how the commerce clause could affect water transport and use is still in the early stages. The US Supreme Court has not addressed the issue of water export regulation for more than thirty years after declaring water an article of commerce (Klein, 2011) until very recently. In Tarrant Regional Water District v. Herrmann, the court held that the interstate treaty between Oklahoma and Texas did not preempt the Oklahoma state water law prohibiting water export, even though the possibility of export was included in the interstate treaty. The provisions in Article VII of the Kansas–Oklahoma Arkansas River

Compact that mention the possibility of the development of conservation storage in one state for the benefit of another state will not be enforceable based on the Tarrant Regional Water District v. Herrmann precedent. However, the remainder of the Compact will remain intact due to the severability clause.

4.13. FISH AND WILDLIFE RELIANCE ON TARGET FLOWS

Sustaining low flows throughout the entire year changes the ecology of the natural river system. Vegetation and animals that would have died down during times of diminished flow or zero flow now can now flourish year round. This can be a marked change from the naturally-occurring system. However, this could increase reliance on the flow to give a false sense of security as supplementing flows might provide unwarranted reliance that those flows would always be available. In reality, once the water quantity storages in the federal reservoirs and state fishing lakes are extinguished, the flows would cease. If the federal fish and wildlife authorities requested or demanded that flows be continued, it would be impossible to do so without water storage available.

Fish and wildlife requests are not predicated upon available water storage to supply the request. If releases were requested for downstream fish and wildlife, the communities or state agencies who have the rights to the water supply storage in the lake may find themselves at odds with the United States Fish and Wildlife Service (USFWS). Water supply storage holders would find themselves in the predicament of being forced to donate water for releases or face penalties from the USFWS. This issue has not arisen in the Verdigris Basin in Kansas so far, but the Verdigris River does contain threatened and endangered mussels. Some rivers in the Verdigris Basin in Kansas were recently listed as critical habitat for the Neosho mucket (USFWS 2015). The development of a conservation plan is now underway in order to prevent future litigation (USFWS 2015).

However, a conservation plan may still not prevent all litigation. In Kansas, water rights can be sold or banked by individuals. Municipalities and industrial water users can participate in the water marketing program or a potential water assurance district. It is still unknown how a conservation plan would affect users in Verdigris basin.

The MOA between KWO and DWR anticipates the possible need for supplemental water quality releases. Under the MOA the quantity of supplemental releases will be based on the instream need, the anticipated channel losses and travel time, and the quantity of storage in the upstream lakes. The conservation plan being developed for Neosho mucket could also incorporate similar provisions.

The Endangered Species Act (ESA) generally preempts state law if water rights are private property. While water rights in Kansas are treated as private property rights, the administration of this act will likely not conflict with application of Kansas water law in the field. Kansas Water Appropriation Act (K.A.R. 5-10-5.) already provides for the pro-rata or other equitable reduction in vested water rights in order to provide sufficient river flow for domestic uses in the administrative regulations. Likewise, all permits issued after 1984 contain the provision that they were subject to reduction based on the minimum desired streamflows.

Because the low flows in the rivers can be artificially manipulated through changing reservoir releases, the issue of whether low-flow releases are state- initiated or federally-initiated should be delineated so that the appropriate party can apply for a Section 10

Incidental Take Permit if the lows will decrease to levels that kill or damage Neosho mucket mussel beds. Even if the issue of federal preemption of state law due to the ESA were not well-defined, the process of applying for a Section 10 Incidental Take Permit would consider the needs of both the water right holders and the endangered species (Craig 2014).

4.14. MUNICIPAL RELIANCE ON TARGET FLOWS

Sustaining flow in the river channel not only induces reliance on that water by flora and fauna, but also by people. The regulation scheme adopted by the State of Kansas did not require that all municipalities be a part of the water marketing program. By not requiring municipalities and other water users to join the water wholesale program, these water users could now be at risk for running out of water during certain times of the year or having to defend litigation against other riparian users continuing to operate under their existing water rights.

Municipalities in Oklahoma also rely on the flows from the Verdigris River. A study recently completed by Qiao et al. (2014) looked at the sustainability of Oologah Lake due to climate change. However, this study assumed that there was no existing or future reservoir storage in the Verdigris Basin in Kansas, which is certainly not the case.

4.15 CONCLUSION

The legal framework that provides for the active water management of the Verdigris Basin as a business operation is possible due to the structure of Kansas water law. The DWR and KWO may consider adding the minimum desirable flowrates in the Verdigris Basin to the Kansas Statutes in addition to having them as a part of USACE operations.

Releases from state fishing lakes help meet the target flowrates, so the targets may be better served as state requirements instead of just as USACE operational parameters. Having the minimum flow targets set as minimum desired streamflows could prevent water users downstream from claiming that their state-issued water rights were infringed by USACE reservoir regulations.

The schedule of minimum reservoir releases should be the same in the MOA between the KWO and the DWR and the MOA between the KWO and USACE as there are currently conflicting provisions during the winter months for Toronto and Fall River Lakes. The MOU between KWO and USACE gives the final decision about the ability to make reservoir releases to the USACE. As KWO has control over all the conservation storage in Elk City, Toronto, and Fall River Lakes, KWO might be better served by keeping the ability to determine whether continued releases are feasible based on current upstream reservoir storage during times of drought based on KWO expertise instead of being determined by USACE.

Leaving USACE the ability to discontinue low-flow releases may not be in the best interest of KWO. KWO has the ability to manage each reservoir as a separate unit while USACE must regulate the reservoirs in the Verdigris Basin as part of a two-level regulation scheme. The reservoirs in the Verdigris are managed as part of the larger Arkansas River system as well as a subsystem of five reservoirs. The Arkansas River Master Water Control Manual provides for some flexibility for the regulation operation of the larger system for flood control, but within the Verdigris Basin subsystem there is little flexibility in flood control (USACE 2012). Although the repercussions of discontinuing low flows from the Kansas federal reservoirs likely would not affect downstream areas past Oologah Lake in Oklahoma nor the larger Arkansas River basin, the ability to manage each reservoir as a separate unit by KWO would be lost. As a large portion of the area relies on federal reservoirs for municipal and industrial water supplies as a primary or secondary source, the ability of KWO to provide these water supplies as low-flow releases or special reservoir releases remains of paramount importance when determining the reliability and dependability of the water supply.

Kansas water law still provides various means to provide for water users. Converting all the vested rights into the current appropriation system was a beneficial and laborious step to modernization. However, there are still some issues that could be addressed to make the system more efficient. Water rights issued after 1984 that are contingent upon adequate river flow available are time-consuming to enforce. The exact quantities of water available for small municipalities should also be specified, either by revising the applicable statutes or by requiring participation in a water assurance program or the water marketing program. Possible impacts to the water marketing program due to potential increased reservoir releases to maintain a potentially higher river flow for the protection of endangered species should be investigated.

In order to avert future problems, the Kansas-Oklahoma Compact Commission should be proactive in including Indian Nations, particularly the Cherokee and Osage Nations, for issues regarding the Verdigris Basin of Oklahoma in its proceedings, activities and reports. The commission may also consider looking at a comprehensive yield study for the subbasins of the Arkansas River, especially in the Verdigris Basin where Kansas has the right under the compact to develop quite a large quantity of storage due to the construction of Oologah Lake in Oklahoma. A yield study could determine the amount of reservoir conservation storage that could be safely developed without effectively cutting off flow to downstream users in Oklahoma.

4.16. ACKNOWLEDGEMENTS

The author wishes to thank Nathan Westrup of the Kansas Water Office, for his dedication to the waters and peoples of the State of Kansas.

4.17. DISCLAIMERS

The views expressed in this paper are those of the author and do not necessarily represent the views of, and should not be attributed to, the U.S. Army Corps of Engineers, the Department of Defense, the Kansas Water Office, the Kansas Department of Agriculture, the State of Kansas, the State of Oklahoma, any municipality in any state, or any Native American tribe. The author is not a member of the Kansas Bar.

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4.19. LIST OF CASES

Brewer-Elliott Oil & Gas Co. v. United States, 260 U.S. 77 (1922)

Choctaw Nation v. Oklahoma, 397 U.S. 620 (1970)

Oklahoma v. Tyson Foods, et al., US 10th Cr. No. 09-5134 (2010)

Tarrant Regional Water District v. Herrmann, 133 U.S. 2120 (2013)

4.20. LIST OF ACTS AND STATUTUES

Administration of water use among vested right holders, K.A.R. 5-10-5 (Authorized by K.S.A. 82a-706a; implementing K.S.A. 82a-704a and K.S.A. 82a-706; effective May 1, 1986)

An act authorizing the construction, repair, and preservation of certain public works on rivers and harbors for navigation, flood control, and for other purposes, Pub. L. No. 87-874, 76 Stat. 1173 (1962)

An act authorizing the construction of certain public works on rivers and harbors for flood control, and for other purposes, Pub. L. No. 77-228, 55 Stat. 639 (1941)

An act authorizing the construction of certain public works on rivers and harbors for flood control, and for other purposes, 58 Stat. 890; 33 U.S.C. 709 (1944)

An act granting the consent of Congress to the States of Kansas and Oklahoma, to negotiate and enter into a compact relating to their interests in, and the apportionment of, the waters of the Arkansas River and its tributaries as they affect such States, Pub. L. No. 84-340, 69 Stat. 631 (1955)

Contracts with U.S. government or agencies for water supplies; subject to future nullification if state assumes certain financial obligations, K.S.A. Title 12 §817b. (1963)

Endangered Species Act, 16 U.S.C. § 1531 et seq. (1973).

Flowage rights to waterworks system intake, K.S.A. Title 12 §852 (1937)

Jurisdiction of certain state agencies saved, K.S.A. Title 12 §2713 (rev. 2004)

Reclamation climate change and water program (SECURE Water Act) Pub. L. No. 111-11, 123 Stat. 1332 (2009)

State Water Plan Storage Act, withdrawal and use of waters; contract for withdrawal; disposal of surplus water, K.S.A. Title 82a -§1305 (rev 1986)

Regulations for use of storage allocated for flood control or navigation and/or project operation at reservoirs subject to prescription of rules and regulations by the Secretary of the Army in the interest of flood control and navigation. 33 CFR 208.11

Water Resources Development Act of 1986, Pub. L. No: 99-662 (1986)

APPENDICES

Tables

Table A.1. List of CMIP3 Models Used

Modeling Center (or Group)	Country	Emission Scenario	Ensemble ID
Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence	Australia	A1B	csiro_mk3_0.1.sresa1b
Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence	Australia	A2	csiro_mk3_0.1.sresa2
US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA	A1B	gfdl_cm2_0.1.sresa1b
US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA	A2	gfdl_cm2_0.1.sresa2
NASA / Goddard Institute for Space Studies	USA	A1B	giss_model_e_r.2.sresa1b
NASA / Goddard Institute for Space Studies	USA	A2	giss_model_e_r.1.sresa2

Table A.1. Continued

Institut Pierre Simon Laplace	France	A1B	ipsl_cm4.1.sresa1b
Institut Pierre Simon Laplace	France	A2	ipsl_cm4.1.sresa2
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	Japan	A1B	miroc3_2_medres.1.sresa1b
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	Japan	A2	miroc3_2_medres.1.sresa2
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data Group	Germany & Korea	A1B	miub_echo_g.1.sresa1b
Meteorological Institute of the University of Bonn, Meteorological Research Institute of KMA, and Model and Data Group	Germany & Korea	A2	miub_echo_g.1.sresa2
Max Planck Institute for Meteorology	Germany	A1B	mpi_echam5.1.sresa1b
Max Planck Institute for Meteorology	Germany	A2	mpi_echam5.1.sresa2
Meteorological Research Institute	Japan	A1B	mri_cgcm2_3_2a.1.sresa1b
Meteorological Research Institute	Japan	A2	mri_cgcm2_3_2a.1.sresa2
National Center for Atmospheric Research	USA	A1B	ncar_ccsm3_0.1.sresa1b

Table A.1. Continued

National Center for Atmospheric Research	USA	A2	ncar_ccsm3_0.1.sresa2
Met Office Hadley Centre	UK	A1B	ukmo_hadcm3.1.sresa1b
Met Office Hadley Centre	UK	A2	ukmo_hadcm3.1.sresa2

Table A.2. List of CMIP5 Models Used

Modeling Center (or Group)	Country	RCP	Ensemble ID
Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology	Australia	4.5	access1-0.1.rcp45
Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology Commonwealth Scientific and Industrial Research Organization/Bureau of Meteorology	Australia	8.5	access1-0.1.rcp85
Canadian Centre for Climate Modelling and Analysis	Canada	4.5	canesm2.1.rcp45
Canadian Centre for Climate Modelling and Analysis	Canada	8.5	canesm2.1.rcp85
National Center for Atmospheric Research	USA	4.5	ccsm4.1.rcp45
National Center for Atmospheric Research	USA	8.5	ccsm4.1.rcp85
Centro Euro-Mediterraneo sui Cambiamenti Climatici	Italy	4.5	cmcc-cm.1.rcp45
Centro Euro-Mediterraneo sui Cambiamenti Climatici	Italy	8.5	cmcc-cm.1.rcp85
Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence	Australia	4.5	csiro-mk3-6-0.1.rcp45

Table A.2. Continued

Commonwealth Scientific and Industrial Research Organization/Queensland Climate Change Centre of Excellence	Australia	8.5	csiro-mk3-6-0.1.rcp85
Institute of Atmospheric Physics, Chinese Academy of Sciences	China	4.5	fgoals-g2.1.rcp45
Institute of Atmospheric Physics, Chinese Academy of Sciences	China	8.5	fgoals-g2.1.rcp85
US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA	4.5	gfdl-cm3.1.rcp45
US Department of Commerce/NOAA/Geophysical Fluid Dynamics Laboratory	USA	8.5	gfdl-cm3.1.rcp85
NASA / Goddard Institute for Space Studies	USA	4.5	giss-e2-r.1.rcp45
NASA / Goddard Institute for Space Studies	USA	8.5	giss-e2-r.1.rcp85
National Institute of Meteorological Research, Korea Meteorological Administration	South Korea	4.5	hadgem2-ao.1.rcp45
National Institute of Meteorological Research, Korea Meteorological Administration	South Korea	8.5	hadgem2-ao.1.rcp85
Met Office Hadley Centre	UK	4.5	hadgem2-cc.1.rcp45
Met Office Hadley Centre	UK	8.5	hadgem2-cc.1.rcp85
Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	Japan	4.5	miroc-esm.1.rcp45

Table A.2. Continued

Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute	Japan	8.5	miroc-esm.1.rcp85
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan	4.5	miroc5.1.rcp45
Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology	Japan	8.5	miroc5.1.rcp85
Max Planck Institute for Meteorology	Germany	4.5	mpi-esm-lr.1.rcp45
Max Planck Institute for Meteorology	Germany	8.5	mpi-esm-lr.1.rcp85
Meteorological Research Institute	Japan	4.5	mri-cgcm3.1.rcp45
Meteorological Research Institute	Japan	8.5	mri-cgcm3.1.rcp85
Bjerknes Centre for Climate Research, Norwegian Meteorological Institute	Norway		noresm1-m.1.rcp45
Bjerknes Centre for Climate Research, Norwegian Meteorological Institute	Norway		noresm1-m.1.rcp85

Table A.3. Monthly of Runoff (in mm) from Coupled Model Intercomparison Project phases 3 and 5 (CMIP3 and CMIP5) Hydrology Dataset Ensemble Means and Observed Data

	Observed Inflow	CMIP3 mean inflow	CMIP5 mean inflow
Oct-79	0.7	24.8	30.7
Nov-79	6.2	28.7	30.9
Dec-79	2.2	18.8	17.4
Jan-80	3.2	13.0	10.5
Feb-80	11.7	15.0	12.0
Mar-80	55.7	16.1	15.3
Apr-80	24.2	14.8	17.3
May-80	5.6	12.5	14.3
Jun-80	1.1	19.5	26.9
Jul-80	0.7	8.9	11.3
Aug-80	0.6	9.2	11.7
Sep-80	0.2	14.8	15.2
Oct-80	0.3	16.1	16.8
Nov-80	0.1	29.5	22.3
Dec-80	0.4	19.7	16.0
Jan-81	0.0	13.2	13.9
Feb-81	0.0	14.1	15.0
Mar-81	0.1	22.9	22.6
Apr-81	0.2	17.3	17.1
May-81	9.3	16.4	19.0
Jun-81	16.1	18.2	15.7
Jul-81	3.8	12.2	5.5
Aug-81	2.0	6.7	7.3
Sep-81	0.2	12.4	13.9
Oct-81	1.5	15.7	14.7
Nov-81	13.6	29.0	27.7
Dec-81	5.5	22.9	19.3
Jan-82	8.7	12.3	10.5
Feb-82	18.1	12.7	10.8
Mar-82	23.7	19.2	17.5
Apr-82	5.3	22.2	15.4
May-82	106.8	20.5	19.5
Jun-82	71.3	22.9	19.5
Jul-82	5.3	21.9	22.2
Aug-82	6.6	8.5	8.6
Sep-82	0.6	13.7	15.9
Oct-82	3.0	12.8	13.3

Table A.3. Continued

Nov-82	1.8	19.7	22.9
Dec-82	11.6	17.9	18.9
Jan-83	4.6	13.0	13.3
Feb-83	25.5	11.1	10.7
Mar-83	27.5	21.2	24.0
Apr-83	92.0	16.6	18.6
May-83	14.3	13.9	16.3
Jun-83	25.9	21.6	23.9
Jul-83	13.3	13.0	18.4
Aug-83	0.4	10.9	14.6
Sep-83	0.2	14.2	19.5
Oct-83	1.2	14.0	16.2
Nov-83	2.2	20.3	27.6
Dec-83	3.3	18.5	21.5
Jan-84	3.3	14.3	15.6
Feb-84	6.8	12.4	13.7
Mar-84	75.1	15.2	19.0
Apr-84	85.9	17.1	14.6
May-84	35.2	20.3	17.5
Jun-84	55.7	17.7	17.0
Jul-84	1.3	6.8	7.3
Aug-84	0.6	5.6	6.0
Sep-84	0.1	8.2	8.2
Oct-84	2.9	8.6	7.5
Nov-84	0.8	17.8	13.9
Dec-84	18.3	15.5	12.6
Jan-85	18.2	11.7	9.2
Feb-85	63.2	10.1	8.5
Mar-85	21.5	21.8	20.7
Apr-85	19.7	16.8	14.1
May-85	34.7	21.6	21.9
Jun-85	38.8	18.6	17.4
Jul-85	3.2	15.6	18.1
Aug-85	18.3	9.4	10.4
Sep-85	9.5	12.9	15.6
Oct-85	72.7	18.6	21.5
Nov-85	68.2	27.7	30.6
Dec-85	18.7	19.1	16.7
Jan-86	6.8	13.9	13.4
Feb-86	9.6	16.1	14.6

Table A.3. Continued

Mar-86	4.9	15.3	13.4
Apr-86	28.8	10.7	9.8
May-86	41.5	12.5	7.8
Jun-86	7.4	23.3	17.2
Jul-86	4.2	19.7	13.6
Aug-86	2.4	7.6	7.0
Sep-86	24.9	12.2	11.6
Oct-86	133.7	18.2	16.6
Nov-86	7.9	29.0	26.4
Dec-86	28.7	19.8	20.3
Jan-87	16.6	14.7	14.1
Feb-87	61.2	13.4	14.1
Mar-87	60.8	20.4	24.0
Apr-87	16.8	20.5	24.0
May-87	56.4	17.6	12.8
Jun-87	8.6	24.8	17.3
Jul-87	5.0	10.7	9.6
Aug-87	6.4	6.3	8.3
Sep-87	1.9	9.6	11.1
Oct-87	1.2	14.2	12.2
Nov-87	9.8	18.4	21.6
Dec-87	40.3	17.4	20.0
Jan-88	20.5	10.6	13.1
Feb-88	6.9	12.8	16.7
Mar-88	41.9	20.5	23.7
Apr-88	104.4	21.1	17.9
May-88	9.0	26.3	29.8
Jun-88	1.4	27.9	28.4
Jul-88	2.2	17.3	14.2
Aug-88	0.5	12.9	11.7
Sep-88	0.1	12.9	10.6
Oct-88	0.1	21.3	15.2
Nov-88	0.2	28.0	31.7
Dec-88	0.3	24.7	27.4
Jan-89	0.2	18.9	22.0
Feb-89	0.2	16.6	16.3
Mar-89	1.9	32.9	36.7
Apr-89	0.6	21.4	19.9
May-89	14.2	16.3	17.2
Jun-89	18.3	14.8	14.4

Table A.3. Continued

Jul-89	6.0	13.5	11.0
Aug-89	29.7	8.7	9.5
Sep-89	42.6	6.2	4.2
Oct-89	5.9	9.4	6.7
Nov-89	2.8	14.8	9.9
Dec-89	1.5	13.3	9.6
Jan-90	11.3	8.5	6.3
Feb-90	20.6	11.9	8.1
Mar-90	78.4	18.3	17.4
Apr-90	16.4	26.2	30.7
May-90	24.6	19.8	25.7
Jun-90	16.1	20.6	24.8
Jul-90	0.8	7.7	6.1
Aug-90	3.2	5.2	4.3
Sep-90	0.1	8.9	10.6
Oct-90	0.0	13.4	13.4
Nov-90	0.5	25.8	30.0
Dec-90	0.1	22.3	26.5
Jan-91	0.5	14.0	13.5
Feb-91	0.2	14.8	9.8
Mar-91	0.5	21.6	24.1
Apr-91	1.7	18.6	20.2
May-91	11.9	24.7	23.4
Jun-91	4.1	12.4	8.9
Jul-91	1.2	13.6	14.3
Aug-91	0.3	5.3	6.0
Sep-91	0.2	12.7	13.0
Oct-91	0.3	11.9	12.7
Nov-91	1.3	19.8	23.2
Dec-91	8.6	14.3	14.1
Jan-92	4.1	14.3	16.8
Feb-92	6.3	14.8	16.1
Mar-92	15.0	22.5	23.6
Apr-92	10.5	18.4	14.9
May-92	2.8	14.6	10.8
Jun-92	46.2	22.7	24.7
Jul-92	29.6	10.8	14.3
Aug-92	28.5	9.2	12.2
Sep-92	7.5	17.3	24.8
Oct-92	4.3	13.6	17.3

Table A.3. Continued

Nov-92	92.2	22.9	25.7
Dec-92	67.1	22.5	21.5
Jan-93	35.2	13.4	12.5
Feb-93	26.1	16.3	12.8
Mar-93	30.9	24.4	18.8
Apr-93	21.0	17.7	12.2
May-93	150.3	14.8	13.4
Jun-93	19.9	15.4	18.5
Jul-93	24.3	23.6	28.0
Aug-93	2.6	8.9	10.2
Sep-93	9.6	16.0	16.0
Oct-93	6.2	16.3	15.8
Nov-93	8.2	27.3	29.7
Dec-93	4.1	21.0	18.8
Jan-94	2.5	14.8	13.7
Feb-94	1.9	15.0	11.6
Mar-94	2.8	18.7	14.2
Apr-94	136.6	16.5	12.2
May-94	27.5	14.9	10.4
Jun-94	2.5	15.8	11.6
Jul-94	2.5	5.9	4.3
Aug-94	1.0	5.8	4.5
Sep-94	0.1	10.7	13.7
Oct-94	0.4	12.6	11.1
Nov-94	7.5	27.8	27.3
Dec-94	3.0	17.3	16.3
Jan-95	1.8	11.6	11.9
Feb-95	1.1	14.5	16.0
Mar-95	43.1	21.4	20.3
Apr-95	16.6	19.6	10.3
May-95	121.1	11.2	9.3
Jun-95	145.5	9.7	10.4
Jul-95	12.3	7.6	8.2
Aug-95	27.0	7.3	6.0
Sep-95	0.9	6.6	6.0
Oct-95	0.3	7.8	10.6
Nov-95	0.3	12.3	11.3
Dec-95	0.8	10.5	10.8
Jan-96	0.6	9.4	9.0
Feb-96	0.6	10.0	8.7

Table A.3. Continued

Mar-96	0.4	13.3	12.3
Apr-96	1.0	14.0	15.4
May-96	3.0	13.6	14.3
Jun-96	2.7	16.7	21.8
Jul-96	1.7	5.2	3.2
Aug-96	1.5	6.2	3.8
Sep-96	7.4	8.1	5.8
Oct-96	4.4	12.7	13.9
Nov-96	35.3	25.0	27.2
Dec-96	14.9	17.4	19.3
Jan-97	3.8	13.2	13.5
Feb-97	45.0	19.1	20.9
Mar-97	21.8	32.1	39.3
Apr-97	47.8	26.4	28.6
May-97	14.7	24.7	28.8
Jun-97	29.8	13.9	17.2
Jul-97	10.6	13.3	9.3
Aug-97	0.9	9.6	6.6
Sep-97	0.5	13.0	6.8
Oct-97	2.4	16.3	5.5
Nov-97	1.7	26.8	11.9
Dec-97	34.9	21.3	16.7
Jan-98	16.4	15.0	11.0
Feb-98	6.7	15.6	12.7
Mar-98	62.3	17.6	20.5
Apr-98	31.2	19.6	23.9
May-98	16.0	25.2	16.8
Jun-98	1.7	20.9	12.0
Jul-98	4.6	10.3	6.6
Aug-98	1.2	6.2	4.8
Sep-98	8.1	14.6	11.2
Oct-98	55.2	15.2	13.5
Nov-98	191.1	22.9	20.8
Dec-98	45.5	19.3	16.4
Jan-99	12.3	11.9	11.7
Feb-99	22.3	14.5	13.8
Mar-99	23.5	25.3	17.7
Apr-99	67.1	19.9	19.4
May-99	30.1	21.4	22.4
Jun-99	83.4	31.0	27.3

Table A.3. Continued

Jul-99	13.5	20.0	18.2
Aug-99	4.9	11.2	7.0
Sep-99	18.9	10.5	9.8
Oct-99	4.9	16.5	16.3
Nov-99	5.1	14.8	14.1
Dec-99	41.4	13.2	11.8
Jan-00	4.6	11.9	9.7
Feb-00	31.5	12.9	11.7
Mar-00	55.8	22.9	26.2
Apr-00	10.5	16.5	20.1
May-00	3.4	13.1	14.6
Jun-00	67.2	8.5	6.4
Jul-00	7.6	8.1	7.6
Aug-00	0.6	7.1	3.3
Sep-00	0.0	13.3	13.8
Oct-00	1.1	10.4	8.8
Nov-00	5.3	12.0	9.4
Dec-00	0.7	15.9	16.5
Jan-01	5.9	13.9	16.4
Feb-01	50.6	13.9	13.5
Mar-01	29.5	18.2	18.1
Apr-01	1.2	19.9	25.5
May-01	3.1	22.5	27.8
Jun-01	66.1	20.6	20.9
Jul-01	7.0	9.9	4.7
Aug-01	1.2	9.0	8.2
Sep-01	26.7	9.8	11.1
Oct-01	1.3	11.9	15.9
Nov-01	0.5	22.0	24.1
Dec-01	0.5	18.4	18.5
Jan-02	0.8	13.2	13.7
Feb-02	1.1	12.3	12.2
Mar-02	1.2	21.9	24.7
Apr-02	7.9	24.4	26.8
May-02	92.4	18.9	20.2
Jun-02	12.3	14.1	15.3
Jul-02	2.8	12.1	12.6
Aug-02	0.5	10.3	11.9
Sep-02	0.1	21.5	21.4
Oct-02	4.4	18.8	14.2

Table A.3. Continued

Nov-02	2.0	21.9	13.4
Dec-02	1.5	12.4	9.8
Jan-03	0.3	10.6	8.5
Feb-03	6.4	13.4	11.8
Mar-03	63.4	26.3	31.0
Apr-03	41.2	17.5	20.2
May-03	21.5	12.6	13.1
Jun-03	11.7	10.0	10.0
Jul-03	0.7	9.8	11.1
Aug-03	4.4	7.6	7.8
Sep-03	9.2	13.1	10.2
Oct-03	22.4	12.2	9.1
Nov-03	1.8	18.3	18.6
Dec-03	3.1	17.8	18.8
Jan-04	15.8	12.9	10.8
Feb-04	15.2	13.2	12.5
Mar-04	87.9	21.4	24.1
Apr-04	36.4	14.8	17.2
May-04	45.8	12.4	13.2
Jun-04	25.1	15.2	13.4
Jul-04	64.6	10.2	10.8
Aug-04	2.6	6.9	5.9
Sep-04	0.4	11.5	9.3
Oct-04	2.6	10.4	10.3
Nov-04	28.3	21.0	24.3
Dec-04	14.3	17.9	19.3
Jan-05	43.1	14.3	15.1
Feb-05	24.2	15.0	16.7
Mar-05	38.9	27.2	31.6
Apr-05	10.4	25.1	28.3
May-05	27.5	16.2	9.6
Jun-05	190.5	23.3	20.5
Jul-05	9.1	13.0	14.1
Aug-05	143.5	7.6	4.2
Sep-05	12.8	10.0	9.8
Oct-05	1.8	12.5	12.4
Nov-05	1.0	21.4	23.2
Dec-05	0.9	20.6	19.2
Jan-06	0.9	18.1	17.3
Feb-06	0.3	14.4	15.1

Table A.3. Continued

Mar-06	0.9	18.6	18.9
Apr-06	18.2	15.9	18.6
May-06	29.2	14.8	14.1
Jun-06	1.5	22.4	21.7
Jul-06	0.6	9.9	10.3
Aug-06	0.6	6.8	5.4
Sep-06	0.1	16.6	13.9
Oct-06	0.2	14.2	10.0
Nov-06	0.4	20.6	19.8
Dec-06	0.5	15.7	16.6
Jan-07	0.6	13.6	12.7
Feb-07	2.9	13.2	11.6
Mar-07	12.7	19.9	16.9
Apr-07	41.4	17.8	14.1
May-07	59.5	18.7	16.3
Jun-07	181.7	19.9	19.6
Jul-07	67.6	10.8	10.6
Aug-07	7.8	6.7	6.8
Sep-07	1.2	22.0	17.2
Oct-07	2.8	14.1	12.8
Nov-07	1.0	17.8	19.4
Dec-07	6.9	13.3	12.5
Jan-08	8.2	11.1	10.7
Feb-08	42.8	16.7	14.3
Mar-08	47.6	19.4	18.1
Apr-08	47.0	18.8	20.6
May-08	121.5	16.9	15.7
Jun-08	141.2	20.8	18.5
Jul-08	18.3	10.2	9.7
Aug-08	61.6	6.1	4.7
Sep-08	80.3	10.2	4.4
Oct-08	16.1	12.1	6.2
Nov-08	9.7	19.7	13.5
Dec-08	11.4	16.4	11.1
Jan-09	6.0	14.4	11.5
Feb-09	7.3	16.8	13.3
Mar-09	37.1	20.9	23.5
Apr-09	88.1	15.2	18.3
May-09	84.5	13.9	13.5
Jun-09	12.0	18.1	13.5

Table A.3. Continued

Jul-09	15.2	12.1	10.8
Aug-09	4.3	6.7	7.0
Sep-09	72.8	8.6	11.1
Oct-09	43.3	9.0	9.9
Nov-09	54.1	18.1	22.4
Dec-09	7.8	16.8	18.8
Jan-10	14.6	12.7	13.5
Feb-10	25.9	16.3	14.2
Mar-10	41.1	19.0	20.3
Apr-10	14.4	18.3	16.4
May-10	47.8	16.9	16.3
Jun-10	50.2	21.3	29.1
Jul-10	49.1	14.3	18.9
Aug-10	3.2	8.7	9.0
Sep-10	12.3	15.8	13.0
Oct-10	1.4	20.0	20.5
Nov-10	0.8	27.1	19.4
Dec-10	0.8	21.9	21.0
Jan-11	0.8	16.8	17.3
Feb-11	4.9	14.1	15.3
Mar-11	14.7	20.8	20.5
Apr-11	5.4	22.0	23.7
May-11	4.5	14.6	17.8
Jun-11	1.6	16.9	16.3
Jul-11	0.1	12.0	9.1
Aug-11	0.0	8.5	7.4
Sep-11	0.0	17.6	14.8
Oct-11	0.0	14.0	11.1
Nov-11	0.7	22.8	25.1
Dec-11	11.4	18.0	18.0
Jan-12	2.0	14.3	14.3
Feb-12	7.3	14.2	12.2
Mar-12	32.6	18.4	16.6
Apr-12	10.8	17.1	18.5
May-12	4.4	11.5	13.4
Jun-12	1.8	14.3	13.1
Jul-12	0.0	11.5	8.5
Aug-12	0.0	7.3	6.5
Sep-12	0.0	15.5	13.5
Oct-12	0.5	21.4	21.4

Table A.3. Continued

Nov-12	0.3	25.4	21.9
Dec-12	0.1	19.9	22.3
Jan-13	0.4	14.2	16.0
Feb-13	0.6	15.0	13.0
Mar-13	0.6	19.0	21.7
Apr-13	10.7	16.8	21.3
May-13	14.7	17.9	18.4
Jun-13	5.2	15.3	10.4
Jul-13	7.9	11.2	12.5
Aug-13	55.5	5.8	6.1
Sep-13	1.1	12.0	10.9
Oct-13	5.8	10.3	8.6
Nov-13	18.0	17.2	14.5
Dec-13	2.7	16.1	13.9
Jan-14	2.0	15.2	10.5
Feb-14	2.0	14.9	12.4
Mar-14	3.5	21.8	24.8
Apr-14	8.5	20.0	19.0
May-14	23.8	21.0	17.6
Jun-14	41.2	22.4	15.1
Jul-14	3.2	18.3	11.7
Aug-14	0.1	7.0	6.0
Sep-14	0.9	12.9	16.4
Oct-14	1.2	10.8	11.1
Nov-14	0.3	25.5	28.3
Dec-14	2.1	15.5	14.3
Jan-15	1.7	10.0	9.5
Feb-15	1.8	15.1	14.2
Mar-15	1.5	22.3	20.6
Apr-15	21.2	18.5	17.9
May-15	133.3	15.9	11.3
Jun-15	19.4	14.5	13.0
Jul-15	10.7	5.7	6.7
Aug-15	0.6	8.5	8.5
Sep-15	0.2	19.1	20.8

Table A.4. Monthly Exceedance Probabilities and Standard Deviation for Monthly Runoff from CMIP3 Hydrology Dataset (October 1979-September 2015) in mm

	P95	P90	P75	p50	P25	P10	P05	sd
January	9.4	10.6	11.9	13.4	14.3	15.0	16.8	2.1
February	10.1	11.9	12.9	14.5	15.1	16.3	16.7	1.9
March	15.2	16.1	18.6	20.9	22.5	25.3	27.2	4.1
April	14.0	14.8	16.6	18.4	20.5	24.4	25.1	3.5
May	11.5	12.5	13.9	16.4	20.5	22.5	24.7	4.2
June	9.7	12.4	14.8	18.6	22.4	23.3	27.9	5.1
July	5.7	6.8	9.8	11.5	13.6	19.7	20.0	4.6
August	5.3	5.8	6.3	7.6	8.9	9.6	10.9	1.8
September	6.6	8.2	9.8	12.9	14.8	17.3	19.1	3.8
October	8.6	9.4	11.9	13.6	16.3	18.8	21.3	3.9
November	12.3	14.9	18.1	21.9	26.8	28.0	29.0	4.9
December	12.5	13.3	15.7	17.9	19.8	21.9	22.5	3.2

Table A.5. Monthly Exceedance Probabilities and Standard Deviation for Monthly Runoff from CMIP5 Hydrology Dataset (October 1979-September 2015) in mm

	P95	**P90**	**P75**	**p50**	**P25**	**P10**	**P05**	**sd**
January	8.5	9.2	10.5	13.3	14.1	16.4	17.3	3.0
February	8.5	9.8	11.7	13.3	15.0	16.1	16.7	2.6
March	13.4	15.3	17.7	20.6	24.1	26.2	31.6	5.8
April	10.3	12.2	15.4	18.6	21.3	25.5	28.3	5.1
May	9.3	10.4	13.2	16.3	19.5	23.4	27.8	5.4
June	9.0	10.4	13.1	17.2	21.7	26.9	28.4	6.1
July	4.3	5.5	7.6	10.8	14.2	18.4	22.2	5.7
August	3.8	4.3	5.9	7.0	8.6	11.7	11.9	2.6
September	4.4	5.8	9.8	11.6	15.2	17.2	20.8	4.7
October	6.2	7.5	10.0	13.3	15.9	17.3	21.4	4.9
November	9.9	11.9	14.5	22.4	27.2	29.8	30.6	6.5
December	9.8	11.1	14.1	18.0	19.3	21.5	22.3	4.1

Table A.6. Monthly Exceedance Probabilities and Standard Deviation for Monthly Runoff from Observed Reservoir Inflow (October 1979-September 2015) in mm

	P95	**P90**	**P75**	**p50**	**P25**	**P10**	**P05**	**sd**
January	0.2	0.4	0.8	3.8	11.3	16.7	20.5	9.8
February	0.2	0.3	1.8	6.9	24.2	42.8	50.6	17.9
March	0.4	0.6	2.8	23.7	43.1	62.3	75.1	25.6
April	0.6	1.2	8.5	16.8	41.2	85.9	92.0	33.4
May	3.0	3.4	9.4	24.6	47.8	106.9	121.5	41.6
June	1.4	1.6	4.1	18.3	55.7	83.4	145.5	51.3
July	0.1	0.7	1.7	5.1	12.3	24.3	49.1	16.6
August	0.1	0.3	0.6	2.0	6.4	28.5	55.5	27.0
September	0.0	0.1	0.1	0.9	9.5	24.9	42.6	19.0
October	0.0	0.2	0.6	1.8	4.9	22.4	55.2	26.5
November	0.2	0.3	0.7	2.0	9.7	35.3	68.2	36.4
December	0.1	0.5	0.8	3.3	14.3	34.9	41.4	16.0

Table A.7. Minitab 17 Descriptive Statistics of Year-Round Monthly Statistics for CMIP3 and CMIP5 Climate Projections and Observations (October 1979 – September 2015)

Descriptive Statistics: OBS, CMIP3_MEAN, CMIP5_MEAN

```
            Total
Variable    Count    N  N*  CumN  Percent  CumPct    Mean  SE Mean  TrMean  StDev
Variance
OBS           432  432   0   432      100     100   19.68     1.49   14.93  31.01
961.71
CMIP3_MEAN    432  432   0   432      100     100  17.282    0.353  16.875  7.333
53.773
CMIP5_MEAN    432  432   0   432      100     100  15.009    0.295  14.769  6.126
37.533


Variable    CoefVar       Sum  Sum of Squares  Minimum      Q1  Median      Q3  Maximum
OBS          157.60   8500.72       581772.66     0.00    1.21    6.64   24.55   191.13
CMIP3_MEAN    42.43  7465.973      152205.483    3.233  12.248  16.702  21.459   52.933
CMIP5_MEAN    40.82  6483.953      113495.206    3.170  10.631  14.075  18.735   39.258

                                                        N for
Variable     Range    IQR                        Mode   Mode  Skewness  Kurtosis    MSSD
OBS         191.13  23.34      0, 0.589000, 0.921000      3      2.71      8.68  673.29
CMIP3_MEAN  49.700  9.211  12.7625, 13.5250, 17.4370      2      0.89      1.66  30.502
CMIP5_MEAN  36.088  8.104                           *      0      0.61      0.32  22.134
```

Table A.8. Minitab 17 Comparison of CMIP3 and CMIP5 Climate Projections (October 1979-September 2015)

Two-Sample Equivalence Test: CMIP5_MEAN, CMIP3_MEAN

```
Method

Test mean = mean of CMIP5_MEAN
Reference mean = mean of CMIP3_MEAN
Equal variances were not assumed for the analysis.


Descriptive Statistics

Variable      N    Mean   StDev  SE Mean
CMIP5_MEAN  432  15.009  6.1264  0.29476
CMIP3_MEAN  432  17.282  7.3330  0.35281


Difference: Mean(CMIP5_MEAN) - Mean(CMIP3_MEAN)

Difference       SE  95% Upper Bound  Upper Limit
   -2.2732  0.45973          -1.5162            0

Upper bound is less than 0. Can claim Mean(CMIP5_MEAN) < Mean(CMIP3_MEAN).


Test

Null hypothesis:         Mean(CMIP5_MEAN) - Mean(CMIP3_MEAN) ≥ 0
Alternative hypothesis:  Mean(CMIP5_MEAN) - Mean(CMIP3_MEAN) < 0
α level:                 0.05

 DF  T-Value  P-Value
835  -4.9446    0.000

P-Value ≤ 0.05. Can claim Mean(CMIP5_MEAN) < Mean(CMIP3_MEAN).
```

Test: Mean(CMIP5_MEAN) < Mean(CMIP3_MEAN)

Table A.9. Bias-corrected Monthly Inflows for the CMIP3 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Median

	Calibration Period (October 1979 – September 2007)		Validation Period (October 2007 – September 2015)		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	4.1	0.9	4.3	1.2	-1.8
February	7.0	1.6	8.3	1.4	-7.6
March	25.1	6.9	23.0	4.4	3.6
April	19.2	6.6	16.7	4.7	4.3
May	26.7	9.8	24.9	9.3	1.7
June	19.5	9.0	20.7	6.9	-1.4
July	5.5	2.7	5.5	3.2	0.1
August	2.2	0.9	2.1	0.4	1.7
September	0.7	0.3	0.8	0.3	-2.8
October	2.1	0.9	2.1	0.7	-0.5
November	2.4	0.9	2.5	0.9	-0.7
December	3.5	0.8	3.3	0.7	1.5

Table A.10. Bias-corrected Monthly Inflows for the CMIP3 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Using Multiple Exceedance Values

	Calibration Period (October 1979 – September 2007)		Validation Period (October 2007 – September 2015)		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.3	1.8	8.8	2.4	-1.8
February	15.2	3.6	18.0	3.0	-7.6
March	25.5	7.1	23.4	4.5	3.6
April	27.1	9.2	23.4	6.7	4.3
May	33.6	12.3	31.3	11.7	1.7
June	32.6	15.1	34.6	11.5	-1.4
July	10.0	5.0	10.0	5.8	0.1
August	6.3	2.6	6.0	1.3	1.7
September	5.0	2.3	5.8	2.4	-2.8
October	8.7	3.6	8.8	2.9	-0.5
November	12.7	4.8	13.0	4.8	-0.7
December	12.0	2.9	11.6	2.3	1.5

Table A.11. Bias-corrected Monthly Inflows for the CMIP3 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Mean

	Calibration Period (October 1979 – September 2007)		Validation Period (October 2007 – September 2015)		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.7	1.8	9.2	2.5	-1.8
February	16.6	3.9	19.7	3.3	-7.6
March	31.5	8.7	28.9	5.6	3.6
April	32.0	10.9	27.7	7.9	4.3
May	36.1	13.3	33.6	12.6	1.7
June	41.2	19.0	43.8	14.6	-1.4
July	10.9	5.5	10.9	6.3	0.1
August	10.7	4.5	10.1	2.2	1.7
September	6.6	3.1	7.6	3.2	-2.8
October	12.0	5.0	12.2	4.1	-0.5
November	17.7	6.7	18.2	6.7	-0.7
December	13.3	3.2	12.8	2.6	1.5

Table A.12. Bias-corrected Monthly Inflows for the CMIP5 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Median

	Calibration Period (October 1979 – September 2007)		Validation Period (October 2007 – September 2015)		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	4.1	1.0	4.2	0.9	-0.2
February	7.2	1.6	7.6	0.6	-3.5
March	25.9	7.8	25.0	3.3	1.7
April	19.1	5.8	19.9	2.6	-2.0
May	26.6	9.7	24.1	4.1	3.8
June	18.8	6.1	16.8	5.4	3.1
July	4.9	2.4	4.7	1.6	0.9
August	2.2	0.8	2.0	0.4	3.8
September	0.7	0.3	0.7	0.3	-1.7
October	1.8	0.7	1.7	0.8	1.2
November	2.2	0.7	2.0	0.5	2.4
December	3.3	0.8	3.1	0.7	2.0

Table A.13. Bias-corrected Monthly Inflows for the CMIP5 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Using Multiple Exceedance Values

	Calibration Period (Oct 1979 – September 2007)		Validation Period (October 2007 – September 2015)		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.0	2.0	8.1	1.7	-0.2
February	16.4	3.6	17.3	1.4	-3.5
March	24.7	7.4	23.8	3.1	1.7
April	27.7	8.4	28.9	3.7	-2.0
May	31.0	11.3	28.1	4.7	3.8
June	36.5	11.8	32.7	10.5	3.1
July	10.2	5.0	9.8	3.3	0.9
August	6.7	2.5	6.0	1.1	3.8
September	5.5	2.0	5.9	2.2	-1.7
October	9.9	3.6	9.4	4.2	1.2
November	14.6	4.6	13.6	3.2	2.4
December	12.2	2.9	11.6	2.6	2.0

Table A.14. Bias-corrected Monthly Inflows for the CMIP5 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Using Multiple Exceedance Values (October 1979 – September 2015)

	Calibration Period (October1979 – September 2007)		Validation Period (October 2007 – September 2015)		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.7	2.1	8.7	1.8	-0.2
February	16.6	3.7	17.5	1.4	-3.5
March	31.5	9.5	30.4	4.0	1.7
April	32.0	9.7	33.3	4.3	-2.0
May	36.1	13.1	32.7	5.5	3.8
June	41.2	13.3	36.9	11.9	3.1
July	10.9	5.4	10.5	3.5	0.9
August	10.7	4.0	9.6	1.8	3.8
September	6.6	2.4	7.1	2.6	-1.7
October	12.0	4.3	11.3	5.0	1.2
November	17.7	5.6	16.5	3.9	2.4
December	13.3	3.1	12.6	2.9	2.0

Table A.15. CMIP3 Bias-corrected Projections that were Significantly Statistically Different that Unbias-corrected Projections Using the Kolmogorov-Smirnov Two-Sample Test

Projection	Month	Confidence Interval
CSIRO_A1B	October	99%
	November	99%
CSIRO_A2	August	95%
	October	99%
	November	90%
	December	95%
GFDL_A1B	August	90%
	September	90%
	October	99%
	November	95%
GFDL_A2	October	95%
	November	99%
GISS_A1B	October	80%
	November	99%
	December	85%
GISS_A2	January	95%
	August	95%
	September	90%
	October	95%
IPSL_A1B	January	95%
	February	85%
	August	99%
	October	99%
	November	99%
IPSL_A2	August	99%
	October	99%
	November	99%
	December	85%
MIROC3-2-MEDRES.1_A1B	August	95%
	September	80%
	October	90%
	November	95%
MIROC3-2-MEDRES.1_A2	October	85%
	November	90%
	December	85%

Table A.15. Continued

MIUB_ECHO_1_G.1_A1B	January	80%
	August	99%
	September	99%
	October	99%
	November	99%
	December	85%
MIUB_ECHO_1_G.1_A2	August	99%
	October	95%
	November	99%
	December	80%
MPI_ECHAM5.1_A1B	January	85%
	August	95%
	October	80%
	November	99%
MPI_ECHAM5.1_A2	January	80%
	August	90%
	October	95%
	November	99%
MRI_CGCM2_3_2_A.1_A1B	January	80%
	August	90%
	October	95%
	November	99%
MRI_CGCM2_3_2_A.1_A2	January	80%
	August	90%
	October	95%
	November	99%
NCAR_CCSM3_0.1_A1B	August	99%
	October	99%
	November	95%
NCAR_CCSM3_0.1_A2	October	90%
	November	95%
UKMO_HADCM3.A_A1B	August	99%
	October	90%
	November	80%
UKMO_HADCM3.A_A2	August	95%
	September	85%
	October	99%
	November	95%

Table A.16. CMIP5 Bias-corrected Projections that were Significantly Statistically Different that Unbias-corrected Projections Using the Kolmogorov-Smirnov Two-Sample Test (October 1979 – September 2015)

Projection	Month	Confidence Interval
ACCESS1-0.1-4.5	August October November	90% 99% 99%
ACCESS1-0.1-8.5	October November	99% 90%
CANESM2.1-4.5	August October November December	90% 99% 95% 80%
CANESM2.1-8.5	September November	80% 99%
CCSM4.1-4.5	August October November	85% 95% 95%
CCSM4.1-8.5	August September October	90% 99% 90%
CMCC_CM.1-4.5	August October November	85% 95% 95%
CMCC_CM.1-8.5	November	90%
CNRM_CM5.1-4.5	September October November	90% 90% 80%
CNRM_CM5.1-8.5	October	95%
CSIRO_MK3-6.0.1-4.5	August October November	90% 95% 95%
CSIRO_MK3-6.0.1-8.5	October November	90% 99%
FGOAL2-G2.1-4.5	August October	99% 85%
FGOAL2-G2.1-8.5	August October November	99% 85% 85%
GFDL_CM3.1-4.5	August November	80% 99%
GFDL_CM3.1-8.5	October November December	90% 85% 80%

Table A.16. Continued

GISS_ER-R.1-4.5	August	85%
	October	99%
	November	99%
GISS_ER-R.1-8.5	October	99%
	November	85%
HADGME_AO.1-4.5	August	85%
	October	99%
	November	99%
HADGME_AO.1-8.5	October	99%
	November	85%
HADGME_CC.1-4.5	October	95%
	November	99%
HADGME_CC.1-8.5	August	95%
	October	95%
	November	99%
IPSL_CM5.1-MR-4.5	August	85%
	October	99%
	November	99%
IPSL_CM5.1-MR-8.5	January	90%
	October	99%
	November	85%
MIROC_ESM.1-4.5	August	95%
	September	95%
	October	95%
	November	99%
MIROC_ESM.1-8.5	August	99%
	September	95%
	October	95%
	November	99%
MIROC5.1-4.5	August	99%
	October	95%
	November	95%
MIROC5.1-8.5	August	90%
	October	99%
	November	90%
MPI-ESM-LR.1-4.5	August	99%
	October	99%
MPI-ESM-LR.1-8.5	August	99%
	October	99%
	November	95%

Table A.16. Continued

MPI-CGCM3.1-4.5	August October November December	99% 95% 95% 85%
MPI-CGCM3.1-8.5	August September October November	99% 85% 99% 95%
NORESM1-M1.-4.5	August October November	80% 99% 99%
NORESM1-M1.-8.5	August September October November	99% 90% 95% 99%

Table A.17. Bias-corrected Monthly Inflows for the CMIP3 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Median (October 1979 – September 2015)

	CMIP3 Mean with Bias Correction Using Factor Developed from Ensemble Median		Observations		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	4.1	9.9	7.7	9.8	7.6
February	7.3	1.7	15.5	17.9	9.5
March	24.6	6.5	29.5	25.6	3.8
April	18.7	6.3	30.6	33.4	7.3
May	26.3	9.6	40.2	41.6	6.8
June	19.7	8.5	40.7	51.9	8.4
July	5.5	2.8	11.4	16.6	7.3
August	2.2	0.8	11.8	27.0	7.4
September	0.7	0.3	9.8	19.0	9.9
October	2.1	0.8	11.3	26.5	7.21
November	2.4	0.9	16.1	36.4	7.82
December	3.4	0.8	11.5	16.0	10.5

Table A.18. Bias-corrected Monthly Inflows for the CMIP3 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Using Multiple Exceedance Values (October 1979 – September 2015)

	CMIP3 Mean with Bias Correction Using Factor Developed from Multiple Exceedances		Observations		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.4	1.9	7.7	9.8	-1.4
February	15.8	3.6	15.5	17.9	-0.4
March	25.0	6.6	29.5	25.6	3.5
April	26.3	8.8	30.6	33.4	2.6
May	33.1	12.1	40.2	41.6	3.4
June	33.0	14.2	40.7	51.9	3.0
July	10.0	5.1	11.4	16.6	1.6
August	6.3	2.4	11.8	27.0	4.3
September	5.2	2.3	9.8	19.0	5.0
October	8.7	3.4	11.3	26.5	2.0
November	12.7	4.7	16.1	36.4	1.9
December	11.9	2.7	11.5	16.0	-0.5

Table A.19. Bias-corrected Monthly Inflows for the CMIP3 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Mean

	CMIP3 Mean with Bias Correction Using Factor Developed from Ensemble Mean		Observations		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.8	2.0	7.7	9.8	-2.2
February	17.3	4.0	15.5	17.9	-2.1
March	30.9	8.1	29.5	25.6	-1.1
April	31.0	10.4	30.6	33.4	-0.3
May	35.6	12.9	40.2	41.6	2.1
June	41.7	18.0	40.7	51.9	-0.4
July	10.9	5.6	11.4	16.6	0.6
August	10.6	4.1	11.8	27.0	0.9
September	6.8	3.1	9.8	19.0	3.2
October	12.0	4.8	11.3	26.5	-0.5
November	17.8	6.6	16.1	36.4	-1.0
December	13.2	3.0	11.5	16.0	-2.1

Table A.20. Bias-corrected Monthly Inflows for the CMIP5 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Median (October 1979 – September 2015)

	CMIP5 Mean with Bias Correction Using Factor Developed from Ensemble Median		Observations		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	4.1	1.0	7.7	9.8	7.6
February	7.3	1.4	15.5	17.9	9.5
March	25.7	7.0	29.5	25.6	3.0
April	19.3	5.2	30.6	33.4	7.0
May	26.1	8.8	40.2	41.6	6.9
June	18.4	5.9	40.7	51.9	9.0
July	4.9	2.3	11.4	16.6	8.1
August	2.1	0.7	11.8	27.0	7.5
September	0.7	0.3	9.8	19.0	10.0
October	1.8	0.7	11.3	26.5	7.4
November	2.2	0.6	16.1	36.4	8.0
December	3.3	0.8	11.5	16.0	10.7

Table A.21. Bias-corrected Monthly Inflows for the CMIP5 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Using Multiple Exceedance Values (October 1979 – September 2015)

	CMIP5 Mean with Bias Correction Using Factor Developed from Multiple Exceedances		Observations		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.0	1.9	7.7	9.8	-0.6
February	16.6	3.3	15.5	17.9	-1.2
March	24.5	6.7	29.5	25.6	3.9
April	28.0	7.6	30.6	33.4	1.6
May	30.4	10.2	40.2	41.6	4.7
June	35.6	11.5	40.7	51.9	2.0
July	10.1	4.7	11.4	16.6	1.6
August	6.5	2.3	11.8	27.0	4.1
September	5.6	2.0	9.8	19.0	4.5
October	9.8	3.7	11.3	26.5	1.1
November	14.3	4.3	16.1	36.4	1.0
December	12.1	2.8	11.5	16.0	-0.7

Table A.22. Bias-corrected Monthly Inflows for the CMIP5 Reservoir Inflow Based on Bias-correction Factor Calculated from the Ensemble Mean Median (October 1979 – September 2015)

	CMIP5 Mean with Bias Correction Using Factor Developed from Ensemble Mean		Observations		
Month	Mean	Std Dev	Mean	Std Dev	Student's t
January	8.7	2.0	7.7	9.8	-2.0
February	16.8	3.3	15.5	17.9	-1.5
March	31.3	8.5	29.5	25.6	-1.4
April	32.3	8.8	30.6	33.4	-1.0
May	35.4	11.9	40.2	41.6	2.3
June	10.2	12.9	40.7	51.9	0.2
July	10.8	5.0	11.4	16.6	0.7
August	10.5	3.7	11.8	27.0	1.0
September	6.7	2.4	9.8	19.0	3.4
October	11.8	4.4	11.3	26.5	-0.4
November	17.5	5.2	16.1	36.4	-0.7
December	13.2	3.0	11.5	16.0	-2.1

VITA

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